THE DEVELOPMENT OF AN AMATEUR BOXING SIMULATION PROTOCOL

Thesis submitted in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy

By Edward Thomson

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Abstract

There is a dearth of research attempting to quantify the external (physical) and internal (physiological) demands of amateur boxing performance. Therefore, the purpose of this programme of research was to investigate the external demands of amateur boxing performance, and subsequently, develop a sport-specific simulation protocol that could replicate these demands and the accompanying physiological responses while appraising the reliability and validity of the attempt.

To achieve this it was necessary initially to identify key offensive and defensive performance indicators and assess the intra- and inter-observer reliability with which such actions could be quantified. Intra-observer reliability was deemed excellent with high agreement (>92%) for all actions identified. Inter-observer reliability was less impressive (>75%), though remained consistently high nevertheless. Subsequently, research utilising this template quantified the offensive and defensive external demands and effectiveness (i.e. frequency of actions deemed successful) according to the independent and interactive influences of contest outcome, weight class and ability using post-contest video analysis. Main effects, two- and three-way interactions were established when appraising the frequency of actions and their outcomes in relation to the independent variables. Whilst the ability of the boxers evidenced the most prominent impact, contest outcome and weight class remained important influences for most actions. Moreover, substantial (CV >30%) within-group variation was evidenced implicating the role of boxer 'styles' and strategies in modifying the demands. The offensive and defensive demands were then supplemented with Global Positioning System (GPS) analyses of the boxers' sport-specific time-displacement movements. Having established the GPS's reliability and validity for assessing the boxing

movements, it was observed that boxers typically moved a distance of 35.9 $m \cdot min^{-1}$ at an average speed of 0.6 $m \cdot s^{-1}$. Such data was amalgamated with the technical demands to produce a boxing-specific simulation protocol that was reflective of the *average* competitive demand and thus had the potential to be a boxing conditioning and fitness test (BOXFIT). Despite providing the most valid external demand to-date, owing to confounding influences and within-group dispersion, application of the typical external demand was shown to afford only an approximation of the actual demands in all boxers.

As such an issue is characteristic of simulation protocols, the BOXFIT was still employed to evaluate the physiological response and appraise the associated reliability and validity. The internal demand was characterised by a high aerobic cardiopulmonary response (peak heart rate > 189 $b \cdot min^{-1}$; peak $\dot{V}O_2 > 55$ $ml \cdot kg^{-1} \cdot min^{-1}$) coupled with a marked indication of anaerobic energy provision (blood lactate = 4.6 ± 1.3 $mmol \cdot l^{-1}$). The reliability of the physiological responses elicited by BOXFIT performance was generally sufficient to enable the detection of moderate effects (i.e. 0.6 x pooled SD) and practically relevant changes in physiological and physical performance owing to training and nutritional interventions. However, the BOXFIT-induced responses underestimated selected markers of internal load (e.g. Mean heart rate ≈ -4.5%), questioning its validity. Thus, application of the average external demand typically approximated, rather than replicated, the actual physiology of boxing. With modifications, the validity of the external demands and internal response could be improved. The BOXFIT might therefore be used as part of a boxer's conditioning, providing a sport-specific means of training and offers an ergonomic framework to assess the impact of systematic, intervention-based changes in boxing-specific exercise physiology.

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Dad, your passing was devastating and there have been few days since that you have not crossed my thoughts. But, I am happy knowing you will be beaming with happiness right now, raising a glass (or twenty) on my behalf. I love and miss you.

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P.s. Allan, you are my hero… Is that OK?

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Abbreviations

AB	Amateur boxer
ABA	Amateur Boxing Association
ABAE	Amateur Boxing Association of England
AIBA	Association Internationalé de Boxe Amateur
ANOVA	Analysis of variance
$b \cdot min^{-1}$	Beats per minute
B_{lac}	Blood lactate
BOXFIT	Boxing and conditioning fitness test based upon average data
BBoC	British Boxing Board of Control
CI	Confidence interval
$CO_{2excess}$	Excess Carbon Dioxide production
CR-10	Category ratio rating of perceived exertion
CV%	Coefficient of variation
EE	Energy expenditure
EE_{aer}	Aerobic energy expenditure
EPOC	Excess post-exercise Oxygen consumption
ES	Effect size
FDR	False discovery rate
FWER	Familywise error rate
g	Grams
G	Gravitational acceleration
GPS	Global positioning system
H^+	Hydrogen
HPA	Hypothalamic-pituitary-adrenal axis
HR_{max}	Maximal heart rate
HR_{mean}	Mean heart rate

HR_{peak}	Peak heart rate
HR-$\dot{V}O_2$	Heart rate-Oxygen uptake
Hz	Frequency per second
kg	Kilogram
$km \cdot hr^{-1}$	Kilometres per hour
ICC	Intraclass correlation coefficient
IQR	Inter-quartile range
$l \cdot min^{-1}$	Litres per minute
LoA	Limits of agreement
LWC%	Large worthwhile change
m	Metres
m^2	Metres squared
$m \cdot min^{-1}$	Metres per minute
$m \cdot s^{-1}$	Metres per second
$ml \cdot kg^{-1} \cdot min^{-1}$	Millilitres per kilogram body mass per minute
$mmol \cdot l^{-1}$	Millimoles per litre
MN	Speed dictated via metronome
MS	Maximal speed
MSFT	Multi-stage fitness test
MWC%	Moderate worthwhile change
N	Newton
NA	Notational analysis
η_p^2	Partial ETA squared
npRQ	Non-protein respiratory quotient
OBLA	Onset of blood lactate accumulation
PA	Performance analysis
Po	Proportion of total agreement

pH	Acidity or alkalinity of a solution
PPM	Pearson product moment
Punches·min^{-1}	Punches per minute
R^2	Coefficient of determination
RER	Respiratory exchange ratio
RPE	Rating of perceived exertion
SD	Standard deviation
SD_{diff}	Standard deviation of test-retest difference scores
SEE	Standard error of the estimate
SEM	Standard error of measurement
TE	Typical error
TMA	Time-motion analysis
$\dot{V}_E$	Volume of expired air
VLWC%	Very large worthwhile change
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake
$\dot{V}CO_2$	Volume of Carbon dioxide

Chapter 1

Introduction

1.1 Amateur boxing

The sport of amateur boxing is popular at a national and international level and since 2006 has experienced the fifth largest increase in participation rates of any sport in England (Smith & Draper, 2007; Sport England, 2013). Despite this, scientific appraisal of the sport has tended to consider only the risks of participation (Bianco et al., 2013) and there is a relative shortage of research describing the physiological requirements of competition and training and/or the characteristic technical and tactical components of performance. Such information could guide a boxer's preparatory conditioning and approach to competition, thereby enhancing his/her sports performance (Bishop, 2008). That the amateur boxing community recognise performance is reliant upon a multifaceted collection of quantifiable training- and performance-based traits (Hickey, 2006) suggests that sport science research could positively influence practice (Bishop, Burnett, Farrow, Gabbett, & Newton, 2006). Additionally, changes to the duration of contest and method of judging have enhanced the virtue of sport science research in amateur boxing since these have likely altered the requisites of successful performance.

Despite the limited research to-date, there is a consensus that amateur boxing performance is typified by repeated, high-intensity phases of exercise which include offensive (punches), defensive and ambulatory movements (Guidetti, Musulin, & Baldari, 2002; El-Ashker, 2011; Davis Wittekind, & Beneke, 2013a; Davis, Benson, Pitty, Connorton, & Waldock, 2014), interspersed with periods of lower intensity activity in which boxers do not attempt to exchange blows and that, from a physiological viewpoint, this necessitates well-developed aerobic and anaerobic capacities (Ghosh, Goswami, & Ahuja, 1995; Smith, 2006; Ghosh, 2010; Arsenau, Mekary, & Leger, 2011; Davis, Leithauser, & Beneke, 2013b; de Lira et al., 2013).

Indeed, throughout a contest boxers perform an average of 1.2 offensive, defensive or locomotive actions each second (Davis et al., 2013a), whilst the induced physiological response is typified by mean heart rates in excess of 180 b·min^{-1} (Ghosh et al., 1995; Khanna & Manna, 2006; Ghosh, 2010; Seigler & Hirscher, 2010; de Lira et al., 2013) and post-exercise blood lactates > 9 mmol·l^{-1} (Khanna & Manna, 2006; Smith, 2006; Davis et al., 2013a). A further attempt (Davis et al., 2013b) to quantify more invasively the internal load of boxing performance has estimated energy provision from aerobic and anaerobic (lactate and phosphocreatine-derived energy) sources as 77% and 23% respectively, reinforcing the requirement of boxers to condition all components of energy provision. Although approaches attempting to quantify the level of oxygen consumption ($\dot{V}O_2$) during amateur boxing have probably underestimated the *true* demand owing to a failure to apply invasive measurements during *actual* bouts, $\dot{V}O_2$ is still typically > 45 ml·kg^{-1}·min^{-1} (Arsenau et al., 2011; Davis et al., 2013b). Such data suggests that amateur boxers should undertake high-intensity (> 90% $\dot{V}O_{2\max}$) interval training given its ability to produce favourable adaptations in aerobic capacity (Bacon, Carter, Ogle, & Joyner, 2013) and lactate tolerance (Laursen & Jenkins, 2002).

Still, our understanding of the physiology associated with amateur boxing competition is largely restricted to field-based measurements of exercise intensity (heart rate and blood lactate) and where attempts have been made to apply more invasive measurements (i.e. $\dot{V}O_2$), methodological limitations (e.g. use of post-exercise measurements to estimate the load *during* performance; Arsenau et al., 2011) reinforce the need for further research, particularly with respect to quantifying accurately the external (i.e. physical movements) and internal (i.e. physiological) demands of participation. Such quantifications of competitive performance would provide important data that could be used to maximise specificity during training (Bridge, Jones, & Drust, 2009; Del Vecchio, Hirata, & Franchini, 2011; Campos, Bertuzzi, Dourada, Santos, & Franchini, 2012).

1.2 Performance analysis and the technical demands of boxing

Quantifying an exercise-induced ‘load’ can be based upon the external or internal demands experienced (Desgorces, Senegas, Garcia, Decker, & Noirez, 2007; Borresen & Lambert, 2008; Lambert & Borresen, 2010); that is the type, duration and number of physical exertions performed by an athlete (external) or the consequent physiological stress (internal) experienced (Lambert & Borresen, 2010; Akubat, Barrett, & Abt, 2013). Importantly, it is necessary to quantify both loads to provide a comprehensive evaluation of the physiological response to a given load of exercise (Scott, Lockie, Knight, Clark, & Janse de Jonge, 2013). Owing to its stronger relationship with physiological adaptation (Impellizzeri, Rampini, & Marcora, 2005), research advocates the prioritisation of measuring internal demand, though practical constraints in the application of physiological measurements during training and competition ensure that quantification of the external demand remains an important measure (Lambert & Borresen, 2010).

A sub-discipline of sport science that can provide measures of external load during actual sports competition is that of performance analysis. Typically, data is collected using notational or time-motion analysis which involves classifying and quantifying behaviours indicative of successful performance (Barris & Button, 2008). The approach can also be used to characterise the physical demands of competition according to independent factors such as ability (Gabbett, 2013a), opposition type and quality

(O'Donoghue, 2009), weight class (Bridge, Jones, & Drust, 2011), playing position (Sykes, Twist, Hall, Nicolas, & Lamb, 2009), and other *situational* variables that might affect performance (Lago, 2012). Whilst it has been applied to several team and individual sports (Hughes & Bartlett, 2002; Dobson & Keogh, 2007; Barris & Button, 2008; Mackenzie & Cushion, 2012) including combat sports (Atan & Imamoglu, 2005; Nunan, 2006; Artioli et al., 2009; Laird & McLeod, 2009; Bridge et al., 2011), performance analysis has seldom been applied to amateur boxing. Indeed, the dyadic interaction between athletes in combat sports provides an opportune context to study competitive sport behaviours (McGarry, 2009; O'Donoghue, 2009) and it is therefore surprising, alongside its evident popularity (Sport England, 2013), that amateur boxing has been the subject of only three performance analyses (El-Ashker, 2011; Davis et al., 2013a; Davis et al., 2014). Nonetheless, the findings of these analyses have provided practically worthwhile data that could enhance boxing training and performance, characterising *some* of the offensive and defensive external demands and aspects of performance distinguishing winning from losing.

However, performance analysis research is known to be situation-specific (Mackenzie & Cushion, 2012) with performance susceptible to contextual influences such as the quality and type of opponent (O'Donoghue, 2009). Consequently, the previous analyses of competitive performance apply only to elite amateur boxing during nine-minute contests (three rounds, each three minutes; El-Ashker, 2011; Davis et al., 2014) and six-minute novice bouts (three rounds, each two minutes; Davis et al., 2013a). Given the diverse contexts within which amateur boxing takes place, it is necessary to apply further performance analyses to encapsulate additional variables that might confound boxing performance, such as contest format (six versus nine minutes), ability (novice regional to elite international competition) and weight class (10 weight classes; 45 kg – 91+ kg). Moreover, the winning and losing ‘profiles’ previously described by El-Ashker (2011) and Davis et al. (2013a) were based upon the number of analyst-determined punches landed, not the real-time decision of the actual judges of the fight, and therefore the purported technical aspects of boxing associated with *actual* winning and losing performances might be inaccurate. Indeed, Davis et al. (2013a) confirm this problem stating that the analyst-determined outcome of a contest in three of sixteen bouts (19%) did not corroborate with the judges’ decision. Therefore, the conclusion that winning boxers threw more punches for example, might be inaccurate.

Whilst both boxing-specific performance analyses have identified particular aspects of offensive and defensive performance typical of winning and losing outcomes, such attempts were beset by methodological problems, not least the inadequate assessments of the reliability of the data collected. The data generated via performance analysis is notoriously unreliable owing to human error (Drust, Atkinson, & Reilly, 2007; Barris & Button, 2008; Carling, Bloomfield, Nelsen, & Bradley, 2008), and the establishment of adequate reliability should therefore underpin any performance analysis (O’Donoghue, 2007). Moreover, the statistical approach to quantify the associated error is important as the data generated does not typically satisfy statistical assumptions (Nevill, Atkinson, Hughes, & Cooper, 2002) and thus requires bespoke approaches. Unfortunately, there has been both a failure to conduct adequate assessments of reliability and apply relevant statistics to the data generated (O’Donoghue, 2007). To this end, the statistical approach of Cooper, Hughes, O’Donoghue, and Nevill (2007) which focuses on the proportion of test-retest agreement, alongside confidence intervals, offers the most comprehensive method suitable for quantifying the reliability of typical performance analysis data.

1.3 Automated analysis and ambulation in amateur boxing

Whilst establishing the reliability of observation is essential in performance analysis, any attempt to quantify the external demand of amateur boxing should include both the technical actions (i.e. punching and defending) and locomotive movements (i.e. boxing-specific steps, strides and jumps that move a boxer round the boxing ring) if it is to be considered valid. Whilst previous performance analyses of competitive amateur boxing have measured *some* of the offensive and defensive demands, they have failed to quantify the locomotive movements of boxers. Although Davis et al. (2013a) recorded the frequency of a variable referred to as 'vertical hip movements' (VHM) (defined as 'any visually identifiable vertical activity of the pelvis during stand and steps', p. 86), this one action is unlikely to reflect the external demand or physiological response to locomotive boxing-specific movements. Indeed, a valid assessment of boxing-specific movement seems improbable using a single video camera (Davis et al., 2013a), and because of limitations associated with manual video analysis, such as the laborious nature of 'coding' (Drust et al., 2007; Carling et al., 2008; Carling, 2013) and low reliability (O'Donoghue, 2004), the use of semi- and fully-automated systems to quantify such movements would seem beneficial given their successful application in many other sports (Barris & Button, 2008; Aughey, 2011).

On the theme of quantifying boxing-specific locomotive movements, global positioning system (GPS) units might afford an examination of the characteristic motions, given their established ability to provide reliable and valid estimates of time-displacement data in a variety of sports (Abt & Lovell, 2009; Aughey, 2011). The application of GPS technology to measure boxing-specific locomotive movements might, however, be severely challenged given its diminished ability to quantify multidirectional movements, incorporating frequent changes of direction, particularly when such movements are performed within a confined space (Duffield, Reid, Baker & Spratford, 2009; Portas, Harley, Barnes & Rush, 2010; Aughey, 2011; Bucheit et al., 2013). Therefore, it is imperative that the reliability and validity of GPS-derived estimates are described to identify its efficacy in providing worthwhile measurements of the external load associated with boxing-specific locomotive movements.

1.4 Simulation protocols

Following a comprehensive 'description' of the competitive environment (i.e. the external demand), it is necessary to identify aspects of performance predictive of success (Bishop, 2008). Whilst it is common-place to employ tests of isolated physical/physiological ability in either laboratory or field settings, there is a need to increase the ecological validity of assessments (Svensson & Drust, 2005; Currell & Jeukendrup, 2008; Reilly, Morris & Whyte, 2009) by increasing the specificity of the movements and metabolic demands (Muller, Benko, Raschner, & Schwameder, 2000), facilitating the identification of systematic improvements in *actual* performance (St Clair Gibson, Broomhead, Lambert, & Hawley, 1998; Wilkinson, Leedale-Brown, & Winter, 2009b). In many sports, performance is the result of complex interactions between a multitude of variables, and reproducing such conditions might afford an ecologically valid assessment of performance-based measurements (Drust et al., 2007; Currell & Jeukendrup, 2008). For example, an observed increase in an athlete's $\dot{V}O_{2max}$ does not necessarily translate to an improved performance, whereas a test or measure incorporating the diverse characteristics of performance including psychological, biomechanical, physiological, physical, technical, tactical and contextual factors, is more likely to be useful for making inferences about sports performance (Svensson & Drust, 2005; Drust et al., 2007; Currell & Jeukendreup, 2008; Aanstad & Simon, 2013).

Accordingly, sport-specific *simulations* of performance have gained popularity given their aptitude for replicating several components of performance, including the internal and external demands (Atkinson, 2002; Drust et al., 2007). Moreover, the use of simulation protocols also permits increasingly invasive measurements of physiological load (e.g. $\dot{V}O_2$ and blood samples) and, owing to experimental control, facilitates the identification of worthwhile intervention-based changes in performance which would not be possible if relying upon *actual* match data with its inherent variability (O'Donoghue, 2004; Gregson, Drust, Atkinson & Di Salvo, 2010). Typically, simulation protocols are preceded by a quantification of the external demands of a sport, permitting a replication of the movement patterns recorded during competition (e.g. Sykes, Nicholas, Lamb, & Twist, 2013). In amateur boxing, there have been two attempts (Smith, Dyson, Hale, Harrison, & McManus, 2000; Davis et al., 2013b) to simulate the competitive environment using the above approach. However, these simulations did not replicate the external demand of competition owing to the limited attempt to quantify the locomotive movement patterns, and the particular aspects of the offensive and defensive actions included were different to competitive performance. Moreover, it appears the internal physiological response was lower than those associated with *actual* bouts, thus questioning their validity in replicating the internal load of competitive performance (Smith, 2006; Ghosh 2010; de Lira et al., 2013).

It is also important that sport-specific simulations are evaluated in terms of their reliability, sensitivity and validity (Drust et al., 2007) to indicate their efficacy as measurement tools. The reliability of a measurement is an important consideration for any instrument in sport science (Atkinson & Nevill, 1998; Atkinson, Nevill, & Edwards, 1999; Hopkins, 2000; Atkinson & Nevill, 2001; Atkinson, 2002; Batterham & George, 2003) as it establishes the consistency of the generated data when administered on a test-retest basis and provides an estimate of the lowest change in performance necessary to detect the *smallest worthwhile change* (Hopkins, 2000; Batterham & George, 2003; Wilkinson, Leedale-Brown, & Winter, 2009a; Waldron, Highton, & Twist, 2013). Moreover, assessing the reliability of the external and internal loads associated with a simulation is of particular importance since a key aspect of a simulation’s development is the degree of ‘control’ or consistency they exert over the demands, which facilitates the detection of systematic changes following purposeful interventions.

Moreover, it is erroneous to assume that a protocol based upon a representative external demand induces a valid physiological response (Bridge, McNaughton, Close, & Drust, 2013). Indeed, research suggests a reduced psycho-physiological stress response (evidenced via decreased hypothalamic-pituitary-adrenocortical (HAP) activation; Filaire, Sagnol, Ferrand, Maso, & Lac, 2001; Moreira et al., 2012; Bridge et al., 2013) reduces the physiological response to a given external load. Therefore, it is important that the internal load imposed during simulations of performance is also validated against that induced during competition (Drust et al., 2007).

1.5 Organisation of the thesis

The programme of research presented in this thesis details the methodical approach undertaken to develop an amateur boxing simulation protocol based upon senior male performance involving a range of weight classes, abilities, contest durations and ring dimensions. This process involved an amalgamation of performance (Chapters 3 and 4) and motion analysis (Chapters 5 and 6), underpinned by assessments of reliability and validity, in order to identify an external demand (incorporating offensive, defensive and locomotive movements) representative of competitive amateur boxing performance. Subsequent to its development (Chapter 6), the physiological response evoked by the simulation was described and the reliability (Chapter 7) and validity (Chapter 8) of this internal load was evaluated to identify its efficacy as a viable framework for replicating the competitive demands of the sport.

Chapter 2

Review of Literature

2.1 Background

Boxing is a combat sport first introduced to the Olympic Games in 688 BC (Smith, 2006; Bianco et al., 2013) though it was not until the 19th century that it was subjected to increasing regulation (Murphy & Sheard, 2006). Previous to this period, it was a bloody and violent sport uncharacteristic of that associated with boxing today as it included wrestling, eye-gouging and the winner was the fighter 'left standing' (Sheard, 2004; Murphy & Sheard, 2006). The introduction of the 'Marquis of Queensberry Rules' in 1865 signified a shift toward boxing as a regulated sport and the establishment of the Amateur Boxing Association (ABA) in 1880, followed by the British Boxing Board of Control (BBoC) in 1929, resulted in amateur and professional codes of boxing (Sheard, 2004; Murphy & Sheard, 2006; Bianco et al., 2013). Today, the two can be distinguished by the contest durations (e.g. elite amateur: 3 x 3 min bouts vs. elite professional: 12 x 3 min), the wearing of head-guards (though no longer for elite male contestants since June 2013; AIBA, 2013a) and vests in amateur boxing and different weight classes (10 and 17 weight classes in amateur and professional codes, respectively).

Amateur boxing is currently participated in by males and females of varying ages at recreational and competitive levels around the world. Its popularity is reflected in the affiliation of 197 nations to the international governing body (Association Internationale de Boxe Amateur (AIBA)); Smith & Draper, 2007). In England, amateur boxing is the most popular combat sport with once-weekly participation by 154,800 individuals making it the 12th most popular sport using this indicator and since 2006 it has experienced the 5th largest increase in participation rates of any sport (Figure 1; Sport England, 2013).

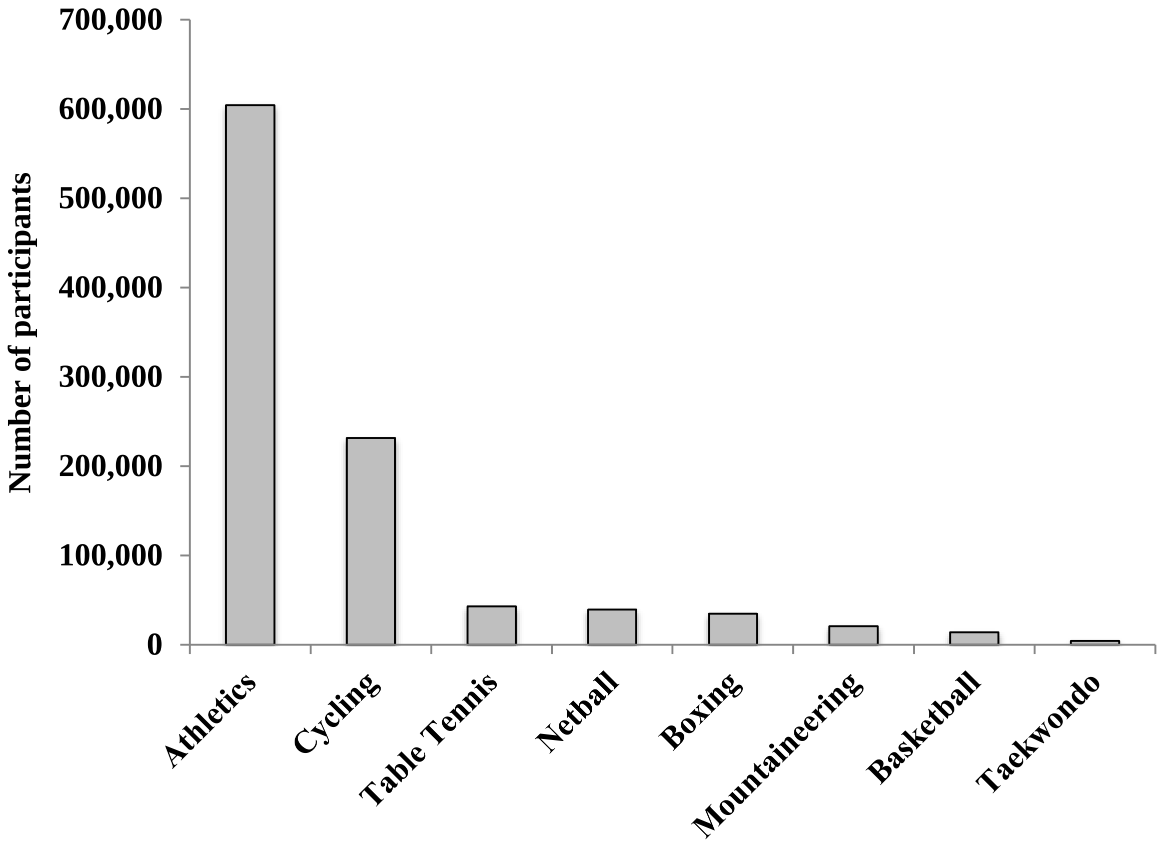

Figure 2.1. Change in once a week participation rates between 2006 and 2013 (Sport England, 2013).

The structure of competitive amateur boxing is such that ‘equality’ is maximised based upon the experience, weight and age of the boxer. The boxer is classed as ‘class “A” novice’, ‘class “B” novice, ‘intermediate’ or ‘open’ level based upon the number of contests they have partaken in and their success in major national competitions (Amateur Boxing Association of England (ABAE), 2007; see table 2.1 for official definitions). In practice, this means that boxers compete only against boxers of the same ability or one level above/below; novice compete against novice or intermediate boxers; intermediate compete against intermediate or open class; open class compete against open or intermediate boxers. Regardless of such classifications, those organising contests are also charged with considering the number of previous contests a boxer has participated in, further ensuring parity between boxers.

Table 2.1. ABAE (2007) definitions of novice (class ‘A’ and class ‘B’), intermediate and open class boxers.

Ability class	Definition
Novice boxer	A novice is a boxer who has not competed in any stage of an Open senior championship. A novice boxer must not compete against an open class boxer other than in a recognised championship.
Class ‘A’ novice	A boxer meeting the ‘novice boxer’ criteria having contested ≤ 10 previous bouts.
Class ‘B’ novice	A boxer meeting the ‘novice boxer’ criteria having contested 11- 20 previous bouts.
Intermediate boxer	A boxer who has: (a) entered and competed in an Open senior championship but not won a regional association title or (b) won a novice class ‘B' title or, (c) won a National Association of Clubs for Young People class ‘C’ title or (d) returned from professional boxing.
Open class boxer	A Boxer who has: (a) won an ABAE Senior Championship Regional Association Title (e.g. Merseyside and Cheshire, Greater Manchester) or (b) boxed at Senior level for his Country.

In addition, the sport is weight-classified into 10 categories (13 for juniors) between 44 and 91+ kilograms (Table 2.2). Finally, ‘school-aged’ (11-14 years), ‘junior’ (15 - 16 years) and ‘youth’ boxers (17-18 years) must not concede more than 12 months in age to their opponent, whilst ‘senior’ boxers may compete against opponents in the age range 19 - 40 years; boxers are not permitted to participate once 41 years old (ABAE, 2007; AIBA, 2013a). Boxing contests are confined to a square boxing ring (4.27 - 6.10

m^2) and last no more than four rounds for all ages and abilities (AIBA, 2008), although round durations do vary. Junior boxers compete for three rounds of one - two minutes and senior boxers compete for three - four rounds of two minutes or three rounds of three minutes. At all levels, a one-minute recovery takes place between rounds.

Table 2.2. Weight categories for senior, youth and junior male and female boxers (AIBA, 2013a)

Weight class	Senior and youth male	Weight class	Senior and youth female	Weight class	Junior boys and girls
N/A	N/A	N/A	N/A	Pinweight	≥ 44 - 46
Light flyweight	≥ 46 - 49	Light flyweight	≥ 45 – 48	Light flyweight	≥ 46 - 48
Flyweight	≥ 49 - 52	Flyweight	≥ 48 – 51	Flyweight	≥ 48 - 50
N/A	N/A	N/A	N/A	Light bantamweight	≥ 50 - 52
Bantamweight	≥ 52 – 56	Bantamweight	≥ 51 – 54	Bantamweight	≥ 52 - 54
N/A	N/A	Featherweight	≥ 54 – 57	Featherweight	≥ 54 - 57
Lightweight	≥ 56 – 60	Lightweight	≥ 57 – 60	Lightweight	≥ 57 - 60
Light welterweight	≥ 60 – 64	Light welterweight	≥ 60 – 64	Light welterweight	≥ 60 - 63
Welterweight	≥ 64 – 69	Welterweight	≥ 64 – 69	Welterweight	≥ 63 - 66
N/A	N/A	N/A	N/A	Light middleweight	≥ 66 - 70
Middleweight	≥ 69 – 75	Middleweight	≥ 69 – 75	Middleweight	≥ 70 - 75
Light heavyweight	≥ 75 – 81	Light heavyweight	≥ 75 – 81	Light heavyweight	≥ 75 - 80
Heavyweight	≥ 81 – 91	Heavyweight	≥ 81	Heavyweight	≥ 80
Super heavyweight	≥ 91	N/A	N/A	N/A	N/A

Note: N/A indicate weight class not used.

Contestants wear 10-12 ounce (283- 340 g) padded leather gloves and are permitted to launch a variety of punches towards the opponent. When adopting either an orthodox (left hand and foot lead the right hand and foot) or southpaw (right hand and foot leading left hand and foot) stance, boxers use jabs, backhands, lead hooks, rear hooks, lead uppercuts, rear uppercuts, inverted jabs and inverted backhands in an attempt to gain an advantage over their opponents. The aim of a competitive contest is to out-score or render the opponent unable to continue (typically referred to as a 'knock-out') However, in contrast to its more illustrious relative professional boxing, the sport seeks to protect its participants by avoiding unnecessary 'punishment' (Jako, 2002). For example, the associated negative effects of receiving blows to the head are reduced by the mandatory wearing of head guards (though no longer by elite male boxers) and gloves posited as having more padding around the knuckle area of the boxer. In addition, the application of 'standing eight counts' in 1964, the approach (Hickey, 2006) and ability of the referee to end a contest when s/he sees fit, the authority of the ring-side doctor to stop the contest indefinitely, and the shorter round and overall contest durations are effective measures imposed in the best interests of the boxers (Jako, 2002). However, a recent decision was taken to remove the use of head guards (AIBA, 2013a; Bianco et al., 2013) based upon a historical comparison of the proportion of knock-outs before and after their mandatory use in 1984; data is not yet available to suggest such a change is contrary to boxer safety.

Research interest in both amateur and professional boxing has, by-and-large, concerned the associated dangers of receiving blows to the head and the potential for acute and chronic traumatic brain injury (Roberts, Allsop, & Bruton, 1990; Ohhashi, Tani, Murakami, Kamio, Abe, & Ohtuki, 2002; Bianco et al., 2005; Zazryn, Finch, &

McCrory, 2006; Zazryn, Cameron, & McCrory, 2006; Loosemore, Knowles, & Whyte, 2008; McCrory, Zazryn, & Cameron, 2007; Miele & Bailes, 2007; Bianco et al., 2013). Importantly, there is a growing body of literature suggesting that amateur boxing does not experience the same consequences associated with prolonged participation as professional boxing (Bianco et al., 2005; Haglund & Bergstrand, 1990, Hazar, Beyleroglu, Subasi, & Or, 2002; Jako, 2002; Loosemore et al., 2007; Massimiliano et al., 2011; Bianco et al., 2013), despite the extremely high impact forces delivered by competitors (Walilko, Viano, & Bir, 2005; Stojsih, Boitano, Wilhelm, & Bir, 2010). Evidently, the protective measures highlighted above are effective. It is rather surprising, though, that researchers (applied sport and exercise scientists) have thus far tended to ignore amateur boxers from the point of view of the physiological stresses and adaptations they experience during competition (and training) and/or the technical and tactical components of their performances. Moreover, given the recognition by the amateur boxing community that success in the sport is dependent on specific, quantifiable factors such as speed and strength (Matthews & Comfort, 2008), power, coordination, agility, stamina (Whiting, Gregory, & Finerman, 1988) and particular aspects of performance, the scope for research is considerable.

To-date, the body of knowledge in this context has been confined to less than twenty studies that have focused upon the physiological profiles of elite amateur boxers (Valentino, Esposito, & Fabozzo, 1990; Guidetti et al. 2002; Smith, 2006; Khanna & Manna, 2006), the heart rate and blood lactate responses of elite amateur boxers in competitive situations (Ghosh et al., 1995; Smith, 2006; Ghosh, 2010; Arsenau et al., 2011; Davis et al., 2013b; de Lira et al., 2013), boxers' performance-related responses to rapid body mass loss (Smith, Hale, Harrison & McManus, 1994; Smith et al., 2000b;

Smith et al., 2001; Hall & Lane, 2001), the effect of sodium bicarbonate ingestion on sparring (a format with no constraints, closely matching an actual contest) performance (Siegler & Hirscher, 2010) and notational analyses of selected aspects of offensive and defensive boxing performance (El-Ashker, 2011; Davis et al., 2013a; Davis et al., 2014).

2.2 The changing nature of amateur boxing competition

At national and international level, amateur boxing has undergone several significant rule changes (Figure 2.2) since its official introduction to the modern Olympic Games (1904) (Bianco et al., 2013). Although the recent removal of head guards for elite senior males could be considered the most controversial given the widespread medical discourse calling for the abolition of boxing altogether (McCrory et al., 2007), arguably the most important changes impacting the performance of boxers concerns the method of scoring and the contest durations.

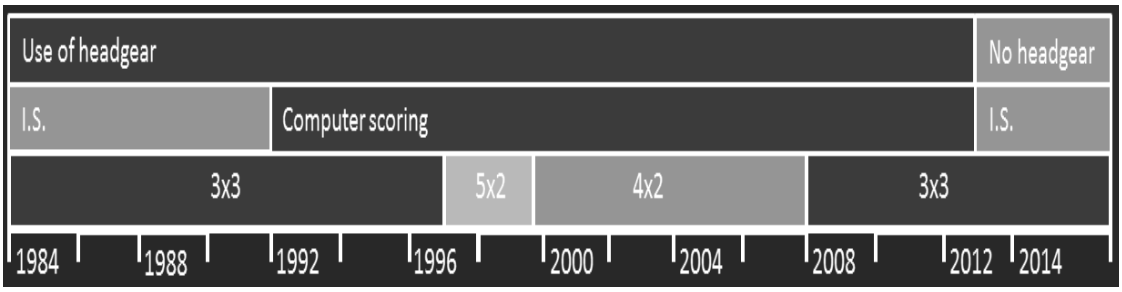

Figure 2.2. Rule changes concerning headgear, judging method and contest format in elite amateur boxing from 1984 to 2014. '3x3', '5x2', '4x2' refer to the number and duration (min) of rounds in bouts. I.S. = Impressionistic scoring.

The method of scoring in amateur and professional boxing has always been a subjective process (Smith, 2006) despite attempts to include increasingly objective measurements

(Pierce, Reinbold, Lyngard, Goldman, & Pastore, 2006). In the period before 1992, scoring was based upon subjective (impressionistic) appraisals by a panel of three expert judges (or two judges and a referee; Smith, 2006), employing what is commonly referred to as the “10 point must system”. Under this system boxers began each round with an arbitrary 10 points and the boxer deemed to have lost the round was subsequently deducted a single point from that total. Moreover, boxers could be further deducted single points for each time they were “knocked down” to the canvas. The winning boxer, provided no injuries or knockouts were observed, was the individual with the highest points total provided this was the case for two or more of the judges’ scores (see table 2.2 for a breakdown of the impressionistic decisions in boxing).

Table 2.3. The impressionistic judging decisions awarded in boxing

	Description
Unanimous	All three judges record a higher total score for the same boxer.
Majority	Two judges record a higher total score for the same boxer, the other judge deems the contest a draw.
Split	Two judges record a higher total score for the same boxer (e.g. red boxer), the other judge deems the opposing boxer to have won (i.e. blue boxer).
Draw	All three judges record the same totals for both boxers OR One judge records a higher total score for boxer “1”, another judge records a higher total score for boxer “2” and the final judge records the same score for both boxers.

Note: the individual judge totals do not bear significance other than determining a binary outcome (i.e. boxer “1” had a higher or lower total score than boxer “2”).

Although it is impossible to locate the judging criteria used to determine the outcome of a round/contest pre-1992, it seems plausible it was aligned to that of professional boxing such that merit was given for “clean punches landed”, “effective aggressiveness”, “ring generalship” and “defence” (Kaczmarek, 1996). Unsurprisingly, subjective appraisals of performance in combat sports (Myers, Nevill, & Al-Nakeeb, 2010), including boxing (Balmer, Nevill, & Lane, 2005), have been found inaccurate (Lee, Cork, & Algranati, 2002), bias (Balmer et al., 2005) and inconsistent (Myers et al., 2010). Consequently, and following a highly contentious decision at the 1988 Seoul Olmpic Games in which a South Korean boxer was awarded a dubious decision (Murphy & Sheard, 2006) over America boxer Roy Jones Jnr., official amendments were made to the process of judging in amateur boxing whereby competitors were instead awarded points for landing punches upon the opponent within a defined scoring zone (see Figure 2.3, below). A scoring ‘blow’ was determined by five ring-side judges using a computer-based method whereby a boxer was awarded a point only when three of five judges awarded a point (within one second) to the same boxer deemed to have landed a scoring blow of sufficient force upon the opponent’s target area without being blocked or guarded (ABAE, 2007). However, what constituted *sufficient force* was not defined objectively and it seemed unlikely that judges could determine the forces associated with landed punches with adequate accuracy or consistency (Myers et al., 2010). Nonetheless, the computer-based system was purposefully introduced to overcome problems associated with the impressionistic judgment (e.g. nationalistic judging bias) about which boxer had performed better over the duration of each round, and subsequently the whole bout (AIBA, 2008; Smith, 2006; Partridge et al., 2005). A comparison of the validity of judging decisions under impressionistic and computer-based scoring has not been undertaken thus whether the objective (i.e. enhancing judge accuracy) was achieved remains unknown. The computer-based scoring was subsequently applied to regional and inter-regional level boxing, albeit judges recorded a running total number of points independent of other judges using a hand-held calculator and at the end of the bout recorded the respective totals for each boxer, with the winner declared according to which boxer the *majority* of judges were in favour of (Hickey, 2006).

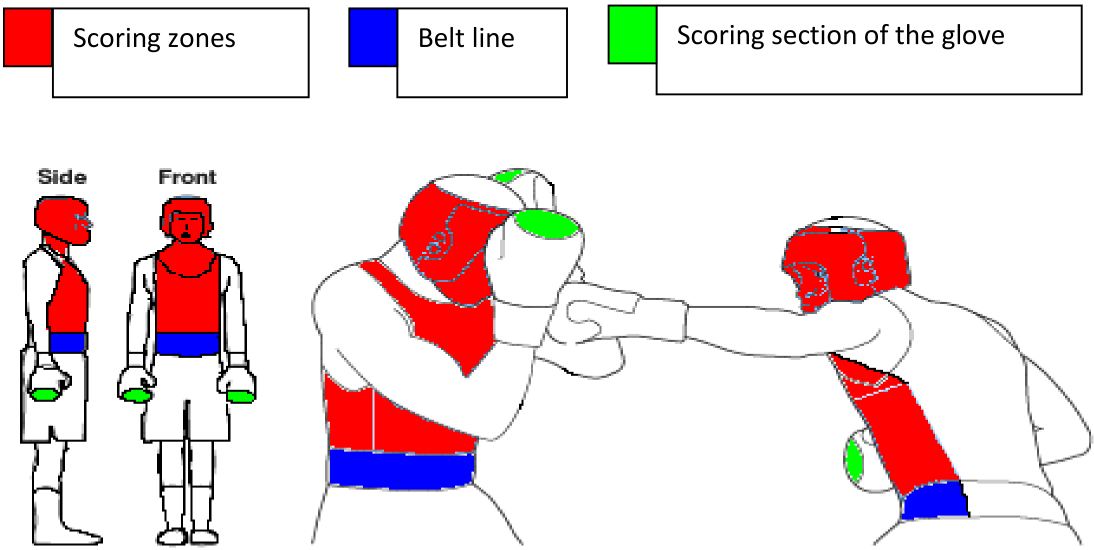

Figure 2.3. The scoring zones, belt line and scoring section of the glove for amateur boxers.

Whilst criticism of computer-based determined outcomes remained (Coalter, Ingram, McCrory, O'Donoghue, & Scott, 1998), its introduction seemed to have led to alterations in the tactics of boxers during a contest, placing greater emphasis on landing single, forceful blows upon the opponent's target area (Smith, 1998, cited in Smith, 2006; Smith & Draper, 2007). Evidence for this was provided in the form of an analysis of the metabolic consequences of fighting under the new and old scoring systems (whilst contest format was the same, 3 x 3 minutes). Significantly higher post-bout blood lactate values were observed for the impressionistic judging format (12.8 ± 3 mmol·l^{-1}) compared to the computerised scoring method (9.5 ± 3 mmol·l^{-1}), suggesting a higher anaerobic demand and a higher volume of punches being thrown under the old scoring system (Smith, 2006).

In addition, the structure of a bout (and therefore the work-to-rest ratios) for boxers competing at national and international levels was altered from that incorporating 3 x 3 minutes (in 1997) and 5 x 2 minutes (in 1999) respectively, to one of 4 x 2 minute rounds (Figure 2.2) (Smith, 2006; Bianco et al., 2013). On the basis of post-contest blood lactate values, the impact of this change appears to have been a greater reliance upon anaerobic energy sources for the 4 x 2 minute contests (13.5 ± 3 mmol·l^{-1}) than the 3 x 3 minute contests (9.5 ± 3 mmol·l^{-1}) and 5 x 2 minutes (8.6 ± 3 mmol·l^{-1}), possibly owing to altered activity patterns within rounds (Smith, 2006). Thus, it is apparent that the changing rubrics of amateur boxing concerning judging and bout durations in particular have physiological, and by inference physical, consequences for amateur boxers and given specificity is a fundamental property of effective conditioning (Muller et al., 2000), the rules should therefore receive due cognisance when preparing for and appraising amateur boxing performance. For example, it is likely that there are differences in the physical and physiological characteristics of male and female boxers and such differences might be reflected in disparate demands during competition. That elite female and male boxers compete in 4 x 2 and 3 x 3 minute bouts, respectively, reinforces this notion and suggests that training should therefore be tailored to the boxer’s individual needs. In addition, as female competitors are compelled to use head guards during bouts, whilst senior male are now (2014) not, this could have a marked impact on the actions performed by either.

More recently (2013), AIBA (2013a) made the decision to remove head guards and revert back to impressionistic scoring for senior male boxers in an effort to facilitate transitions between the semi- (World series boxing) and professional (AIBA pro boxing) models governed by AIBA. The impact of such changes on boxing performance and the associated physiological response remains unknown though given previous research findings (Smith, 2006; Ghosh, 2010), it appears likely the demands are again changed.

In addition to rule changes enforced by the governing body and the obvious change of opponent between bouts, the competitive environment is further modified by contextual variables largely determined by the ability of a boxer. The ABAE and AIBA provide ample opportunity for boxers to compete and they typically contest regionally before progressing to inter-regional and national bouts/competitions. If a senior boxer progresses beyond regional and inter-regional competition, and is consistently successful at the national level, then it is plausible that those boxers might subsequently compete internationally at tournaments permitting qualification for the Olympic Games, deemed the pinnacle of amateur boxing. A consequence of such progression for male senior boxers – an advance from bouts of 3 x 2 minute then 4 x 2 minute rounds during regional and inter-regional contests, to 3 x 3 minute round bouts when competing nationally and internationally (ABAE, 2009) - is altered demands. Moreover, it is quite typical of national and international tournaments to use the maximum permissible contest ring size (6.1 m2) compared to regional and inter-regional bouts which utilise smaller rings (usually 4.27 (14 ft), 4.88 (16 ft) or 5.49 m2 (18ft) pending monetary or host venue constraints). Such drastic changes to the fundamental work-to-rest ratios and dimensions of the contest ring undoubtedly impact on the absolute demands made of boxers, as reflected in recent performance analyses by Davis et al. (2013a, 2014) who established a difference of ≈ 31% in the frequency of punches during each round between international elite standard boxing over 9 minutes (≈ 65 punches) and regional novice boxing over six minutes (≈ 45 punches). Together, the inconsistent formats of the competitive environment (i.e. age, weight class, ability and thus contest duration and ring size) are likely to influence the physical, physiological, technical and tactical demands of a contest such that the preparation undertaken by a boxer ought to be specific to the expected demands. Additionally, boxers, coaches and researchers should duly consider such inconsistent conditions when appraising performance.

Although research has detailed some isolated facets of boxing performance facilitating comparison of boxing performance across a number of rules, it is likely each boxer possesses a unique amalgamation of psychological, biomechanical, physiological, anthropometrical and physical traits that constrain a boxer to perform in a given way. To this end, boxers are often purported as possessing a '*style'* of boxing that is likely to influence the physical, technical and tactical demands of their own performance, as well as that of their opponents (Hickey, 2006). Perhaps owing to their subjective identification, there is no data describing the performances of boxers utilising different styles though coaching manuals make reference to 'aggressive fighter', 'stylist', 'counterpuncher', 'high-tempo' and 'flair' styles as well as those employing an amalgamation of these (Table 2.2.). For example, anecdotal and coaching-based observations suggest counterpunching boxers attempt to make opponents miss with attacks before countering with punches (Hickey, 2006) and this can lead to contests characterised by extended periods of inactivity. This is particularly evident when two counterpunching boxers compete as they frequently feign movements in an attempt to mislead their opponent into believing an opportunity to land an attack exists, before subsequently countering (Hickey, 2006).

Owing to a boxer's style and interaction with the opponent, amongst several other confounding influences then, the competitive environment is likely to be characterised by unpredictability and a wide-range of demands. That the fundamental aspects of competitive boxing evidence high variance (e.g. number of punches thrown per minute by elite amateur boxers' coefficient of variation ≈ 34%; Davis et al., 2014) reinforces this supposition. Attempts to describe boxing performance should therefore acknowledge the potential influence of styles and future research could explore the performances of boxers with varying styles. Moreover, coaching definitions of styles infer the weight class of a boxer might be associated with the demands suggesting 'lighter' boxers are more likely to adopt 'high-tempo' strategies boxing throwing many punches and so the interactions between confounding variables (e.g. weight class and boxer style) might be a further consideration in the sport.

Table 2.4. Typical boxing styles and their description (Hickey, 2006)

Style	Description
Aggressive fighter	Press forwards, at times willing to receive punches in order to move close to the opponent and perform powerful 'bent-arm' punches (i.e. hooks and uppercuts).
Stylist	Use footwork and long-range punching (i.e. jabs and rear hand cross punches) to present a 'moving target', often content winning rounds rather than attempting to inflict injurious, forceful punches.
Counterpuncher	Agile boxers attempting to make their opponent miss or purposefully defend an attack before returning punches toward the opponent and subsequently moving out of punching range.
High-tempo	'Energetic' boxers relying upon a high volume of punches to unsettle the opponent. Usually found in the lighter weight classes.
Flair	Unpredictable boxers who do not typically conform to 'traditional' methods of boxing. Characteristically keeps guard very low, switches stance sporadically and throws punches from unorthodox positions.

2.3 The physiological profile of an amateur boxer

From the limited research available, it seems that success in amateur boxing (as with other combat sports) depends on the participant applying attacks (punches) accurately with strength, velocity and power, whilst avoiding being hit in return (Heller et al., 1998; Yoon, 2002; Franchini, Del Vecchio, Matsushigue & Artiolli, 2011; El-Ashker, 2011; Davis et al., 2013a). Defences and footwork are typically performed at high intensities and add to the demands placed upon competitors during a contest (Smith, 2006). Although such demands (the exact work-to-rest ratios) remain unknown, this intermittent sport is known to involve short duration, high-intensity bursts of activity interspersed by periods of lower activity in which boxers are not visibly attacking or defending (Hemmings, Smith, Graydon, & Dyson, 2000; Guidetti et al., 2002; Khanna & Manna, 2006; Smith, 2006; El-Ashker, 2011; Davis et al., 2013a). Such activity relies on both aerobic and anaerobic energy sources (Davis et al., 2013b) and has been shown to elicit a high cardiovascular response during competition and high (8 - 15 $mmol \cdot l^{-1}$) post-contest or sparring blood lactate values (Ghosh et al., 1995; Smith, 2006; Ghosh, 2010; Arsenau et al., 2011; Davis et al., 2013b; de Lira et al., 2013). Whilst short bursts of activity rely primarily on the degradation of stored phosphocreatine (PCr) and adenosine triphosphate (ATP) and nonaerobic synthesis of glucose and glycogen (Davis et al., 2013b), the maintenance of intermittent exercise and the recovery during intervals are mainly supported by oxidative phosphorylation (Gastin, 2001; Glaister, 2008; Franchini et al., 2011; Davis et al., 2013b). In effect, it appears that amateur boxing is a complex sport with numerous physiological competencies desirable for successful performance (Guidetti et al., 2002).

A rare investigation of note by Guidetti et al. (2002) reported on the morphological, anthropometric and physiological characteristics of elite level Italian middleweight boxers (75 - 81 kg; light-heavyweight equivalent in England). Their study observed strong positive relationships between the current international (AIBA) rankings and measures of maximal oxygen uptake ($\dot{V}O_{2max}$) (r = 0.81), lactate threshold (r = 0.91, wrist girth (r = 0.78) and hand grip strength (r = 0.87). However, whilst the measurement techniques used to determine $\dot{V}O_{2max}$ and lactate threshold could be considered criterion methods (i.e. the use of incremental treadmill running), the concomitant measurement of $\dot{V}O_{2max}$ and blood lactate might have affected the accuracy of either measurement (Midgley, Bentley, Luttikholt, McNaughton, & Millet, 2008). In addition, the external validity of maximal isometric strength is questionable, particularly in a sport such as boxing which involves dynamic intra- and inter-limb contractions (Wilson & Murphy, 1996; Frost, Cronin, & Newton, 2010). Still, the ability to deliver high forces when punching and clinching (the component of competition whereby boxers seemingly wrestle using the upper body to defend or move the opponent) is important in boxing (Smith et al., 2000; Smith, 2006), suggesting measurements related to force production are appropriate in amateur boxing.

Nevertheless, strength is defined as the peak force developed over an indeterminate duration during a maximal contraction (Wilson & Murphy, 1996; Harris, Cronin, & Keogh, 2007) and given the need to punch the opponent and avoid being hit in return, the ability to generate high forces over brief periods of time (i.e. punching an opponent before moving away/defending oncoming punches) would appear desirable. Measurements quantifying the *rate* of force development (RFD) alongside maximal force might therefore be advantageous (Aagard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). The RFD represents the greatest slope of the force-time curve (Wilson & Murphy, 1996) and owing to Newton's second law of motion ($F_{net} = m \times a$; where F_{net} is the sum of all external forces acting on the object, 'm' is the mass of the object and 'a' the acceleration), the RFD is related to movement speed. That is, for a given mass (i.e. engaged musculature when punching) a boxer can only manipulate the resultant force by affecting the acceleration of the movement, and therefore measurements such as RFD better reflect the dynamic component of athletic performance (Frost et al., 2010). Indeed, boxing punches typically involve contractions of 553 – 607 ms and it is therefore important that boxers are able to attain maximal force within this time to avoid the delivery of submaximal forces (Piorkowski, Lees, & Barton, 2011). Moreover, punches thrown within combinations have lower delivery times (e.g. 217 ± 69 ms for a rearhand cross) and with human muscle unlikely to reach maximum force within 300 ms (Aargard, Simonsen, Andersen, Magnusson, & Poulsen,

2002) the RFD likely provides an important measurement for boxers. However, owing to the typical use of isometric tests when examining RFD, the relationship between RFD and dynamic athletic performance is often limited (Murphy & Wilson, 1996) due to differing motor unit activation patterns, and so enhanced movement specificity should underpin sport-specific assessments of RFD.

More recently, iso-inertial assessments of strength that determine the maximal load an individual can move in a single attempt (i.e. one repetition maximum) have become popular and are now viewed as the criterion measurement of strength owing to their strong relationship with athletic performance (Castro-Pinero et al., 2010; Frost et al., 2010). Consequently, the finding that amateur boxing performance is related to handgrip strength represents an invalid and outdated approach that might be an artefact of the ranking system used to relate boxing *ability* to physiological variables. That is, those boxers who had undertaken more bouts in the previous 12 months, and therefore potentially more training, were likely to be those with a higher rank and so the relationship could have simply related training status, not boxing ability, to isometric strength. Researchers and applied practitioners should therefore interpret this finding with caution.

Whilst measurements related to strength might be useful, quantifications of power likely provide comparatively eminent data in boxing as this defines the product of force and velocity (Harris et al., 2007); both important qualities in boxing (Smith et al., 2000; Piorkowski et al., 2011) given the need to deliver punches with injurious potential whilst simultaneously reducing the opportunity of a defence and counter by the opponent. Biomechanically, all movement in sports performance is governed by the force-velocity-power inter-relationship and obtaining maximal power necessitates optimised values of force and velocity (Travis et al., 2014). Peak values of power are characteristically reached during ‘explosive actions’ (Haff, Whitley, & Potteiger, 2001) which typifies punching in amateur boxing, and so measures relevant to power could provide useful information to coaches and boxers. Surprisingly, only a single study has quantified the power of punches in boxing owing to the need for sophisticated technology as well as difficulties identifying the individual contribution of force and velocity to punch power (Frost et al., 2010). Walilko et al. (2005) reported values of 8,014 ± 3,724 W when analysing maximal effort punches in elite boxers, far higher than, for example, ballistic bench press movements (557.9 W; Cronin McNair, & Marshall, 2003). That the power in punching appears high suggests it is an important property of boxing performance that should be a feature of the preparatory exercises undertaken by boxers.

Guidetti et al. (2002) also suggested estimated percent body fat was unrelated to boxer ranking, which would seem to contradict the view that success in weight-classified combat sports is facilitated by low levels of body fat (Heller et al., 1998; Yoon, 2002; Artioli et al., 2009; Franchini et al., 2011). However, this finding might have been a consequence of the homogeneity of the sample in terms both of their body fat levels (14.5 ± 1.5 %) and ability ranking (Atkinson & Nevill, 1998). Other research has reported high mesomorphy among elite boxers (Khanna & Manna, 2006), and reinforces the notion that a combination of high musculature and low body fat content is advantageous in amateur boxing.

2.4 The physiological demands of amateur boxing contests

The predominant focus of research into amateur boxing exercise physiology has been on the oxygen uptake ($\dot{V}O_2$), heart rate and blood lactate responses of boxers to various laboratory-based and sport-specific exercises. As $\dot{V}O_{2max}$ is considered a key determinant of endurance performance and reflects the ability of the cardiovascular system to provide oxygen to meet muscle demand (Joyner & Coyle, 2008), it has received due attention. During exercise, those with a high $\dot{V}O_{2max}$ display improved oxygen delivery and extraction at the muscle level, increased muscle blood flow, superior blood and haemoglobin volume, and an efficient oxygen utilisation during strenuous exercise (Levine, 2008). Accordingly, this facilitates a larger provision of energy via oxidative phosphorylation, simultaneously reducing the reliance upon anaerobic pathways (i.e. ATP-PCr and glycolytic pathways). Consequently, the onset of anaerobic energy production and its associated negative side effects is delayed (Gastin, 2001; Tomlin & Wenger, 2001). Additionally, an enhanced aerobic system facilitates recovery during intermittent, high-intensity exercise by increasing lactate and hydrogen proton removal and dissipating heat more readily (McMahon & Wenger, 1998; Tomlin & Wenger, 2001; Glaister, 2008). Thus, the boxer possessing enhanced aerobic abilities could maintain a higher exercise intensity and recover to a greater extent between rounds potentially improving competitive boxing performance.

Based on treadmill running protocols, $\dot{V}O_{2max}$ values upwards of 59 $ml \cdot kg^{-1} \cdot min^{-1}$ have been reported for elite senior boxers (aged 17 – 34 y) in several studies (Arsenau, Mekary & Leger, 2011; Khanna & Manna, 2006; Smith, 2006), and slightly lower values ($\approx$ 55 $ml \cdot kg^{-1} \cdot min^{-1}$) for Italian (Guidetti et al., 2002) and Indian elite amateur boxers (Ghosh et al., 1995). Differences in $\dot{V}O_{2max}$ between groups may be related to the type of training undertaken and the mean body mass of the participants (weight class) as Khanna & Manna (2006) revealed significantly lower $\dot{V}O_{2max}$ values in heavier boxers. Consequently, that the $\dot{V}O_{2max}$ was 6.3 ml·kg^{-1}·min^{-1} lower in Italian boxers compared to English boxers was possibly due to a higher body mass in this sample (Italian boxers: 77.4 ± 1.4 kg versus English boxers: 62.5 ± 10.8 kg) (Guidetti et al., 2002; Smith, 2006). However, heavier boxers tend to spar at a lower relative oxygen cost compared to lighter boxers (Arsenau et al., 2011) yet at a higher percentage of $\dot{V}O_{2max}$. Together, such findings suggest the physical exertions of heavier boxers during competitive performance might be lower than their lighter counterparts owing to a reduced aerobic fitness (McMahon & Wenger, 1998; Mohr, Krustrup, & Bangsbo, 2003).

The $\dot{V}O_{2max}$ values reported for male amateur boxers are not high when compared to elite endurance distance runners, who record values of 70 - 80 ml·kg·min^{-1} (Zavorsky, Montgomery, & Pearsall, 1998). However, they sit well with those of elite senior wrestlers (53 - 56 ml·kg·min^{-1}), mixed martial artists (55 ± 6.6 ml·kg·min^{-1}), elite male taekwondo competitors (53.9 ± 4.4ml·kg·min^{-1}), judoka (47.3 ± 10.9 ml·kg·min^{-1}) and sumo wrestlers (31.1 ± 1.3 ml·kg·min^{-1}) (Heller et al., 1998; Yoon, 2002; Markovic, Misigoj-Duraković , & Trninic, 2005; Beekley, Abe, Kondo, Midorikawa, & Yamauchi, 2006; Butios & Tasika, 2007; Sbriccoli, Bazzucchi, Di Mario, Marzattinocci & Felici, 2007; Matsushigue, Hartmann, & Franchini, 2009). Moreover, de Lira et al. (2013) and Davis et al. (2013b) recorded mean and peak Oxygen uptakes of ≈ 45 ml·kg·min^{-1} and ≈ 50 ml·kg·min^{-1} during rounds. Although the values might be somewhat inaccurate owing to questionable methods (i.e. estimated $\dot{V}O_2$ and use of an invalid simulation protocol), they further document the high aerobic demand made of boxers. Importantly, cardiovascular fitness is a key attribute for a successful boxer given the substantial aerobic demand during contests (or sparring) and the consistent occurrence of near-maximal heart rates (Ghosh et al., 1995; Chatterjee, Banerjee, Majumdar & Chatterjee, 2006; Smith, 2006; Ghosh, 2010; de Lira, 2013). Indeed, during the last two rounds of a 4 x 2 minute open sparring situation, Smith (2006) recorded higher heart rates (> 200 b·min^{-1}) than those elicited during treadmill running to volitional exhaustion. More recently, Davis et al. (2013b) estimated aerobic energy provision to be 77% of the total energy yield during novice boxing of three rounds, each two minutes in duration, further endorsing the necessity for boxers to possess well developed aerobic metabolic pathways and prepare for a high aerobic demand during competition.

Heart rate data from five other studies serve both to reinforce the physicality (high intensity) of boxing competition and sparring, and highlight the impact of bout progression and duration. Among amateur male boxers engaged in competitive (3 x 3 minutes) selection trial contests, Ghosh et al. (1995) reported mean heart rates of 173 ± 6, 179 ± 6, and 182 ± 5 b·min^{-1} for rounds one, two and three, respectively, whilst Khanna and Manna (2006) reported similar values of 170 ± 6, 177 ± 5, and 183 ± 5 b·min^{-1}. Moreover, such intensities were also evident among male and female boxers engaged in 3 x 2 minute open sparring; 175 ± 11, 183 ± 6, and 186 ± 7 b·min^{-1}, respectively (de Lira et al., 2013) and male boxers sparring over four rounds, three minutes in duration; 177 ± 3, 180 ± 3, 181 ± 3 and 183 ± 3 b·min^{-1}, respectively (Siegler & Hirscher, 2010). That two and three minute rounds induce similar mean heart rates suggests the demands made of boxers are rather immediate and sustained throughout each round. Indeed, de Lira et al. (2013) described the typical heart rate response within a 2-minute round whereby there was a rapid rise within the initial ≈20s, before approaching maximal values at the cessation of each round. For the 4 x 2 minute format, however, Ghosh (2010) documented higher heart rates (≈ 14 $b \cdot min^{-1}$) than other durations. This is postulated as being due to a greater emphasis upon performing more frequent repeated bursts of high intensity activity, involving punches and dynamic footwork, earlier in the contest. Higher post-contest lactate values have also been recorded supporting the idea of a higher physiological demand during this format (Smith, 2006). Such an observation appears logical given the shorter rounds, in consort with three rest intervals (rather than two), provide enhanced conditions to maximise the exercise intensity.

Notwithstanding the objective data referred to above, it should be acknowledged that the physiological demands of an individual bout or spar are context-dependent. That is, performances are influenced by the *quality* and *type* of opponent (O'Donoghue, 2009) as well as several other factors referred to collectively as 'situational variables' (Lago, 2012). In football for example, Gregson et al. (2010) reported a coefficient of variation of 30.8 ± 11.2% for match-to-match total sprint distance during competitive soccer matches; a value which varied further according to the season analysed, playing position and possession. In the published research to-date, information about the body mass, ability level and style of opposition, has been omitted, all of which could affect the dynamics of a contest. In addition, the age of the boxer, the total number of wins, losses and the stance adopted ('orthodox' or 'southpaw') and outcome of his/her preceding bout are known to be predictive of the outcome of a contest (Warnick & Warnick, 2007; Gursoy, 2009). Therefore, the assumption that all the documented intensity measures of competitive situations have involved opponents of an equal weight classification, ability level and style that does not perturb performance from the norm, is likely to be false. To adequately appraise performance in this instance, researchers can either apply experimental control over the demands of the exercise, reducing the ecological validity or increase sample size substantially (Batterham & Hopkins, 2005) which might be challenging. Yet, the standard deviations for heart rates and blood lactate values of all known sparring and contest situations are < 10 $b \cdot min^{-1}$ and 3.2 $mmol \cdot l^{-1}$, respectively, suggesting consistently high metabolic demands regardless of the context (Ghosh, 1995; Smith, 2006; Ghosh et al., 2010).

2.5 The physiological demands of training in amateur boxing

Perhaps unsurprisingly, documented research on the training practices of amateur boxing is sparse. Although some cross-sectional data on the demands of some types of training (e.g. punch-bag exercise) and open sparring sessions have been reported, it remains largely unknown how (or whether) amateur boxers reach adequate levels of conditioning, and how responsive they are to specific training interventions. Besides, the absence of an ecologically valid boxing fitness test (to act as a dependent variable) makes it difficult to establish the efficacy of particular training regimes. Indeed, owing to the complex nature of the competitive environment in boxing, it is unlikely an individual test assessing a single aspect of fitness could offer more than a rudimentary evaluation of the requirements of competitive boxing (Drust et al., 2007). In reality, training methods are typically established by means of ‘trial and error’ within the boxing team (Arsenau et al., 2011) and these practices are passed on from former boxers (some of whom become coaches) to current boxers. Several recent recommendations for there to be a focus encompassing structured high-intensity, aerobic interval training, ensuring that a high level of blood lactate tolerance is achieved (> 9 $mmol \cdot l^{-1}$) (Ghosh et al., 1995; Khanna & Manna, 2006; Smith, 2006; Ghosh, 2010; Davis et al., 2013a) have yet to filter down to the boxing fraternity (Hickey, 2006) though Smith (1998, cited in

2006) did report application of high-intensity interval ‘pad work’ (a form of exercise replicating the sport-specific demands) which induced favourable physiological responses. Moreover, it is now appreciated that sport-specific strength training (i.e. punching exercises employing resistance) should be incorporated into a boxer’s regime (Matthews & Comfort, 2008), though given the aforementioned issues it seems also unlikely that resistance training is a habitual aspect of a boxer’s preparation in amateur boxing, particularly sub-elite performers.

Attention has very recently been paid to quantifying the oxygen cost of typical boxing exercises, such as punching a punch bag, engaging in ‘pad-work’ (in which a boxer punches a partner’s pads or gloves) and sparring. Using a novel method of analysing oxygen uptake that involved boxers being connected to a metabolic gas analyser immediately post-exercise (in order to overcome the associated problems of wearing a gas mask during sparring), Arsenau et al. (2011) reported average values of 43.4 ± 5.9, 41.1 ± 5.1, 24.7 ± 6.1, 30.4 ± 5.8 and 38.3 ± 6.5 ml·kg·min^{-1} for sparring, pad-work and punching a punch bag freely at predetermined paces of 60, 120 and 180 punches·min^{-1}, respectively. Although the method of gas analysis was validated using treadmill exercise (r = 0.96, standard error of estimate = 1.6 ml·kg·min^{-1}), it required the boxer to be attached to a metabolic gas analyser (Moxus Modular Metabolic System, USA) after the final round of exercise and to exert themselves at the same intensity as the previous exercise, using footwork and punching a partner’s pads. Clearly, the validity of the *actual* oxygen uptake data obtained was dependent upon the ability of the boxers to replicate their prior activity whilst attached to the system and does not provide information about the metabolic responses *during* performance. Nevertheless, the authors validated the post-exercise measurements of $\dot{V}O_2$ finding no significant differences between the approach adopted to overcome practical constraints to gas analysis in boxing and that of continuous measurements of $\dot{V}O_2$. Therefore, the findings of Arsenau et al. (2011) likely approximate the aerobic demand during some boxing exercises and the post-exercise method of gas analysis could be used to provide useful data to inform a boxer's preparation.

Further scrutiny of the Arsenau et al. (2011) study reveals that the gym-based sparring yielded mean heart rates (91.7 ± 4.3 % of maximal heart rate (HR_{max})) and blood lactates (9.4 ± 2.2 $mmol·l^{-1}$) that were significantly higher than the 'simulated' laboratory-based sparring, although the punching frequency was consistent ($P > 0.05$) across conditions (35.7 ± 9.9 and 34.9 ± 7.1 $punches·min^{-1}$) for the gym and laboratory sessions, respectively. This implies that the intensity during the gym environment is higher, and that the $\dot{V}O_2$ measured during the laboratory simulation (43.4 ± 5.9 $ml·kg·min^{-1}$) is an underestimate of the 'true' value of sparring (Arsenau et al., 2011) despite efforts to replicate the external demand between conditions. Thus, factors other than the number of punches performed influence the consequent physiological demands with the ability to manipulate punch forces (Hall & Lane, 2001) and the additional psychophysiological demands (Moreira et al., 2012) potentially explaining this observation. Moreover, that Arsenau et al. (2011) observed increases in heart rate across the simulated rounds, suggests a concomitant progressive increase in oxygen demand.

Interestingly, the $\dot{V}O_2$ data reported specifically for pad-work (41.1 ± 5.2 $ml·kg·min^{-1}$) was analogous to those reported for a simulated Muay Thai boxing match (42.5 ± 2.2 $ml·kg·min^{-1}$), where fist punches, elbows, knees, kicks and defensive blocks were performed using pads over 3 x 3 minutes (Crisafulli et al., 2009). However, within Arsenau et al.'s (2011) study, the differences between sparring and pad-work-induced heart rate, blood lactate, rating of perceived exertion (RPE), $\dot{V}O_2$, and percentage $\dot{V}O_{2peak}$ were all non-significant ($P > 0.05$). Of note though, was that punching frequency was considerably higher during pad-work (61.4 ± 7.9 punches·min^{-1}) than sparring (34.9 ± 7.1 punches·min^{-1}; $P < 0.05$). This form of boxing exercise is widely used by the amateur boxing community in the preparation of boxers for forthcoming bouts and, whilst it might not be physiologically dissimilar to sparring, it is acknowledged that the amount of punches delivered has to be higher in pad-work in order to facilitate this (Hickey, 2006). Indeed, it is plausible the external demand during non-competitive boxing training must be higher than competitive situations if it is to induce a similar internal physiological load, as research has demonstrated that there is an increased stress hormone response owing to the psychological state of boxers in anticipation of competitive boxing (Obminski, Stupnicki, Eliasz, Sitkowski, & Klukowski, 1993), and this response raises the physiological response for a given intensity. Nevertheless, the pad-work performed in the above study cannot be said to have replicated the demands observed during sparring as participants were reported to have performed only four separate combinations in a predetermined routine, with no mention of footwork or defensive actions. Where pad-work was arranged to replicate competition via high-intensity 8 x 1-minute rounds (Smith, 1998, cited in Smith, 2006), blood lactate values similar to those reported for competition (> 9 mmol·l^{-1}) were observed.

The findings of Arsenau et al. (2011) serve to highlight the moderate-to-high aerobic demand placed upon amateur boxers during various boxing-specific exercises. Of these, sparring produces the largest aerobic demand, followed by pad-work and the various intensities of punching a punch bag. More potent, however, is the realisation that when these exercises are not performed in the boxer’s ‘natural’ environment, lower physiological responses (heart rates and blood lactate concentrations) are produced.

2.6 The contribution of anaerobic energy provision

Whilst a high aerobic capability may be advantageous in training and competition, success in the sport, given its periodically explosive nature, undoubtedly demands a contribution from the anaerobic component of energy provision (Ghosh et al., 1995; Guidetti et al., 2002; Smith, 2006; Ghosh, 2010; Davis et al., 2013b). Such glycolytical turnover is evidenced by post-contest blood lactate values in excess of 9.5 mmol·l^{-1} (Ghosh et al., 1995; Smith, 2006; Ghosh, 2010; Davis et al., 2013a, 2013b; Hanon, Savarino, & Thomas, 2015), which are similar to other combat sports, such as wrestling (10 – 15 mmol·l^{-1}; Yoon, 2002; Karnincic, Tocilj, Uljevic, & Erceg, 2009), taekwondo (3.4 – 14.1 mmol·l^{-1}; Bouhlel et al., 2006; Butios, & Tasika, 2007; Bridge et al., 2009; Matsushigue et al., 2009), modern and Olympic forms of Wushu (4.4 - 12 mmol·l^{-1}; Ribeiro, de Castro, Rosa, Baptista, & Oliveira, 2006; Artioli et al., 2009), mixed martial arts (15 ± 4.4 mmol·l^{-1}; Amtmann, Amtmann & Spath, 2008) and judo (12 ± 1.8 mmol·l^{-1}; Degouette et al., 2003; Franchini et al., 2011). The differences across these sports reflect the varying durations and work-to-rest ratios of exercise, the fitness and ability levels of the athletes, and the different actions required during competition.

The above post-exercise values are considerably higher than reported for other intermittent, high-intensity sports, such as tennis (1.8 – 2.8 mmol·l^{-1}; Fernandez-Fernandez, Sanz-Rivas & Mendez-Villanueva, 2009), elite rugby union match-play (4.7

– 7.2 $mmol \cdot l^{-1}$; Deutsch, Maw, Jenkins & Reaburn, 1998), female and male basketball match-play (3.2 – 6.8 $mmol \cdot l^{-1}$; Matthew & Delextrat, 2009; Narazaki, Berg, Stergiou & Chen, 2009; McInnes, Carlson, Jones & McKenna, 1995) and elite football players (2 – 10 $mmol \cdot l^{-1}$; Bangsbo, 1994; Bangsbo, Mohr & Krustrup, 2006; Bangsbo, Iaia & Krustrup, 2007), suggesting that amateur boxing is performed at a higher intensity. Given its relative brevity (i.e. 6 – 9 minutes versus 90 minutes in soccer), boxing likely affords an increased reliance upon anaerobic sources of energy provision as the deleterious effects of such high-intensity exercise (i.e. fatigue) can be maintained for a comparatively shorter duration (Gastin, 2001; Cairns, 2004; Robergs, 2001; Robergs, Ghiasvand, & Parker, 2004). This supposition is reinforced by the critical power construct relating exercise intensity to the time-to-exhaustion (McLellan & Cheung, 1992; Jones, Vanhatalo, Burnley, Morton, & Poole, 2010) such that sports involving relatively brief contest durations result in significant anaerobic contributions. Indeed, given the frequent need to produce high forces when punching (Smith et al., 2000) and perform other actions at a high intensity (i.e. defences and footwork), Davis et al. (2013b) estimated anaerobic energy yield during six minutes of amateur boxing to be 23%. Therefore, the ability to maintain exercise intensity without suffering the potential deleterious effects associated with intra-muscular pH decline and lactate increases would be advantageous in an activity such as boxing.

In addition to a well-developed anaerobic capacity, the fractional utilisation of $\dot{V}O_{2max}$ before the onset of H^+ and/or blood lactate accumulation might be a fundamental concern in boxing performance (Khanna & Manna, 2006). Although defined differently across studies (Svedahl & MacIntosh, 2003; Faude, Kindermann, & Meyer, 2009), this intensity relates to the ‘lactate threshold’, or the accumulation of blood lactate up to a predetermined level (e.g. onset of blood lactate accumulation (OBLA) defined as 4 mmol·l^{-1}) or a distinguishable point at which production of lactate and/or H^{+} outweighs the rate of clearance of muscular metabolites (Jones & Carter, 2000; Billat, Sirvent, Py, Koralsztein, & Mercier, 2003; Faude et al., 2009). Exercise intensities at or above these thresholds are accompanied by non-linear increases in metabolic, respiratory and perceptual strain (Jones & Carter, 2000) often resulting in exercise cessation. Notwithstanding the obvious necessity for amateur boxers to possess high aerobic capability to meet the energetic demands and facilitate recovery between rounds (Davis et al. (2013b), the boxer with the higher lactate threshold could potentially maintain a high exercise intensity whilst avoiding or delaying the accumulation of fatiguing substances.

Guidetti et al. (2002) found that individual lactate threshold (expressed in ml·kg·min^{-1}) to be the strongest determinant of successful amateur boxing performance (r = 0.91, P <0.01). However, lactate threshold expressed as a percentage of $\dot{V}O_{2max}$ (78.4 ± 2.6 %) was *not* related to successful amateur boxing performance. This suggests that it is those individuals with both a high $\dot{V}O_{2max}$ and high absolute lactate threshold who have an advantage. Using 2 and 4 mmol·l^{-1} to define aerobic and anaerobic threshold intensities, respectively, during treadmill running, Smith (2006) reported the only other known values for boxers performing laboratory lactate threshold tests. At 2 mmol·l^{-1}, the boxers were running at a mean velocity of 10.4 ± 1.5 km·hr^{-1}, with a corresponding heart rate of 151 ± 10 b·min^{-1} and $\dot{V}O_{2max}$ of 2.7 ± 0.4 l·min^{-1}. At OBLA (4 mmol·l^{-1}; Faude et al., 2009), they were running at a mean velocity of 13.4 ± 1.1 km·hr^{-1}, with a corresponding heart rate of 174 ± 8 b·min^{-1} and $\dot{V}O_{2max}$ of 3.42 ± 0.52 l·min^{-1} (68% $\dot{V}O_{2max}$). Taking OBLA as the point above which an individual begins to rely heavily upon anaerobic sources of energy provision, the lactate threshold was determined as 86 ± 6% of $\dot{V}O_{2max}$. Whilst the use of a fixed blood lactate concentration provides an objective means of determining the corresponding exercise intensity, and 4 $mmol \cdot l^{-1}$ may represent an equilibrium between muscle and blood lactate, it ignores individual variability and may not provide valid measures across different modes of exercise (Svedahl & MacIntosh, 2003). Nevertheless, the lactate thresholds reported for amateur boxers are high (78.4 and 86% $\dot{V}O_{2max}$) relative to typical values of between 50 – 80% $\dot{V}O_{2max}$ in highly trained individuals (Jones & Carter, 2000).

2.7 Nutrition and weight loss in amateur boxing

In addition to the physiological profile, it is also important that the nutritional status of a boxer is monitored given that competitors often reduce body mass in the period preceding a bout (Hall & Lane, 2000; Smith et al., 2000; Smith et al., 2001; Smith, 2006). For example, in senior international male boxers mean body mass 21 days pre-competition was 6.9% (range: 6.0 – 8.3%) above competition weight (Smith, 2006). Attempts to reduce body weight below a ‘natural’ mass are concerned with reducing adipose tissue and body fat values of 9.1 ± 2.3 % suggest low body fat content is desirable in amateur boxers (Smith, 2006). This is also the case for professional boxing (Morton, Robertson, Sutton, & MacLaren, 2010) and many other weight-classified combat sports whereby a majority of athletes (56-100% of athletes across various combat sports) engage in weight loss procedures (Franchini, Brito, & Artioli, 2012) in anticipation of gaining a physical and psychological advantage over an opponent (Hall & Lane, 2001; Smith, 2006). Providing muscle mass and physical/physiological ability are maintained, reducing adiposity and thus body weight *could* improve performance, increasing physical/physiological ability when expressed relative to body mass

(Sundgot-Borgen & Garthe, 2011; Sundgot-Borgen et al., 2013). However, the proposed benefits are seldom realised and body weight reductions are characteristically detrimental to many aspects of performance (e.g. endurance, high-intensity, strength, power) and health (Fogelholm, 1994; Sundgot-Borgen & Garthe, 2011; Sundgot-Borgen et al., 2013) because methods used to induce such losses are inappropriate. Still, it appears the desire to reduce body mass remains prevalent (Franchini et al., 2012) and so the ability to detect performance decrements represents an important endeavour.

Typically, reductions in mass are achieved during gradual (7 - 21 days) and rapid phases (< 7 days) (Fogelholm, 1994; Smith et al., 2000; Smith, 2006) using 'active' (i.e. increased or excessive exercise) and 'passive' (i.e. restricting energy and fluid intake and heat exposure to impose sweating using saunas, additional layers of clothing or vapour impermeable suits) methods (Smith, 2006). More severe approaches include the use of diet pills, laxatives, diuretics and self-induced vomiting (Sudgot-Borgen et al., 2013). Gradual weight loss is accomplished through the attainment of negative energy balance in the region of 500 – 1,000 kcal·d^{-1} (Fogelholm, 1994); the methods employed to produce this deficit are primarily active with less emphasis upon passive practices (Smith, 2006; Franchini et al., 2012). During rapid weight loss, passive methods play an increasingly influential role (Smith, 2006; Franchini et al., 2012; Sundgot-Borgen et al., 2013) and athletes undertake such endeavours anticipating that the deleterious effects of rapid weight loss can be reversed during the period between weigh-in and competition (Lambert & Jones, 2010). In amateur boxing, this time period can vary greatly with regional to national ability boxers provided with 2 - 6 hours recovery whereas international competitions can include a 24-hour recovery period (Smith, 2006); it is unlikely the former situation provides adequate time to restore fluid and muscle glycogen deficits (Lambert & Jones, 2010). Consequently, rapid weight loss methods can negatively impact the health, biochemistry and performances of athletes and so gradual methods of weight loss are recommended (Fogelholm, 1994; Lambert & Jones, 2010; Brito et al., 2012; Franchini et al., 2012; Sundgot-Borgen et al., 2013).

An important physiological consequence of rapid weight loss concerns hypohydration and when water losses ≥ 2% of body mass are experienced, sports performance is often impacted, particularly during aerobic, submaximal exercise (Sawka & Noakes, 2007). Additionally, increasing levels of dehydration are associated with further declines in aerobic performance (American College of Sports Medicine (ACSM), 2007), meaning boxing performance, given its reliance upon oxidative phosphorylation (Davis et al., 2013b), could be reduced. The mechanisms by which aerobic exercise ability is reduced with hypohydration are unique yet multifaceted and likely act in an integrated manner (Sawka & Noakes, 2007). They include increased hyperthermia and cardiovascular strain typified by reduced total plasma volume, cardiac output and skeletal muscle blood flow and systemic and muscle oxygen delivery, altered muscle metabolism and central nervous system function and increased perception of effort (ACSM, 2007; Gonzalez-Alonso, Crandall, & Johnson, 2008; Sawka & Noakes, 2007). Moreover, hypohydration has also been shown to induce changes in brain morphology and intra-cranial volumes, so those athletes involved in combat sports involving high accelerations of the brain, are increasingly susceptible to concussive and contusive injuries of the brain (Dickson et al., 2005; Kempton et al., 2010, 2011).

Nevertheless, amateur boxing involves frequent, repeated actions typically performed at high intensities throughout the contest (Smith, 2006; El-Ashker, 2011; Davis et al., 2013a) and hypohydration is unlikely to reduce every physical and physiological component important to boxing performance (Smith et al., 2000). Research appraising the effects of hypohydration on high-intensity endurance (maximal intensity exercise lasting ≥ 30 s but ≤ 120 s) has produced inconsistent findings (ACSM, 2007; Judelson et al., 2007) owing to inter-study methodological differences whereby exacerbating (e.g. inadequate recovery from prior exercise used to induce hypohydration) and attenuating (i.e. use of endurance versus strength-trained individuals) factors have influenced the validity of findings (Judelson et al., 2007). Summarising data from 27 studies that did satisfy methodological concerns however, Judelson et al. (2007) concluded hypohydration likely impedes high-intensity exercise performance by ≈ 10% and hypohydration therefore limits aerobic and anaerobic energy provision important to boxing performance. Moreover, hypo-hydration is known to affect cognition, which may further impede boxing performance (Cian et al., 2000), though laboratory tests of cognitive abilities such as perception and reaction time might not transfer to competitive boxing performance.

That amateur boxing is also dependent upon anaerobic pathways of energy provision (Davis et al., 2013b; Gastin, 2001) suggests performance could be further impacted by weight loss because this can lead to depleted muscle glycogen stores (Fogelholm, 1994; Lambert & Jones, 2010; Brito et al., 2012; Franchini et al., 2012; Sundgot-Borgen et al., 2013). Given the ATP - PCr system is limited beyond 10 seconds (Bogdanis, Nevill, Boobis, & Lakomy, 1996; Gastin, 2001), glycolysis plays an increasingly important role in anaerobic energy provision, maintaining exercise intensity by converting blood glucose or muscle glycogen into three molecules of pyruvate, converting nicotinamide adenine dinucleotide (NAD) into the reduced form ($NADH^+$), thus liberating two or three ATP molecules if glucose or glycogen were degraded, respectively (van Someren, 2006; Jeukendrup & Gleeson, 2010). Although two or three ATP molecules appear a small yield, the high rate of breakdown compared to the oxidative system ensures a higher exercise intensity can be maintained in contrast to the oxidative system alone, and it also provides a more rapid means of energy whilst the cardiovascular system is adjusting to the demands, delivering oxygen to the working muscles (Jeukendrup & Gleeson, 2010). Moreover, blood glucose and muscle glycogen is typically available in abundance and so can make important contributions to high-intensity exercise. However, high-intensity exercise and low carbohydrate intake typical of energy restriction and weight loss are precursors for muscle glycogen depletion (Balsom, Gaitanos, Soderluind, & Ekblom, 1999), thus boxers might experience reduced stores, decreasing its availability for glycolysis.

Given that energy supplied via this pathway is of central importance to high-intensity exercise including that associated with boxing (Smith et al., 2000; 2001; Seigler & Hirscher, 2010; Hanon et al., 2015), depleted muscle glycogen stores could negatively affect performance (Balsom et al., 1999). Owing to a reduced availability of the substrate (i.e. muscle glycogen) for use within glycolysis, energy provision is comparatively reliant upon oxidative phosphorylation (which provides ATP at slower rates) and so performance is typified by reduced exercise intensities (Jeukendrup & Gleeson, 2010). Moreover, low glycogen stores also result in the earlier onset of fatigue because the rate of ATP resynthesis via fat oxidation cannot meet muscular demand because of the suppressed ability of carnitine to transport free-fatty acids into the mitochondria for oxidation (van Loon, Greenhaff, Constantin-Teodosiu,, Saris, Wagenmakers, 2001; Jeukendrup & Gleeson, 2010), or high levels of potassium reducing cell excitability (Lima-Silva et al., 2013).

To avoid such negative corollaries, combatting the decrements includes the use of tapering exercise programmes, providing the athlete with a high carbohydrate diet containing adequate energy and increasing fluid intake (Lambert & Jones, 2010). However, such practices result in body mass increases and thus negate the objective of reducing body mass to enter a weight classification below the athlete's natural body mass. The decision thus rests with the athlete and coaches and is based on the perceived benefit to sporting abilities related to success (Lambert & Jones, 2010). The techniques employed by weight-classified athletes have been passed from athlete to athlete, or coach to athlete and have changed little in ≈ 25 years (ACSM, 1996; Hall & Lane, 2001; Morton et al., 2010) and given this practice seems likely to continue, quantifying the negative effect of weight loss would appear useful.

To this purpose there have been several attempts to establish the effects of hypohydration and weight loss (restricting both fluid and energy intake) in combat sports (Degouette et al., 2006; Koral & Dosseville, 2009; Mendes et al., 2013), including amateur boxing (Smith et al., 2000, 2001; Hall & Lane, 2001). Although it appears lowering body mass can affect some physical and physiological capabilities, these changes have typically failed to reduce performance using sport-specific ergometry or simulations of bouts (Smith et al., 2000, 2001; Mendes et al., 2013). Still, given the prevalence of weight loss in amateur boxing (Smith, 2006), the use of simulations based upon unrepresentative exercise (i.e. circuit-training exercises; Hall & Lane, 2001) or dated performance (1994 Commonwealth games; Smith et al., 2000, 2001), a reappraisal of weight loss practices in amateur boxing using a simulation protocol that more adequately replicates the demands of the sport appears necessary.

2.8 An introduction to performance analysis of sport

Although physiological and nutritional assessments of training and competing in sport have provided valuable insights to the internal physiological response, relying upon laboratory-based assessments results in low external validity, describing only the internal load (Aanstad & Simon, 2013), and if physiological assessments are applied in the ‘field’, sports typified by a complex interaction of physical, psychological, technical and tactical components mean it is unlikely physiological measurements adequately characterise the *actual* demand (Drust et al., 2007). A method often utilised to overcome such limitations is to apply a performance analysis (c.f. referred to as ‘motion’ analysis where the motions of the athletes across the playing area is of interest; Drust et al., 2007). Whilst relying extensively upon video-based technology, the aim of such an approach is to enhance sporting performance through the analysis of the movements and the technical and tactical relationships exhibited between competitors or teams during competition or training (Hughes & Bartlett, 2002; O’Donoghue, 2005; Barris & Button, 2008). With an emphasis on producing valid and reliable data, ‘performance indicators’ are derived from theoretical models of performance which categorize an aspect of performance, thought to be of benefit, they should be clearly defined, relevant (James, Mellalieu, & Jones, 2005; O’Donoghue, 2010), and relate to, or discriminate, a successful performance or outcome (Hughes & Bartlett, 2002). Moreover, since coaches fail to accurately recall the exact events during training and competition (Laird & Waters, 2008), the output of performance analysis is typically used to supplement their understanding of the competitive environment, with a view to improving the provision of feedback and future performances (Franks & Goodman, 1986; Barris & Button, 2008; McGarry, 2009). Performance analysis has been frequently used (Lago, 2009) in many team sports including soccer (Reilly & Thomas, 1976; Bangsbo, Nørregaard, & Thorsoe, 1991; Bloomfield, Polman, & O’Donoghue, 2007; Rampinini, Impellizzeri, Castagna, Coutts, & Wisløff, 2009; Clark, 2010; Tenga, Kanstad, Ronglan, & Bahr, 2009; James et al., 2012; Pulling, Robins, & Rixon, 2013) and rugby (league and union) (McLean, 1992; Sykes et al., 2009; Sykes, Twist, Nicholas, & Lamb, 2011; Vaz, Mouchet, Carreras, & Morente, 2011; Kempton, Sirotic, Cameron, & Coutts, 2013), though its application is becoming increasingly popular in individual sports such as racquet sports (O’Donoghue & Ingram, 2001; O’Donoghue, 2009; Hughes, Burger, Hughes, Murray & James, 2013) and combat sports (Atan & Imamoglu, 2005; Nunan, 2006; Laird & McLeod, 2009; Bridge et al., 2011; Davis et al., 2013a).

When performance indicators are used to compare individuals or teams, their values should not be presented in isolation, such as the total occurrence of an action. Instead, indicators should also be expressed in relative terms, as ratios or percentages, to provide a measure of efficiency (Hughes & Bartlett, 2002). For example, a football team might be observed to have a high number of attempts on target, but expressing this indicator as a ratio of the total number of attempts at goal might modify the relationships observed, such that per shot on target, the team was performing worse. Moreover, it is necessary to relate the observations to those of a population of interest because data presented in isolation fails to provide adequate context to interpret such data (O’Donoghue, 2005; Mackenzie & Cushion, 2012). Accordingly, comparisons are drawn between groups in an attempt to appreciate the influence of factors that might influence competitive performance; to-date these have, for example, included match outcome (Jones, Mellalieu, & James, 2004, Cstaljay, O’Donoghue, Hughes, & Dancs, 2009), quality and rank of opposition (O’Donoghue, Mayes, Edwards, & Garland, 2008; O’Donoghue, 2009; O’Donoghue & Cullinane, 2011), match location (Taylor, Mellalieu, James, & Shearer, 2008), possession in invasion games (Bradley, Lago, Rey, & Diaz, 2013), match status (i.e. scoreline) (Redwood-Brown, O’Donoghue, Robinson, & Neilson, 2012), ability (Sirotic, Coutts, Knowles, & Catterick, 2009), weight (Bridge et al., 2011) and player position (James et al., 2005). Such information has provided valuable insight to the understanding of the competitive environment (Mackenzie & Cushion, 2012).

However, the research findings of performance analysis have been criticised on the grounds it is descriptive rather than explanatory (Glazier, 2010). Indeed, this is a condemnation made of sports sciences more generally, but a body of high-quality descriptive research should underpin any attempt to address a research question (Bishop, 2008). Another criticism often aimed at the majority of research in the area is that the key performance indicators and consequent findings often present outcome-based statistics that fail to consider the processes contributing to emerging patterns of performance (McGarry, 2009; Glazier, 2010; Mackenzie & Cushion, 2012). Such information could offer an explanation, as opposed to a description, of the findings of performance analysis research (McGarry, 2009). It is argued that the competitive environment of any sport is the consequence of collective interactions between players (McGarry, 2009) and cannot therefore be explained by the aggregate components of performance (e.g. passing, crossing, shooting in soccer). To this end, dynamic systems theory has been proposed as a viable framework from which emergent patterns of behaviour can be identified at the ‘inter-personal’ level (Perl, 2004; McGarry & Walter, 2007; Glazier, 2010), though it seems it is yet to replace the ‘reductionist’ approach to sports analysis.

Despite these criticisms, owing to the relationship between the external load (e.g. distance covered, frequency of an action) and physiological response to exercise (Gabbett, 2004; Lambert & Borresen, 2010), the results of performance analyses can also be used to provide sport- or position-specific training programs for athletes as they can provide an insight into the energy system(s) being utilised relative to the corresponding fundamental movement patterns (Del Vecchio et al., 2011; Franchini, Artioli, & Brito, 2013). Information about the work-to-rest ratios, sprint speeds and durations, the duration of rest periods and the frequency of directional changes and sport-specific movements and skills can be incorporated to allow the development of conditioning and simulation protocols employing an external demand representative of competition (Kingsley, James, Kilduff, Dietzig, & Dietzig, 2006; Bridge et al., 2011; 2013a; Waldron et al., 2013; Sykes et al., 2013). For example, following a quantification of the offensive and defensive demands of competitive taekwondo Bridge et al., (2011) developed a sport-specific simulation incorporating ‘fighting’ (i.e. turning kicks, pushes), ‘preparatory’ (i.e. bounces, slides and steps), ‘non-preparatory’ (i.e. active movement) activity and periods of inactivity (Bridge et al., 2013). Affording control of the exercise intensity amongst other parameters (i.e. timing of rest periods; e.g. Nicholas, Nuttall, & Williams, 2000), researchers then apply measures that would not be permitted during competitive performance (e.g. $\dot{V}$O, heart rate or blood sampling) to provide insight to the physiological demands of the sporting situation (Taylor, 2003; Dobson & Keogh, 2007; Drust et al., 2007).

2.9 Methods of performance analysis

The complexity of performance analysis can vary greatly (Randers et al., 2010). At the most basic level, manual video-based time-motion analysis (TMA) can be used to identify the motions of a sporting competitor during training or competition (Barris & Button, 2008). The typical process when appraising the motions of athletes involves the collection of video recordings of sports performance, with researchers attempting to objectively classify the movements of the contestants during the course of a game; the generated data often includes the frequency, speed and durations and the corresponding distances covered (Taylor, 2003; Bishop & Wright, 2006; Dobson & Keogh, 2007; Hurnik, Unierzyski, & O'Donoghue, 2008; King, Jenkins & Gabbett, 2009). Where applicable, some studies have also assigned a subjective intensity rating to the movement, which offers a potential insight into the physiological demand of the action (Bloomfield et al., 2004; Davidson & Trewartha, 2008; D'Auria & Gabbett, 2008; King et al., 2009). Likewise, notational analysis (NA) is often based upon manual video analysis addressing the use of sport-specific skills and their tactical application during match-play (Hughes & Bartlett, 2002). More recently however, it is argued any aspect of analysis of the competitive environment, regardless of the features of analysis, should be classified under the umbrella term 'performance analysis' (O'Donoghue, 2010), and there are calls to amalgamate such measurements in order to more fully understand sports performance (Glazier, 2010).

To-date, manual methods of performance analysis have provided useful data that has developed understanding of the competitive performance requirements (James, 2006) and made a positive impact upon players and coaches in the applied environment (Reeves & Roberts, 2013). Moreover, given its particularly applied nature it is sometimes the only sub-discipline able to apply measurements during *actual* performance (O'Donoghue, 2006). That is, video-based methods of analysis do not necessitate invasive measurements that are often forbidden, thus offering an externally valid representation of the competitive performance (Drust et al., 2007). However, whilst video-based, manual methods of data collection are convenient, inexpensive and practicable, they have several limitations.

The process of manual notational analysis is laborious, particularly when the desire is to assess a large number of performance indicators or competitors and researchers therefore tend to limit the scope of their analysis to a few individuals during a single sporting contest (Dobson & Keogh, 2007; Barris & Button, 2008). Clearly, this makes it difficult to generalise the findings across competitive situations, abilities and positions, and to other teams/competitors (Dobson & Keogh, 2007) as a 'typical' performance profile might not have been established (Hughes et al., 2001; O'Donoghue, 2005; Butterworth, O'Donoghue, & Cropley, 2013). Manual methods of performance analysis have also revealed low intra- and inter-observer reliability, which is problematic when attempting to assess systematic changes in performance (O'Donoghue, 2004; Drust et al., 2007; Carling et al., 2008).

Owing to these limitations, the development and application of semi- and fully automated systems has increased exponentially in recent years alongside the increased reliance upon technology in everyday aspects of life (Barris & Button, 2008; Carling et al., 2008; Mackenzie & Cushion, 2012). As athlete and coach feedback is an important goal in performance analysis, technology has enhanced its provision, increasing the quantity and quality of data collected during sports performance (Liebermann et al., 2002; Carling et al., 2008). Moreover, the collected data affords improved estimates of the motions of athletes compared to manual, video-based methods (O'Donoghue, 2004).

Still, the use of technological systems in performance analysis can be problematic owing to the expense involved, the lack of available computational facilities, the potential need for fixed cameras around stadia (Carling et al., 2008) and the situation-specific reliability and validity (Aughey, 2011; Bucheit et al., 2013). Moreover, many analysis systems also assume players move only in a forward direction, failing to detail sport-specific sideways or backwards movements, and they do not adequately detail physical contacts, skill execution or the sequence in which such exertions occur in combination with motion analysis (Carling et al., 2008); consequently automated systems still necessitate human operation to supplement automatically collected data. Such limitations question the validity with which semi- and fully-automated systems can characterise the demand of performance, particularly in sports where the demand is not predominated by the locomotive activity of athletes.

Despite such criticisms, the use of semi- and fully-automated systems is pervasive in elite sport (Scott et al., 2013) and the permission by national governing bodies for the use of GPS during competition, in addition to its portability, has further enhanced its appeal in motion analysis (Carling, et al., 2008; Aughey, 2011). GPS technology has been subjected to frequent assessments of reliability and validity under a number of conditions where the speed, distance and path taken during exercise has been manipulated (Aughey, 2011). Whilst earlier evidence suggested the reliability and validity of GPS estimates of speed and distance are reduced during movements performed at high speeds (Coutts & Duffield, 2008), along non-linear paths incorporating acute changes of direction (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010a) and for movements performed in confined playing spaces (Duffield, Reid, Baker, & Spratford, 2009), the advent of 10 Hz GPS units have improved the accuracy and consistency of GPS estimates (Aughey, 2011; Varley, Fairweather, & Aughey, 2012). Interestingly, 10 Hz units have also demonstrated improved accuracy and reliability compared to 15 Hz units (Johnston, Watsford, Kelly, Pine, & Spurrs, 2013), suggesting a sampling rate 'threshold' when estimating sport-specific ambulation. However, the additional 5 Hz in the units was achieved by supplementing 10 Hz units with tri-axial accelerometer data (Aughey, 2011; Johnston et al., 2013a) which have been reported to possess poor reliability (Bucheit et al., 2013).

Still, GPS technology is generally accepted as a useful means of assessing the physical demands imposed on players and it better avoids the subjectivity of activity coding (Dobson & Keogh, 2007). Importantly, this ensures the process is relatively non-laborious or time-consuming compared to manual motion analysis. GPS can also be synchronised with metabolic measurements (e.g. $\dot{V}$O, heart rate or blood sampling) to provide further insight into the demands of the movements (Larsson, 2003). Indeed, GPS has been applied to training and competitive environments assessing the external demands according to player position (McLellan, Lovell, & Gass, 2010, 2011; Cahill, Lamb, Worsfold, Headey, & Murray, 2013), ability (Gabbett, 2013a), opposition (Gabbett, 2013b), and has been used to document training load (Scott et al., 2013) and the fatigue response to an intensified period of matches (Johnston et al., 2013), evidencing its wide-ranging efficacy as a viable ergonomic tool in sport sciences.

Despite the obvious benefits of GPS technology to characterise the physical performance during team sports, they do not operate indoors, are affected by the timing of measurements (Larsson, 2003) and questions remain about their reliability and validity at high speeds (> 20 km·hr^{-1}; Varley et al., 2012) over short distances (Duffield et al., 2009; Jennings et al., 2010a, 2010b; Aughey, 2011; Waldron, Worsfold, Twist, & Lamb, 2011). Given the number of sports performed indoors, it therefore remains necessary to apply video-based manual methods of performance analysis. Moreover, for many sports it could be argued that the external demand of competitive performance is not determined by the locomotive patterns of athletes; instead, technical-based actions incorporating high force and speed production might represent the physical exertions with improved accuracy (Yoon, 2002; Bridge et al., 2011). Alongside the identification of external demand, this allows the skill-based behaviours and the strategic approaches of competitors or teams to be examined. Subsequently, comparisons can be drawn between for example winning and losing performances, different ability levels, playing positions and competition formats; often revealing important differences between such groups.

Regardless of the methods used during performance analysis, sport scientists, coaches and athletes ought to be aware that there tends to be a great deal of variation around the reported means (standard deviation or range) (Gregson et al., 2010) and this should be considered when utilising the data in both research and applied contexts. Whilst the reported means are typically utilised initially, in applying data to a conditioning or simulation protocol, it is important to prepare athletes for the ‘worst-case’ scenario (i.e. highest demand possible) (Dobson & Keogh, 2007, Amtmann, 2012) and training programmes ought to therefore incorporate the *range* of measurements recorded.

Moreover, protocols should be tailored to ensure they meet the needs of forthcoming competition according to independent variables such as the quality of opposition, match location and scoreline (Lago, 2012) otherwise they risk being unrepresentative of the competitive environment; this could lead to inadequate athlete preparation and assessment.

2.10 Performance analysis of boxing

Numerous individual sports have been subjected to performance analysis, including squash (McGarry & Franks, 1994), tennis (Hurnik et al., 2008; O'Donoghue & Ingram, 2001), canoeing and kayaking (Hunter, Cochrane & Sachlikidis, 2008), and middle-distance running (Brown, 2005). Likewise, combat sports such as karate (Nunan, 2006; Laird & McLeod, 2009), Greco-Roman and freestyle wrestling (Atan & Imamoglu, 2005), Judo (Dijkstra & Preenen, 2008), and taekwondo (Kazemi, Waalen, Morgan, & White, 2006; Wojtas, Unierzyski, & Hurnik, 2007; Kazemi, Casella & Perri, 2009; Kazemi, Perri & Soave, 2010; Kwok, 2012) have been scrutinised. Notably, information has emerged on the typical actions performed by winners and losers (Atan & Imamoglu, 2005; Laird & McLeod, 2009; Kazemi et al., 2009; Kazemi et al., 2010) and beginners and experts (Calmet, Miarka & Franchini, 2010). Currently, only two studies (El-Ashker, 2011; Davis et al., 2013a) have attempted a performance analysis of contemporary amateur boxing competition comparing some of the offensive and defensive demands made of boxers during elite and novice boxing, respectively. Two previous studies (Smith, 1998, cited in Smith et al., 2000; Smith et al., 2001) utilised video analysis of amateur boxing to reveal that an average of 108-112 punches were thrown each three minute round during elite level contests, with over half being thrown in five-second bursts of seven punches. However, the data relate to performances in the

1994 Commonwealth Games and World Championships and fail to provide any information regarding the frequency and types of defences and movements recorded during competition.

El-Ashker's (2011) study compared the technical performance aspects of winners and losers competing in an elite national event. These indicators included offensive (straight, hook and uppercut punches, lead and rear hand punches, the total number of punches directed to the head or body and the number of punches in combinations of ≥ 2) and defensive actions (arm, foot and trunk defences). Furthermore, the offensive and defensive movements were notated with regard to their effectiveness, that is, whether the offensive actions yielded a punch 'landing' upon the opponent target and whether the defensive actions prevented the opponent from landing a punch, and the 'efficiency' of the actions (i.e. percentage of actions deemed successful). A key finding was that the use of straight punches was the favoured method of attacking among the winners, who both aimed and landed more of these punches towards and upon the opponent's head than the losers. In contrast, the amount of straight punches aimed at the body differed only between winners and losers in round one, with a similar amount of straight punches landed to the body in both groups in rounds two and three. Accordingly, the author suggested amateur boxers should spend a considerable amount of time training and utilising these punches in competitive, non-contest situations (i.e. sparring). Hooks and then uppercuts were the next favoured methods of punching, but their frequencies did not differentiate the winners and losers across each round. Instead, the total number of punches thrown, independent of whether they landed or not, by winners was higher in every round (though only significantly so in rounds two and three; $P < 0.05$), as was the number of two and three-plus punch combinations. This suggests that an aggressive approach, with a high number of punches, thrown in combinations of ≥ 2, is desirable for success in elite Egyptian amateur boxing competition. With respect to defensive skills, El-Ashker (2011) reported no differences between winners and losers (for the total number of defences or the amount of defensive actions performed with the arms and trunk). Losers did perform more foot defences than winners, but in round one only. However, there was a more pronounced decline in the frequency of both offensive and defensive actions over the duration of the contest (especially between rounds one and three) for losers. Nonetheless, the winning boxers also displayed a reduction in their offensive and defensive outputs across rounds, suggesting that fatigue was common in both groups, albeit less marked among the winners.

Whilst novel, the findings in El-Ashker's (2011) paper are, however, questionable owing to several limitations of the study design. The 'winners' and 'losers' were not determined in conjunction with the real-time judges' decisions. Instead, they were determined on the basis of the number of successful punches landed, as notated by novice analysts. That is to say, the winners and losers referred to in the research were not necessarily the same individuals declared victorious by the judges. Consequently, El-Ashker's corresponding 'winning' and 'losing' performance profile may be inaccurate. In addition, the analysts were amateur boxing referees, who were relatively inexperienced in performance analysis. The three weeks of 'serious preparation' (El-Ashker, 2011, p.358) training they received might not have fully familiarised them with the notational process, and it is recognised that some individuals require more training than others (Hughes, Cooper, Nevill, & Brown, 2003). A final criticism of the study concerns the thoroughness of the reliability analysis conducted. Only three of the sixteen variables identified were subjected to intra- and inter-observer reliability analysis; the findings of the three cannot be assumed to apply to the remaining 13 given the dissimilarities between the actions (i.e. attacking and defending movements). Moreover, the statistical approach to reliability adopted by El-Ashker (2011) is also questionable given the application of a correlation coefficient (Atkinson & Nevill, 1998), parametric *t*-tests and typical error to assess absolute bias. That is, frequency counts used in performance analysis are often non-normally distributed and should be analysed accordingly (Cooper et al., 2007). El-Ashker (2011) failed to check the distribution of the data thus questioning the reliability of the data.

More recently, Davis et al. (2013a) completed a performance analysis of the demands in novice amateur boxing of three rounds, each two minutes in duration. Similar to the previous analysis (El-Ashker, 2011), winning boxers were found to perform a higher number of punches in total, land successfully more frequently and perform more combinations of punches; winning boxers also employed counter-attacks following a defensive action. Despite the depth of analysis (where offensive performance was concerned), the study was beset by similar limitations as the El-Ashker (2011) research. In particular, the outcome of the contest was again based upon the number of analyst-determined punches landed instead of the judges' decisions, and the outcome of intra-observer analyses was not reported despite the authors' admission that defensive actions were 'hard to categorize accurately'. Consequently, the winning and losing 'profiles' might not accurately reflect the *actual* performance of these sub-groups and Davis et al. (2013a) highlighted the extent of the issue stating that 19% of outcomes were not consistent with the judge-determined decision. The previous analyses have still contributed to the understanding of some of the performance requirements of successful amateur boxing. Yet, sports performance is known to vary according to a number of ‘situational variables’ (Lago, 2012) and it is therefore pertinent that future research reveals further influences upon performance, such as the weight class (Bridge et al., 2011) and gender of the athletes (Falco, Landeo, Menescardi, Bermejo, & Estevan, 2012) to better understand amateur boxing performance.

2.11 Reliability issues in performance analysis

Regardless of its sophistication, for performance analysis to have a valuable impact upon sport in general and its athletes in particular, the data generated needs to be valid and reliable. That is, the observation and subsequent classification of the performance indicators need to be comprehensive regarding the focus of the analysis and the act of recording such events needs to be reproducible (reliable). This is a requirement for the use of performance analysis data in all contexts, including academic, coaching, media and scoring applications utilised within sports (O’Donoghue, 2007). The use of a performance analysis system with low reliability may lead to erroneous findings, the adoption of incorrect training practices and sub-optimal tactics during competition. Additionally, reliability testing can be used to identify those analysts who require further training prior to using the system and can draw attention to performance indicators with low reliability regardless of the analyst. This potentially indicates a problem with the operational definition of a particular action or movement which can subsequently be reappraised to facilitate its identification (Hughes et al., 2003).

Owing to the reliance upon human operation within performance analysis, it is widely held that the data generated using this methodology is susceptible to errors (Drust et al., 2007; Barris & Button, 2008; Carling et al., 2008). Highlighting the limited reliability of manual performance analysis, O’Donoghue (2004) revealed wide 95% ratio limits of agreement (i.e. 1.05 x/÷ 34) for inter-observer reliability when appraising the motions of soccer players. Clearly, a worst-case error equating to 39% of a dependent variable would unlikely be sensitive enough to identify the often marginal gains or decrements associated with sports performance, particularly if one also considers the high within-athlete and match-to-match variability inherent in sports performance (Rampini, Coutts, Castagna, Sassi, & Impellizzeri, 2007; Gregson et al., 2010). Reliability assessments therefore provide an indication of the sensitivity of a measurement tool whereby systematic improvements, or decrements, in performance must exceed the combined bias and random error components of reliability (Atkinson & Nevill, 1998; Drust et al., 2007; Beckerman et al., 2001; Wilkinson et al., 2009a).

The characteristic assessment of reliability in performance analysis involves intra- and inter-observer methodologies (Drust et al., 2007). To establish intra-observer agreement, an individual analyses the same contest on two or more separate occasions, with a predetermined period of time in between the analysis (i.e. > 2 weeks between each analysis) to prevent analysts recalling how actions were previously defined (Williams, Hughes, O'Donoghue & Davies, 2007). The break between analyses minimizes the chances of the analyst assigning values to actions from memory. However, this method of reliability does not allow the system to be considered objective (O'Donoghue, 2007). A high level of agreement using intra-observer analysis simply demonstrates that the analyst can use the system consistently. However, the analyst's understanding of the events may not be the same as another individual's and therefore the system cannot be considered objective (O'Donoghue, 2007). For an analysis template to be objective, the system must be independent of individual analysts.

However, intra-observer reliability may demonstrate improving familiarisation and thus reliability for a single observer.

As a result of the limitations associated with intra-observer reliability testing, inter-observer agreement is the favoured method for demonstrating a performance analysis template as being objective and reliable. This entails the data of an individual's observation being compared across different analysts (Williams et al., 2007). The benefit of the method concerns the ability to utilise several observers with different levels of experience and knowledge of the sport. Providing acceptable reliability has been achieved, the system can therefore be shown to be independent of individual analysts. Furthermore, utilising analysts of different abilities (i.e. novice versus expert analyst) allows conclusions to be drawn regarding acceptable levels of error for different ability groups (Cooper et al., 2007). That is to say, acceptable levels of error for a novice may be equal to or less than ten percent, whilst an expert analyst should strive to record test-retest observations within five percent accuracy. Furthermore, this method can establish whether knowledge of the sport or actions being assessed is required for a reliable analysis. Williams and O'Donoghue (2006) established high levels of reliability when using two experienced netball players despite complex defensive actions requiring analysis concluding that an understanding of the behaviours being notated was essential and potentially more important than agreement of the wording of the operational definitions. Despite inter-observer reliability being hypothetically more important than intra-observer reliability in order to establish a system's objectivity and reliability, research has tended to report both forms to further demonstrate its efficacy for assessing sporting performance.

Recently, the issue of reliability in PA has justly received attention, notably with regard to the appropriate method of choice for establishing agreement between observations (O’Donoghue, 2007). Current recommendations for the most appropriate reliability statistic are disparate with advocates of Yule’s Q test (James, Taylor, & Stanley, 2007), the Kappa coefficient (Sim & Wright, 2005; Choi, O’Donoghue, & Hughes, 2007), a weighted Kappa statistic (Robinson & O’Donoghue, 2007), a visual plot of percentage error (Hughes, Cooper, & Nevill, 2002, 2004; Hughes et al., 2003), a standard percentage error statistic (Williams et al., 2007; Worsfold & Macbeth, 2009), a modified percentage error statistic with mean absolute error (Brown & O’Donoghue, 2007) and a method proposed by Cooper et al. (2007). However, numerous reasons such as the reliability statistic being too stringent or lenient, the methods not being applicable with various levels of data and the potential for certain reliability methods to conceal errors, means no universally accepted method exists for assessing the reliability of categorical (non-parametric) data, such as that typically generated during performance analysis.

Such non-conformity clouds the issue of which existing performance analysis models are indeed reliable and which technique should be employed when seeking to develop a new performance analysis template. Arguably, there is a need for consensus and standardisation. In this vein, the statistical approach described by Cooper et al. (2007) has virtue in that it is relatively simple to comprehend and is suitable for much of the data recorded in performance analysis which typically do not lend themselves to parametric statistical techniques (Hughes et al., 2002; Nevill, et al., 2002; Brown & O’Donoghue, 2007; Choi et al., 2007; James et al., 2007). Cooper et al. (2007) advocate a method which incorporates the non-parametric treatment of test-retest data (Bland &

Altman, 1999) and the recommendations of Nevill et al. (2001) that 95% of the observed differences should be recorded within a reference value thought to be of ‘no practical importance’. This latter point is particularly important as it necessitates analysts to be knowledgeable about the sport under scrutiny and accordingly come to a decision beforehand about how large the test-retest differences in the observations of their performance indicators need to be before they are considered ‘important’. Such an approach is closely aligned to recommendations that relate measurement error (both systematic and random contributions) to some analytical goal (Nevill & Atkinson, 1998). In effect, the decision on whether the analysis of the performance indicators is reliable is not dependent upon a statistic being above or below an arbitrary value but based on how many events are observed within pre-defined limits of acceptability (given that perfect agreement between test and retest is the analyst’s goal).

Cooper et al.’s tutorial focused on numerous performance indicators of a particular sport (rugby union) and demonstrated that their technique was sensitive to the level of expertise of the analyst. That is, a less experienced analyst was shown to be less reliable than someone with more experience. Whilst it was argued that such a technique was applicable to the field of performance analysis generally, regardless of the sport analysed, it has yet to be applied to a scenario other than the original one described. Nevertheless, the methods utilised within this approach allow a comprehensive, yet flexible assessment of the data sets with regards to acceptable levels of systematic and random bias producing individual reliability statistics for performance indicators separately as opposed to relying upon ‘summary’ statistics. This results in a more ‘sensitive’ analysis whereby those actions evidencing low reliability can be reappraised in order to improve the consistency of their identification.

2.12 Performance profiling

In addition to inadequate assessments of reliability within performance analysis (Hughes et al., 2002), there has also been a failure to fully appreciate several issues regarding the context in which a performance takes place, the observation of behaviours being unequal in merit and the relationships between behaviours and the corresponding outcomes (McGarry, 2009). Furthermore, the results have tended to be descriptive rather than explanatory (Glazier, 2010). For this reason, analysts have sought to develop systems capable of more extensively describing the behaviours and actions exhibited by athletes and teams during the diverse conditions of their sporting environments (Glazier, 2010). Early attempts utilised a stochastic approach to analysing and predicting the behaviours of competitors during squash match-play (McGarry & Franks, 1994). Using past data, the stochastic analysis presents a mathematical representation of the contest such that the probability of the transition from one state of behaviours (actions performed by competitors) to another state can be predicted. Whilst relative stability of behaviour was exhibited by squash players competing against the same opponent, the analysis was unable to predict future behaviours against different opponents, thus suggesting that performance during a sporting contest is context and time-dependent (McGarry, Khan, & Franks, 1999; Lames & McGarry, 2007), markedly dependent upon situational variables such as the quality and type of opponent (McGarry & Franks, 1994; O'Donoghue, 2009). Unlike sports where the outcome is dictated by physical and physiological determinants (e.g. endurance sports and $\dot{V}O_{2max}$, lactate threshold and running economy; Bassett & Howley, 2000; Midgley, McNaughton, & Jones, 2007), performance involving tactical interactions between opponents is inherently variable (O'Donoghue, 2005) and the presentation of a performance profile must undergo scrutiny if it is to be representative of the population of interest.

In presenting such profiles, researchers have tended to assume that the gathered data is representative of a ‘typical’ performance even though performance is inherently variable (Drust et al., 2007; Gregson et al., 2010) owing to the different contexts of performance (e.g. competing against different opponents or abilities). However, a proposed method for negating the influence of opposition effects, amongst other confounding influences, upon performance analysis data involves the establishment of ‘normative’ or ‘performance profiles’ (Hughes, Evans, & Wells, 2001; O’Donoghue, 2005; O’Donoghue et al., 2008; Butterworth et al., 2013) which are considered to better reflect features of sports performance.

Hughes et al. (2001) advocated the establishment of stable means over numerous games/contests allowing the results of such analysis to be presented as being more representative of a typical performance. The cumulative means (i.e. the total occurrences of the action divided by the number of contests assessed) are reported for individual indicators alongside the number of games required for these means to stabilise within acceptable limits of error (typically one, five and ten percent). When the cumulative mean lies within these predetermined limits of acceptable error, it can be concluded that the value is representative of a ‘typical performance’. Whilst the approach improved the objectivity of performance analyses, permitting identification of an adequate sample size (to establish stable cumulative means), the methodology has been criticised as it does not quantify the variability inherent in performance, merely calculating the mean on a match-by-match basis, and to be considered a ‘normative’ profile it should relate the data to a ‘reference population’ of interest from which comparisons can be drawn. Moreover, some performance indicators are unlikely to ‘stabilise’ at any point rendering the approach redundant in such instances (James et al., 2005) and it is important that athletes prepare for a range of demands including the ‘worst-case’ scenario to ensure adequate overload and hence a maximised training stimulus (Koutedakis, Metsios, & Stavropoulus-Kalinoglu, 2006).

Accordingly, O’Donoghue (2005) proposed an alternative approach for establishing performance profiles by including the mean values of the performance indicators along with the spread of the typical performance using the upper and lower quartiles of performance. These values were subsequently placed within percentiles generated from the performances of a large sample of competitors or teams (O’Donoghue, 2005). Typically, a radar chart is used to facilitate a comprehensive analysis whereby all indicators can be included on a single chart (Butterworth et al., 2013). In addition, the established performance profile can be manipulated to represent various competitive conditions (O’Donoghue et al., 2008). For example, a performance against a higher ranked opponent is likely to differ to that against a lower ranked opponent, and consequently the method allows the establishment of typical performance for various competitive conditions (O’Donoghue et al., 2008).

Finally, James et al. (2005) advocated a profiling method whereby the typical performance, alongside 95% confidence intervals, was identified thus providing an indication of where the *true* population value is likely to fall based upon the observations made and this should account for the changing contexts within which performance takes place. James et al. (2005) presented it as a viable framework for profiling performance using a rugby exemplar that revealed several position-specific requisites of performance. Together, the profiling methods of O’Donoghue (2005) and

James et al. (2005) offer a means to circumvent the contextual influences on performance, improving the applicability of performance analysis to competitive performance. Still, given the extent of performance variation both between and within athletes/teams the methods of profiling should provide additional information about the range of likely demands given particular confounding influences to ensure training and strategies are not based upon the typical performance or that including a narrow sub-set of performances (e.g. the inter-quartile range). For example, if the demands associated with the 75th percentile were adopted to characterise the 'likely' upper load of competition, and an athlete ensured training reflected such demand, there remains a notable probability that the actual demands of a given match could exceed those of the upper quartile. In this instance, the athlete is unlikely to have induced sufficient overload in training to meet the demands. Thus, athletes should utilise the entire range of demands to inform training preparing for the highest possible metabolic demands (Dobson & Keogh, 2007).

2.13 From performance to laboratory- and field-based analysis

However, while reliable descriptions of the competitive performance are worthwhile, it is also necessary to identify variables predictive of successful performance (Bishop, 2008) in an attempt to explain *why* performance might differ and this should involve a multidisciplinary framework providing a holistic assessment of the traits underpinning sporting performance (Glazier, 2010; Carling, 2013). As these traits can systematically adapt to training-based interventions or ergogenic aids (Drust et al., 2007), it has become customary practice to observe and quantify them during competition and pre- and post-intervention (Currell & Jeukendreup, 2008). For example, it might be that successful boxers perform more punches, also landing a higher percentage of these punches (performance analysis), but an assessment of aerobic capacity (physiological) and the speed of punch delivery (biomechanical) might be causally related to these aspects of competitive performance and the boxers would therefore benefit from training these components (Bishop, 2008). Moreover, reliance upon competitive data to establish intervention-based changes in performance may be problematic due to considerable match-to-match variations in physical performance (Drust et al., 2007; Gregson et al., 2010; Sykes et al., 2013). That is, if a boxer significantly improved his/her $\dot{V}O_{2max}$ a resultant increase in the physical exertions (i.e. number of punches) during competitive boxing might not occur. Accordingly, it is commonplace to employ relevant tests of physiological capacity that permit adequate methodological control and isolate a particular variable(s) of interest when evaluating the efficacy of interventions.

The physiological testing of athletes has increased exponentially in recent years (Impellizzeri & Marcora, 2009) on account of the perceived need to identify important aspects of performance, profile athletes, establish the efficacy of training programmes and provide support for using untested (anecdotal) training methods (Currell & Jeukendrup, 2008; Reilly et al., 2009). Such testing can be laboratory- or field-based, with the advantages and caveats associated with either condition fundamentally explained by the notion of specificity. Laboratory-based methods typically provide higher reliability yet lower ecological validity (Schabort, Hopkins, Hawley, & Blum, 1999; Svensson & Drust, 2005; Sirotic & Coutts, 2008), whilst field assessments tend to demonstrate lower levels of reliability yet higher ecological validity due to an enhanced specificity (Drust et al., 2007; Prins, Terblanche, & Myburgh, 2007; Reilly et al., 2009; Wilkinson et al., 2009a; Aanstad & Simon, 2013). The inclusion of both testing conditions, alongside match analysis data, over the duration of a training uni/mesocycle facilitates a comprehensive analysis of an athlete (Reilly et al., 2009).

The challenge associated with physiological assessments of athletes is to combine the experimental control of the laboratory environment with the ecological validity of tests performed using the sport-specific movements of the sport (Wilkinson et al., 2009a; Aanstad & Simon, 2013). Whilst early laboratory-based ergometers provided a valid method of assessing performance in linear, endurance sports and those with simple techniques (e.g. cycling), laboratory testing has failed to fully replicate the demands of competition for many sports (Currell & Jeukendrup, 2008; Nunan, 2009; Reilly et al., 2009). A lack of sport-specific ergometers largely explained this, alongside the variability in energy systems, muscle groups and skill performances (Drust, Reilly, & Cable, 2000). Accordingly, many ergometers have been developed since to enhance specificity in the laboratory (Reilly et al., 2009), replicating some of the movements associated with canoeing, ice-hockey, rowing, sailing, skiing, swimming and boxing (Smith et al., 2000; Ingham, Whyte, Jones, & Nevill, 2002; Cunningham & Hale, 2007; Holmberg & Nilsson, 2008; Reilly et al., 2009). This provides higher levels of ecological validity by facilitating the replication of the movement patterns employed during competition (Reilly et al., 2009; Wilkinson et al., 2009a). Whilst such an approach might afford reasonable predictions of performance in endurance sports, caution is still required when applying the results of such assessments to those of competitive game-sports, even where the mode of exercise is similar to the event (Reilly et al., 2009), as tests evaluating selected physical parameters do not reflect the match performance, which is the result of a complex interaction of psychological, biomechanical, physical, technical, tactical and contextual factors (Svensson & Drust, 2005; Drust et al., 2007; Currell & Jeukendreup, 2008; Aanstad & Simon, 2013). Yet, a low-to-moderate relationship between a physiological test and match performance might still be practically important (Drust et al., 2007).

Not surprisingly, a trend has emerged towards the development of field-based methods of evaluating player performance (Nunan, 2009; Reilly et al., 2009; Aanstad & Simon, 2013). As such tests improve the ecological validity of player assessments (Wilkinson et al., 2009a), particularly those not involving linear endurance exercises (Reilly et al., 2009), they are likely to provide more useful data for coaches and athletes during the design of conditioning programs. An additional consequence of their enhanced specificity is that they facilitate the identification of small, yet worthwhile changes in performance that may go unobserved when using non-specific testing protocols (St Clair Gibson et al., 1998; Wilkinson et al., 2009a). In many sports, there are a large amount of variables with complex interactions that determine success and it is through the replication of the specific movements, metabolic loads and tactical features of performance that the most valid assessment of performance takes place (Drust et al., 2007; Currell & Jeukendrup, 2008). For example, the competitive physical demand in a multiple-sprint team invasion game is composed of intermittent high (striding, high-intensity running, sprinting) and low (standing, walking, jogging) intensity exercise, sport-specific movements (e.g. jumping, shuffling, sideward and backward running) and frequent changes of direction (Bloomfield, Polman, & O’Donoghue, 2004; Hale & O’Donoghue, 2007). Appraising a soccer player’s physical ability therefore, a laboratory-based test might include a rudimentary analysis of his $\dot{V}O_{2max}$ using linear treadmill running, whereas field-based tests could incorporate concurrent assessments of endurance, agility and speed (Aanstad & Simon, 2013), offering improved ecological validity.

Still, the use of field tests during player fitness assessments does not guarantee adequate ecological validity (Aanstad & Simon, 2007). For example, a popular field test used to assess soccer-specific fitness is the Yo-Yo intermittent recovery test (Bangsbo, Iaia, & Krustrup, 2008). Whilst the test is reliable (Krustrup et al., 2003; Thomas, Dawson, & Goodman, 2006), possesses discriminant validity (Mohr et al., 2003) and is related to high-intensity distance covered during a competitive match (coefficient of determination, R^2, = 0.51; Krustrup et al., 2003), it does not replicate many of the internal and external demands of soccer performance (Aanstad & Simon, 2013). For example, the distance covered during Yo-Yo performance is typically < 2 km (Krustrup et al., 2003) and < 700 m lasting 10 - 20 and 5 – 15 minutes in duration, for IR1 and IR2 versions, respectively. Such values do not approximate those seen during match play (i.e. ≈ 10 - 12 km distance covered, 90 minutes duration (Stolen, Chamari, Castagna, & Wisloff, 2005; Di Salvo et al., 2007). Moreover, the test fails to replicate other demands associated with soccer match-play, such as the acyclic exercise intensity, irregular rest periods and frequent sport-specific movement patterns with and without a ball (Drust et al., 2000). Essentially, a test that isolates particular traits and subsequently relies upon the assumption that a 'high' level of performance during such assessment is indicative of improved sports performance is problematic. Whilst field tests afford a comparatively valid analysis of match-related aspects of performance in comparison to laboratory-based evaluations, they do not replicate the sports demands with adequate precision (Svensson & Drust, 2005; Drust et al., 2007).

2.14 Sport-specific simulations

Attempting to circumvent the limitations of laboratory and field-based assessments of physical and physiological aptitude, researchers have sought to develop sport-specific *simulations* of competitive performance (Drust et al., 2007). Their use typically satisfies the requirement for specificity during training and testing (Muller et al., 2000) and increases the ecological validity of player assessment by replicating the internal (physiological response) and the external load (physical movements) of competition (Mujika, McFadden, Hubbard, Royal & Kahn, 2006; Di Salvo et al., 2007; Drust et al., 2007; Carling et al., 2008; Wilkinson, 2009a). However, attempting to replicate both the metabolic and external physical demands in sports typified by dynamic, intermittent exercise patterns alongside the execution of frequent technical skills with adequate reliability and validity, is challenging (Van Rossum & Wijbenga, 1993; Wilkinson et al., 2009a).

Simulations are typically realised following an earlier identification of the external movement demands through performance analysis (Sykes et al., 2013; Bridge et al., 2013; Davis et al., 2013b). For example, Sykes et al. (2009) used Prozone$^{©}$ to record the total distance covered, work-to-rest ratios, and percentage time spent in specific locomotive categories both with and without the ball in play, subsequently informing a rugby league match simulation protocol (Sykes et al., 2013). Moreover, their development is worthwhile given the inability to obtain invasive measurements (e.g. $\dot{V}O_2$ and blood samples) during *actual* competition that could inform the conditioning practices of an athlete (Bridge et al., 2013). Additionally, considerable within- and between-match variability exists in the external demand made of players (O'Donoghue, 2004; Gregson et al., 2010) due to confounding situational variables impacting player performance, such as the quality and type of opposition (O'Donoghue et al., 2008; O'Donoghue, 2009), possession of the ball in soccer (Gregson et al., 2010), match status (i.e. current score; Redwood-Brown et al., 2012) and venue (i.e. home or away; Lago, 2012). Therefore, reliance upon competition data would prevent the identification of systematic changes owing to intervention-induced improvements or decrements in performance (Drust et al., 2007; Carling et al., 2008; Bridge et al., 2013; Waldron et al., 2013). Accordingly, simulations of performance typically regulate exercise intensity whilst permitting invasive and sensitive measurements that would identify *real* changes in performance. In this way, they can be used as part of an athlete's conditioning offering a replication of the demands of competition (Kingsley et al., 2006).

Moreover, they can and should be tailored to specific competitive situations thus potentially replicating a range of demands. For example, Waldron et al. (2013) modified the demands of a rugby league simulation, previously applied generically to rugby players of any position (Sykes et al., 2013), to better characterise the specific demands of interchanged players. Such changes resulted in a substantially different external and internal demand to the original protocol thus enhancing the ecological validity of the measurements. The development of increasingly specific simulation protocols appears to represent a fruitful area of research given the number of generic simulations currently in existence whilst application of simulations possessing enhanced ecological validity could also induce a more potent training stimulus providing applied benefits also.

Currently, team sport simulations include those developed in soccer (Nicholas, Williams, Lakomy, Phillips, & Nowitz, 2000; Bishop, Blannin, Robson, Walsh, & Gleeson, 1999; Drust et al., 2000; Nicholas et al., 2000; Rahnama, Reilly, Lees, &

Graham-Smith, 2003; Thatcher & Batterham, 2004; Oliver, Armstrong, & Williams, 2007; Mirkov, Nedeljkovic, Kukolj, Ugarkovic, & Jaric, 2008; Williams, Abt, & Kilding, 2010), rugby union (Roberts, Stokes, Weston, & Trewartha, 2010), rugby league (Waldron et al., 2013; Sykes et al., 2013), netball (Gasston & Simpson, 2004), volleyball (Sheppard et al., 2007) and water-polo (Mujika et al., 2006). For individual sports, they have been formulated for use in squash (Kingsley et al., 2006; Wilkinson et al., 2009a; 2009b), tennis (Davey, Thorpe, & Williams, 2003), taekwondo (Bridge et al., 2013), karate (Nunan, 2006), ju-jitsu (Moreira et al., 2012), Muay Thai boxing (Crusafulli et al., 2009) and amateur boxing (Davis et al., 2013b). Whilst earlier attempts to simulate the competitive environment were based upon general replication of the movement patterns of athletes (Nicholas et al., 2000), more recent attempts have included sport-specific technical actions, such as passing and shooting in soccer (Williams et al., 2010; Russell, Benton, & Kingsley, 2011) and offensive kicking actions in taekwondo (Bridge et al., 2013). The addition of technical actions increases the ecological validity of simulation protocols and reveals the impact of match-related changes in skilled performance (Zeederberg et al., 1996; Ali et al., 2007).

In prescribing training and assessments of performance, applied practitioners should attempt to maximise the concept of specificity (St Clair Gibson et al., 1998; Muller et al., 2000). Simulation protocols overcome the low validity of physical and physiological tests evaluating isolated athlete traits thereby affording an ecologically valid means of documenting the physiological response. Moreover, given the variability in physical performance and limited opportunity to quantify the internal demand of competition, simulations offer a means of detecting systematic changes in physical and technical performance owing to intervention, and may also be used during training to prepare athletes for match demands.

2.15 Measurement and evaluation aspects of performance assessment

Regardless of the actions incorporated to ensure ecological validity, it is necessary to quantify test-retest measurement error (i.e. reliability) as this is a pre-requisite to a test's validity (Atkinson & Nevill, 1998; Hopkins, 2000; Batterham & George, 2003). Moreover, the establishment of measurement error is crucial for estimating its sensitivity (Wilkinson et al., 2009b); that is, its ability to detect *meaningful* changes in the variable of interest. Typically, reliability is established via a quantification of measurement error when test conditions are repeated on two or more occasions (Atkinson & Nevill, 1998).

The reliability of a performance test is known to be influenced by the nature of the test (i.e. time-to-exhaustion, constant intensity and time-trial tests) and within a laboratory setting evidence suggests that assessments affording improved validity also possess increased reliability (Currell & Jeukendreup, 2008). Therefore, during laboratory-based assessments of endurance performance for example, time-trials have been advocated (Currell & Jeukendreup, 2008). However, in attempting to improve the validity of athlete assessments, there has been an increase in the use of field tests. A consequence of this approach is that field-based tests typically display reduced levels of reliability owing to diminished control of variables likely to influence performance (Drust et al., 2007; Reilly et al., 2009; Wilkinson et al., 2009a; Aanstad & Simon, 2013). Field-based assessments of performance that involve exercise to exhaustion have evidenced only moderate reliability (Krustrup et al., 2006), whereas those involving exercise intensity over a fixed duration typically present good reliability (e.g. Nicholas et al., 2000; Waldron et al., 2013; Sykes et al., 2013).

Unfortunately, not all simulation protocols have been subjected to assessments of the repeatability of the external or internal demands (Bridge et al., 2013; Davis et al., 2013b). Where the reliability of soccer performance tests *has* been assessed, for example, a generally favourable view for both skill performance and physiological simulations has been reached (Currell & Jeukendreup, 2008). During many of the available simulation protocols, the external demand is typically regulated, by an audio cue, and it therefore seems plausible that this improves the reliability of the external and internal physiological responses given the often reported close relationship between physical movements and the induced internal load (Lambert & Borresen, 2010). Perhaps this explains the apparent dearth of simulations subjected to test-retest assessments of reliability. Simulation protocols incorporating technical demands have reported questionable reliability (Williams et al., 2010). It appears that more should be done to establish the consistency of the external (where it is not closely regulated) demand and the consequent physiological response if simulations are to be confidently applied in the research or applied environments (Currell & Jeukendreup, 2008). This appears pertinent as one of the main purposes of developing a simulation is to avoid reliance upon match data when attempting to detect systematic changes in performance. That is, high performance variability between respective matches would make it unlikely a *real* change could be detected, unless a large sample size was at the researcher's disposal (Batterham & Atkinson, 2005), whereas the use of a simulation with controlled conditions would facilitate this.

Indeed, measurement error is composed of systematic bias and random error components (Atkinson & Nevill, 1998; Batterham & George, 2003) and quantifications of these components might increase the use of simulations in the applied environment. Systematic bias concerns non-random variations between trials in test-retest conditions (Atkinson & Nevill, 1998; Batterham & George, 2003), which can be positive or negative. For example, a learning effect may lead to systematically higher scores across trials whereas fatigue would cause diminished scores when compared to previous values. It is argued however, that a well-controlled study is sufficient to reduce systematic changes between trials and that a significant systematic difference between test-retest trials is indicative of tests performed under inconsistent conditions (Lamb, 1998; Hopkins, 2000). Random error results from several sources including biological (e.g. circadian rhythm) and mechanical sources (e.g. alterations in the calibration of equipment), in addition to inconsistencies in the measurement protocol (e.g. a lack of standardisation between trials) (Atkinson & Nevill, 1998; Hopkins, 2000), and it this component of measurement error that is most problematic because it reduces the ability of a test to detect *real* change. Referred to as the sensitivity of a test, the random variation should thus be quantified to identify the limits beyond which genuine changes in performance are likely to have taken place (Hopkins, 2000).

The most appropriate reliability statistic for assessing both components of measurement error has been an area for debate within medical (Bland & Altman, 1986), clinical (Rankin & Stokes, 1998; Bruton, Conway & Holgate, 2000) and sporting contexts (Atkinson & Nevill, 1998; Lamb, 1998; Hopkins, 2000). Advocates of the ICC (Fleiss & Cohen, 1973; Rankin & Stokes, 1998; Weir, 2005), 95% limits of agreement (95% LoA) (Nevill & Atkinson, 1997; Atkinson & Nevill, 1998; Lamb, 1998; Rankin &

Stokes, 1998; Lamb, Eston & Corns, 1999), CV% and standard error of measurement (TE; also known as typical error) (Batterham & George, 2003; Hopkins, 2000) exist. A consensus has not been established for the most appropriate reliability tenet within sports science despite the plaudits associated with the various methods. No individual measure is thought to provide a sufficient quantification of reliability and therefore a combination of methods may provide the best indication of relative and absolute reliability (Atkinson & Nevill, 1998; Bruton et al., 2000).

The preferred approaches for quantifying absolute agreement of ratio scale measurements are the TE, also expressed as a CV% and the 95% LoA. The CV% is a simple method that generates a dimensionless statistic facilitating comparison across measurement tools. It is calculated in several ways, though the simplest calculation would be to express the standard deviation as a percentage of the mean value (e.g. a mean power output of 400 ± 20 W would generate a coefficient of variation of 5%; Hopkins, 2000). However, the statistic assumes heteroscedasticity in the data and lacks practical meaning as arbitrary thresholds of 5 and 10% have been chosen to indicate acceptable reliability instead of being related to analytical goals (Atkinson & Nevill, 2001). The TE assesses the within-subject, random variation of repeated measurements. Smaller variation indicates improved reliability. It is calculated using the standard deviation of the test-retest differences (SD_{diff}) and is given by the formula: $SD_{diff}/\sqrt{2}$ *or* $SEM = SD\sqrt{1} – ICC$ (Atkinson & Nevill, 1998; Hopkins, 2000). However, the statistic only considers 68% of the sample's differences and fails to acknowledge the presence of heteroscedastic data, which is common in variables relevant to sports science.

The 95% LoA technique addresses the amount of agreement between repeated measurements (Bland & Altman, 1986; Lamb, 1998) and is calculated using the mean (bias) plus or minus the SD_{diff} multiplied by 1.96. The 95% LoA have been criticised as being excessively stringent and the conclusion of a measurement tool being reliable or not ultimately depends on the researcher's interpretation of the limits (Hopkins, 2000). However, the method has gained popularity within sports science. This is due to the numerous benefits associated with its use, including the observation that reliability is expressed in the actual units of measurement, displays the level of systematic and random error separately, is not vulnerable to sample heterogeneity and is easily related to analytical goals (Nevill & Atkinson, 1997; Atkinson & Nevill, 1998; Lamb, 1998). The method also has the benefit of providing a visual indication of systematic bias and random error using the so-called 'Bland-Altman plots'.

There is currently no 'gold-standard' reliability statistic with advocates both of the TE (particularly in conjunction with CV% and worthwhile change) (Hopkins, 2000) and 95% LoA (Nevill & Atkinson, 1998). Interestingly, the two are related statistics (Atkinson & Nevill, 1998; Hopkins, 2000), with TE and CV% providing a less stringent reflection of random error that includes 68% of the random variation instead of 95%, as is the case with 95% LoA. Researchers evaluating the reliability of a test should therefore consider the impact upon relevant analytical goals when selecting the more stringent 95% LoA or the comparatively liberal TE and CV% (Batterham & George, 2003). It would appear the 95% LoA are the more popular of the two statistics with a plethora of research employing the statistic (Baba, Nagashima, Nagano, Ikoma, & Nishibata, 1999; Pyne, Boston, Martin, & Logan, 2000; Peterson, Czerwinski, & Siervogel, 2003; Cooper, Baker, Tong, Roberts, & Hanford, 2005; Gamelin, Berthoin,

& Bosquet, 2006; Little & Williams, 2006). Recently however, application of the CV% to the *smallest worthwhile change* (Hopkins, 2000; Beckerman et al., 2001; Bucheit, Spencer, & Ahmaidi, 2010; Waldron et al., 2013) has emerged as a method which establishes the reliability of a variable and identifies the sensitivity of the measurement, an important characteristic of a tool as it establishes the minimum change necessary to establish that a *real* difference in performance has occurred (Currell & Jeukendreup, 1998). Essentially, the CV% has been used to set boundaries for meaningful change, relating the CV% to percentage changes in performance which are typically based upon effect size estimates and observed changes following intervention. Akin to relating the noise (variation) of a measurement to the signal (changes in performance), the expected changes must therefore exceed the associated noise to establish that a genuine change in performance has occurred.

Appropriate statistical methods for quantifying measurement error provide an indication of the efficacy of a measurement tool. The reliability of new sport-specific assessment tools and protocols must be quantified before being applied in sports and exercise science (Tong, Bell, Ball, & Winter, 2001). Furthermore, the contribution of systematic bias and random error separately provides important information with regards to the sources of diminished reliability and avoids generalising measurement error (Atkinson & Nevill, 1998). Improved reliability is associated with increased sensitivity to changes in performance. For example, using the 95% LoA to demonstrate, if $\dot{V}O_{2\text{max}}$ during a running assessment had a bias of + 1 ml·kg·min^{-1} and random error of ± 4 ml·kg·min^{-1}, the actual value obtained on the retest could be between + 5 ml·kg·min^{-1} to -3 ml·kg·min^{-1} of the previous value. Therefore, coaches and athletes should be satisfied or concerned if an athlete exhibits scores ≥ +5 or ≥ -3 ml·kg·min^{-1}. With wider limits, it makes it increasingly difficult to detect real or worthwhile changes due to training or detraining effects. Narrower limits mean smaller alterations in performance can be recorded (or noticed). In the above example, if the recorded $\dot{V}O_{2\max}$ was 40 ml·kg·min^{-1}, the random error represents 10% of the measurement. As mentioned previously, whether this is acceptable or not is a consideration for the interested researcher.

2.16 Validity and sport-specific simulation protocols

Although adequate repeatability across test-retest trials is important and a prerequisite for validity (Atkinson & Nevill, 1998), it does not in itself reflect a tool's practical efficacy. That is, a simulation *could* induce a physiological response that consistently underestimates the *actual* demand. Accordingly, it is necessary that the validity of the physiological response to a simulation protocol is assessed. Unfortunately, the criterion condition on which simulations are based is the competitive environment, which does not typically permit match-play physiological measurements during competition and is inherently variable match-to-match (Drust et al., 2007; Carling, 2013).

The approach of most research groups has therefore been to *assume* a valid internal physiological response occurs provided the external demands have been replicated (Davey et al., 2003; Kingsley et al., 2006; Waldron et al., 2013; Bridge et al., 2013; Davis et al., 2013b; Sykes et al., 2013), or approximate the demands of competition according to previous research (Bishop et al., 1999; Drust et al., 2000; Nicholas et al., 2000; Roberts et al., 2010; Williams et al., 2010; Chaabene et al., 2012). However, a *true* validation of a protocol would require the same participants to perform both a competitive match and the simulation (Drust et al., 2007); such an approach has been the exception (Thatcher & Batterham, 2004; Bridge et al., 2013).

In attempting to validate a taekwondo-specific simulation protocol Bridge et al. (2013) used previously collected data of the external demands during competitive taekwondo performance (Bridge et al., 2011). Accordingly, participants competed in a competitive bout and two weeks later performed the taekwondo simulation. Despite the similar external demand between conditions, significant and moderate-to-large effects in the physiological response to either condition were established, with the simulation inducing a reduced physiological response. The difference was attributable to a reduced ‘stress response’ evidenced by lower circulating adrenaline and noradrenaline (Bridge et al., 2013) during the simulation. Thus, for a given external workload it is erroneous to assume a representative internal physiological response under competitive and simulation conditions. Indeed, Arsenau et al. (2011) recorded a significantly lower physiological load when appraising similar external demands when comparing boxing sparring and a lab-based simulation of such sparring highlighting within boxing, the potential role of psychological stressors. This therefore questions the validity of all protocols, including those of boxing, relying upon previous analysis of the physical demands of competition to induce a valid internal load. Indeed, the association between external and internal demand is at times weak-to-moderate (Impellizzeri, Rampinini, & Marcora, 2005; Scott et al., 2013). Such a finding does not necessarily render a simulation worthless as researchers can manipulate the external demand accordingly if it is desirable to induce a valid metabolic response (Thorlund, Michalsik, Madsen, & Aagaard, 2008; Waldron et al., 2013).

2.17 Boxing-specific performance tests and simulation protocols

Similar to dynamic sports associated with unique actions and demands (Wilkinson et al., 2009a), amateur boxing has provided a challenge to physiologists attempting to replicate the sport’s competitive environment. Similar to other sports, perhaps this is partly responsible for a dearth of available performance tests and simulation protocols (Drust et al., 2007). This also seems surprising given the sport’s worldwide popularity (Smith & Draper, 2007), the high internal and external demand during competition and the added complexity of it being a sport classified by weight. To the author’s knowledge there have been attempts by only three research groups to develop amateur boxing performance tests or simulations (Smith et al., 2000; Hall & Lane, 2001; Davis et al., 2013b). Arguably, the ecological validity of all attempts to replicate the internal and external demands of the sport were questionable owing to the nature of the exercise performed during the test/protocol and/or the equipment used to assess performance. Hall and Lane (2001), in assessing the effects of rapid weight loss upon mood and ‘boxing’ performance, devised a circuit training task in conjunction with amateur boxers to mimic the demands of amateur boxing competition. However, their protocol, incorporating non-specific circuit training exercise (sequential ‘burpees’ and press-ups), does not mimic the demands of a sport involving frequent, repeated high-intensity sport-specific activity patterns involving punching, defensive manoeuvres and locomotive movements performed in isolation and amalgamations (El-Ashker, 2011; Davis et al., 2013a). This might explain why no differences were seen in test performance (i.e. number of performed burpees’ and press-ups) when performing the protocol pre- and post-rapid weight loss of 5.16% body mass. In addition, test validation was performed by questioning the amateur boxers as to the extent the protocol replicated the physical demands of competition, which lacks scientific rigour.

Smith et al. (2000) initially developed a boxing-specific punch force dynamometer to assess performance. The ergometer was able to distinguish maximal punch force between elite, intermediate and novice boxers for rear (elite: 4,800 ± 227 N; intermediate: 3,722 ± 133 N; novice: 2,381 ± 116 N; $P < 0.05$ between all groups) and lead (elite: 2,847 ± 225 N; intermediate: 2,283 ± 126 N; novice: 1,604 ± 97 N; $P < 0.05$ between all groups) hand straight punches. Possessing a tool with discriminant validity, a performance simulation was undertaken with the primary aim being to elucidate the impact of rapid methods of weight loss (i.e. 3 - 4% body mass reduction via dehydration, Smith et al., 2000; ≈ 3% body mass reduction through concurrent energy and fluid restriction; Smith et al., 2001) upon boxing performance. However, quantifications of the induced physiological responses were restricted to the customary measurements of heart rate and blood lactate levels and were not subjected to assessments of reliability and the validity of the internal physiological load seems questionable given the peak end of simulation heart rate was ≈ 183 $b \cdot min^{-1}$, and post-contest blood lactates were ≈ 6 $mmol \cdot l^{-1}$; both lower than the recorded maximum heart rate during sparring and post-bout lactates (Smith, 2006). Such discrepancies were established despite using novice boxers to simulate the external demands of elite competition, suggesting the induced internal load was invalid. Although the simulation involved sport-specific movements incorporating linear locomotive movements, punching and feigned defences, it was based upon aged analysis (1994 Commonwealth Games), questioning its ecological validity if applied to current boxers. Still, at the time it represented the most valid appraisal of the external and internal demands of elite boxing performance, providing eminent data concerning the high cardiovascular demand of the sport.

Following the identification of some of the external demands during competitive novice boxing bouts over 3 x 2 minutes bouts, Davis et al. (2013b) developed an amateur boxing simulation protocol and subsequently documented the aerobic and anaerobic responses to competitive amateur boxing using a metabolic gas analyser. The simulation revealed that 77% of energy provision was from aerobic sources whereas anaerobic alactic and lactic pathways contributed 19% and 4%, respectively. These findings questioned previous suggestions that boxing was characterised by anaerobic demand to the magnitude of 70 – 80 % of energy provision (Ghosh et al., 1995; Khanna & Manna, 2006) and provided eminent data that could inform a boxer's preparation for competition.

However, questions remain over the validity of the simulation as the external demands used during the simulation were informed by a performance analysis (Davis et al., 2013a) that evaluated intra-analyst reliability only and did not present the results of the reliability analysis, despite referring to problems in identifying actions during the analysis. Moreover, to document the locomotive actions of boxers, Davis et al. (2013a) identified an action referred to as VHM which is unlikely to reflect the external or internal demand of a boxer's movement during a bout. Additionally, several differences were also seen between offensive and defensive competitive and simulation performances (e.g. 2.5 times the number of defences in competition were incorporated into the simulation). Finally, the induced physiological response during the simulation did not undergo any assessment of reliability or validity in the manner mentioned previously, questioning the accuracy of the study's conclusions. Indeed, the low heart rate responses (e.g. peak heart rates < 174 b·min^{-1}) suggest the protocol failed to induce the desired internal load (Smith, 2006; Ghosh 2010; de Lira et al., 2013).

Alongside typical physiological measures such as heart rate, blood lactate and ratings of perceived exertion, a dependent measure of *performance* should be incorporated (Lenetsky, Harris, & Brughelli, 2013). This should possess the sensitivity to track changes in athletic performance and detect the smallest worthwhile effect (Currell & Jeukendreup, 2008). As an example, sprint performance has been utilised as a dependent measure in several protocols assessing team player fitness (Nicholas et al., 2000; Oliver et al., 2007; Sykes & Twist, 2011; Highton, Twist, Lamb, & Nicholas, 2013). This facilitates an assessment of systematic changes in performance owing to conditioning and nutritional interventions (Currell & Jeukendreup, 2008; Reilly et al., 2009). Due to the multi-faceted nature of competitive boxing performance, dependent measures of performance have been difficult to establish. Nevertheless, in the sport of boxing where the fundamental means of affecting the outcome of a contest is through the application of punches (Lenetsky et al., 2013), the amount of force produced when punching appears a logical choice and has been frequently used as a measure of boxing performance. This has included direct measurements of the impact forces generated between a boxer's glove and object (e.g. wall mounted force plate) whilst other studies have quantified the accelerations generated upon impact (Atha, Yeadon, Sandover, & Parsons, 1985; Smith et al., 2000; Smith et al., 2001; Walilko et al., 2005; Pierce et al., 2006; Smith, 2006; Beckwith, Chu, & Greenwald, 2007; Helmer et al., 2010; Stojsih et al., 2010; Piorkowski et al., 2011). Accelerations are recorded based upon the Newtonian law (Force = mass * acceleration) such that for a given 'effective' mass, increased accelerations lead to higher punch forces. Where force has been the dependent variable, measures have been achieved using a punch force dynamometer (Smith et al., 2000; Dyson, Smith, Fenn, & Martin, 2005; Dyson, Smith, Martin & Fenn, 2007) and flexible force sensors located within the knuckle region of the boxing glove, and/or the fabric of the vests and head guards worn by competitors. Regardless of the method for recording force data, increased levels of force have been associated with higher ability groups and those deemed victorious within bouts (Smith et al., 2000; Pierce et al., 2006; Hahn et al., 2010). This seems intuitive since there is an obvious requirement for boxers to deliver forceful punches in order to register scoring blows, as determined subjectively by the ring-side judges, and potentially injure the opponent. As such measures of this variable possess discriminant validity (Impellizzeri & Marcora, 2009) simulation protocols ought to therefore quantify this aspect of performance to establish the magnitude of improvements or decreases in performance on account of interventions.

2.18 Conclusions

This review has discussed several pertinent aspects of the physiology associated with amateur boxing training and competition. In comparison to other sports there is a dearth of scientific knowledge describing and quantifying the necessary requirements of successful performance. However, it is clear that boxing significantly taxes both the aerobic and anaerobic (lactate and phosphocreatine components) energy systems (with mean heart rates typically > 170 $b \cdot min^{-1}$ and post-contest blood lactate > 9.5 $mmol \cdot l^{-1}$). Whilst informative, such data only provides information relevant to the internal physiological response and would fail by itself to prepare athletes for a competitive demand characterised by a complex amalgamation of physical, psychological, technical and tactical aspects. To this end, performance analysis has been shown to offer a viable framework to characterise many of the demands during sports performance and it has been used to describe some of the components of successful amateur boxing performance. However, previous to the application of a performance analysis it is necessary to establish the reliability and validity with which the actions and movements of the athletes can be identified. Whilst performance analysis has been used to contrast the movements and actions of different sub-groups, it has also been used to develop sport-specific simulation protocols which permit a controlled environment and invasive measurements; a necessary method of data collection if sport scientists are to detect systematic changes in performance owing to *genuine* changes in performance.

Previous attempts to simulate the external and internal demand of competitive amateur boxing have afforded some valuable measurements and findings, the likes of which would not have been possible during *actual* competitive boxing. However, the validity of all simulations remains questionable and even those protocols relying upon previous analyses of the external demands have failed to replicate the movement patterns and actions performed with necessary precision and the resultant internal load has underestimated the *actual* physiological response to amateur boxing performance. Accordingly, there remains a need to develop a simulation protocol that accurately reflects the external and internal demands of competitive amateur boxing in order that the effects of important interventions can be established. Given the dearth of research in the sport documenting necessary components of physiological fitness, alongside the potential deleterious effects associated with rapid weight loss (Hall & Lane, 2001; Smith et al., 2000; Smith et al., 2001; Smith, 2006), progress would seem timely. Moreover, the protocol could be used by boxers and coaches in the applied setting as a conditioning tool enhancing specificity, particularly if it were to replicate the highest demands observed, and it could also monitor fitness and changes owing to desirable (i.e.

conditioning, nutritional) and undesirable (i.e. rapid weight loss, inactivity owing to injury) changes in aspects of performance. To this end, it could identify ‘baseline’ values for a given performer or group of boxers (e.g. novice vs elite boxers) thus informing overload and progression within training identifying specific strengths and weaknesses relative to within- or between boxer comparisons.

Accordingly, the aims of the current research are to document reliably the external competitive demands of senior male amateur boxing competition and develop a reliable and valid simulation protocol that reflects *both* the external and internal demands of amateur boxing performance. Such a protocol could be used to invasively research the physiological responses to amateur boxing whilst maintaining adequate control of the experimental conditions. The decision to include only male senior boxing performance within the research was based upon the comparatively low participation rates by, and therefore access to, female amateur boxers. Given the consequent low sample size attainable, representative data for female boxing was unlikely to be gathered in the current research.

Chapter 3

The development of a reliable amateur boxing performance analysis template.

The contents of this chapter form the basis of the following publications and presentation:

Thomson, E., Lamb, K., & Nicholas, C. (2013). The development of a reliable amateur boxing performance analysis template. *Journal of Sports Sciences, 31(5),* 516-528.

Thomson, E., Nicholas, C., & Lamb, K. (2011). An assessment of the reliability of a new amateur boxing performance analysis template. British Association of Sport and Exercise Sciences annual conference, University of Essex, 6th – 8th September.

Thomson, E., Nicholas, C., & Lamb, K. (2011). An assessment of the reliability of a new amateur boxing performance analysis template [abstract]. *Journal of Sports Sciences, 29(2*), S22-S23.

3.1. Introduction

Recent changes to the scoring mechanism within amateur boxing (Amateur Boxing Association of England (ABAE), 2009; AIBA, 2008) mean that competitors now are rewarded an unlimited amount of points for landing blows (hits) of ‘sufficient’ force upon the opponent target area, whereas previously the scoring (and the outcome of a contest) was based on impressionistic judgements (Partridge et al., 2005; Smith, 2006; AIBA, 2008). This has subsequently led to alterations in the tactics of boxers within a contest and placed a greater emphasis on landing single, forceful blows from smaller combinations of punches (Smith, 2006) than throwing combinations containing many punches. In addition, the work-to-rest ratios for elite and ‘open’ class amateur boxers have been altered from 4 x 2 minute rounds to 3 x 3 minute rounds (AIBA, 2008), which is likely to have had an impact on the boxers’ activity patterns within rounds and the accompanying physiological responses.

Given the emerging pre-eminence of performance analysis, these variations to the sport provide an enticing opportunity for the development of a boxing-specific model that will inform coaches and their fighters in the manner established in other sports. Nonetheless, regardless of the sophistication of such an analysis, for performance analysis to have a valuable impact upon the sport in general and its participants in particular, the data generated needs to be valid and reliable. That is, the observation and subsequent classification of the characteristics of the sport (its ‘performance indicators’) need to be comprehensive and the act of recording such events needs to be reproducible (reliable). With such prerequisites satisfied, the analysis could be used to appraise performance according to a multitude of confounding influences and/or inform the external demands of a sport-specific simulation protocol.

The issue of reliability in performance analysis has recently been highlighted with respect to the appropriate statistical method for establishing agreement between test-retest observations (see section 2.11). In this vein, the statistical approach described by Cooper et al. (2007) has virtue in that it provides a comprehensive examination of reliability, yet remains relatively simple to understand and applicable to non-parametric data which often emerges within performance analysis (Nevill et al., 2002; Choi et al., 2007; Hughes et al., 2002; James et al., 2007). Although Cooper et al. (2007) evidenced the merits of the approach using a rugby union exemplar, it has yet to be applied to another scenario and thus its applicability to the field of performance analysis generally remains unknown.

3.1.1. Study aims:

(i) To present a performance analysis system for the assessment of the movement demands associated with an amateur boxing contest such that aspects of performance could be quantified and used to inform a sport-specific simulation protocol.

(ii) To assess, in the manner of Cooper et al. (2007), the reliability of the analyst(s) (operator) employing the system.

(iii) To determine the impact of the analyst's previous experience of performance analysis and amateur boxing upon the system's reliability.

3.1.2. Research questions:

(i) How consistently can the movement characteristics of amateur boxing be quantified?

(ii) Does the level of expertise (familiarity with the sport and with the processes of performance analysis) affect the consistency of the observations?

3.2 Methods

3.2.1 Classification of performance indicators

A boxer's performance in a given contest can be appraised simplistically in terms of whether it yielded a victory or a defeat, or more quantitatively in terms of the number of points accrued over the duration of a contest. Notwithstanding the significance of winning by stopping or knocking out an opponent, the events (actions) that lead to the awarding of points by the judges provide the justification and material for performance analysis. Such actions can be described in a typology that defines seven offensive and twelve defensive movements, and four feinting actions (see Tables 3.1-3.3, below), some of which can be identified as occurring in isolation and others in combinations. The quality of such actions can be noted with reference to their intended targets (on the opponent's body) and their outcomes (successful, undetermined or unsuccessful). It is notable here that the lead author, an experienced amateur boxer (25 previous contests) and coach within the sport (> 3 years) initially identified the performance indicators that influence a successful or unsuccessful performance and provided operational definitions for each. The validity of this process was strengthened via consultation with a senior ABAE coach and another experienced amateur boxer (25 previous contests).

In the context of this study, such performance outcomes were determined visually during post-fight video analysis. In essence, offensive actions were deemed as 'successful' when the attack/punch made visible contact with the opponent's target area, 'undetermined' when the attack/punch made contact with the opponent target area though was unlikely to satisfy the judging criteria regarding the awarding of points (e.g. the punch was partially blocked or deflected) and ‘unsuccessful’ when the attack/punch failed to make contact with the opponent’s target area. Although it was not possible to corroborate these outcomes with the judges’ points allocations, it was reasonable to presume that both ‘undetermined and ‘unsuccessful’ attacks/punches would not have yielded points, whereas ‘successful’ attacks/punches, in meeting the ABAE’s (2009) criteria for the awarding of points, would. Therefore, actions deemed to be ‘successful’ may differentiate a victory from a loss. The punches identified included the lead jab, rear hand cross, lead hook, rear hook, lead uppercut and rear uppercut (Table 3.1). Defensive variables were identified in the same manner. A ‘successful’ defence resulted in the attack/punch failing to land upon the target area, ‘undetermined’ defences led to the attack/punch making contact with the defendant though was unlikely to affect the score of the contest (e.g. punch lands upon defendant target area after being initially blocked/avoided), and an ‘unsuccessful’ defence resulted in the attack/punch making visible contact with the defendant’s target area despite his attempts to avoid the attack/punch. Moreover, ‘successful’ defences and ‘undetermined’ defences are unlikely to alter the contest score, whereas ‘unsuccessful’ defences might facilitate the awarding of a point to the aggressor. The following defensive variables were identified: block both arms, block lead arm, block rear arm, clinch, duck, foot defence, lean backwards, push, slip left, slip right, roll clockwise and roll counter-clockwise (Table 3.2). Furthermore, feinting motions, although potentially less crucial to the outcome of a contest, were identified as: lead hand, rear hand, head/body and foot feints (Table 3.3). The lead and rear hands were contingent upon the stance adopted by the boxer. That is to say, boxers adopting an ‘orthodox’ stance have the left hand as the lead hand and the right hand as the rear hand; ‘southpaw’ stances are the opposite to this.

Whilst an important facet of successful performance (Hickey, 2006), boxing-specific ambulation was not included within the template as pilot analyses established that the prospective key performance indicators, which were reliant upon manual analysis of the video recordings, lacked validity and reliability. Despite the intention to simulate the movement patterns of boxers in subsequent chapters the identification of appropriate dependent variables permitting accurate characterisation of the physiological demand of such movements was not possible. Unsurprisingly, owing to their dynamic nature (Carling, & Bloomfield, 2013), the consistency with which such movements could be identified was also limited. The decision was thus taken to omit locomotion from the analysis.

3.2.2 Design

An amateur boxing contest involving two male senior competitors (Light Middleweight, 67 – 71 kg) was chosen at random from a group of contests (*n* = 42) recorded as part of on-going research. All the boxers provided written informed consent for their fights to be recorded and their performances to be analysed subsequently by the lead researcher and his co-workers. Ethical approval for the study was granted by the Faculty of Applied Sciences Ethics Committee.

The contest was recorded with two digital cameras (Canon MV700, Japan) from two adjacent sides of the boxing ring at an angle of 90°. It was a 3 x 2 minute contest in a square ring (4.88 m^2) between a 23 year old male (24 previous contests, classed as a ‘novice’ boxer; boxer ‘A’) and a 21 year old male (45 previous contests, classed as an ‘open’ boxer; boxer ‘B’). Performance analysis was conducted post-contest and generally viewed at one quarter of normal playback speed (12.5 frames per second). However, the analyst was permitted to rewind the contest and watch events frame-by-frame if necessary. This was justified given the number of actions to notate (25), the speed and complexity of certain movement patterns, particularly those involving combinations, and the desire to capture accurately their outcomes. In the main, the contest was analysed with the footage from just one of the cameras, with the second camera being used to corroborate any event that was unclear from the first. In practice, the two camera angles were used interchangeably, depending upon the location and positioning of the boxers and the referee. The captured data were transferred to a personal computer and subsequently analysed using the Dartfish TeamPro software (version 4.0, Switzerland).

3.2.3 Contest analysis

For each boxer separately, the events were 'tagged' via the bespoke template (Figure 3.1) in a sequential manner (Figure 3.2), commencing with the offensive actions (Table 3.1) and feints (Table 3.3), followed by the defensive actions (Table 3.2). For each strategic offence observed, the overall target and outcome was identified, along with the total number of punches thrown. Thereafter, each individual punch within the attack was coded separately and similarly labelled with its target and outcome. This process was repeated for each strategic defence observed, a difference being the total number of punches *defended*. Where necessary, the analyst was permitted to code multiple, individual defences simultaneously, regardless of the number of oncoming punches. Additional actions or events occurring in the contest were also notated, that is, the round and its duration, the round and time at which the referee stopped the contest (to issue a warning for example), warnings issued by the referee (for ducking below waist line, excessive holding of an opponent, hitting while holding, dissent and miscellany), eight-second counts issued and the manner in which the contest was won (points verdict, referee stopped contest and knockout).

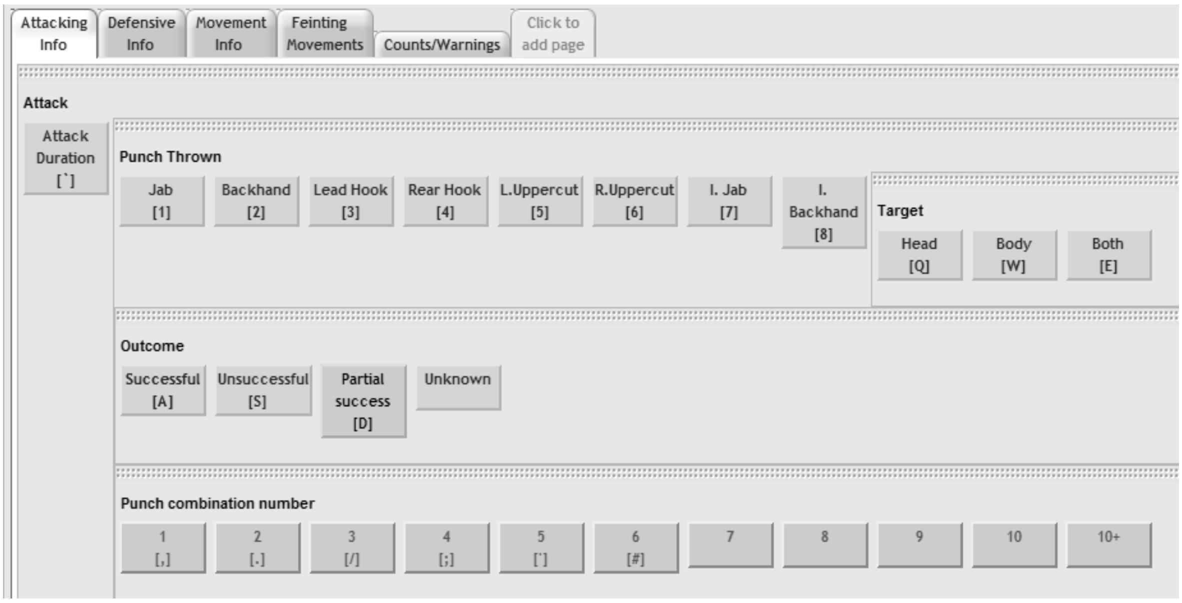

Figure 3.1. Dartfish analysis template for the coding of offensive behaviours.

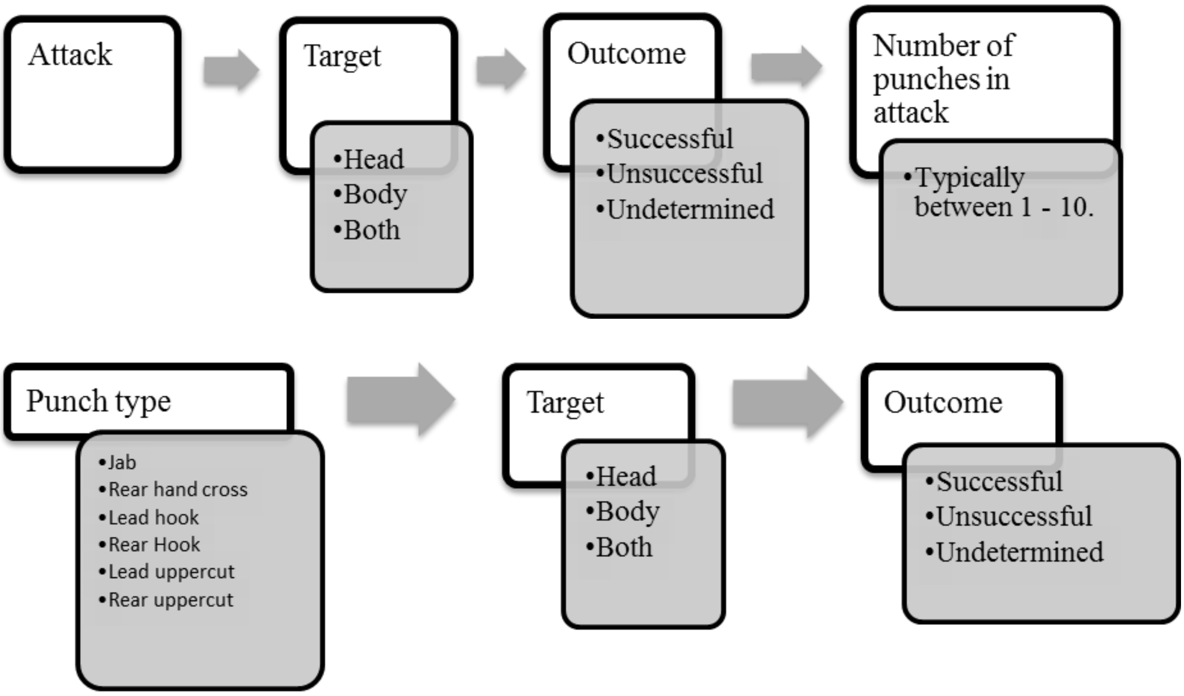

Figure 3.2. A schematic representation of how offensive actions were recorded.

Table 3.1: Boxing-specific offensive actions recorded.

Types of attack	Definition
Attack	Any punch or combination of punches performed by a boxer. This indicator is a continuous event in that the duration of the attack is recorded. A^1,A^2,A^3
Jab	A straight punch from the lead hand that moves along the sagittal plane (the central visual line) from anterior to posterior. A^1,A^2
Rear hand cross	A straight punch from the rear hand that moves along the sagittal plane (the central visual line) from anterior to posterior. A^1,A^2
Lead hook	A punch from the lead hand that moves along the transverse axis in a sideward ‘sweeping’ motion. A^1,A^2
Rear hook	A punch from the rear hand that moves along the transverse axis in a sideward ‘sweeping’ motion. A^1,A^2
Lead uppercut	A punch from the lead hand that moves along the sagittal plane and the longitudinal axis beginning with a downward projection and ending with an upward projection. A^1,A^2
Rear uppercut	A punch from the rear hand that moves along the sagittal plane and the longitudinal axis beginning with a downward projection and ending with an upward projection. A^1,A^2

Table 3.2: Targets of offensive boxing-specific actions.

Target of attack	Definition
Head (A^1)	A punch is labelled as being aimed towards the head if it visibly lands on the opponent’s head or misses the head of the opponent.
Body (A^1)	A punch is labelled as being aimed towards the body if it visibly lands on the opponent’s body or misses the body of the opponent.
Both (A^1)	Only attacks can be labelled as such. An attack is labelled as being aimed towards ‘both’ when the combination of punches involves at least one punch aimed towards the head and one punch towards the body.

Note: If a punch landed fully upon the arms of the opponent, the analyst made an inference as to whether the punch was destined to land upon the head or body target area, had the punch not been defended. * Each action was labelled with respect to its target (A1) **and** outcome (A2)**.**

Table 3.3: Offensive outcome classifications.

Outcome of attack	**Definition**
Successful attack/ punch (A^2)	A punch is labelled successful when it visibly lands on the opponent's target area. The punch must land directly with the knuckle part of a closed glove on any part of the front or sides of the head or body above the belt line of the opponent. For an attack to be labelled as such, at least one punch must be deemed successful.
Unsuccessful attack/ punch (A^2)	A punch is labelled unsuccessful when it visibly fails to land on the opponent's target area. For example, the punch may land clearly on the arms of the opponent or completely miss the opponent. For an attack to be labelled as such no punches must be labelled as successful or undetermined.
Undetermined attack/ punch (A^2)	A punch is labelled undetermined when it is partially blocked or deflected yet still lands on the opponent's target area making a visible impact. That is, the punch landed is not a clean punch. For example, a punch may partially land on the arm of an opponent yet still make some form of contact with the opponent's target area. For an attack to be labelled as such no punch should be deemed successful yet at least one punch should be deemed as undetermined.

Table 3.4: Boxing-specific defensive actions recorded.

Types of Defence	**Definition**
Defence	Any defence/ combination of defences performed by a boxer. This indicator is a continuous event in that the duration of the attack is recorded. D^1, D^2, D^3
Slip left	Movement of the head and/or trunk to the left in order to avoid a punch. D^1, D^2
Slip right	Movement of the head and/or trunk to the right in order to avoid a punch. D^1, D^2
Lean backwards	Movement of the head and/or trunk and/or flexion of the rear leg leaning the boxer's target area (predominantly the head) away from the attacker in order to avoid a punch. D^1, D^2
Duck	Movement achieved by flexion of the knee joints and/or trunk in order to lower the boxer's target area (predominantly the head) in order to avoid a punch. D^1, D^2
Role clockwise	Movement of the head and trunk whereby the boxer's target area (predominantly the head) is moved in a circular motion beginning with movement to the left. D^1, D^2
Role anti-clockwise	Movement of the head and trunk whereby the boxer's target area (predominantly the head) is moved in a circular motion beginning with movement to the right. D^1, D^2
Block/parry with lead arm	Movement of the lead arm whereby it deflects an oncoming punch away from the target area or placement of the arm over the target area so the punch lands on the arm instead of the target area. D^1, D^2
Block/parry with rear arm	Movement of the rear arm whereby it deflects an oncoming punch away from the target area or placement of the arm over the target area so the punch lands on the arm instead of the target area. D^1, D^2
Block both arms	Movement of both arms whereby the arms are positioned in a manner that attempts to cover the boxer's own target area so that the punch lands on the arm instead of the target area. D^1, D^2
Foot defence	Movement whereby the boxer transports his centre of mass away from the attacker to avoid punches directed towards them. D^1, D^2
Clinch	Movement whereby a boxer holds an opponent's body and/or arms with one or both of his arms to prevent or hinder the opponent's punches or movements. D^1, D^2

* Each defensive action was labelled with respect to its target (D^1) and outcome (D^2).

Table 3.5: Targets of defensive boxing-specific actions.

Target of defence	**Definition**
Head (D^1)	A defence is labelled as such if it was performed in order to protect the individual's head.
Body (D^1)	A defence is labelled as such if it was performed in order to protect the individual's head.
Both (D^1)	A defence is labelled as such if it was performed in order to protect the individual's body.

Table 3.6: Defensive outcome classifications.

Outcome of defence	**Definition**
Successful defence (D^2)	A defence is deemed successful if it led to the punch missing the target area or failing to visibly land on the target area.
Undetermined defence (D^2)	A defence is deemed undetermined if it the oncoming punch or punches initially blocked or avoided yet still made some form of contact with the defendants target area.
Unsuccessful defence (D^2)	A defence is deemed unsuccessful if it failed to prevent the punch landing on the target area.

3.2.4 Intra- and inter-observer reliability analysis

The full contest (three rounds) was analysed on two occasions four weeks apart by the lead author and subjected to intra-observer reliability analysis. Subsequently, his first round data (initial analysis) was used as a reference against which the performances of two other observers were compared, thereby enabling an assessment of the inter-observer reliability (agreement). The two observers were an amateur boxer (AB; 25 previous contests) who had no previous experience of performance analysis but was also an experienced boxing coach, and a knowledgeable performance analyst, though not previously of boxing. On different occasions, each individual was given the operational definitions of the performance indicators to read before being exposed to the test data in the Dartfish programme. Where necessary, clips of example boxing footage were shown to aid their understanding of the performance indicators. The task took approximately 5.5 hrs for AB and 4 hrs for the experienced analyst (excluding breaks).

3.2.5 Statistical analyses

The method proposed by Cooper et al. (2007) was used to quantify the intra- and inter-operator reliability of the performance analysis model described above. Whilst the reader is referred to their article for an in-depth explanation of this methodology, it originates from Bland and Altman's (1999) paper on assessing agreement when the distributions of the data do not satisfy the assumption of normality. The reliability statistics generated were for each boxer individually and likewise for each performance indicator.

A feature of the methodology proposed by Cooper et al. (2007) was their division of a selected sport performance (an 80-minute rugby union match) into discrete two-minute time cells, yielding approximately 40 cells (depending on the amount of over-time played) of data. This 'sample' of data was deemed sufficient to enable a worthwhile test-retest analysis in the absence of access to a large number of separate matches and the greater amount of time needed to analyse them. It was posited that for the performance indicators chosen (e.g. numbers of passes and tackles), such a time period was appropriate due to their relatively frequent occurrences and, implicitly, that there would be few, if any, 'empty' cells. Arguably, therefore, longer time cells would suit the analysis of infrequent events and/or longer sports performances (e.g. a three-day cricket match), and shorter ones for the analysis of rapidly occurring events and/or shorter performances (e.g. a boxing contest). Accordingly, a 10 s time cell (12 per round, up to 36 per bout) was chosen for the current study. However, since the reliability of the analyst, as determined by the statistical technique described below, is likely to be influenced by the length (and therefore frequency) of the cells in a given performance, this selection was given due consideration, relative to other durations (5, 20, 30, 40, 60 and 120 s) and the experience of the analyst (expert versus novice).

A median sign test was computed to assess the null hypothesis of no significant systematic bias between the test and retest scores (frequency counts) of each action. Subsequently, the observed proportion of agreement was calculated. This involved the *a priori* determination of the proportion of differences that was greater than some reference value deemed to be of no 'practical importance' (Nevill et al., 2001). Somewhat arbitrarily, Cooper et al (2007) selected a reference value of ±1 (actions) for their rugby data, but they acknowledged that the type and frequency of the performance data would have a bearing on the choice of this value. In the case of an amateur boxing contest, many offensive actions (punches) and defences are performed during a bout (e.g. >112 punches per round during a 3 x 3 minute contest; Smith et al., 2001) with the chances of a knockout blow resulting from a single successful attack/punch or unsuccessful defence being relatively small. Furthermore, the final number of points awarded to competitors is often less than 10 (European Boxing Confederation, 2011), implying that the frequency of specific point-yielding actions is low. On this basis, a judgement was made that the boxing analyst should strive for a narrow reference range (margin of error), in order to minimise the likelihood of missing one of the few, pivotal actions in a round/bout. Accordingly, Cooper at al.'s reference value of ±1 seemed appropriate in this context, along with a target of proportion of total agreement of ≥ 95%.

The degree of *perfect* agreement, *p*o, was calculated for each indicator as the correctly observed proportion (*r*) out of the total observed number (*n*) of the test-retest scores entered ($Po = r/n$), along with degree of agreement within the reference value of ±1. Approximate confidence intervals were then calculated for these proportions of agreement (upper 95% CI = $Po + (1.96 \times SE(Po))$; lower 95% CI = $Po - (1.96 \times SE(Po))$). The results described below pertain to boxer A, and unless indicated otherwise, can be assumed to be very similar to those for boxer B.

1.3 Results

3.3.1 Intra-observer agreement

The median sign test revealed no significant differences ($p > 0.05$) between the analyst's test and retest observations for the offensive performance indicators of boxer A (Table 3.7). The proportion of total agreement (Po) was between 95 – 100%. When the reference value of ± 1 was considered (Po ± 1), values of 100% in all cases were determined. When the outcome of each particular action (i.e. its 'success') of boxer A was considered separately to its mere occurrence, the proportion of agreement was often 100%, and no less than 92%. For Po ± 1, the agreement was 100% for all indicators. In addition, considering the target of the punches separately from the frequency of the action, the proportion of Po was 100% for actions aimed towards the head, 86% for those aimed to the body and 100% for those attacks including punches aimed to both the head and body. For Po ± 1, agreement was 100% for each target. Such findings regarding the action, target and outcome were largely representative of defensive data.

Table 3.7. Summarised intra-observer test-retest values for the offensive actions of the amateur boxer using 10 second time cells – boxer A.

Performance indicator	Median (sign test)	Po = 0 (%)	95% Confidence Interval (%)	Po ± 1 (%)	95% Confidence Interval (%)
Attack	*P* = 1.00	100	100 to 100	100	100 to 100
Jab	*P* = 1.00	100	100 to 100	100	100 to 100
Rear hand cross	*P* = 1.00	95	87 to 100	100	100 to 100
Lead hook	*P* = 1.00	97	92 to 100	100	100 to 100
Rear hook	*P* = 1.00	95	87 to 100	100	100 to 100
Lead uppercut	*P* = 1.00	97	92 to 100	100	100 to 100
Rear uppercut	*P* = 1.00	100	100 to 100	100	100 to 100
Inverted jab	*P* = 1.00	100	100 to 100	100	100 to 100
Inverted backhand	*P* = 1.00	100	100 to 100	100	100 to 100

Key: Po = proportion of total agreement; Po ± 1 = proportion of agreement within the reference value of ± 1; N/A = not applicable.

Table 3.8 serves to illustrate the non-parametric method for determining the reliability of test-retest data for individual performance indicators. In particular, it provides the Po for each indicator (e.g. Backhand PA = 35/37 = 0.95). Whilst a total of 27 backhands were recorded in both observations, indicating a reliable analysis, perfect agreement was not established with the analyst failing to record the same number of backhands during time cells 30 and 37. For the block with right arm, 36 time cells agreed, with only a single error occurring in time cell 34.

Table 3.8. Intra-observer reliability data for an offensive (backhands) and defensive action (block with the right arm) recorded by the expert analyst into the 36 ten-second time cells. Data represent boxer A only.

Cell number	**Backhand**	**Backhand retest**	**Backhand: same data in test retest**	**Block right arm**	**Block right arm retest**	**Block right arm: same data in test retest**
1	0	0	Yes	1	1	Yes
2	3	3	Yes	1	1	Yes
3	0	0	Yes	0	0	Yes
4	0	0	Yes	1	1	Yes
5	1	1	Yes	1	1	Yes
6	1	1	Yes	0	0	Yes
7	0	0	Yes	1	1	Yes
8	0	0	Yes	0	0	Yes
9	0	0	Yes	0	0	Yes
10	0	0	Yes	0	0	Yes
11	1	1	Yes	0	0	Yes
12	0	0	Yes	2	2	Yes
13	1	1	Yes	4	4	Yes
14	0	0	Yes	1	1	Yes
15	1	1	Yes	2	2	Yes
16	1	1	Yes	0	0	Yes
17	0	0	Yes	0	0	Yes
18	0	0	Yes	1	1	Yes
19	0	0	Yes	0	0	Yes
20	1	1	Yes	0	0	Yes
21	3	3	Yes	0	0	Yes
22	0	0	Yes	1	1	Yes
23	1	1	Yes	1	1	Yes
24	1	1	Yes	2	2	Yes
25	1	1	Yes	1	1	Yes
26	1	1	Yes	2	2	Yes
27	0	0	Yes	1	1	Yes
28	2	2	Yes	2	2	Yes
29	0	0	Yes	1	1	Yes
30	0	1	No	0	0	Yes
31	0	0	Yes	1	1	Yes
32	0	0	Yes	1	1	Yes
33	1	1	Yes	0	0	Yes
34	1	1	Yes	0	1	No
35	3	3	Yes	0	0	Yes
36	1	1	Yes	1	1	Yes
37	2	1	No	0	0	Yes
Total	**27**	**27**	**Yes = 35** **No = 2**	**29**	**30**	**Yes = 36** **No = 1**

3.3.2 Inter-observer agreement

3.3.2.1 Reference analyst versus AB analyst

The agreement between the analyses of the reference (lead author) and the AB was less impressive than that for the intra-observer reliability analysis, though it is noteworthy that there was no systematic bias between the observers for any performance indicator (Table 3.9). Moreover, total agreement occurred for the majority of indicators and for all indicators when the ±1 range was considered. When those actions identified in both the test and retest were analysed for the outcome, Po was 75–100% and 100% for Po ± 1. Moreover, Po was 92% and for Po ± 1 agreement was 100% when the analysts identified the target of the actions. Again, findings regarding the offensive actions, targets and outcomes were largely representative of defensive data.

Table 3.9. Summarised inter-observer test-retest values (reference versus AB analyst) for the offensive actions of the amateur boxer using 10 second time cells– boxer A.

Performance indicator	Median (sign test)	Po = 0 (%)	95% Confidence Interval (%)	Po ± 1 (%)	95% Confidence Interval (%)
Attack	*P* = 1.00	100	100 to 100	100	100 to 100
Jab	*P* = 1.00	100	100 to 100	100	100 to 100
Rear hand cross	*P* = 0.50	83	62 to 104	100	100 to 100
Lead hook	*P* = 1.00	92	76 to 100	100	100 to 100
Rear hook	*P* = 0.50	83	62 to 100	100	100 to 100
Lead uppercut	*P* = 1.00	92	76 to 100	100	100 to 100
Rear uppercut	*P* = 1.00	100	100 to 100	100	100 to 100

Key: Po = proportion of total agreement; Po ± 1 = proportion of agreement within the reference value of ± 1.

3.3.2.2 Reference analyst versus expert performance analyst

For all performance indicators there was no systematic bias between analysts (Table 3.10) and the degree of total agreement was 100% in most cases. . Where those actions identified in both the test and retest were analysed for the target and outcome, PA was 92–100% and 100% for PA ± 1. Appraising the reliability of the defensive actions, targets and outcomes, no systematic bias was established, PA was 92 – 100% and PA ± 1 100% for all performance indicators.

Table 3.10. Summarised inter-observer test-retest values (reference versus expert performance analyst) for the offensive actions of the amateur boxer using 10 second time cells– boxer A.

Performance indicator	Median (sign test)	Po = 0 (%)	95% Confidence Interval (%)	Po ± 1 (%)	95% Confidence Interval (%)
Attack	$P = 1.00$	100	100 to 100	100	100 to 100
Jab	$P = 1.00$	92	76 to 100	100	100 to 100
Backhand	$P = 1.00$	92	76 to 100	100	100 to 100
Lead hook	$P = 1.00$	100	100 to 100	100	100 to 100
Rear hook	$P = 1.00$	92	76 to 100	100	100 to 100
Lead uppercut	$P = 1.00$	92	76 to 100	100	100 to 100
Rear uppercut	$P = 1.00$	100	100 to 100	100	100 to 100

Key: Po = proportion of total agreement; Po ± 1 = proportion of agreement within the reference value of ± 1.

3.3.3 Effects of time cell duration on reliability.

It is apparent in Figure 3.3 that the percentage agreement (Po) declines with increasing time cell duration. Using 5 s time cells, agreement for the reference analyst was 71/73 (Po = 97%). However, this falls to 2/3 (Po = 67%) agreement if the contest was assessed round by round (1 x 120 s cell). Such disparity is more pronounced for the AB analyst, with agreement reaching zero percent when the time cell was ≥ 60 seconds. Therefore, if a 95% agreement threshold was utilised for acceptable reliability, time cell durations > 10 seconds would not be adequate for the expert analyst to investigate the amount of rear hooks thrown by the boxer in question. It is clear that the adjustment of time cells possesses the potential to enhance or decrease reliability.

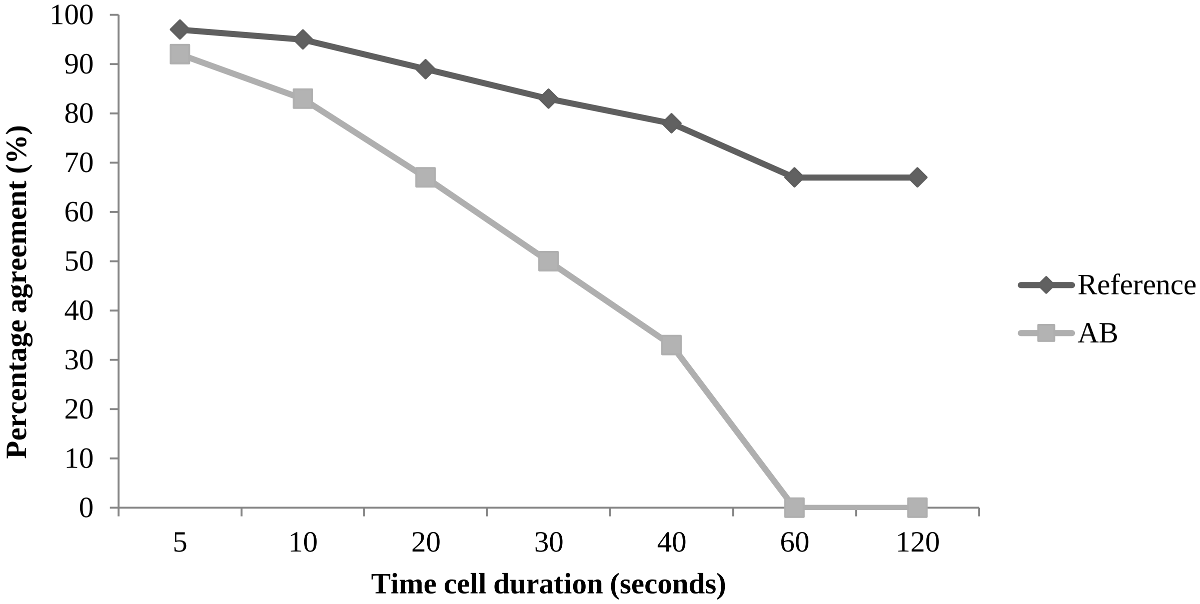

Figure 3.3. An example of the changing inter-reliability (for the reference and AB analysts) with altered time cell duration for the rear hook.

Figure 3.4 (below) highlights further how the degree of error (in this case, intra-operator) relates to the duration of the time cells. Where no error is observed (attacks), changing time cell durations has no impact. Where errors are observed, Po is ≥ 92% when using 5 s time cells; when using 120 s time cells, Po is between 67 - 100%. Moreover, the higher the error for a particular action (e.g. rear hook), the larger the decline in Po as cell duration increases.

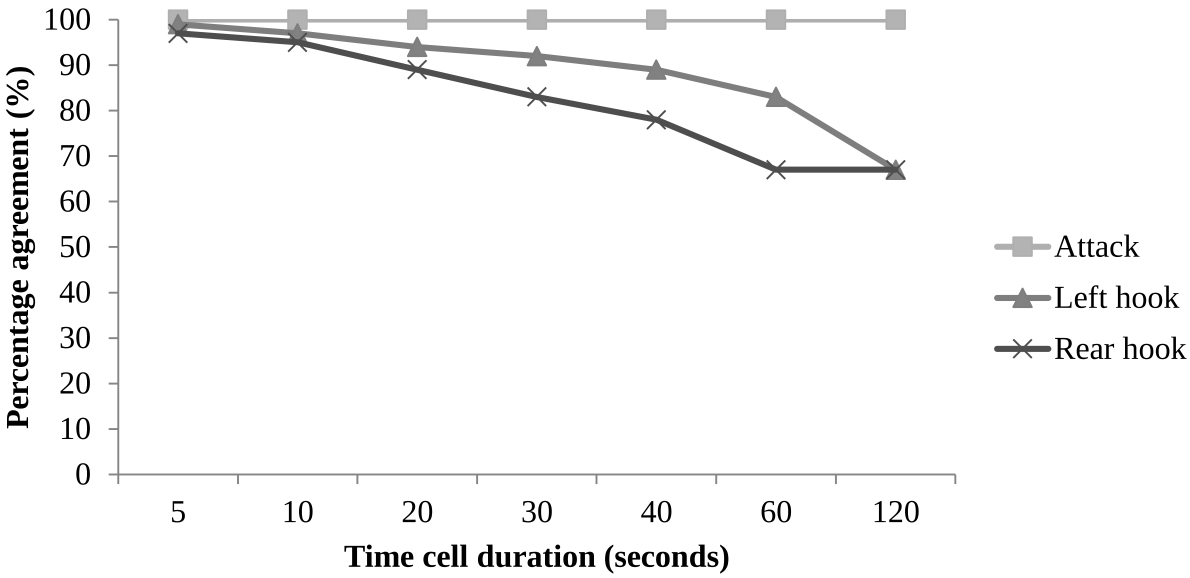

Figure 3.4. An example of the changing intra-reliability (reference analyst) with altered time cell duration.

3.4 Discussion

This paper has presented a unique performance analysis model (template) for amateur boxing and reported on its reliability through intra- and inter-observer comparisons. The template was established through content validity procedures by two experienced amateur boxers with coaching experience and an advanced level amateur boxing coach. This yielded the identification of 19 performance indicators (actions), with assignable values reflecting the intended target and outcome. In its current form the template is designed to be used via video reply post-contest of successive, discrete 10 s cells, and *not* specifically by a highly trained performance analyst.

In adopting an appropriate statistical approach for data of this kind, it emerged that the level of *intra*-observer reliability was excellent, with the test-retest frequency scores (of each time cell) for most indicators demonstrating 100% agreement, and better than 91% agreement across all indicators. When the pre-specified tolerance zone (reference value) of ± 1 counts was considered, all the performance indicators were notated accurately over the repeat trials. For the *inter*-observer analysis, the degree of perfect agreement was lower than intra-observer, but was nevertheless excellent for both the AB and the expert analyst, with all but one indicator showing 100% agreement within the reference value of ± 1. It is clear that given adequate familiarisation with the performance template, an amateur boxing contest (filmed from at least two camera angles) can be reliably notated by individuals neither particularly experienced in boxing nor in performance analysis.

That the level of inter-observer reliability was somewhat inferior to the intra-observer reliability was not unexpected and has been observed previously in soccer (O'Donoghue, 2004; Tenga et al., 2009). It is plausible that this could be due simply to the observer's lack of familiarity with the analysis template and/or the sport of boxing, or a degree of imprecision in the operational definitions of the performance indicators (James et al., 2007). In the case of the latter, as the actions are performed in a very dynamic environment, any disparity between the number of observations was likely due to the misclassification of events, rather than not being coded at all. An example of this occurred when the AB coded two events as rear hooks whereas the reference analyst coded them as rear hand crosses, producing four errors. Now whilst the operational definitions should be clear enough to distinguish between these two different punches, in certain situations they share many characteristics, making it very difficult to distinguish between them. Such an incidence is recognised as a recurrent problem in performance analysis (Hughes et al., 2003). Moreover, for certain indicators, the dynamic nature of the contest alone will inevitably lead to some errors both between, and within observers (Hughes et al., 2002; James et al., 2007) and it is reasonable to expect this.

Similar levels of reliability were seen in the two inter-observer conditions (reference analyst versus AB; reference analyst versus expert performance analyst) across most performance indicators, and demonstrates that the use of the template does not require expert knowledge of the sport's actions (i.e. expert performance analyst, limited amateur boxing knowledge) or expertise in performance analysis (i.e. AB, no previous performance analysis experience). This is probably because most of the actions identified are fundamental, gross movements that are easy to discern and notate.

It is interesting to note that inter-observer reliability was inferior (albeit, not substantially) to intra-observer when specific attention was afforded to the more qualitative aspect of the boxing performance, the outcomes (successful, undetermined or unsuccessful) of the individual actions. Whilst it has been previously postulated that more qualitative evaluations introduce error between observations (Tenga et al., 2009), in the current analysis this was only apparent between observers. That is, for intra-observer agreement, the level of reliability was very similar for the total frequencies of the actions and the outcome values assigned to them. For inter-observer agreement, there was some variability in the agreement proportions for the outcomes, though at a level not dissimilar to that for the quantitative indicators. Accordingly, our positive appraisal of the inter-observer reliability of the performance analysis was not diminished when the success of the actions was considered.

A distinctive element of the present study was the assessment of the impact of time cell duration upon the reliability analyses. When error was present for particular indicators (e.g. rear hook), an increase in time cell duration (yielding fewer time cells) was seen to augment the error (decrease the percentage test-retest agreement) via the calculation adopted, regardless of the observer. This was a consequence not of there being an increase in the absolute number of errors (over the course of the bout, this was a fixed value) as the sampling frame was increased, but because it reduced the number of cells that were in agreement relative to the total number of cells. Whilst this is simply an artefact of where the cell boundaries are placed (time-wise), the choice of time cell will directly affect the reliability statistics computed (including the estimate of the 95% confidence intervals) and how favourably they will be interpreted. Moreover, this will have a bearing on the comparability of the reliability statistics from studies involving other sport-specific templates, and in certain instances (involving 'similar' sports) there might be a case for standardising the time cell duration.

Another factor that could influence the magnitude of the reliability statistics generated by the current method is the occurrence of the actions, that is to say, regardless of an action having, for example, zero or ten test-retest agreements in a time cell, the analysis would generate the same outcome; agreement. Therefore, those actions that are recorded infrequently, or not at all, may demonstrate perfect reliability, whereas this might not be the case if the action was performed more frequently. Taking the lead uppercut as an example, the statistical analysis produced a Po of 36/37, or 0.97 (97%). However, of five potential agreements, only four were correctly identified. Using only those time cells where the action was performed, Po would be 4/5 = 0.8 (80%). This represents a relatively large decline in reliability for this indicator. Therefore, researchers assessing reliability using the current technique should be cognisant of the total frequency of the action before being certain of its reliability. It may be more appropriate to include only those time cells where the action actually occurred in either test or retest when calculating the proportions of agreement. Future research may establish best practice with regards to this issue.

The system proposed only assesses the offensive and defensive movement patterns of the competitors (though could be used to establish technical effectiveness also [i.e. proportion of actions deemed successful]). The performance of a competitor in any sporting contest is largely affected by the context, opponent and the dynamic nature of the sport (Grehaigne, Bouthier, & David, 1997; McGarry, Anderson, Wallace, Hughes, & Franks, 2002; McGarry, 2009; O'Donoghue, 2009; Tenga et al., 2009). This implies that the current template may not fully describe the movements or actions during amateur boxing contests. Future research in the sport may seek to explain the impact of various opponents and contexts upon amateur boxing performance given their presence in other sports (O'Donoghue, 2009).

The performance analysis system described in this paper is a somewhat laborious method of post-hoc analysis of amateur boxing contests, with 19 performance indicators, each requiring two or three further evaluations once identified. Therefore, the development of an analysis template with fewer performance indicators would be necessary if the goal was to analyse boxing contests in real-time (O'Donoghue, 2008). However, analysts should carefully consider what actions are appropriate for inclusion in a condensed template to ensure analysis remains informative to coaches and boxers.

Conversely, future research could expand the analysis template by including the movement/orientation of the boxers around the ring, and in doing so contribute to the development of a more comprehensive profile of an individual's performance. Although fundamental to boxing performance, facilitating offensive and defensive movements (Hickey, 2006), the boxing-specific motions were omitted from the current appraisal of performance as pilot analyses revealed that the potential key performance indicators lacked validity and could not be determined consistently when employing manual video analysis. Amateur boxing is habitually performed indoors and therefore GPS technology could not be applied to determine the motions of boxers. To this purpose, radio frequency-based systems which provide time-displacement data indoors might circumvent this issue providing valid accounts of boxing-specific movements (Rhodes, Mason, Perrat, Smith, & Goosey-Tolfrey, 2014).

Moreover, analysts should be cognisant that modifying the current template to describe additional characteristics of performance will likely increase the time required to analyse a contest and potentially make interpretation of data arduous. The inclusion of additional performance indicators would also necessitate further reliability assessments. Nevertheless, the system in its current form has the potential to elucidate the demands and movement patterns of amateur boxing competitors and therefore may inform the training and competitive practices of the amateur boxer. Research utilising the current template in the development of a boxing simulation performance protocol, intended as a sport-specific conditioning tool, is now ongoing.

This study has demonstrated that a novel performance analysis template can yield consistent (reliable) observations of the key movement characteristics occurring in a pre-recorded amateur boxing bout. Importantly, where a reference or ‘error’ limit ± 1 is set, the template can be used reliably by different operators, having varying experiences of performance analysis. Whilst the comprehensive nature of the current template (in terms of the number and type of actions recorded, their targets and outcomes) has rendered the process a rather lengthy one, the depth of the analysis in both quantitative and qualitative terms provides the basis for scrutiny by coaches seeking to identify specific markers of successful performances. Potentially, the template could be streamlined to facilitate a more rapid performance analysis, and indeed be readily adapted for the professional version of the sport. Moreover, the template has enabled the identification of most movement characteristics typical of boxing bouts (excluding the movement of the boxers around the ring). In the contemporary manner of other sports, such data could be transposed into a simulation protocol for the purpose of administering boxing-specific conditioning and monitoring the effects of performance-enhancing interventions.

Chapter 4

Performance analysis of competitive amateur boxing performance by contest outcome, weight classification and ability

The contents of this chapter form the basis of the following presentations:

Thomson, E., Lamb, K., & Nicholas, C. (2012). Performance analysis of winning and losing competitive amateur boxing performances. International Convention on Science, Education & Medicine in Sport, Scottish Exhibition & Conference Centre, Glasgow, 19th – 24th July.

Thomson, E., Lamb, K., & Nicholas, C. (2013). The offensive and defensive demands of competitive amateur boxing: A comparison of elite and non-elite performances. Annual congress of the European College of Sport Science, National Institute of Physical Education of Catalonia, 26th – 29th July.

4.1. Introduction

Since amateur boxing's inception under the auspices of the International Olympic Committee in 1902, the sport has experienced several rule changes (Bianco et al., 2013) that have enhanced the virtue of examining the specific actions performed during competition. In particular, changes to the scoring mechanism in 1992 (Bianco et al., 2013) mean that boxers are now awarded a single point when three of the five judges, within a single second, deem a blow of 'sufficient force' has landed upon the opponent target area (Hickey, 2006). Previously, scoring (and the outcome of a contest) was based upon impressionistic conclusions about which boxer had performed better over the duration of each round (Smith, 2006; AIBA, 2008). As a consequence, anecdotal evidence has suggested that amateur boxing performance has changed to accommodate this, with emphasis now placed upon the boxer landing single, forceful blows from attacks involving few punches (Smith, 2006), rather than throwing many punches in the hope that the judges would perceive s/he was being aggressive and dominating the round.

Despite its potential to assess the external demand of sports competition, performance analysis has been applied to amateur boxing only twice (El-Ashker, 2011; Davis et al., 2013a). However, both analyses are beset by several limitations thereby justifying the merit of further performance analysis of the sport. Interestingly, some empirical evidence (post-exercise blood lactate levels) reported by Smith (2006) implied that boxers competing in contests judged impressionistically exercised at a higher intensity (12.8 ± 3 mmol·l^{-1}) than those in contests employing the new 'computer' scoring method (9.5 ± 3 mmol·l^{-1}) over three 3-minute rounds. It was assumed that the volume of punches thrown during bouts prior to this rule change was responsible for this, reinforcing the anecdotal view of the boxing community that boxers now throw fewer punches than they did.

Another significant modification to amateur boxing in 2008 involved its duration; the contest being lengthened from eight minutes (4 x 2 minute rounds) back to nine minutes (3 x 3 minute rounds) as was the case pre-1996 for elite and national standard boxers. Such an increase, coupled with a decrease in the total in-fight recovery time (from three to two minutes), will have heightened the physiological demands of the sport and impacted upon the boxers' movement patterns, and possibly performance outcomes (win or loss). However, little is currently known about such demands, other than competitive situations require high aerobic and anaerobic contributions (Ghosh et al., 1995). Our understanding of the actions and movements that produce such a physiological response is limited.

El-Ashker (2011) and Davis et al. (2013a) compared some of the offensive and defensive actions of winning and losing competitors in elite and novice contests, respectively. Both studies concluded that adopting an aggressive approach with a high volume of straight punches, thrown in combinations of ≥ 2, was indicative of a successful outcome. Additionally, winning performance was associated with a high ratio of successful defences to total defences, whereas losing performances were characterised by the occurrence of 'fatigue', as defined by a drop in the frequency of offensive and defensive actions across the three rounds (El-Ashker, 2011). Moreover, counter attacking movements following defensive actions were also important to successful performance (Davis et al., 2013a). Notwithstanding the agreement between these studies, particular weaknesses in the design of each render such conclusions questionable. For example, that the intra- and inter-observer reliability of most (13) of the 16 performance indicators was not established in the El-Ashker (2011) research, raises doubts about the objectivity and reliability of the researcher's performance analysis template (O'Donoghue, 2007). Likewise, Davis et al. (2013a) assessed only 'internal consistency' and failed to report the relevant reliability statistics. Moreover, the 'winners' and 'losers' in both studies were not necessarily the same as those determined by the real-time judges as victory was designated by relatively inexperienced performance analysts simply on the basis of the number of successful punches landed by each contestant. Consequently, the winning (and losing) 'performance profile' might not have represented that of the *actual* winner (or loser). Indeed, the judges' decision in 19% (three of sixteen contests) of the bouts in the Davis et al. (2013a) analysis did not reflect that of the analyst-determined outcome, reinforcing such a reproach.

Whilst yet to be established, the profile of a 'typical' winning or losing amateur boxing performance will no doubt vary according to the boxer's experience and ability, and weight classification. Moreover, that lower ability (regional/ inter-regional) bouts are contested over six minutes within smaller boxing rings (14 ft [4.27 m^2] & 16 ft [4.88 m^2]) compared to that of higher ability boxing which typically involves bouts of nine minutes (three rounds, each three minutes) within larger rings (18 ft [5.49 m^2) & 20 ft [6.1 m^2]) suggests the contest format and ring might affect the demands associated with boxing. Given the impact of confounding influences in other sports (Mackenzie & Cshion, 2012), it seems plausible that 'situational variables' such as the outcome, weight class, ability and ring size would modify the competitive environment thus warranting consideration. Moreover, that performance within game sports is multifaceted (McGarry, 2009; Glazier, 2010) means the independent effects and the interaction between these variables should receive due cognizance (Taylor et al., 2008). Contest outcome aside, only anecdotal evidence exists that, for example, heavier boxers perform fewer actions overall than lighter boxers or that smaller ring sizes increase the offensive and defensive demands during bouts and it also plausible that the performance of heavier boxers compared to lighter boxers might be influenced differently when competing within smaller or larger rings.

4.1.1. Study aims:

(i) To provide a comprehensive analysis of the physical, technical and tactical demands of competitive amateur boxing.

(ii) To consider the impact of several contextual conditions on the demands; that is:

   a. Contest outcome (win, lose)
   b. Weight classification (‘light’, ‘middle’, ‘heavy’ boxers)
   c. Standard of competition (regional, national)

4.1.2. Research questions:

(i) What are the physical, technical and tactical demands of competitive amateur boxing?

(ii) How do the different contextual conditions of amateur boxing (i.e. contest outcome, weight classification, standard of competition) modify the demands of competition?

4.2 Methods

4.2.1 Participants

A convenience sample of amateur boxers was recruited between the months of February and June 2010, coinciding with ethical approval for the study and the cessation of the amateur boxing season, respectively. Moreover, the recorded contests were staged at boxing events accessible to the researcher, and thus within the North West of England, with verbal recruitment the employed strategy to enlist participant boxers when an event was attended by the researcher. This resulted in eighty-four English amateur boxers (mean ± SD) (age: 21.3 ± 3.1 y; body mass: 68.1 ± 11.4 kg; previous contests 24 ± 19 bouts) volunteering to take part in the study. The performances were distributed across all 10 weight classes (see Figure 4.1), two contest formats (six-minute bouts: three rounds, each two minutes, and nine-minute bouts, three rounds, each three minutes), three different sized contest rings (4.9, 5.5 and 6.1 m^2), and regional and national level competition (see Table 4.1). Regional level boxing consisted of inter-club contests whereas national level bouts were those contested within the 'elite' national championships (ABAE, 2007).

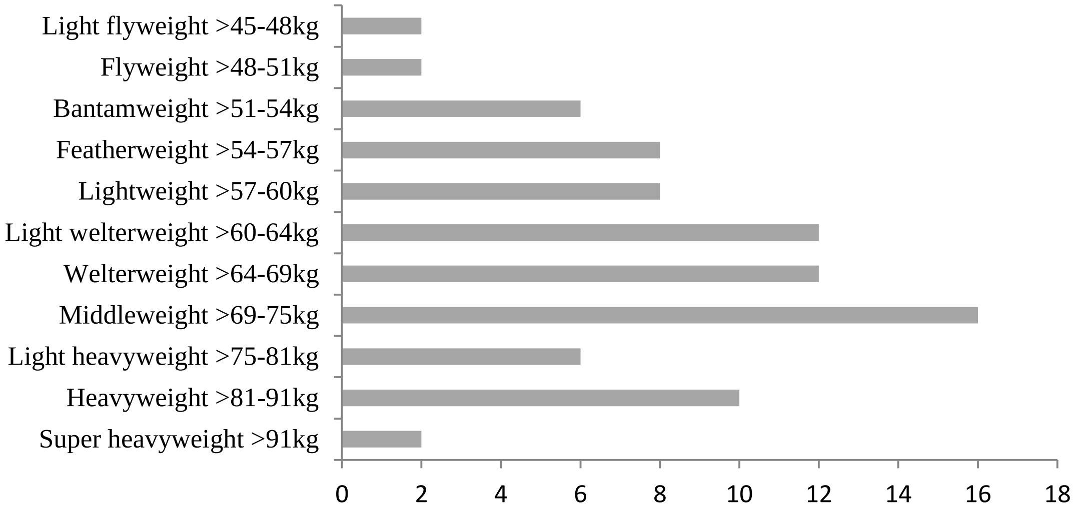

Figure 4.1. The number of performances (*x*-axis) within respective weight classes. Note: weight classes according to ABAE (2007) were used, not those of AIBA (2013) as contests preceded the rule changes of 2013.

Table 4.1. The number of bouts within specific weight classes according to contest format, ring size and standard of competition.

	Six	**Nine**	**4.9 m^2**	**5.5 m^2**	**6.1 m^2**	**Regional**	**National**
Light flyweight	2	0	0	2	0	2	0
Flyweight	0	2	0	0	2	0	2
Bantamweight	2	4	2	2	2	2	4
Featherweight	0	8	0	0	8	0	8
Lightweight	6	2	2	4	2	6	2
Light welterweight	12	0	6	6	0	12	0
Welterweight	6	6	2	4	6	6	6
Middleweight	10	6	4	6	6	10	6
Light heavyweight	2	4	0	4	2	4	2
Heavyweight	6	4	0	8	2	8	2
Super heavyweight	2	0	0	2	0	2	0

According to definitions of the ABAE (2007), there were 19 class ‘A’ novice, 26 class ‘B’ novice, 22 intermediate and 17 open class performances (see Table 2.1 for definitions of each ability). A more comprehensive overview of the study sample according to the weight class, contest format, ring size and tournament is available within Appendix 1.

The boxers competed for a range of amateur boxing clubs, predominantly from across the North West of England. Contests took place as part of the ABAE elite championships (‘national’; n = 32) or regional boxing shows hosted by individual amateur boxing clubs (‘regional’; n = 52). All participants provided written informed consent for their contest to be recorded and subsequently analysed. Institutional ethical approval for the study was granted by the Faculty of Applied Sciences Ethics Committee, along with supplemental approval from the regional ABAE governing body.

4.2.2 Procedures

Forty-two contests were recorded at six different ABAE approved venues over a period of four weeks. All the venues were located within the bounds of the Merseyside and Cheshire regional ABAE governing body. The 42 contests were recorded with two digital cameras (Canon MV700, Japan) from two adjacent sides of the boxing ring at an angle of 90°. The bouts were performed in an ABAE (2009) standard square ring (4.27 – 6.1 m^2) and, according to the ability of the boxers, were competed over three rounds of two (n = 26) or three minutes (n = 16), interspersed with one minute of rest. Video analysis was conducted post-contest and generally viewed at a speed of one quarter of normal viewing speed (12.5 frames per second). However, given the number of actions to record and the speed and complexity of certain movement patterns, the analyst re-wound the contest and viewed events frame-by-frame where necessary. For the most part, the contest was analysed using the footage from only one camera angle, whilst footage from the other angle was used to verify events that were not clear from the first camera angle. The two camera angles were thus used interchangeably, depending upon the location and orientation of the two boxers and the referee. The captured footage was transferred to a personal computer and subsequently analysed using the Dartfish TeamPro software (version 4.0, Switzerland).

4.2.3 Performance analysis template

Boxing-specific actions were identified as measures of performance, including match classification, technical and tactical indicators of performance (Hughes & Bartlett, 2002). For an in-depth description of the performance analysis template, the reader is referred to Chapter 3. Briefly, given that the aim of a boxing contest is to out-score or knock-out an opponent, it was considered that the actions influencing such outcomes provide the material for performance analysis. As knock-outs are relatively uncommon in amateur boxing (Jako, 2002), the actions performed that merit points being awarded by the ringside judges provide the quantifiable elements during a contest. Consequently, offensive, defensive and feinting performance indicators were defined, with the premise being that offensive actions yield points and defensive actions prevent points. Feinting actions, though potentially less critical to the score (and outcome) of a contest, are frequent events and can act as precursors to point-scoring movements. Accordingly, six attacking (lead jab, backhand cross, lead hook, rear hook, lead uppercut and rear uppercut), four feinting (lead hand, rear hand, trunk and foot feints) and 12 defensive variables (block both arms, block lead arm, block rear arm, clinch, duck, foot defence, lean backwards, push, slip left, slip right, roll clockwise and roll counter-clockwise) were identified by the lead author (an experienced amateur boxer of 25 previous contests and coach for more than three years) and corroborated by another amateur boxer (25 previous contests) and a senior level ABAE coach. Such actions provided a comprehensive assessment of the pertinent actions in amateur boxing and provided a specific means of assessing boxing performance.

Each offensive and defensive action was further notated with regard to its intended target and outcome. Specifically, each offensive action was labelled as ‘successful’, or ‘undetermined’, or ‘unsuccessful’ depending upon the observed level of contact between the punches thrown and the opponent’s target area. Although it was not possible to verify the level of success with the judges’ allocation of points, ‘successful’ punches potentially satisfy the ABAE’s (2009) criteria for the awarding of points, whereas ‘undetermined’ (negligible contact between glove and target area) and ‘unsuccessful’ (complete miss of target area) punches do not. Defensive variables were notated in a similar manner. That is to say, a ‘successful’ or ‘undetermined’ defence was reflected by the opponent’s attack/punch failing to land in line with the conditions for the awarding of a point, whereas an ‘unsuccessful’ defence allowed an opponent’s punch to fulfil the point-scoring criteria. Feinting actions, once identified, received no further classification. The designation of the ‘lead’ and ‘rear’ hands was dependent upon the stance assumed by the boxer. Therefore, boxers adopting an ‘orthodox’ stance led with their left and had the right hand as the rear hand; a ‘southpaw’ stance was the reverse of this (Gursoy, 2009).

The *intra*- and *inter*-observer reliability of the performance analysis template have been assessed previously (Chapter 3) using the methods outlined by Cooper et al. (2007). For intra-reliability, no systematic bias was evident between observations, and the proportion of *perfect* agreement was 92 – 100% for all indicators. Where a *reference* value (error margin) of ± 1 counts was used, 100% agreement was established for every indicator. Likewise, for the inter-observer comparison, there was no significant bias between observers and the proportion of perfect agreement exceeded 92% for most indicators, and was 100% for all but one indicator within the specified margin of error. Thus, it was deemed that the template demonstrated an acceptable level of reliability for the assessment of the movement demands of a competitive amateur boxing contest.

4.2.4 Contest analysis

For each boxer, the actions were notated with the template described above, commencing with the identification of offensive and feinting actions, followed by defensive actions. For each offensive action (punch), the overall target and outcome were identified (‘tagged’), along with the total number of punches thrown during the ‘attack’ (Figure 4.2). This process was repeated for the defensive actions, with the number of punches *defended* identified (Figure 4.3). Where required, the analyst coded several individual defensive actions simultaneously, irrespective of the number of oncoming punches. Additional aspects of the contest were also recorded, such as the round number and its duration, the round and time at which the referee stopped the contest (to issue a warning, for example), the types of warnings issued by the referee (ducking below the waist line, excessive holding of an opponent, hitting while holding, dissent and miscellany), the number of eight-second counts issued and the manner in which the contest was won (points verdict, referee stopped contest and knock-out).

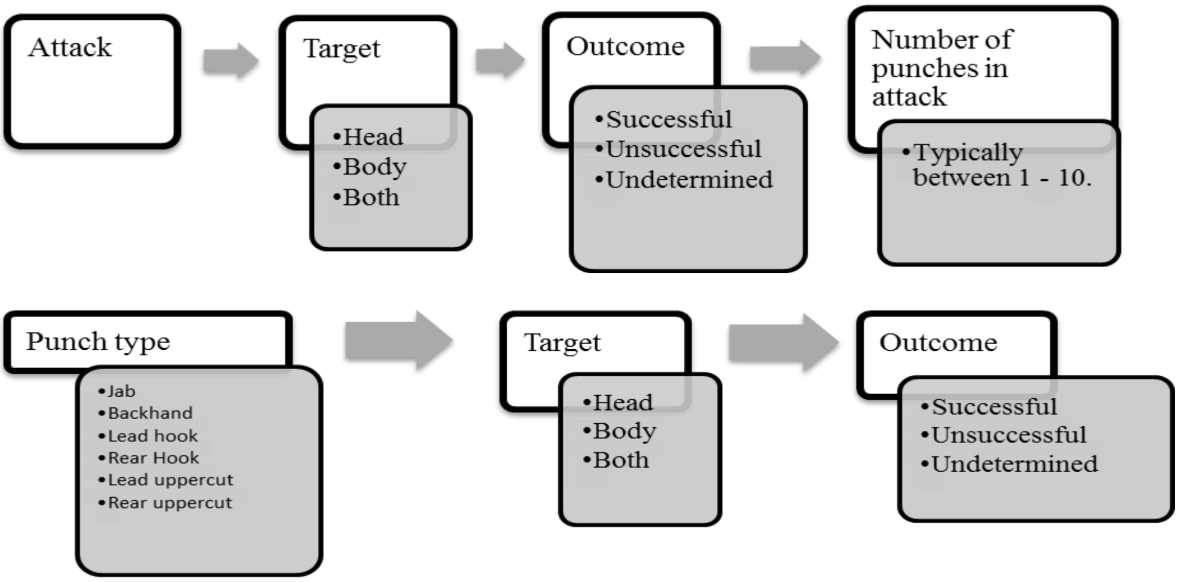

Figure 4.2. A schematic representation of how offensive actions were recorded.

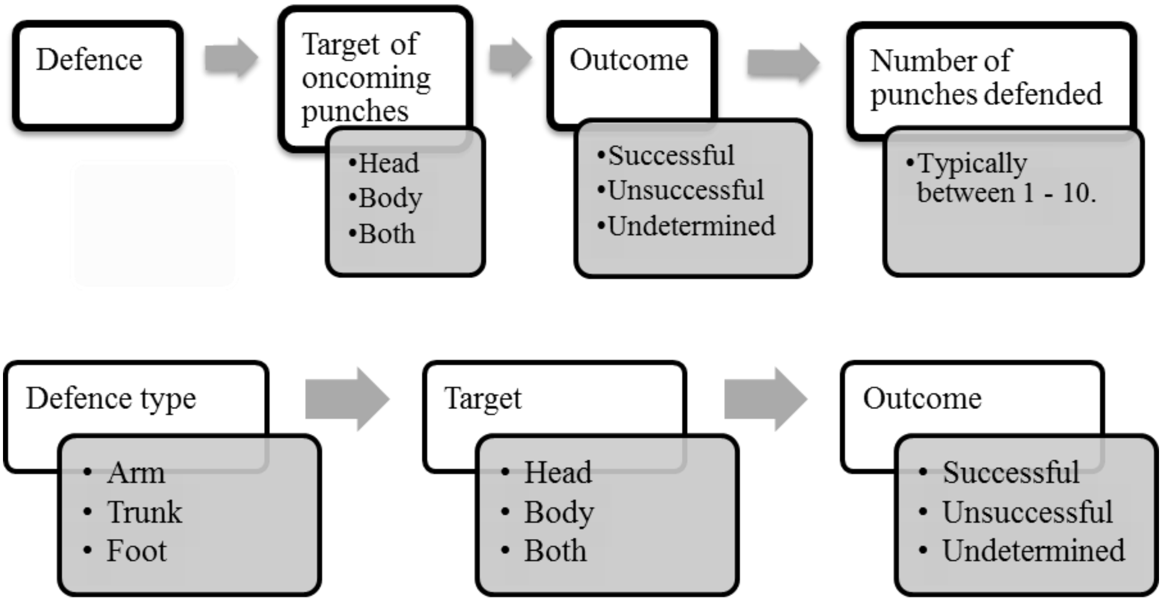

Figure 4.3. A schematic representation of how defensive actions were recorded.

4.2.6 Statistical analysis

For each performance indicator separately, typical performance was represented using normative performance percentiles (O'Donoghue, 2005). Using all performances collectively, this involved the calculation of 19 percentiles from 5-95% using increments of 5%; percentiles corresponding to 0 and 100% represented the minimum and maximum values within the sample. Raw data was thus expressed relative to the performance of the sample. The mean was used to represent the typical performance whilst the minimum, inter-quartile range (IQR) (using ± 0.67SD) and maximum values recorded for each sample were also determined conveying the within-group distribution of scores (O'Donoghue, 2013). Moreover, to quantify the between-subject, within-group variability in relation to the mean, the typical error expressed as a coefficient of variation (CV%) was employed where the standard deviation of group scores was divided by the overall mean (Paton & Hopkins, 2006). To characterise the overall variability of each group, the average CV% for collective offensive (e.g. jabs, rearhand crosses, hooks, uppercuts) and defensive (arm, trunk, foot) key performance indicators were calculated thus evidencing the variability associated with the frequency and success of offensive and defensive behaviours. Owing to observed between-subject CV% of < 5% in elite cyclists competing in track, road and mountain biking events (Paton & Hopkins, 2006), variability was deemed as 'low' (<5%), 'moderate' (5 to 9.9%) or 'high' (≥ 10%; Roberts et al., 2006).

Data were analysed using log-linear and logit modelling (Nevill et al., 2002; Taylor et al., 2008; Tabachnick & Fidell, 2013) where the behavioural frequencies (e.g. quantity of punches) and associated outcomes (e.g. quantity of successful punches) were modelled according to the contest outcome (using judge-determined decision), weight class (‘Light’, ‘Middle’ and ‘Heavy’) (Table 4.2) and ability (regional, national). Moreover, the comparison between ability groups was synonymous with distinct ring sizes such that all regional contests were competed within 4.9 (n = 14) or 5.5 m^2 (n = 38) rings where all national standard contests were held within 6.1m^2 (n = 32) rings. All data satisfied concerns regarding independence, the ratio of cases to variables and expected cell frequencies (Tabachnick & Fidell, 2013).

Table 4.2. The weight groupings used for analysis

Group	**AIBA (2013a) classification**
Light	Light flyweight > 46-49 kg
	Flyweight > 49-52 kg
	Bantamweight > 52-56 kg
	Lightweight >56-60 kg
Middle	Light welterweight > 60 – 64 kg
	Welterweight >64-69 kg
	Middleweight >69-75 kg
Heavy	Light heavyweight > 75-81 kg
	Heavyweight > 81-91 kg
	Super heavyweight >91 kg

For each performance indicator separately, a contingency table based upon the one- (e.g. win), two- (e.g. win, lightweight boxer) and three-way (e.g. win, lightweight boxer, national standard) associations identified the observed cell frequencies, from which a log-linear model was produced (Field, 2013). Beginning with a saturated model (i.e. outcome x weight x ability interaction) and then employing a backward elimination process (Field, 2013), the simplest fitting model was identified by removing as many higher order associations and main effects as possible whilst maintaining adequate fit between the observed and expected cell frequencies (Tabachnick & Fidell, 2013). Associations were deemed to contribute to the resulting model when their removal resulted in a significant difference between the observed and expected (i.e. predicted) cell frequencies. The resulting model therefore includes only those associations necessary to reproduce the observed frequencies. The likelihood ratio statistic was used to evaluate that the expected frequencies produced by the model were not significantly different (P < 0.05) from the observed data (Taylor et al., 2008). Moreover, wherever two- or three-way interactions were retained, lower-order associations were implicitly included thus for example, a model fit including the interaction between outcome and weight intuitively includes the main effects of each independent variable also.

Within the study the saturated, log-linear model was:

$$\ln(F_{ijk}) = \theta + \lambda_i^O + \lambda_j^W + \lambda_k^A + \lambda_{ij}^{OW} + \lambda_{ik}^{OA} + \lambda_{jk}^{WA} + \lambda_{ijk}^{OWA}$$

where the natural log for the expected frequency for a given cell ($\ln(F_{ijk})$) was the geometric mean of all cell log frequencies (θ) and the parameter estimates (λ) according to the outcome (O), weight class (W) and ability (A). Positive and negative parameter estimates for each main effect and interaction remaining within the model indicate the extent model constants (θ) increase or decrease, respectively. As parameter estimates equate to zero across categories of an independent variable, they will be presented for the winning and regional performances only with the losing and national performance parameter estimates representing the additive inverse. Moreover, by taking the exponent of each parameter estimate a multiplicative factor was derived such that the change in behaviour frequency could be specified (Taylor et al., 2008). For example, a parameter estimate of -2 produces a multiplicative factor change of 0.14 resulting in the cell frequency being 86% of the model constant of the contingency table.

Although log-linear analyses do not require assumptions of normality to be satisfied, the Kolmogorov-Smirnov test was used to justify the descriptive statistics included within the O'Donoghue (2005) profiling and the use of the CV%. All analyses were undertaken using SPSS (Version 17.0; Chicago, IL). Statistical significance in all tests was set at $P \leq 0.05$.

4.3. Results

4.3.1. Performance profiling of amateur boxing according to contest outcome, weight class and ability.

Percentile bandings, from which performance was contrasted are presented in tables 4.3. and 4.4. Whilst there were 12 groups in total, the following results focus upon three examples whereby the outcome, weight class and ability were contrasted independently whilst the other factors were held constant.

Table 4.3. Normative percentile values for the total frequencies performed by boxers.

Percentile (%)	**Attacks**	**Punches**	**Jab**	**Rear hand cross**	**Lead hook**	**Rear hook**	**Lead uppercut**	**Rear uppercut**	**Defences performed**	**Arm defence**	**Trunk defence**	**Foot defence**
0	51	77	9	3	9	1	0	1	19	9	5	2
5	63	102	25	11	16	2	1	1	42	11	9	2
10	68	113	29	16	17	3	1	1	44	18	13	5
15	70	134	35	23	21	3	1	2	51	19	15	6
20	74	136	44	26	24	5	1	2	55	21	17	8
25	82	141	45	28	27	8	1	2	57	23	18	10
30	85	151	47	31	31	11	2	2	60	26	20	12
35	89	154	49	33	33	12	2	3	61	27	21	13
40	92	158	54	37	38	14	3	3	65	29	22	15
45	95	166	57	40	42	18	3	4	70	32	24	16
50	99	181	58	45	43	21	4	4	76	33	24	17
55	101	187	59	46	47	23	5	6	77	35	27	19
60	109	192	63	48	48	27	5	6	80	37	28	21
65	113	197	75	49	52	29	7	7	84	40	32	22
70	120	210	87	51	59	31	7	9	85	44	34	23
75	124	224	93	53	64	32	7	10	87	48	36	24
80	133	235	96	55	70	36	8	15	94	50	37	26
85	144	241	102	57	72	41	10	21	101	53	43	29
90	155	291	116	65	84	48	13	24	112	65	50	32
95	168	344	125	72	88	54	18	27	126	78	52	35
100	191	395	143	87	117	77	42	46	143	105	57	61

Table 4.4. Normative percentile values for the total frequencies of successful actions performed by boxers.

Percentile (%)	**Attacks**	**Punches**	**Jab**	**Rear hand cross**	**Lead hook**	**Rear hook**	**Lead uppercut**	**Rear uppercut**	**Defences performed**	**Arm defence**	**Trunk defence**	**Foot defence**
0	12	15	1	1	1	0	0	1	8	2	4	1
5	21	26	2	4	3	1	1	1	15	6	6	2
10	23	32	5	5	5	1	1	1	18	7	7	4
15	27	34	7	8	6	2	1	1	22	8	9	4
20	32	40	9	9	8	2	1	1	23	8	11	6
25	36	47	10	9	9	4	1	1	24	9	13	7
30	36	52	12	10	10	4	1	2	26	11	13	8
35	38	54	13	10	11	5	1	2	27	12	14	8
40	41	55	16	12	12	6	1	2	31	13	15	10
45	44	55	16	13	13	7	2	2	34	15	16	11
50	46	60	17	14	14	9	2	2	36	17	17	12
55	48	66	20	15	14	9	3	3	36	17	17	13
60	50	68	23	16	15	11	3	3	38	18	19	14
65	53	70	24	17	17	11	4	4	40	19	20	16
70	56	73	26	18	20	12	4	6	41	20	22	17
75	60	79	29	21	21	14	4	6	44	22	23	19
80	61	84	32	25	22	16	5	8	45	23	25	20
85	68	89	36	28	24	18	7	10	55	25	28	22
90	81	105	40	29	31	22	8	11	58	27	32	24
95	102	154	43	31	43	28	11	16	61	36	37	26
100	115	170	72	43	62	35	26	23	82	64	42	44

4.3.1.1. Performance profiling of amateur boxing comparing contest outcome only.

Within winning, middleweight amateur boxers of regional ability noteworthy dispersion was evident. For many performance indicators the range traversed 12-18 percentile bandings whilst the IQR spanned 25-40%. The typical performance was characterised by percentile bandings of 35-65%.

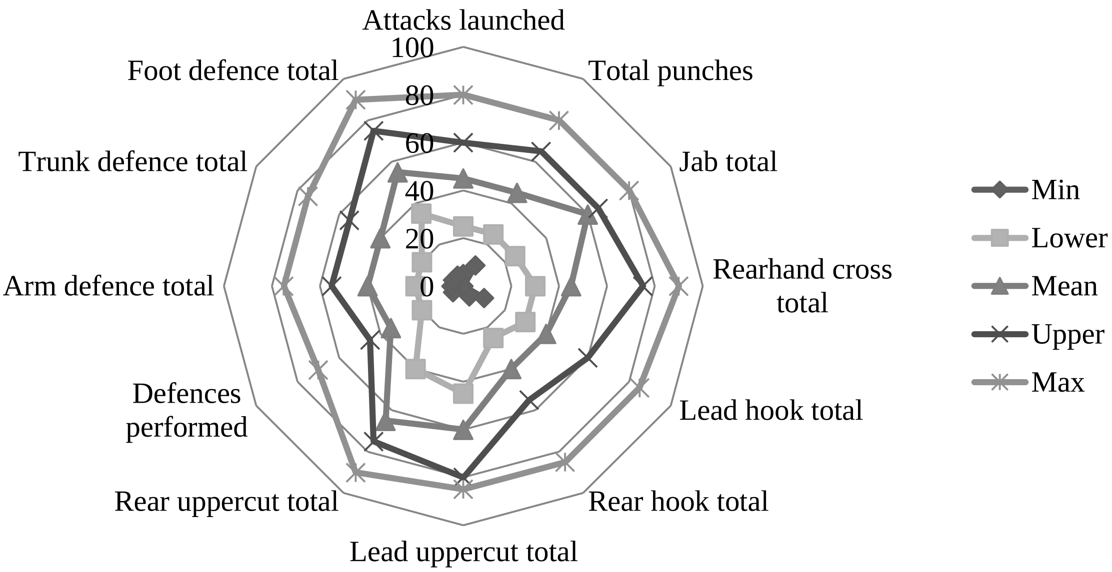

Figure 4.4. A normative performance profile reporting the total action frequencies for winning, middleweight amateur boxers of regional ability.

Where the frequency of successful actions was considered, the profiles of these boxers were similarly dispersed. That is, the range represented 70-90% whilst the IQR spanned 25-50%. Where the outcomes of offensive movements were concerned, performance was consistently higher than the 50th percentile though defensive performance, excepting foot defences, was lower (40th percentile).

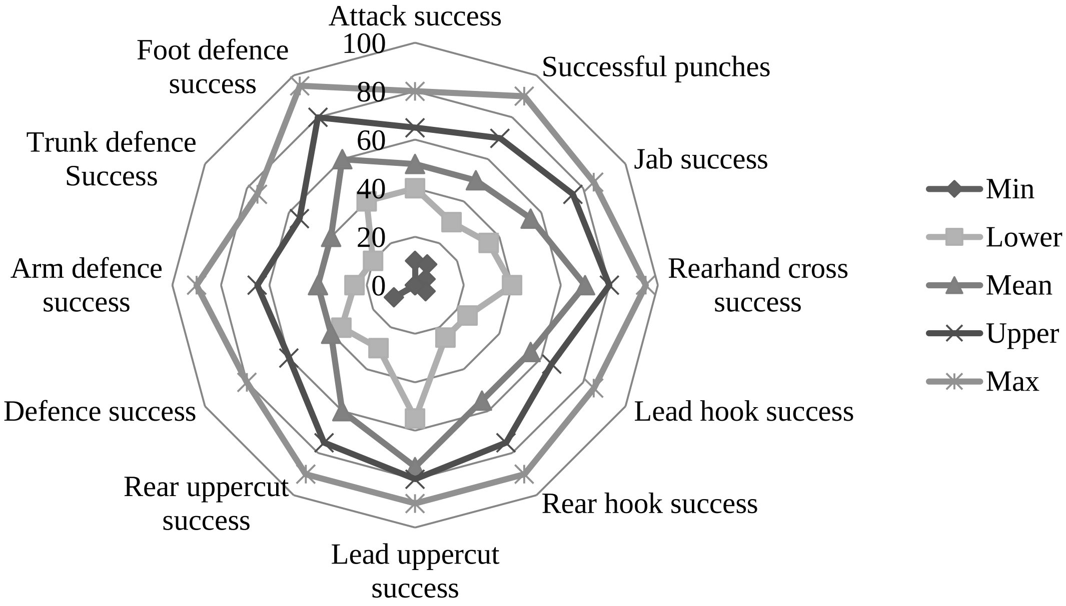

Figure 4.5. A normative performance profile concerning the frequencies of success actions for winning, middleweight amateur boxers of regional ability.

Comparing the above profile to that of losing, middleweight amateur boxers of regional ability, notable differences were apparent. Excluding the rear hooks performed, the typical performance in this group was characterised by lower offensive frequencies for all key performance indicators whereas defensive performance, excepting foot defences, was associated with higher percentiles. Notwithstanding these differences, within-group performance still evidenced similarly wide dispersion (minimum and maximum range = 65-100% and IQR = 30-65%).

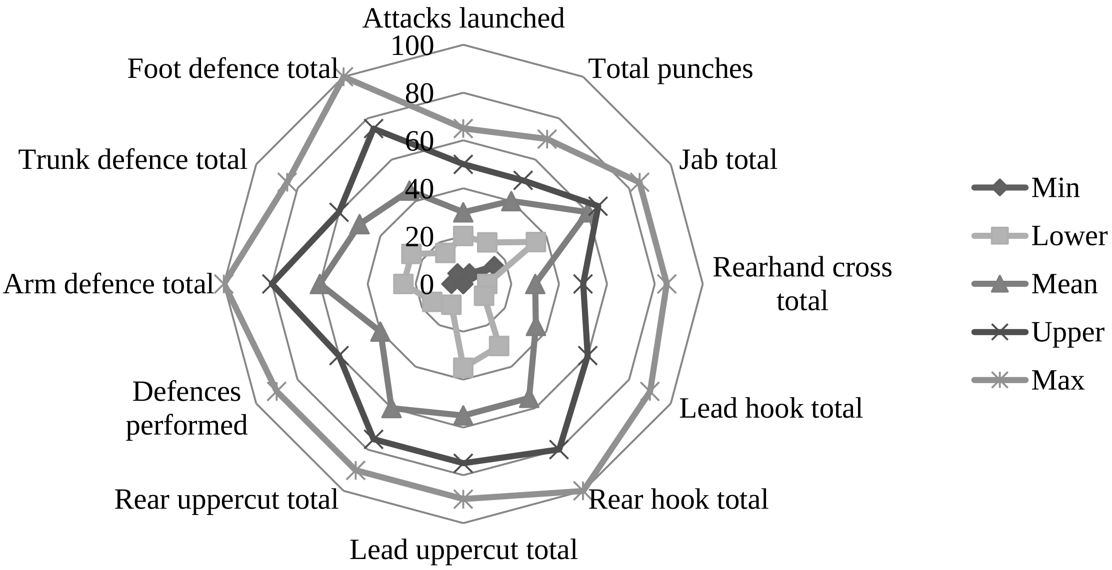

Figure 4.6. A normative performance profile reporting the total action frequencies in losing, middleweight amateur boxers of regional ability.

Contrasting the frequency of successful actions between the winning and losing, middleweight boxers of regional ability clear differences were again established. That is, the percentiles established for offensive key performance indicators were lower in the losing boxers (rear uppercut success was equal however) whilst the frequencies of successful defensive movements were lower.

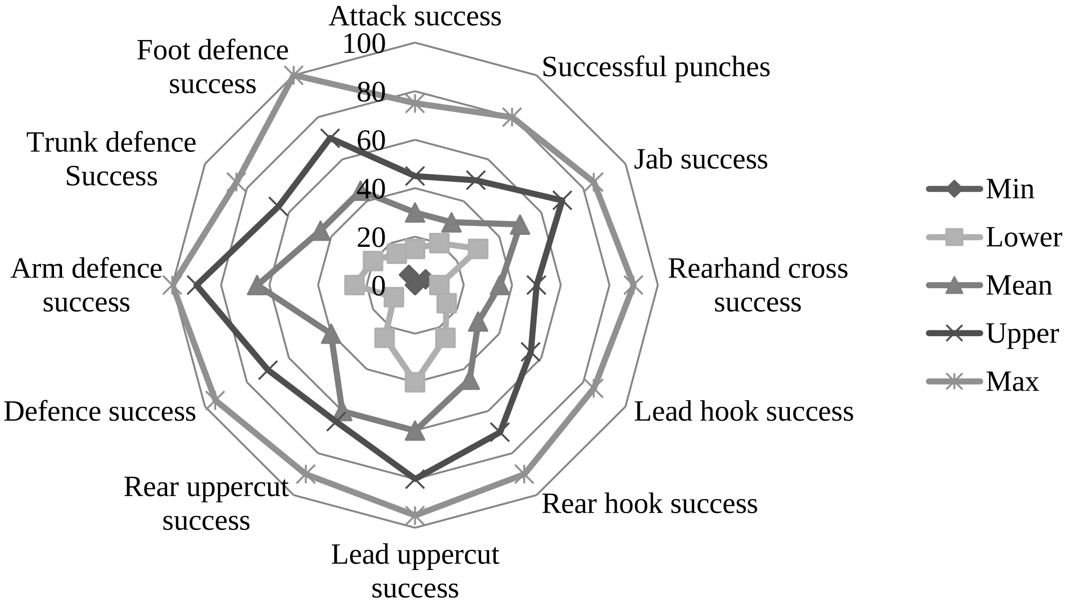

Figure 4.7. A normative performance profile concerning the frequencies of success actions for losing, middleweight amateur boxers of regional ability.

4.3.1.2. Performance profiling of amateur boxing comparing weight class only.

The performance profile of losing, lightweight boxers contesting national standard bouts in relation to the total frequencies of actions performed is presented in figure 4.8. The frequency of offensive actions was consistently higher than the majority of the sample (i.e. 50%) with percentiles between 50-70%. Typical defensive performance was associated with percentiles >70%. Again, wide within-group dispersion was established with the range and IQR for key performance indicators representing 50-95% and 15-45%, respectively.

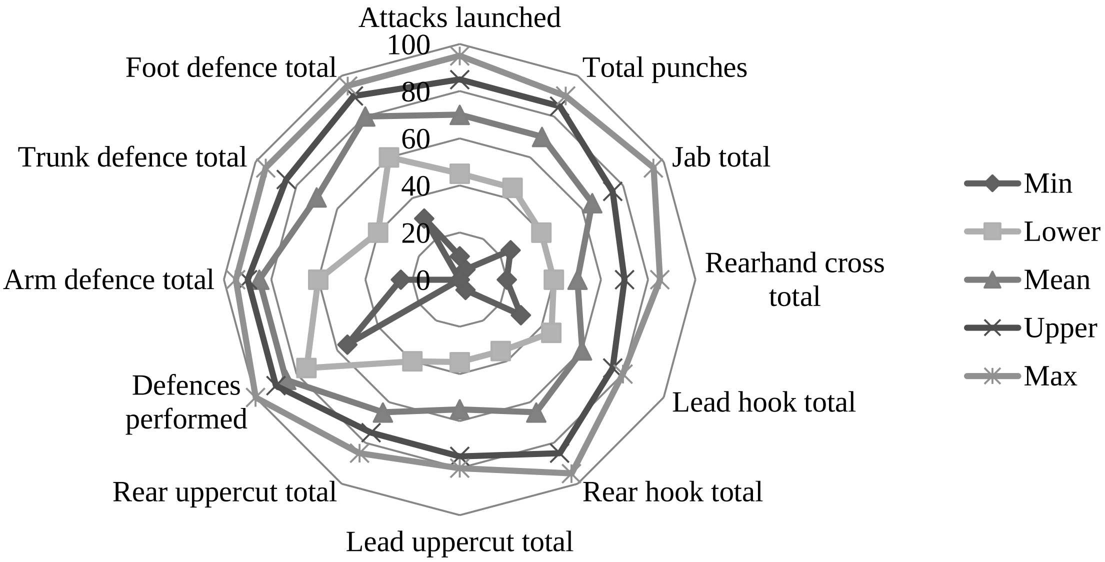

Figure 4.8. A normative performance profile reporting the total action frequencies for losing, lightweight amateur boxers of national ability.

Whilst the typical frequency of successful punches, jabs and rearhand crosses were within the bottom 40%, hook and uppercut success was within the top 45% of performances. The percentile bandings concerning typical defensive performance lay between 60-70%. Dispersion was again an evident feature of performance in these boxers spanning 45-100% and 10-60% for the range and IQR, respectively.

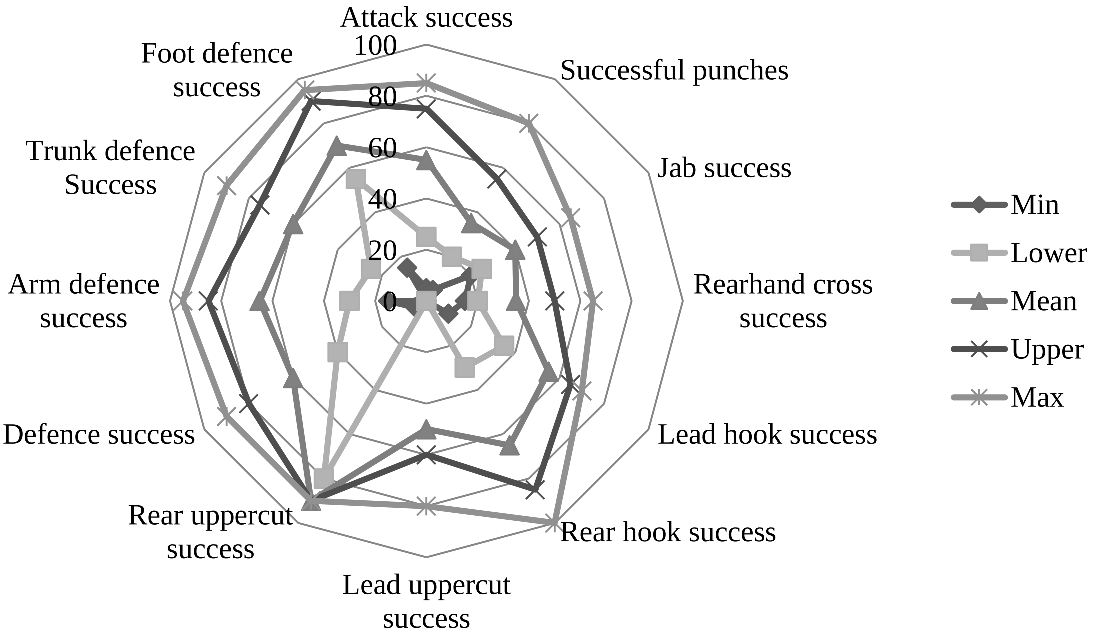

Figure 4.10. A normative performance profile concerning the frequencies of success actions in losing, lightweight amateur boxers of national ability.

Contrasted to losing, lightweight amateur boxers of national ability the typical performance of middleweight equivalents (i.e. same outcome and ability) involved more attacks and punches (70% vs 75% for both indicators) which was informed by a higher frequency of rear hand crosses, lead hooks and lead uppercuts. Defensive performance was typified by a decreased number of defences in total, owing to comparatively fewer arm and foot defences. Commensurate with previous observations, within-group performance evidenced wide dispersion (minimum and maximum range = 30-95% and IQR = 15-65%).

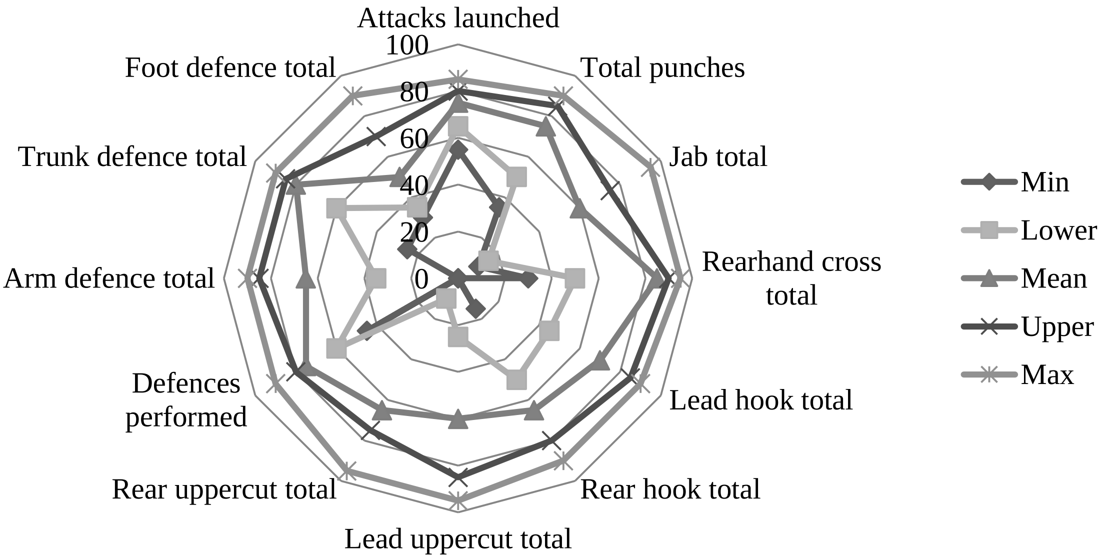

Figure 4.11. A normative performance profile reporting the total action frequencies in losing, middleweight amateur boxers of national ability.

Performance by losing, middleweight amateur boxers of national ability was characterised by more successful attacks (+10% vs. lightweight counterparts) and successful punches (+35% vs. lightweight counterparts) which was informed by more successful jabs, rear hand crosses, lead hooks and lead uppercuts. The representative defensive performance in this group involved an increased frequency of successful defences in total (+15%) and trunk (+20%) defences when contrasted to the light equivalents boxers. Across actions, the range (60-90%) and IQR (20-60%) were consistent with previous observations.

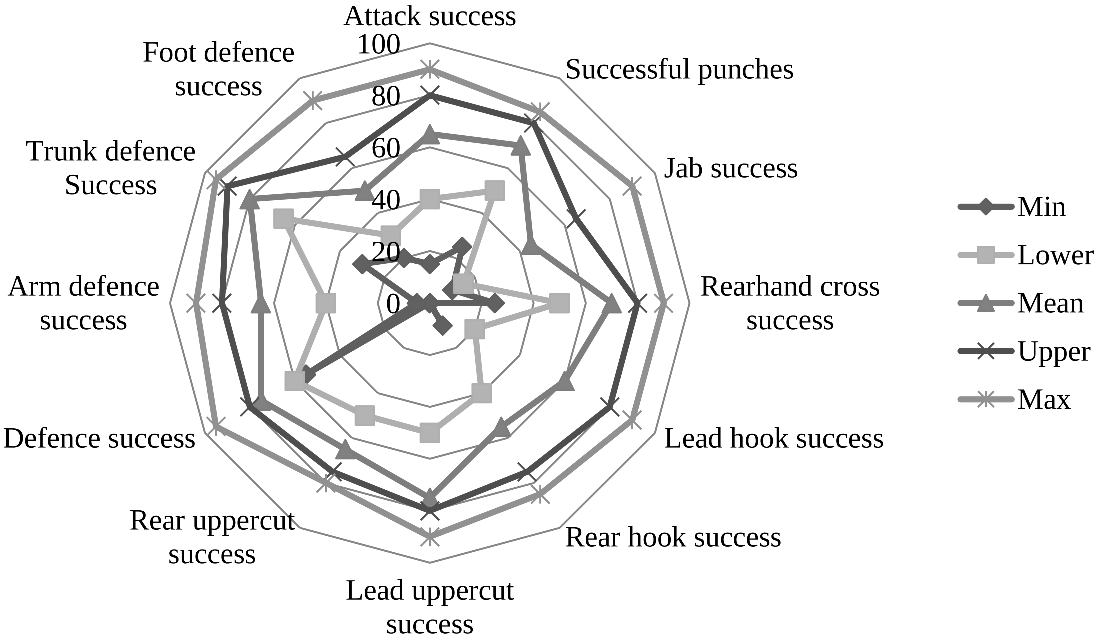

Figure 4.12. A normative performance profile concerning the frequencies of success actions for losing, middleweight amateur boxers of national ability.

4.3.1.3. Performance profiling of amateur boxing comparing ability only.

To appraise the influence of ability only, the normative data of the winning, middleweight, national standard boxers will be contrasted to the equivalent group (winning, middleweight, regional) data which is detailed above (Figures 4.3. and 4.4.).

Contrasted to winning, middleweight amateur boxers of regional ability the typical performance of national standard equivalents (i.e. same outcome and weight) involved more attacks (+20%) and punches (+5%) which were supported by a higher frequency of jabs (+5%) and lead hooks (+15%). Similar to the winning, middleweight, regional performance, within-group dispersion lay between 20-85% and 10-45% for the range and IQR, respectively.

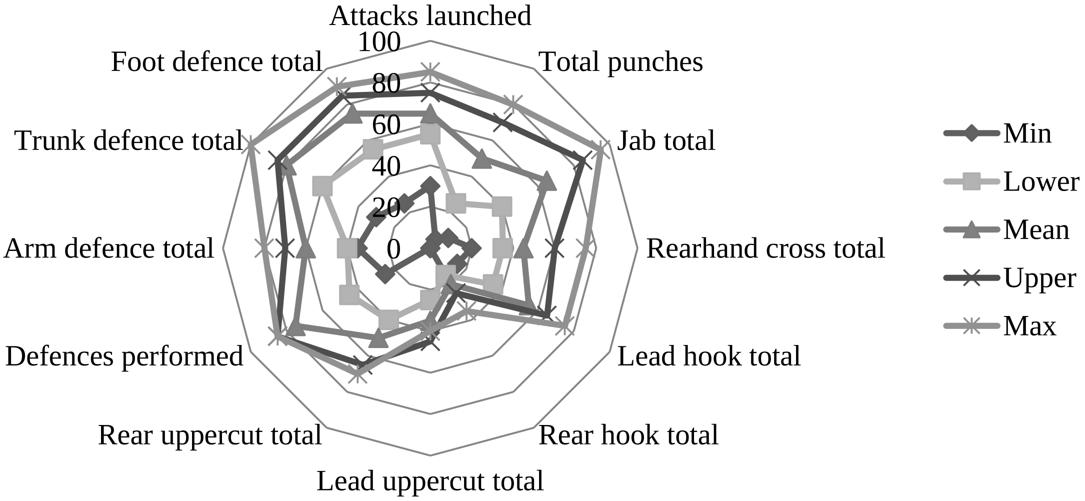

Figure 4.13. A normative performance profile reporting the total action frequencies for winning, middleweight amateur boxers of national ability.

Comparing the normative frequency of success, performance by winning, middleweight amateur boxers of national ability involved percentile bandings that were 15% higher for the number of successful attacks successful attacks though the number of punches landed successfully was similar (both 50th percentile). Where individual punch-types were appraised, the national standard boxers landed more jabs (+10%) and lead hooks (+5%), a similar quantity of rear hand crosses (70th percentile) but fewer rear hooks (-35%), lead (-40%) and rear (-10%) uppercuts than the regional equivalents. Defensive performance was superior in the national standard group with percentiles +10% to +40% higher than the regional counterparts.

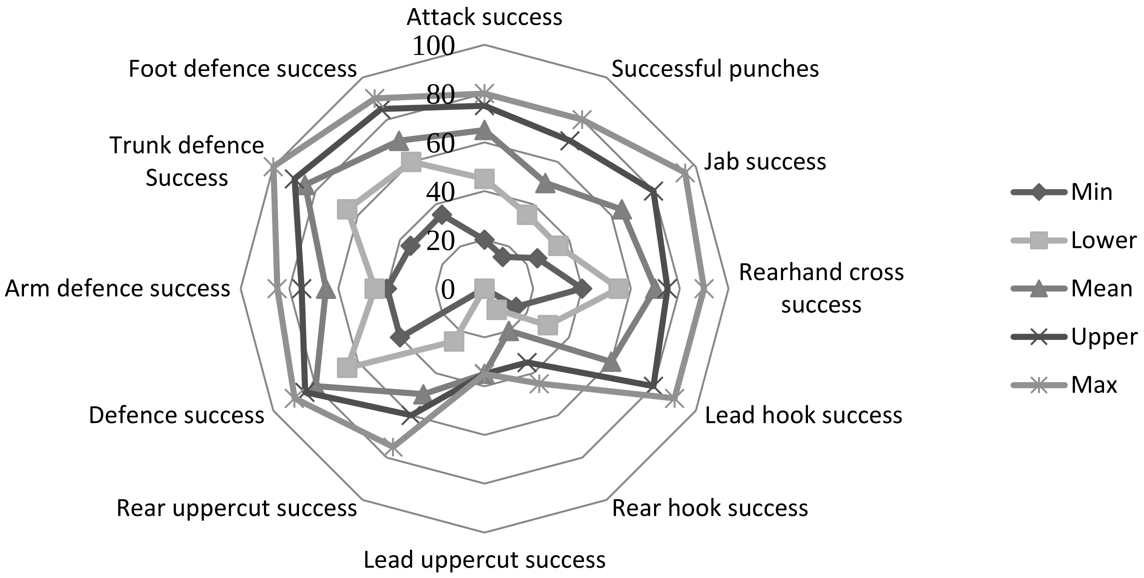

Figure 4.14. A normative performance profile concerning the frequencies of success actions for winning, middleweight amateur boxers of national ability.

4.3.2. The CV% of offensive and defensive performance aspects of performance

The between-subject, within-group variability was deemed high for all groups and all collective actions. Whilst some groups evidenced substantially high CV% (e.g. Lose, Middle, Regional) other groups demonstrated improved consistency (i.e. Win, Heavy, National) though CV% still remained high. Consistent trends in improved consistency for offensive or defensive total or successful action frequencies were not established though defensive success was lower than offensive success in ten of twelve groups.

Table 4.5. Between-subject, within-group variation of the frequency of total and successful offensive and defensive behaviours (CV%).

	Offensive total	**Defensive total**	**Offensive success**	**Defensive success**
Win, Light, Regional	24.86	33.10	37.79	34.48
Win, Middle, Regional	47.79	39.51	52.56	40.46
Win, Heavy, Regional	57.44	52.39	62.57	68.40
Win, Light, National	47.05	34.26	58.13	31.54
Win, Middle, National	41.52	30.75	47.44	29.35
Win, Heavy, National	29.96	22.70	38.44	14.12
Lose, Light, Regional	33.25	35.03	29.21	19.74
Lose, Middle, Regional	57.09	60.12	61.78	65.51
Lose, Heavy, Regional	58.45	63.93	64.81	57.15
Lose, Light, National	49.78	45.56	52.08	47.76
Lose, Middle, National	55.81	40.64	53.38	36.21
Lose, Heavy, National	52.53	11.98	58.43	12.58

4.3.3. The influence of contest outcome, weight class and ability on behavioural frequency.

The three-way log-linear analysis produced final models that included main effects only, two- and three-way interactions suggesting the frequencies were dependent upon the situational variables. Specifically, the models concerning the total punches, jabs, lead uppercuts and trunk defences performed retained all effects indicating the highest order interaction (outcome x weight x ability) was significant. There were also several key performance indicators where two-way interactions (attacks launched, backhand cross, rear hook, foot defence) and main effects (attacks launched, lead hook, rear uppercut, defences performed, arm defence) were significant.

Table 4.6. Resultant model fit parameters for the total frequency of key performance indicators in amateur boxing according to the outcome (O), weight class (W) and ability (A).

	Model	Likelihood ratio X^2	d.f.	*P*-value
Attacks launched	[W * A] [O]	5.5	5	0.356
Total punches	[O * W * A]	0.0	2	1.000
Jab	[O * W * A]	0.0	2	1.000
Backhand cross	[O * W]	15.6	6	0.016
Lead hook	[O] [A] [W]	8.1	7	0.324
Rear hook	[O * W] [W * A]	6.1	3	0.106
Lead uppercut	[O * W * A]	0.0	2	1.000
Rear uppercut	[W] [A]	9.6	8	0.291
Defences performed	[A]	15.6	10	0.112
Arm defence	[O] [A]	17.0	9	0.052
Trunk defence	[O * W * A]	0.0	2	1.000
Foot defence_	[O * W] [W * A]	3.2	3	0.362

Retained interactions and main effects are enclosed within square brackets. For example, [O * W] would indicate a significant interaction between outcome and weight.

Where the main effect outcome was concerned, excepting the reduced frequency of lead uppercuts, winning performance was associated with an increased offensive output (attacks launched, total punches and backhand cross) but fewer arm and trunk defences. Main effects for each weight were somewhat sporadic though generally there were reduced frequencies for the ‘lighter’ and ‘middle’ weight group of boxers with increased frequencies for the ‘heavy’ group. Consistently reduced frequencies were associated with regional boxing performance with nine of twelve key performance indicator frequencies significantly lower than the model constant. Outcome-by-weight interactions typically involved increased frequencies for winning performances by ‘lighter’ boxers, decreased frequencies for the ‘middle’ weight boxers with little change from the model constant for winning ‘heavy’ boxers. Noteworthy once more was the influence of ability such that regional performance by ‘lighter’ boxers was associated with significantly reduced action frequencies though regional ‘middle’ and ‘heavy’ boxing both resulted in four positive and one negative change from the model constant. Finally, there were several behaviours across each of the three-way interactions evidencing both positive and negative changes from the model constant with no apparent directional trend in parameter estimates.

Table 4.7. Log frequency (95% CI) and parameter estimates for the total frequency of key performance indicators in amateur boxing according to the outcome (O), weight class (W) and ability (A).

Model effect	Attacks launched	Total punches	Jab	Backhand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut	Defences performed	Arm defence	Trunk defence	Foot defence
Constant	4.62 (4.59 to 4.69)	5.22 (5.15 to 5.28)	4.11 (4.03 to 4.18)	3.66 (3.59 to 3.73)	3.91 (3.84 to 3.98)	3.03 (2.89 to 3.16)	1.58 (1.36 to 1.79)	2.08 (1.93 to 2.24)	4.33 (4.28 to 4.38)	3.6 (3.54 to 3.67)	3.25 (3.16 to 3.33)	2.7 (2.58 to 2.82)
Win	0.06	0.06	-	0.19	-	-	-0.41	-	-	-0.12	-0.14	-
Light	-	-0.11	-	-	-	-	-	-0.51	-	-	-	-
Middle	-	-	-	-	-0.18	-0.23	-	-	-	-	-	0.21
Heavy	-	0.16	-	-	0.19	-	-	0.66	-	0.13	-	-
Regional	-0.18	-0.2	-0.11	-	-0.22	-0.23	-	-0.27	-0.17	-0.18	-0.12	-
Win * Light	-	0.11	-	-	-	0.43	0.58	-	-	-	-	-0.41
Win * Middle	-	-0.1	-	-0.2	-	-0.32	-	-	-	-	-	-
Win * Heavy	-	-	-	0.11	-	-	-0.80	-	-	-	-	0.38
Win * Regional	-	-	-	0.08	-	-	0.44	-	-	-	-	-
Regional * Light	-0.12	-0.19	-0.24	-0.15	-	-0.25	-0.53	-	-	-	-	-0.32
Regional * Middle	-	0.15	-	-0.02	-	0.46	-	0.32	-	0.14	-	-
Regional * Heavy	-	-	0.15	0.17	-	-0.21	-	-	-	-	0.22	0.31
Win * Regional * Light	-	-	-	0.08	-	-	-	-	-	-	-0.20	-
Win * Regional * Middle	-	0.07	0.12	0.06	-	-	-	-	-	-	-	-
Win * Regional * Heavy	-	-0.1	-0.22	-0.14	-	-	0.58	-0.26	0.10	-	0.26	-

Note: Data is presented where parameter z-score was >1.96 (Tabachnick & Fidell, 2013) only thus indicating a significant change from model constant. All other non-significant parameter estimates (± 95% CI) can be found in appendix 8, chapter 4.

Given parameter estimates sum to zero across an independent variable, omitted values (e.g. national) are the additive inverse of those presented.

4.3.4. The influence of contest outcome, weight class and ability on behavioural success

Again, the models produced indicated that the frequencies of the successful actions were dependent upon main effects, two- and three-way interactions. Specifically, the models concerning the arm and trunk defences retained all effects signifying the highest order interaction (outcome x weight x ability) was significant. There were also several behaviours where two-way interactions (attacks launched, total punches, jab, rear hook, lead uppercut, foot defence) and main effects (attacks launched, backhand cross, lead hook, rear uppercut, defences performed) were significant.

Table 4.8. Resultant model fit parameters for the total frequency of successful key performance indicators in amateur boxing according to the outcome (O), weight class (W) and ability (A).

	Model	Likelihood ratio X^2	d.f.	*P*-value
Attacks launched	[W * A] [O]	5.1	5	0.409
Total punches	[O * W] [W * A]	3.2	3	0.362
Jab	[O * A]	12.5	8	0.130
Backhand cross	[O]	11.0	10	0.359
Lead hook	[O] [A] [W]	7.1	7	0.418
Rear hook	[O * W] [W * A]	5.1	3	0.167
Lead uppercut	[O * W] [O* A]	5.6	4	0.230
Rear uppercut	[W] [A]	11.2	8	0.192
Defences performed	[A]	8.9	10	0.545
Arm defence	[O * W * A]	0.0	2	1.000
Trunk defence	[O * W * A]	0.0	2	1.000
Foot defence_	[O * W]	7.7	6	0.263

In appraising the frequency of successful actions, there remained only two models (arm and trunk defence) retaining significant parameter estimates within higher-order (three-way) interactions; the direction of such estimates did not follow a consistent pattern. Where two-way interactions were considered regional-by-light performance was associated with negative parameter estimates and thus decreased frequencies whereas regional-by-middle performance was related to positive parameter estimates. Outcome-by-weight interactions were largely inconsistent in producing either positive or negative parameter estimates. However, main effects for winning performance were invariably positive for several offensive actions, negative for ‘light’ and ‘middle’ performances though positive where the performance of the ‘heavy’ group was concerned. Finally, appraising the influence of ability in amateur boxing performance, several parameter estimates were again negative inferring reduced frequencies compared to those associated with the model constants.

Table 4.9. Log frequency (95% CI) and parameter estimates for the frequency of successful key performance indicators in amateur boxing according to the outcome (O), weight class (W) and ability (A).

Model effect	Attacks launched	Total punches	Jab	Backhand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut	Defences performed	Arm defence	Trunk defence	Foot defence
Constant	3.85 (3.77 to 3.94)	4.15 (4.05 to 4.24)	2.94 (2.85 to 3.03)	2.63 (2.53 to 2.73)	2.82 (2.74 to 2.90)	2.09 (1.91 to 2.26)	1.16 (0.99 to 1.32)	1.64 (1.46 to 1.82)	3.55 (3.50 to 3.60)	2.8 (2.73 to 2.87)	2.87 (2.79 to 2.94)	2.39 (2.27 to 2.50)
Win	0.14	0.17	0.22	0.32	0.16	-	-	-	-	-	-	-
Light	-0.17	-0.22	-	-	-	-	-	-	-	-	-	-
Middle	-	-	-	-	-0.23	-	-	-	-	-	-	-
Heavy	0.22	0.27	-	-	0.22	-	-	0.70	-	-	-	-
Regional	-0.26	-0.25	-0.14	-	-0.21	-0.32	-	-0.36	-0.13	-	-	-
Win * Light	-	0.15	-	-	-	0.53	0.54	-	-	-	-	-0.38
Win * Middle	-	-0.14	-	-	-	-	-	-	-	-	-	-
Win * Heavy	-	-	-	-	-	-	-0.76	-	-	-	-	0.36
Win * Regional	-	-	-0.19	-	-	-	0.44	-	-	-	-	-
Regional * Light	-0.23	-0.23	-	-	-	-0.48	-	-	-	-	-	-0.28
Regional * Middle	0.16	0.20	-	-	-	0.52	-	-	-	-	-	-
Regional * Heavy	-	-	-	0.24	-	-	-	-	-	-	-	-
Win * Regional * Light	-	-	-	-	-	-	-	-	-	-	-0.24	-
Win * Regional * Middle	-	-	-	-	-	-	-	-	-	-	-	-
Win * Regional * Heavy	-	-	-	-	-	-	-	-	-	0.25	0.27	-

Note: Data is presented where parameter z-score was >1.96 (Tabachnick & Fidell, 2013) only thus indicating a significant change from model constant. All other non-significant parameter estimates (± 95% CI) can be found in appendix 8, chapter 4.

4.4 Discussion

Collectively, the results herein provide a comprehensive assessment of amateur boxing performance, including offensive and defensive behaviours. The research supplements existing data in relation to contest outcome (El-Ashker, 2011; Davis et al., 2013a; Davis et al., 2014) but also provides the first assessment of boxing performance considering weight class and ability groups as independent variables. Moreover, the interaction(s) between independent variables, known to affect the observable characteristics of performance in other sports (Lames, 2006; Lames & McGarry, 2007; Taylor et al., 2008; Mackenzie & Cushion, 2013), were also given due consideration. Such data could be used by amateur boxers and coaches to inform training practices and tactics during competition. That there were several two- and three-way interactions evident also suggests effective evaluation of amateur boxing performance ought to consider the interaction between independent variables rather than main effects alone (Taylor et al., 2008) and suggests performance is a complex and dynamic environment (McGarry, 2009). Whilst aspects of boxing, such as movement around the ring, were omitted from the performance analysis, the rules and definitions judges adhere to when scoring an amateur contest were closely related to the offensive and defensive key performance indicators selected. Thus, the current study could also provide valuable information regarding the efficacy of judging in amateur boxing; a pertinent application given the known bias of boxing judges (Balmer, Nevill, & Williams, 2003; Balmer et al., 2005).

The first section of the results described and compared the performance profiles of several groups. Previous attempts to describe amateur boxing have reported mean values ± the standard deviation focussing upon typical performance only. However, performance indicators are inherently unstable features of athletes involved in game sports (Lames & McGarry, 2007) and to provide a comparatively objective and informative analysis of performance, data should be normalised and dispersion described (O'Donoghue, 2005; Jones, James, & Mellalieu, 2008). Consequently, the methodology adopted included the use of percentile bandings whereby the typical performance and associated dispersion was established (O'Donoghue, 2005) allowing an absolute (i.e. use of raw values in tables 4.3 and 4.4) and relative (i.e. percentiles in relation to peer-group) analysis of boxing performance. Coaches and boxers can therefore use the data to better guide practice and competitive strategies given the typical and range of expected demands of competition.

Using these profiles, descriptive differences were drawn highlighting the potential influence of specific independent variables (e.g. comparing a win vs. lose whilst weight and ability were held constant) in boxing. Comparing winning and losing profiles in middleweight boxers of regional standard, it was revealed winning boxers performed more offensive actions and also had a higher probability of success with these actions whereas the losing equivalents (losing, middleweight, regional) had lower offensive output and success but higher defensive output and success. Such an observation appears logical given the judging criteria was based solely upon offensive actions thus performing these actions more frequently will increase the incidence of successes (assuming efficiency is unaltered) resulting in a higher probability of victory. Such an observation has been reported previously in bouts using computer-based judging (Davis et al., 2014). Losing boxers performing more defences is likely a consequence of the more frequent offensive actions performed by the winning opponent. Thus, within competition boxers might benefit from an increasingly offensive approach to contests.

In appraising weight class profiles, comparisons were drawn between losing, national standard boxers of light and middleweight categories. Whilst both groups typically evidenced percentile bandings within the top 50% of performances where the offensive and defensive demand was concerned, likely owing to longer bouts (nine vs six minutes bouts; ABAE, 2007), the middleweight group generally exhibited higher offensive frequencies and lower defensive frequencies. Where the outcome was considered middleweight boxing was associated with improved performance, recording higher percentile classifications for nine of twelve key performance indicators. Anecdotal evidence suggests boxers of increased body mass perform fewer actions thus the contrary observation herein might be due to the context-dependent dynamics within the contests of each group (Glazier, 2010). Still, rather than assuming decreased demands owing to increased body mass coaches and boxers should be cognisant that this supposition might not feature in all bouts. Therefore, appropriate training and strategies ought to be considered accounting for the potential range of demands independent of a boxer's weight class (Dobson & Keogh, 2007).

The comparisons of winning, middleweight boxers of either regional or national standard ability revealed the offensive output of higher ability boxing was higher in eight of twelve key performance indicators and the frequency of success of such actions was higher for seven of twelve indicators, particularly those where defensive movements were considered. Such notable differences are likely due to fights being contested over six and nine minutes for regional and national boxers, respectively. Defensive proficiency has been found to differentiate amateur boxing outcomes (Davis et al., 2014) so it is possible those winning bouts over a prolonged period of time are those reaching the national standard thus reinforcing the importance of defence in amateur boxing performance.

Noteworthy in all performance profiles was wide dispersion, spanning 4-20 percentile bands when the range was used and 2-13 bands when the IQR was utilised. Furthermore, the CV% was used to quantify the within-group variability for groups of actions and outcomes (offensive and defensive) with high values established. Whilst erratic performance is a characteristic trait of sports performance the values herein exceed the variability of time-motion demands evidenced in soccer (Gregson et al., 2010) and rugby league (Kempton, Sirotic, & Coutts, 2014; Kempton, Sullivan Bolsborough, Cordy, & Coutts, 2015), despite there being fewer degrees of freedom in a dyadic sport such as amateur boxing (McGarry, 2009). However, this study involved the analysis of discrete technical actions rather than motions across a playing area and the CV% are consistent with previous observations appraising the technical demands of rugby league (Kempton et al., 2015). Whilst the locomotory demands of athletes are influenced by the situational variables, it seems plausible technical demands are comparatively erratic owing to the need to amalgamate multi-factorial internal considerations (e.g. athlete technical ability, decision-making, task requirements, physical and physiological ability, anthropometry) and context-dependent factors (e.g. opponent characteristics, tactics, match status) (Kempton et al., 2015). Moreover, it appears plausible the opposition likely influence the technical demands more so than the need to ‘follow’ possession given such actions are used to achieve the fundamental objectives of sport (e.g. a goal in soccer, scoring a knockout or point in amateur boxing).

Although the outcome, weight class and ability might affect the nature of amateur boxing performance, it seems unlikely these variables alone would explain such inconsistency given the CV% associated with other sports appraising similar independent variables did not produce such high values (Gregson et al., 2010). Specifically, the brevity of a boxing match might exacerbate the CV% in comparison to sports of a longer duration given the increased variability when comparing shorter within-match periods to full matches (Kempton et al., 2013). Additionally, the crude division of ability based upon regional or national standard bouts likely influenced within-group disparity given the perception-action coupling of boxers of the ‘same’ ability could have been dissimilar (Handford, Davids, Bennett, & Button, 1997; Glazier, Davids, & Bartlett, 2003). Consequently, boxers of the same group might respond differently when presented with similar stimuli reducing within-group technical consistency.

Using log-linear modelling, the independent and interactive influence of contest outcome, weight class and ability upon the frequency of key offensive and defensive indicators was examined. There were several actions influenced significantly by main effects, two and three-way interactions reinforcing previous findings in other game sports that performance is multifactorial and affected by numerous situational variables (Taylor et al., 2008; Passos, Araujo, & Davids, 2013). Due cognizance of the independent variables evident in particular contests is therefore warranted to accurately appraise the demands of amateur boxing and boxers ought to prepare for a diverse range of demands owing to the situational variables of competitive boxing.

Performance was characterised by 104 (95% CI: 99 – 109) individual attacks and 184 (179 – 189) punches supporting the belief amateur boxing involves frequent repeated, high-intensity efforts (Smith, 2006). Thus, amateur boxing is characterised by brief attacks involving few punches confirming the view that the change in scoring to a computer-based method has been suggested as altering the tactical approach adopted during competition such that boxers attempt to land easily discernible, forceful punches to register points with the judges (Smith, 2006). Furthermore, given the reduced time to react to brief attacks, it is possible the potential for a counter-attack by the opponent is also reduced. Single punches are also typically used to set up subsequent attacks and prevent an opponent from attacking (Hickey, 2006) further explaining boxers' reliance upon such attacks.

Of the punches performed, the jab was performed most frequently (Table 4.5). This is despite it being the least efficient punch (≈ 31% success). This punch is posited as being the most important punch type as it possesses injurious potential whilst setting up more forceful attacks (Hickey, 2006). Furthermore, the jab has the lowest delivery time, thus giving an opponent less time to defend (Piorkowski et al., 2011). Following the jab, the backhand and lead hook were the punches thrown most frequently; approximately a third of these punches were landed successfully (34 - 36% success). These punches are typically thrown to cause injury and/or score a point (Hickey, 2006) and are known to generate higher peak forces at impact (Smith et al., 2000; Smith, 2006) than the jab. The rear hook was typically performed 21 times during bouts with similar success (≈ 39%) to the backhand and lead hook. This punch again generates high forces and is thus used to inflict injury and register points with the judges (Hickey, 2006). Its decreased frequency might be due to the comparatively slower delivery time (Piorkowski et al., 2011). In agreement with previous research (El-Ashker, 2011; Davis et al., 2013a), the lead and rear uppercuts were performed less frequently than other punches. The reason for this remains unknown though it has been suggested that it is the most difficult punch type to master (El-Ashker, 2011). Moreover, the uppercut provides the shortest distance between a boxer and the target (Hickey, 2006; Hristovski, Davids, Araujo, & Button, 2006) and throwing it might therefore afford the opponent increased opportunity to counter-attack. Future research however is warranted to confirm this deduction.

Boxers performed fewer defences than attacks suggesting they did not attempt to defend every attack performed by the opposing boxer. Given the score of a contest can be influenced through offensive and defensive movements, the data therefore confirm a preference for influencing the score using attacking methods (Davis et al., 2013a) despite a similar probability of success (i.e. 45% vs. 46% for defence and attack, respectively). Still, under the computer-scoring method defences are not of equal merit to attacks as they only prevent an opponent from registering a point whereas attacks potentially increase the score of a boxer. Thus, given the aim of a contest is to *outscore* an opponent, boxers should prioritise attack over defence.

A preference for defending using the arms was established, followed by trunk and foot defences (Table 4.5). Previous research both supports (El-Ashker, 2011) and contrasts this observation (Davis et al., 2014) which might be due to varying operational definitions (James et al., 2007), varying levels of boxing expertise in the analysts and the different samples of each study. However, previous research has not considered the outcome of defensive movements, merely reporting their frequency. Thus, the present research is the first to establish the most effective form of defence advocating the use of foot defences given their effectiveness (73% deemed successful). The success of this action might be due to foot defences typically moving the boxer out of the opponent's range (arm length) of punching, whereas trunk and arm defences typically entail the boxer remaining within the opponent's range (Hickey, 2006).

Moreover, arm defences were possibly the least successful (45%) because they require a boxer to position his own arms in such a way that prevents a punch from reaching the desired target area. Consequently, within a very short time (e.g. delivery time of 217 ± 69 $m \cdot s^{-1}$ for rear hand crosses; Piorkowski et al., 2011) boxers must react to identify the punching arm (e.g. left or right), type of oncoming punch (e.g. straight, hook or uppercut) and the target (e.g. head or trunk) before manoeuvring their own arm into position and progressively complex decisional tasks are known to elicit depreciated reaction-time and accuracy (Delignieres, Brisswalter, & Legros, 1994; McMorris & Keen, 1994; Brisswalter, Arcelin, Audiffren, & Delignieres, 1997; McMorris & Graydon, 1997; Draper, McMorris, & Parker, 2010). Still, if a boxer does move their arm into an appropriate position, the punch might transcend the attempt to block or deflect it owing to the high forces involved (Hickey, 2006). Consequently, when performing trunk and arm defences, the boxer is comparatively susceptible to receiving a punch if still within range of the opponent, potentially explaining the lower success rate of these actions. Surprisingly, the most efficient defence-type (i.e. foot defences) was performed least frequently and the least efficient defence (i.e. arm defences) was utilised most often. However, given arm and trunk defences are used more frequently, it is possible such defences provide opportunities to counter as opponents are typically within punching range (Hickey, 2006; Hristovski et al., 2006). The present study did not attempt to quantify the frequency or accuracy of counter attacks though it has been suggested that defences incorporating arm defences should be used to initiate a counter attack (Davis et al., 2013a).

The frequency of offensive and defensive actions was modified according to all three independent variables, either as main effects or interactions. In amateur boxing, research has documented some of the performance differences according to contest outcome (El-Ashker, 2011; Davis et al., 2013a). However, these previous investigations presented winning and losing profiles using the analysts' quantification of landed punches by respective boxers, not the judges' verdict (El-Ashker, 2011; Davis et al., 2013a). Indeed, Davis et al. (2013a) acknowledged 19% of the judge-determined winning boxers did not land the higher quantity of successful punches. Thus, the 'winning' and 'losing' activity profiles presented in the El-Ashker (2011) and Davis et al. (2013a) research might be inaccurate. The current research used the ringside judges' decisions to determine a winning and losing performance. Consequently, whether a boxer landed more successful punches does not bias the findings.

Log-linear analysis revealed the outcome of a boxing contest influenced ten of twelve behaviours where the frequency of the actions and outcomes were considered. Generally, winning performance was characterised by an overall increase from model constants where the number and success of offensive actions were considered alongside fewer defences using the arm and trunk. Under the previous 'impressionistic' method of judging it was supposed amateur boxers applying the higher quantity of attacks were viewed favourably (though there is no available data to support this belief) but, the data herein suggests high offensive output remains an important facet of successful performance. Thus, the development of a ‘positive’ impression might lead judges to award points more readily to a particular boxer and based upon a given probability, performing more offensive actions increases the likelihood of landing a scoring blow and thus winning a bout. Moreover, there are references within the rules to giving more merit to the boxer ‘deemed to have attempted to strike first or initiated the attacks’ (ABAE, 2007, p.67) so a more aggressive approach could influence the judges interpretation of punch performance given this stipulation. Moreover, the efficiency of many performance indicators was higher in winning boxers. This strengthens the supposition that the change from impressionistic methods of judging to the computer-based point scoring system has placed on emphasis upon the *quality* of a boxer’s actions also. Consequently, technical mastery of such skills (i.e. jab, rearhand cross, lead hook) should be a priority for boxers.

Anecdotally, it is suggested performance differs between weight classes in amateur boxing and whilst research has highlighted physiological (Smith, 2006) and biomechanical differences between boxers of various weights (Smith et al., 2000; Walilko et al., 2005), a performance analysis across boxing weight classes has yet to be undertaken. Analysis revealed weight class contributed to the frequencies of ten key performance indicators and nine key performance indicators where the outcome was considered thus confirming anecdotal observations and findings in other combat sports (Bridge et al., 2011; Santos, Franchini & Lima-Silva, 2011) that weight class impacts performance. In boxing, physiological differences have been established and thus may contribute to varying performances across weight classes (Smith et al., 2000; Khanna &

Manna, 2006) despite attempts to ensure parity between competitors via weight classes (Smith, 2006; Morton et al., 2010).

The final variable considered was the ability of the boxers. The virtues of such a consideration concern its use within talent ID (Waldron & Worsfold, 2010), whilst enhancing the tactical understanding of competition (Lupo, Tessitore, Minganti, & Capranica, 2010) and training specificity (Sirotic et al., 2009). Ability had the most prevalent impact upon performance influencing the frequency and success, of ten and eleven key performance indicators, respectively. Typically, regional bouts of six minutes duration were associated with decreases in offensive and defensive output compared to national standard bouts competed over nine minutes. That boxers competing in shorter bouts evidenced lower external demands seems logical, though such a comparison has not previously been undertaken. Such data is fundamental in understanding the external demands of the sport and essential in preparing boxers for competition (Mohr, Krustrup, Andersson, Kirkendal, & Bangsbo, 2008). From this perspective, boxers competing in different contest formats require individualised training sessions in order to prepare for the demands of forthcoming contests and those boxers transitioning between contest formats should be cognizant of the expected changes in performance. Assuming the absolute external demand is reflective of the internal physiological load experienced (Akubat, Barrett, & Abt, 2013) boxers performing over nine minutes are likely to require a higher level of conditioning. That the duration of exercise is related to the contribution of different energy systems (Gastin, 2001) means boxers competing over a longer duration require higher reliance upon aerobic sources of energy provision (Davis et al., 2013b). Thus, boxers competing in nine-minute contests should ensure training stresses the aerobic energy system through means such as high-intensity interval training given its ability to improve aerobic fitness (Tomlin & Wenger, 2001; Laursen & Jenkins, 2002).

It emerged that the efficiency of offensive and defensive performance (i.e. percentage deemed successful) was comparable between standards of boxers. Although higher ability sports performers have been shown to possess better game-specific psychology (Williams, 2000; Ward & Williams, 2003), anthropometry, physiological and match-related skill performance (Reilly et al., 2000), boxers are generally matched based upon their ability and previous experience, ensuring parity between competitors. Indeed, the ABAE (2009) rule book contains guidelines concerning age, weight and ability to maintain equality during competition. Consequently, whilst higher ability boxers might possess increased physiological fitness (Guidetti et al., 2002), and improved perceptive and anticipatory ability (Williams, 2000), because the opponent is likely to possess similar characteristics the outcomes of skilled actions are directly influenced by the opposing boxer’s technical ability (McGarry, 2009; Glazier, 2010). Consequently, a superior offensive ability, for example in higher ability boxers, is possibly negated by the opponent possessing high defensive ability. This may explain the equivalent technical attacking performance between national and regional groups. Nevertheless, higher ability boxers must maintain skilled actions over a longer duration and thus should train to ensure fatigue does not reduce technical performance (Royal et al., 2006).

Despite the current study providing the most comprehensive analysis of amateur boxing performance to date, revealing the importance of outcome, weight class and ability, there are limitations representing future avenues for research. First, anecdotal evidence suggests the interaction between the two boxers, and in particular the style utilised by each boxer, influences the nature of a contest and this viewpoint is supported by dyadic observations of attacker-defender coordination in sports performance (Passos et al., 2008; Morgan, Williams, & Barnes, 2013). In boxing for example, it seems logical that a contest between a ‘counterpuncher’ and an ‘aggressive fighter’ compared to a bout between two ‘counterpunchers’ would result in different demands (Hickey, 2006). Consequently, the data and the associated variability presented herein is likely a facet of the styles of the boxers competing within each contest according to the outcome, weight and ability, so might not accurately reflect the demands of individual contests between specific styles of boxers for a given set of situational variables. Given the situational variables considered and likely inclusion of several styles within the sample, the variability should be interpreted by coaches and boxers to identify the likely bandwidth of demands according to particular situational variables. Moreover, given the subjectivity currently involved in identifying boxing styles, objectively classifying these might prove difficult. Future research ought to therefore define boxing styles and elucidate their influence given they likely moderate the demands.

That the ability groups were synonymous with distinct contest durations (six versus nine-minute bouts) and different ring dimensions (4.9 and 5.5 m^2 versus 6.1 m^2) indicates the presented data and parameter estimates for this variable could vary due to either ability, contest duration or ring dimensions acting alone or in consort. Given progression from regional to national and international boxing is typically accompanied by movement from six- to nine-minute bouts and larger contest ring dimensions, it is likely that an appraisal of the independent influence of these factors necessitates experimental control. However, given national standard boxers are more likely to compete in larger rings sizes over nine-minute bouts, and vice versa for lower ability boxers, the analysis reflects valid competitive conditions.

Finally, the division of the sample into 12 groups resulted in two groups represented by only two performers and so the data of these groups might not provide an accurate account of boxing performance. Such groups involved light- and heavyweight regional and national standard boxing. Given the requirement for a high sample sizes to detect meaningful differences in the presence of variability (Batterham & Atkinson, 2005), future research ought to address the role of the situational variables in these groups utilising increased sample sizes.

The findings reinforce the belief that the sport requires frequent, repeated actions producing a high external load (Smith, 2006; El-Ashker, 2011; Davis et al., 2013a) and coaches and boxers should use the information to inform their approach to training and competition. However, in designing a specific training program, practitioners should be cognisant of large inter-individual differences in the external demands made of boxers preparing for the ‘worst-case demand’ (Dobson & Keogh, 2007; Sirotic et al., 2009). As variables known to influence physical and technical performance in other sports include the quality and type of opposition, match phase (i.e. first versus second half in team sports) and location (i.e. home versus away match), and the current score, future research might therefore examine further situational variables that impact upon amateur boxing performance, adding further specificity to preparation and competitive strategies. Moreover, the analysis has provided an outcome-focussed analysis of amateur boxing performance and so future research might consider the dyadic interaction underpinning boxing performance (McGarry, 2009; Morgan et al., 2013).

Chapter 5

Concurrent validity and test re-test reliability of a Global Positioning System (GPS) for assessing boxing-specific movements.

5. 1 Introduction

Performance in sport is multi-faceted, requiring a unique amalgamation of attributes. Achieving an optimum adaptation of these traits requires exercise training and performance assessments that embrace the notion of specificity (Muller et al., 2000). In order to maximise specificity, a quantification of sports performance is essential (Reilly, Morris & Whyte, 2009). In many sports the movements and orientations of competitors are fundamental aspects of their performance outcomes and therefore the ability to capture such objective data contributes to the design of specific coaching and training programs. Recent technological advances in movement analysis have yielded several systems capable of gathering such data in real-time (Barris & Button, 2008). Global Positioning System (GPS) technology is one such system and it is now frequently used to quantify sport-specific movements, or their so-called ‘demands’ (Coutts & Duffield, 2008; Townshend, Worringham, & Stewart, 2008; Cunniffe, Proctor, Baker, & Davies, 2009; Barbero-Alvarez, Coutts, Granda, Barbero-Alvarez, Castagna, 2010; Gabbett, 2010; Gray, Jenkins, Andrews, Taaffe, & Glover, 2010; Coutts, Quinn, Hocking, Castagna, & Rampinini, 2010). Owing to strong relationship between the movement demands and the physiological response (Lambert & Borresen, 2010), such data is pivotal for the development of conditioning programs and performance tests (Duffield et al., 2009).

In using any measurement tool, an assessment of its reliability and validity is necessary to identify its practicality (Atkinson & Nevill, 1998; Hopkins, 2000; Atkinson & Nevill, 2001; Currell & Jeukendreup, 2008; Impellizzeri & Marcora, 2009). Whilst the validity and reliability of GPS technology has been frequently assessed in sports involving linear and multi-directional team sport-specific movements (Coutts & Duffield, 2008; Jennings, Cormack, Coutts, Boyd, & Aughey, 2010b; Barbero-Alvarez et al., 2010; Gray et al., 2010; Portas et al., 2010; Waldron et al., 2011; Johnston et al., 2013b), cricket-specific (Petersen, Pyne, Portus & Dawson, 2009) and court-based movements (Duffield et al., 2009), owing to technological constraints it has been seldom considered in sports typically contested indoors. Moreover, such sports may not lend themselves to an assessment using GPS given their smaller playing areas and fewer linear movements (Duffield et al., 2009; Portas et al., 2010).

One sport predominantly performed indoors, where the movement patterns of its participants are integral to its outcomes, is amateur boxing. Boxers are typically positioned side-on, adopting either an ‘orthodox’ or ‘southpaw’ stance whereby one leg leads the other (Hickey, 2006; see Chapter 3). From this stance, they perform a variety of multi-directional movements including shuffles, steps, jumps and pivots (Hickey, 2006). Importantly, the seemingly intricate movements of boxers performed within a confined space (4.27 – 6.10 m^2) present challenging conditions for valid and reliable assessments of their specific movement patterns using GPS (Duffield et al., 2009; Petersen et al., 2009; Portas et al., 2010; Aughey, 2011). Indeed, currently, no data exists documenting the characteristics (e.g. frequencies, durations, speeds, and distances) associated with these movements. Given the near-linear relationship between the speeds of human locomotion and energy cost (McArdle, Katch, & Katch, 2007, Powers & Howley, 2007), an examination of boxing-specific movement alongside other measures of competitive demands, could therefore be used to inform the training of boxers and the design of ecologically valid measurement tools based upon replications of the movement patterns involved (Muller et al., 2000; Kingsley et al., 2006; Wilkinson et al., 2009).

5.1.1. Study aim:

To assess the concurrent validity and reliability of GPS measurements of boxing-specific movements in order that the technology be used to quantify the ambulatory demands of competition and inform a sport-specific simulation protocol.

5.1.2. Research question:

How accurately and consistently can GPS technology document boxing-specific locomotive movements?

5.2 Methods

5.2.1 Participants

A single boxer (age: 25 y; stature: 1.78 m; body mass: 73 kg) provided written informed consent to participate in the study, which was granted approval by the Faculty of Applied Sciences Ethics Committee. The same individual was used during all trials in order to eliminate between-participant variability and enable numerous repeat trials (Duffield et al., 2009; Peterson et al., 2009; Gray et al., 2010).

5.2.2 Design

During a single day (conditions: ‘dry’; temperature: 22.0 °C; humidity: 54%) and on an artificial 3G football pitch, the participant completed two trials incorporating 10 repetitions of 13 different amateur boxing-specific movements (Table 5.1.) that had been developed following the approach adopted by Duffield et al. (2009), and in conjunction with two senior level ABAE coaches and another experienced amateur boxer (25 previous contests). During six of the movements, measures of mean speed ($\text{km}\cdot\text{hr}^{-1}$) and distance covered (m) were recorded concurrently using an infra-red timing system (Brower timing systems, Utah, USA) and a portable GPS device (5 Hz; GPSports, Canberra, Australia). For the other seven movements, distance covered (m) was the only concurrent measure recorded as given their brevity, no criterion measure of mean speed was available.

5.2.3 Procedure

The participant performed a self-selected warm-up for approximately 15 minutes that included skipping, light jogging, stretching and shadow boxing exercise (Smith et al., 2000; Smith et al., 2001). Two timing gates were set at zero and 6.10 m apart (corresponding to the maximum boxing ring width (ABAE, 2009)) and at a height of 60 cm (Cronin & Templeton, 2008). The environmental conditions were dry, 16.2 °C and 32 % humidity. The GPS unit was activated and allowed 15 minutes to obtain a satisfactory satellite signal before its use (Waldron et al., 2011). The number of satellites accessed ranged between 9 and 11 during the testing session. The GPS unit (dimensions = 90 x 45 x 5 mm; mass = 86 g) was housed in a purpose-made vest between the scapulae, in line with the lower cervical spine, and sampled movement data at a rate of 5 Hz.

Whilst maintaining a boxing stance, the movements were completed at maximal speeds or at a velocity dictated by a metronome. The pace of the metronome dictated when the participant was to take a single boxing-specific stride and was based upon a performance analysis of movements representative of the ‘observatory’ period (i.e. when boxers are not exchanging blows) (Silva, Del Vecchio, Picanco, Takito, & Franchini, 2011) during amateur boxing competition. This afforded an examination of movement speeds typical of actual competition (0.6 - 0.8 $m \cdot s^{-1}$). The 13 movements assessed are outlined in table 5.1 and included linear and curvilinear movements, acute changes of direction, movement of different distances and intensities thus providing a comprehensive assessment of the efficacy of GPS technology within boxing given the movements are those known to reduce the validity and reliability of GPS-estimates (Aughey, 2011).

Movement times were recorded using a wireless receiver (Brower timing systems, Utah, USA) accurate to 0.01 s. Data were subsequently downloaded to a personal computer using SPI EZY (V2.1, GPSports, Canberra, Australia) and speed-distance data were determined using Team AMS software (V2.1, GPSports, Canberra, Australia). Speeds of < 0.1 $km \cdot hr^{-1}$ identified the participant as ‘stationary’, and increases above this velocity were used to denote the initiation of a trial, from which timing gate duration was used as the criterion determination of the associated GPS-derived distance (Peterson et al. 2009; Waldron et al., 2011).

Table 5.1. Details of the boxing-specific movements used to assess the validity and reliability of GPS-derived speed and distance estimates.

	Description		Description
1	Linear movement of 6.10 m performed in the sagittal plane at maximal speed.	8	Single posterior linear boxing-specific movement of 0.8 m performed in the sagittal plane at maximal speed; akin to one horizontal jump whilst remaining in a boxing stance.
2	Linear movement of 6.10 m performed in the sagittal plane with speed dictated by a 1 Hz metronome.	9	Combined anterior and posterior linear boxing-specific movement of 1.6 m (2 x 0.8 m) performed in the sagittal plane at maximal speed; akin to two horizontal jumps whilst remaining in a boxing stance.
3	Linear movement of 6.10 m performed in the frontal plane at maximal speed.	10	Single rightward linear boxing-specific movement of 1.0 m performed in the frontal plane at maximal speed; akin to one horizontal jump whilst remaining in a boxing stance.
4	Linear movement of 12.20 m anterior then posterior performed in the sagittal plane at maximal speed.	11	Single leftward linear boxing-specific movement of 1.0 m performed in the frontal plane at maximal speed; akin to one horizontal jump whilst remaining in a boxing stance.
5	Agility-based circuit totalling 10 m (5 x 2 m continuous movements in the sagittal and frontal planes) and four 90° changes of direction performed at maximal speed.	12	Combined left and rightward linear boxing-specific movement of 2.0 m (2 x 1 m) performed in the frontal plane at maximal speed; akin to one horizontal jump whilst remaining in a boxing stance.
6	Multi-planar (circular) movement of 14.4 m (2.3 m radius to approximate maximum distance a boxer might circle during an actual bout) performed at maximal speed.	13	Multi-planar (circular) movement of 5.02 m (0.8 m radius to coincide with average participant arm length where arm length = ∑ radiale-stylion length, acromial-radiale length, mid-stylion-dactylion length (cm)) performed at maximal speed.
7	Single anterior linear boxing-specific movement of 0.8 m performed in the sagittal plane at maximal speed; akin to one horizontal jump whilst remaining in a boxing stance.		

5.2.4 Statistical Analysis

Descriptive statistics (mean ± SD) were calculated for all variables over the two trials of 10 boxing movements. The presence of systematic bias between criterion and GPS-derived estimates of average speed and distance was assessed using a paired and one-sample *t*-test, respectively. The absolute bias and random error was quantified using 95% limits of agreement (Bland & Altman, 1986; Lamb, 1998; Nevill & Atkinson, 1997). The validity of the GPS-derived estimates of average speed and distance were also assessed expressing the percentage difference between criterion and GPS-derived values (%bias ± 95 confidence intervals (CI) = [(criterion – GPS estimate) /criterion)*100] (Jennings et al., 2010a, 2010b). The standard deviation of the %bias provided the standard error of the estimate (%SEE ± 95% CIs) (Hopkins, 2000; Pyne, 2008; Peterson et al., 2009; Portas et al., 2010).

Absolute test-retest reliability of the GPS measures was assessed using typical error (TE) (Hopkins, 2000), paired samples *t*-tests and 95% limits of agreement respectively (Bland & Altman, 1986; Lamb, 1998; Nevill & Atkinson, 1998). Normality and homoscedasticity checks on the test-retest differences (errors) were performed using the Shapiro-Wilk and Pearson’s product-moment correlation coefficient, respectively, and were found to be satisfactory. Typical error was also expressed as a coefficient of variation (CV%), classified as ‘good’ (<5%), ‘moderate’ (5 to 9.9%) or ‘poor’ (≥ 10%; Roberts et al., 2006). Data analyses were performed using Microsoft Excel (Version 2010, Redmond, WA) and SPSS (Version 17.0; Chicago, IL). Statistical significance in all tests was set at $P \leq 0.05$.

5.3 Results

As highlighted in Table 5.2, systematic bias was evident between the timing gate and GPS-derived measures of average speed for each movement drill (*P* < 0.01). This included both under- and over-estimations by the GPS, and 95% of the differences ranging between, for example, -0.23 and 0.08 km·hr^{-1} for movement 2, and 2.02 to 2.26 km·hr^{-1} for movement 5. However, the %bias was typically < 11% and %SEE <3% for all movements.

Table 5.2. Validity of GPS-derived measurements of average speed (km·hr^{-1}) in boxing-specific movements.

Movement	**Timing gates (km·hr^{-1})**	**GPS (km·hr^{-1})**	**95% LoA**	**%Bias ± 95% CI**	**%SEE ± 95% CI**
1 ^{MS}	8.04 ± 0.3	7.20 ± 0.35	0.84 ± 0.46*	10.64 ± 1.27	2.88 ± 1.23
2 ^{MN}	2.72 ± 0.13	2.80 ± 0.17	-0.08 ± 0.16*	-2.82 ± 1.30	2.96 ± 1.30
3 ^{MS}	8.28 ± 0.32	7.69 ± 0.39	0.59 ± .047*	7.17 ± 1.31	2.99 ± 1.31
4 ^{MS}	6.99 ± 0.18	7.10 ± 0.16	-0.12 ± 0.21*	-1.67 ± 0.71	1.61 ± 0.71
5 ^{MS}	7.06 ± 0.39	5.38 ± 0.24	1.68 ± 0.45*	23.73 ± 0.99	2.27 ± 0.99
6 ^{MS}	8.03 ± .013	8.25 ± 0.31	-0.22 ± 0.44*	-2.68 ± 1.22	2.78 ± 1.22

*Significant difference (bias), *P* < 0.01.
MS = at maximum speed, MN = at metronome-dictated speed.

In eight of thirteen movements (see Table 5.3), no systematic bias was evident between the reference and estimated measures of distance (*P* > 0.05). Again, the GPS provided both under- and over-estimations of the criterion measurements. Typically, where significant differences between systems were evident, the systematic bias and SEE were <10% and <4% of the reference measure, respectively. For movement 5, which demonstrated the highest level of bias, 95% of the differences ranged between 1.86 and 2.97 m for a distance of 10 m, whereas the SEE was <3%. For movement 2, the 95% LoA were better confined within -0.50 and 0.32 cm. Whilst the %bias was typically lower for movements 7-13 (-0.62 to 3%), the %SEE for movements 7-13 (5.74 – 11.80%) were generally higher than other movements.

Table 5.3. Validity of GPS-derived measurements of distance (m) in boxing-specific movements.

Movement^1	**Reference distance (m)**	**GPS (m)**	**95% LoA**	**%Bias ± 95% CI**	**%SEE ± 95% CI**
1 ^{MS}	6.1 ± 0	5.51 ± 0.14	0.59 ± 0.28*	9.67 ± 2.3	2.3 ± 1.01
2 ^{MN}	6.1 ± 0	6.19 ± 0.21	-0.09 ± 0.41	-1.46 ± 2.57	3.40 ± 1.49
3 ^{MS}	6.1 ± 0	5.74 ± 0.24	0.36 ± 0.47*	5.90 ± 3.96	3.96 ± 1.73
4 ^{MS}	12.2 ± 0	12.44 ± 0.31	-0.24 ± 0.61*	2.62 ± 1.81	2.54 ± 1.11
5 ^{MS}	10 ± 0	7.59 ± 0.28	2.42 ± 0.55*	24.15 ± 2.81	2.81 ± 1.23
6 ^{MS}	14.4 ± 0	14.91 ± 0.48	-0.48 ± 0.94*	-3.29 ± 2.72	3.32 ± 1.45
7 ^{MS}	0.8 ± 0	0.81 ± 0.09	0.00 ± 0.19	-0.62 ± 8.38	11.80 ± 5.17
8 ^{MS}	0.8 ± 0	0.79 ± 0.08	0.01 ± 0.15	1.25 ± 8.51	9.85 ± 4.32
9 ^{MS}	1.6 ± 0	1.615 ± 0.10	-0.02 ± 0.19	-0.94 ± 3.99	6.18 ± 2.7
10 ^{MS}	1.0 ± 0	1.03 ± 0.08	-0.03 ± 0.14	-3.0 ± 5.02	7.33 ± 3.21
11 ^{MS}	1.0 ± 0	1.03 ± 0.07	-0.03 ± 0.14	-3.0 ± 5.02	7.33 ± 3.21
12 ^{MS}	2.0 ± 0	2.05 ± 0.11	-0.05 ± 0.22	-2.5 ± 3.6	5.74 ± 2.51
13 ^{MS}	5.02 ± 0	4.93 ± 0.31	0.10 ± 0.60	1.97 ± 3.52	6.12 ± 2.67

*Significant difference (bias), *P* < 0.01.

[1] MS = at maximum speed, MN = at metronome-dictated speed

The test-retest reliabilities of the GPS measures of average speed are displayed in Table 5.4. No systematic bias (range -0.35 to 0.28 km·hr^{-1}) was evident between trials for any movement (*all P* > 0.05). The random error component of the 95% LoA was more variable; from 0.23 (movement 10) to 1.28 km·hr^{-1} (movement 3), whereas the typical error was relatively small (ranging from 0.08 to 0.44 km·hr^{-1}) and in all movements apart from 2, 7 and 8, the CV% were ≤ 5%.

Table 5.4. Reliability of GPS-derived measurements of average speed (km·hr^{-1}) in boxing-specific movements.

Movement[1]	**GPS trial 1**	**GPS trial 2**	**95% LoA (km·hr^{-1})**	**Typical error (km·hr^{-1})**	**CV (%)**
1 ^{MS}	7.33 ± 0.39	7.05 ± 0.25	0.28 ± 0.96	0.35	4.4
2 ^{MN}	2.73 ± 0.20	2.86 ± 0.09	-0.13 ± 0.44	0.16	5.5
3 ^{MS}	7.52 ± 0.42	7.87 ± 0.28	-0.35 ± 1.28	0.44	4.6
4 ^{MS}	7.08 ± 0.18	7.1 ± 0.15	-0.04 ± 0.49	0.18	2.0
5 ^{MS}	5.31 ± 0.29	5.44 ± 0.16	-0.13 ± 0.42	0.15	2.5
6 ^{MS}	8.18 ± 0.33	8.38 ± 0.27	-0.20 ± 0.84	0.30	3.6
7 ^{MS}	2.37 ± 0.23	2.38 ± 0.19	-0.01 ± 0.68	0.24	6.8
8 ^{MS}	2.64 ± 0.30	2.50 ± 0.14	0.14 ± 0.51	0.18	5.9
9 ^{MS}	2.51 ± 0.15	2.44 ± 0.12	0.07 ± 0.34	0.12	4.1
10 ^{MS}	2.81 ± 0.11	2.82 ± 0.12	-0.01 ± 0.23	0.08	2.2
11 ^{MS}	2.74 ± 0.20	2.78 ± 0.19	-0.04 ± 0.43	0.16	4.7
12 ^{MS}	2.78 ± 0.10	2.78 ± 0.09	0.00 ± 0.27	0.10	2.6
13 ^{MS}	4.06 ± 0.16	4.04 ± 0.20	0.02 ± 0.40	0.14	2.8

[1] MS = at maximum speed, MN = at metronome-dictated speed

The reliability analysis of the GPS-derived estimates of distance (Table 5.5) yielded non-significant biases (-0.09 to 0.12 m, $P > 0.05$) for all movements and random errors between 0.08 to 1.58 m. The typical error was < 0.58 m for all movements, and for ten of them, the CV was ≤ 5%.

Table 5.5. Reliability of GPS-derived measurements of distance (m) in boxing-specific movements.

Movement[1]	GPS trial 1 (m)	GPS trial 2 (m)	95% LoA	Typical error (m)	CV (%)
1 ^{MS}	5.51 ± 0.14	5.51 ± 0.15	0.00 ± 0.39	0.14	2.3
2 ^{MN}	6.25 ± 0.23	6.13 ± 0.17	0.12 ± 0.54	0.19	2.5
3 ^{MS}	5.70 ± 0.27	5.78 ± 0.22	-0.08 ± 0.50	0.18	2.7
4 ^{MS}	14.89 ± 0.44	14.94 ± 0.54	-0.05 ± 1.57	0.57	3.4
5 ^{MS}	7.54 ± 0.27	7.63 ± 0.30	-0.09 ± 0.78	0.28	3.1
6 ^{MS}	14.89 ± 0.44	14.94 ± 0.54	-0.05 ± 1.58	0.58	3.4
7 ^{MS}	0.81 ± 0.09	0.79 ± 0.10	0.03 ± 0.30	0.11	8.4
8 ^{MS}	0.76 ± 0.10	0.82 ± 0.04	-0.06 ± 0.21	0.08	5.8
9 ^{MS}	1.58 ± 0.08	1.65 ± 0.11	-0.07 ± 0.26	0.09	4.8
10 ^{MS}	1.04 ± 0.08	1.02 ± 0.06	0.02 ± 0.15	0.06	4.1
11 ^{MS}	1.04 ± 0.07	1.02 ± 0.08	0.02 ± 0.08	0.03	1.4
12 ^{MS}	2.05 ± 0.12	2.05 ± 0.12	0.00 ± 0.35	0.12	4.9
13 ^{MS}	4.89 ± 0.33	4.96 ± 0.30	-0.07 ± 1.03	0.37	6.2

[1] MS = at maximum speed, MN = at metronome-dictated speed

5.4 Discussion

In accordance with previous research, the results of the current analysis demonstrate systematic differences between GPS-derived estimates compared to known distances and timing gate-derived calculations of speed for several movements (Macleod, Morris, Nevill, & Sunderland, 2009; Gray et al., 2010; Jennings et al., 2010a; Waldron et al., 2011). Nevertheless, practitioners can account for systematic bias when interpreting GPS-derived data (Duffield et al., 2009; Waldron et al., 2011) and the validity of the GPS estimates were comparable, if not better, than evidenced in previous research employing GPS technology (e.g. Macleod et al., 2008; Duffield et al., 2009; Jennings et al., 2010a). Moreover, test-retest assessments of measurement error established GPS technology as a reliable means of analysing the average speed and distance covered during boxing-specific movements.

However, in consort with previous research there were some findings suggesting questionable accuracy. In particular, application of the absolute 95% limits of agreement revealed a worst-case error of 44% (1.68 ± 0.45 $\text{km}\cdot\text{hr}^{-1}$; $P < 0.01$) for average speed and 30% (2.42 ± 0.55 m; $P < 0.01$) for distance, respectively, in relation to the criterion. During movement 5, for a criterion speed of 7.06 $\text{km}\cdot\text{hr}^{-1}$, it was 95% likely that the corresponding timing gate-determined speed could lie between 3.93 and 6.83 $\text{km}\cdot\text{hr}^{-1}$. Clearly, such wide limits, which significantly underestimate criterion speed, could be problematic if appraising the movement demands of the sport. Given the near-linear relationship between movement speed and energy expenditure (McArdle et al., 2007), prescribing exercise based upon error of 44% could result in a markedly different physiological load being applied to athletes and if an invalid movement speed was further confounded by distance-related errors, the total energy expended would not adequately characterise the physiological load of that movement/sport.

Unsurprisingly, such error was associated with an *agility-based* circuit consisting of a 10 m path and four 90° changes of direction. However, such a difference was based predominantly upon a systematic bias between criterion and GPS estimates (movement 5 % bias = 24.15) which can be accounted for statistically (Duffield et al., 2009; Waldron et al., 2011). Given the low %SEE such a correction would provide an acceptably accurate estimate of the criterion value. Moreover, the %SEE was far superior to those reported previously for walking (8.9 ± 2.3%), jogging (9.7 ± 2.8%), striding (11.0 ± 3.1%) and sprinting (11.7 ± 3.0%) over a 10-metre course that also included four 90° changes of direction. Interestingly, the %SEE is a less stringent reflection of random error including 68% of the random variation instead of 95%, as is the case with 95% LoA, and practitioners should therefore consider the impact upon relevant analytical goals (Batterham & George, 2003) when employing either statistic.

As with previous conclusions, movements involving more linear movements, fewer changes of direction and lower speeds yielded favourable validity for both average speed and distance estimates (MacLeod et al., 2008; Duffield et al., 2009; Jennings et al., 2010a; Portas et al., 2010). For example, during a 6.1 m movement with the pace dictated by a metronome (movement 2), the 95% limits of agreement indicated speed error ranging between only -0.24 and 0.08 $km \cdot hr^{-1}$, despite the presence of systematic bias. Moreover, estimates of distance for the same linear movement revealed an error of ≤ 8% for 95% of the sample data (-0.09 ± 0.41 m).

The current findings are consistent with previous observations applying 5 Hz GPS devices to assess linear, curvilinear and multidirectional movements of different distances and speeds (Witte & Wilson, 2004; Townshend et al., 2008; Duffield et al., 2009; Peterson et al., 2009; Gray et al., 2010; Jennings et al., 2010a; Portas et al., 2010). That is, GPS measurements provide improved estimates of average speed and distance under conditions involving increasingly linear paths with no change of direction. Where curvilinear paths and changes of direction are incorporated, sampling rate has been implicated as affecting the accuracy of measures (Duffield et al., 2009; Johnson et al., 2013). Although the sampling rate used in this study (5 Hz) has indicated favourable validity across a number of movement paths, it is possible that acute changes of direction alongside insufficient sampling rates limit the opportunity for accurate positional measures to be recorded (Gray et al., 2010; Portas et al., 2010; Aughey, 2011). Indeed, recent evidence suggests 10 and 15 Hz units have improved the validity and reliability of movement analysis (Castellano, Casamichana, Calleja-González, Roman, & Ostojic, 2011; Johnson et al., 2013). The use of 5 Hz units may present a distorted movement path that fails to adequately replicate the exact path taken by the unit/individual (Gray et al., 2010). Additionally, the exact path taken by the boxer may be different to the intended path, potentially deteriorating congruence between criterion and GPS estimates further (Coutts & Duffield, 2010; Portas et al., 2010). With the exception of movement 5 which included several acute (90°) changes of direction known to reduce the accuracy of GPS technology (Aughey, 2011), GPS-derived estimates offer a valid means of assessing boxing-specific movements; particularly if systematic bias is accounted for using statistical approaches (Waldron et al., 2011).

Besides the linearity of the movement, the *intensity* of the effort is known to have a direct influence upon the accuracy and repeatability of the speed and distance estimates (Witte & Wilson, 2004; Aughey, 2011). For example, Jennings et al. (2010a) assessed the validity of GPS-derived estimates (over 10, 20, and 40 m) across different movement intensities (walking, jogging, striding and sprinting) and reported that the SEE increased alongside the speed (intensity) of movement (e.g. SEE = 21.3 ± 5.8% and 30.9 ± 5.8% for walking and sprinting, respectively). Where speed was reduced in the current study (between movements 1 and 2), the validity of GPS measures of average speed and distance generally improved (see Tables 5.1 and 5.2). In the case of movement 1, however, the comparatively rapid change in linear position probably limited the opportunity for positional measures to be recorded, consequently diminishing its validity and reinforcing previous evidence that the GPS units are affected by the intensity of movement, even at lower speeds (i.e. < 8 km·hr^{-1}; Duffield et al., 2009).

In addition to the influence of movement intensity, recent research has demonstrated that movements performed over higher distances typically exhibit improved GPS estimates (Peterson et al., 2009; Jennings et al., 2010a; Aughey, 2011) than over shorter distances. Indeed, Jennings et al. (2010a) reported SEEs (± 90% CI) of 30.9 ± 5.8%, 17.0 ± 3.6% and 11.9 ±2.5% for 10 m, 20 m and 40 m sprinting splits, respectively. Consequently, the small distances assessed herein (0.8 – 14.4 m) presented challenging conditions for an accurate assessment of movement characteristics using a GPS device (Duffield et al., 2009). Nevertheless, the validity and reliability of the GPS-derived estimates were largely acceptable for all the movements selected, and support the potential for employing GPS devices to estimate distances covered not only by boxers, but by other athletes whose movements are confined to a small performing area. Such a conclusion can be drawn if employing either validity statistic (i.e. 95% LoA and %SEE) as (i) systematic bias can be statistically accounted for (Waldron et al., 2011), (ii) random error typically represented < 10% of the criterion value, and (iii) %SEEs were lower than previously reported for a range of movements, including those known to increase the accuracy of GPS estimates of distance covered (i.e. walking).

The reliability of the GPS device in estimating average speed and distance across all 13 movements was considered to be good, with (i) no significant bias between observations, (ii) generally narrow limits of agreement, (iii) low typical error, and (iv) CV% deemed good-to-moderate (Roberts et al., 2006). Nevertheless, the CV% are higher than in previous research (Peterson et al., 2009) that has assessed the reliability of the same model of GPS (SPI EZY) during movements of comparable speeds. That is, during walking (≤ 7.2 km·hr^{-1}) and jogging (7.2 - 12.6 km·hr^{-1}) their CV% of 0.7% and 2.9%, respectively, are superior to those of the current study. However, during boxing-specific movements it is likely that larger accelerations and decelerations occur during each stride, which possibly impacts negatively on the accuracy of the GPS (Jennings et al., 2010b). Furthermore, the CV% reported by Peterson et al. (2009) assessed movements over large distances (8,800 m and 2,400 m, respectively), which, as alluded to above, enhances the repeatability of GPS measurements (Jennings et al., 2010a; Gray et al., 2009).

Whilst it is difficult to relate the current findings to analytical goals owing to a dearth of research documenting the movement characteristics of amateur boxing, it is likely that the movements performed during *actual* competitive situations are typically slower than those utilised here. For example, although plausible, a boxer is unlikely to perform a movement covering the complete width of a ring (i.e. 6.1 m^2) at maximal boxing-specific speeds (≈ 8 $km \cdot hr^{-1}$), as is the case during movements one and two of the present study. Consequently, the use of GPS *in situ* would likely benefit from the lower speeds of movement and provide an improved accuracy and reliability (Gray et al., 2010). Moreover, individual competitive movements are more likely to reflect movements 8 – 13, which were more accurate and reliable than the other movements. On this basis, it is concluded that GPS can be applied in competitive amateur-boxing situations, and in the manner of previous performance analysis research, it has the potential to collect movement-related data that can be used to quantify the movement 'demands' of the sport and enable the development of a simulation protocol for the purpose of athlete conditioning and/or fitness monitoring.

Chapter 6

The development of an amateur boxing conditioning and fitness test (BOXFIT)

6.1. Introduction

Understanding and enhancing sports performance requires a description of the competitive environment and subsequent identification of attributes or traits likely to influence performance (Bishop, 2008; Reilly et al., 2009). As many of these traits can adapt in response to external interventions, such as training (or conditioning), it has become common-place across all sub-disciplines of sports science to observe and quantify them both pre- and post-training, as well as during competition (Currell & Jeukendrup, 2008). Such practices provide worthwhile knowledge about the competitive conditions experienced by sports performers ('athletes') which, in principle, can facilitate the optimisation of their training (Bishop, 2008).

Within the sub-discipline of exercise physiology, the quantification of performance is achieved using a range of methods, involving either laboratory or field-based assessments (Bishop, 2008). In recent years, there has been a marked growth in the number of both types of assessments (Impellizzeri & Marcora, 2009) as it has become desirable to identify essential indictors of successful performance, profile athletes and establish the efficacy of training or nutritional interventions (Currell & Jeukendrup, 2008; Lidor, Cote, & Hackfort, 2009; Reilly et al., 2009). Whilst laboratory-based assessments are generally posited as being more reliable than field-based (Wilkinson et al., 2009), it is recognised that there is a need to maximise their ecological validity in order that they are sensitive to genuine changes in sporting performance (Atkinson & Nevill, 2001; Currell & Jeukendrup, 2008; Reilly et al., 2009; Wilkinson et al., 2009a). Thus, the challenge exists to develop sport-specific assessments or tests (Muller et al., 2000) that replicate the particular movement patterns observed (external load) and physiological demands (internal load) imposed during actual competition (Wilkinson et al., 2009a; Lambert & Borresen, 2010; Scott et al., 2013). Accordingly, sport-specific *simulations* of performance have begun to emerge as useful ergonomic tools capable of inducing replicable internal physiological loads and assessing the physiological demands of sports (Kingsley et al., 2006), the efficacy of nutritional interventions (Highton et al., 2013) and identifying differences between ability groups (Chaabene et al., 2012).

To-date, whilst team sports account for many of the available simulations (Nicholas et al., 2000; Roberts et al., 2010; Williams et al., 2010; Waldron et al., 2012; Sykes et al. 2013), some have been developed for individual sports, particularly racquet sports (Chin et al., 1995; Kingsley et al., 2006; Wilkinson et al., 2009). In contrast to the earliest attempts which sought to replicate the general movement patterns of team players, the more recent simulation protocols have incorporated sport-specific technical actions (Williams et al., 2010; Bridge et al., 2013) and considered the physical performance of particular sub-groups of performers, such as inter-changed players (Waldron et al., 2012). Within individual *combat* sports, which are characterised by their large numbers of technical actions (Del Vecchio et al., 2011; El-Ashker, 2011; Bridge et al., 2011; Davis et al., 2013a), specific simulations have emerged for karate (Beneke, Beyer, Jachner, Erasmus, & Hutler, 2004; Nunan, 2006; Doria et al., 2009), taekwondo (Campos et al., 2012; Bridge et al., 2013b), Muay Thai boxing (Crisafulli et al., 2009) and novice amateur boxing (Davis et al., 2013b), and in conjunction with acute physiological measures, have provided important data that have characterised the pre-requisites of competition.

One combat sport yet to receive significant attention regarding the development of ecologically valid performance protocols is boxing. This is somewhat surprising given the high documented internal (Ghosh et al., 1995; Smith, 2006; Ghosh, 2010) and external (El-Ashker, 2011; Davis et al., 2013a, Davis et al., 2014) loads produced. Previously, attempts to replicate the demands of competitive boxing have relied upon non-specific exercise (Hall & Lane, 2001) and aged performance data (1994 Commonwealth games) (Smith et al., 2000) or failed to adequately regulate the exercise intensity (Davis et al., 2013b). Moreover, the few attempts made thus far to simulate boxing performance have failed to replicate the movements of boxers around the ring. Whilst Davis et al. (2013a) quantified a variable known as VHM this variable is unlikely to provide a valid reflection of the external demands associated with boxing movements. To that end, global positioning system (GPS) units are more suited to an examination of the characteristic motions, given their proven ability to provide estimates of time-displacement data in a variety of sports (Aughey, 2011).

Finally, previous attempts to simulate amateur boxing have failed to communicate and fully justify the specific technical actions and movements incorporated, further limiting their application in research and applied environments. Although simulation protocols are typically developed using the mean external demand of large cohorts of athletes (e.g. Sykes et al., 2013), researchers ought to evidence the applicability of these simulations to specific sub-groups of athletes given the disperse nature of sports performance (Gregson et al., 2010). In boxing, the outcome (El-Ashker, 2011; Davis et al., 2013a; Davis et al., 2014), method of judging, weight class, ability, ring size, contest duration and styles of the boxers involved are factors that could modify the demands (see chapter 4) and so a simulation based on the average demand ought to undergo an appraisal of its validity when characterising the demand of specific subgroups. Moreover, if a simulation failed to approximate the typical demands of amateur boxing according to situational variables, subsequent amendments to the proposed movements could be applied to ensure it does more accurately reflect those evidenced during competition. Given a prominent intention in the development of simulation protocols concerns enhanced specificity within physical and physiological assessments of performance, this is a pertinent task.

In order to accommodate this, it was necessary initially to attempt to identify and quantify typical boxing-specific movements. Given the inherent constraints on the use of GPS during competitive amateur boxing (occurring indoors), an alternative strategy was required. Accordingly, the use of GPS during sparring bouts (outdoors) was considered to provide a viable imitation ('Phase 1'). Secondly, the data generated via this approach had to be assessed in terms of its validity and reliability ('Phase 2'), and thirdly, data on the boxing movements had to be combined with the previously determined technical actions (Chapter 4) in order to formulate the boxing simulation protocol ('Phase 3'). Appraisal of the simulation's external validity necessitated a comparison with specific subgroups ('Phase 4') and, given its importance in modifying amateur boxing demand, two groups of different ability (and thus contest duration) were therefore selected for this purpose.

6.1.1. Study aims:

(i) To quantify the locomotive demands of amateur boxing during competitive sparring.

(ii) To assess the validity and reliability of the GPS-derived estimates of speed and distance obtained during sparring.

(iii) To amalgamate the locomotive and technical (i.e. offensive and defensive movements) demands, affording a simulation of amateur boxing.

(iv) To address the validity of a simulation protocol based upon average demands.

6.1.2. Research questions:

(i) What are the locomotive demands associated with amateur boxing during competitive sparring?

(ii) How accurate and consistent are quantifications of locomotive demand during sparring in amateur boxing.

(iii) How accurately would a simulation protocol based upon the average demands characterise those of specific sub-groups?

6.2. Methods

6.2.1. Participants

Twelve amateur boxers (age 23 ± 1 y, body mass 61.6 ± 6.5 kg, stature 1.75 ± 0.08 m, years of experience 6 ± 2 y, previous contests 15 ± 8) were recruited to perform open sparring, outdoors (Phase 1). Based upon the movement profiles of Phase 1, a single participant (age: 25 y; stature: 1.78 m; body mass: 73 kg, years of experience 10 y, previous contests 25) was recruited to assess the validity and reliability of GPS estimates of a boxing-specific pilot movement profile (Phase 2). Institutional approval for the empirical procedures was granted by the Faculty of Applied Sciences Ethics Committee, and the use of performance data in developing the simulation was approved by the regional ABAE governing body.

6.2.2. Procedures

6.2.2.1. Phase 1: Identification of movement profiles

Based upon previous research described in this thesis (see Chapter 5), GPS units were employed to estimate the distances travelled and the average speeds of the boxers' movements during 'open' sparring situations. Such spars closely replicate the conditions experienced during competitive contests as no restraints are applied to the boxers. During six 'open' spars conducted outdoors in a 4.88 m^2 boxing ring, twelve amateur boxers were equipped with a 5 Hz non-differential GPS unit (dimensions = 90 x 45 x 5 mm; mass = 86 g) (SPI Pro, GPSports, Cranberra, Australia) positioned between the scapulae. The same two units were used in all trials to minimise between-unit variation (Buchheit et al., 2013). The GPS unit was activated and operated in the manner described previously (see Chapter 5). The environmental conditions were dry and the temperature and humidity were 18.1 °C and 41 %, respectively.

Prior to each sparring bout, the boxers performed a 15-minute, self-selected warm-up that included skipping, light jogging, dynamic stretching and shadow boxing exercise (Smith et al., 2000; Smith et al., 2001). Based upon their ability classification (National/Regional), they subsequently competed for 3 x 3 (n = 6) or 3 x 2 (n = 6) minutes interspersed with one minute rest (10 s standing, 50 s seated). The boxers' movements during each round were recorded throughout and the data were subsequently downloaded to a personal computer using SPI EZY (V2.1, GPSports, Canberra, Australia). Speed and distance data were determined using Team AMS software (V2.1, GPSports, Canberra, Australia).

Additionally, each sparring contest was recorded with two digital cameras (Canon MV700, Japan) placed at adjacent sides of the ring (Chapter 4). Footage was analysed using a purpose-developed template in an attempt to quantify the direction of the boxers' movements. Five subjectively-determined directions were subsequently identified (see Figure 6.1) and the frequency of movements in each direction recorded. The intra-observer reliability (Cooper et al., 2007) of this analysis (see below) was examined using the 6-minute movement profile of a boxer (age: 23 y; stature: 1.76 m; body mass: 72.3 kg) randomly selected from the sample of 12.

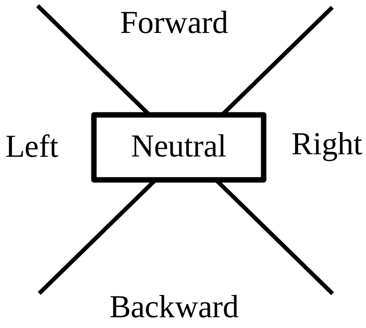

Figure 6.1. Diagram displaying the five movements identified.

6.2.2.2. Phase 2: The reliability and validity of a pilot movement profile

Based upon the identification (video analysis) and quantification of movements (GPS) during Phase 1, a pilot movement profile was developed and a single boxer on one day (conditions: 'dry'; temperature: 16.0 °C; humidity: 77%), twice performed 10 repeated trials of boxing-specific movements. Following each trial, the boxers were given three minutes passive recovery which was sufficient to lower their heart rates to pre-exercise levels. Using discreet movements of 1 m which were dictated by an audio cue, a decagon with a centre-point was marked out on a 4G synthetic pitch. Beginning at a point on the outer decagon, the boxer moved forwards to the centre, moved backwards and then left (11 times) or right (3 times) to the required marker. This cycle was repeated 14 times during each minute (42 m), for a total of three minutes (126 m). This provided an estimate of the accuracy of GPS-derived estimates produced during the open sparring.

6.2.2.3 Phase 3: Identification of offensive and defensive actions

As described previously in this thesis (see Chapter 4), a performance analysis was conducted in order to profile the offensive and defensive actions performed during competitive boxing. Whilst such analysis established several differences in specific aspects of boxing performance according to the outcome, weight and ability of the boxers, the intention was to develop a simulation protocol capable of approximating the demand of amateur boxing independent of the situational conditions. Having developed such a protocol, researchers, coaches and boxers alike can then tailor the movements of the simulation to meet the specific demands made of a group or individual boxer according to the contextual influences (e.g. styles of the boxers, outcome, weight class, ability and method of judging).

Based upon the log-linear analysis of chapter 4, the most notable influence on boxing-specific behaviour frequencies was that of ability, likely owing to the different contest durations. Thus, in an attempt to negate the impact of contest duration upon performance, further analysis was undertaken using the relative frequencies (i.e. number of actions per minute of a contest) rather than the absolute values. Employing a mixed design, three-way ANOVA (outcome [two levels], weight class [three levels] and ability [two levels]) with repeated measures (round number), such analysis (see Appendix 2) established that the *overall* technical offensive and defensive demand did not typically differ ($P > 0.05$) between groups or across rounds when expressed relative to the respective contest durations (i.e. six and nine minute bouts, respectively). Although some significant differences remained (e.g. the demand within lightweight, regional, losing performances was typically lower than other groups), a decision was made to utilise a movement plan based upon a standardised minute within the BOXFIT, independent of three of the principal factors that potentially influence boxing performance. Using this standardised minute, two and three minute rounds could be applied pending the expected bout length of a boxer. Moreover, the average is the favoured descriptive of central tendency, best approximating all values within a particular sample (O'Donoghue, 2012) and so the data informing the technical actions of the simulation protocol reflected the average frequency of actions of all the competitors (n = 84). This version of the boxing simulation will be referred to as the BOXFIT from hereon.

6.2.2.4 Phase 4: The validity of the BOXFIT

Despite the approach taken in developing the BOXFIT, chapter 4 revealed wide within-group dispersion, evidenced via the range, IQR and CV% as well as significant differences when evaluating the influence of contest outcome, weight class and standard of competition. Therefore, despite the characteristic use of cohort averages to simulate the competitive environment in other sporting protocols, the average of two specific sub-groups (Group one = winning, middleweight, *regional* standard boxers [2 minute rounds] [$\text{BOXFIT}_{\text{W,M,R}}$]; Group two = winning, middleweight, *national* standard boxers [3 minute rounds] [$\text{BOXFIT}_{\text{W,M,N}}$]) were contrasted to two and three minute versions of the BOXFIT. Such comparisons were selected owing to the number of behaviours influenced significantly by the standard of boxing (see parameter estimates of table 4.5 and 4.7).

6.2.3 Statistical analysis

6.2.3.1 Variability of GPS and video analysis estimates of movement (Phase 1)

A two-way mixed design ANOVA (Fallowfield, Hale, & Wilkinson, 2005; O'Donoghue, 2012) was employed to assess the variability of the GPS-derived distances covered in the ring - absolute (m) and relative ($\text{m}\cdot\text{min}^{-1}$) - and average speed due to the effects of round (one, two or three) and round duration (two- versus three-minute). In addition, a two-way repeated measures ANOVA assessed the variability of the direction of movement (forward, backward, neutral, left, right) alongside round effects. Where appropriate, significant ANOVA effects were followed-up with Bonferroni-adjusted to reveal where pair-wise differences existed. Such *post-hoc* tests were either independent samples (between-group) or paired samples (within-group) *t*-tests. Statistical significance was set at $P \leq 0.05$. The magnitude of variance explained by main or interaction effects was quantified using partial eta squared (η_p^2) values of 0.01 (small), 0.06 (medium) and ≥ 0.14 (large) (Field, 2009; Richardson, 2011). For pair-wise comparisons, accompanying Cohen's effect sizes were calculated as: $d = (\bar{x}_1 - \bar{x}_2)$ / SD; where $\bar{x}_1$ and $\bar{x}_2$ represent the two sample means and SD the pooled standard deviation (Richardson, 2011).

6.2.3.2 Reliability of the movement template (Phase 2; Figure 6.1)

The method proposed by Cooper et al. (2007) was used to quantify the intra-operator reliability of the movement protocol (Figure 6.1). A randomly selected spar was divided into 36 time cells, each 10 seconds in duration (Chapter 1), and the frequency of each movement direction in each cell was recorded. The analysis proceeded in the manner described previously in this thesis (see Chapter 2), and importantly, agreement on a test-retest basis was classified according to *perfect* agreement (PA) and using a reference value of ± 1 count (PA ± 1). In each condition, a proportion of agreement of $\geq 95\%$ was used to indicate sufficient reliability. The reference value (± 1) was selected to concur with previous performance analysis research in boxing (Cooper et al., 2007), whilst attempting to minimize the quantity of permissible errors.

6.2.3.3 Validity and reliability of GPS measures of sparring movements (Phase 2)

The 95% limits of agreement (Atkinson & Nevill, 1998; Bland & Altman, 1986) were employed to examine the validity of GPS estimates of average speed and distance against the known values of the pilot movement profile (i.e. section 2.2.2.). Additionally, validity was assessed by expressing the percentage difference between criterion and GPS-derived values (%bias ± 95 confidence intervals (CI) = ((criterion – GPS estimate) /criterion)*100) (Jennings et al., 2010a, 2010b). The standard deviation of the %bias provided the standard error of the estimate (%SEE ± 95% CIs) (Hopkins, 2000; Pyne, 2008; Peterson et al., 2009; Portas et al., 2010)

Absolute test-retest reliability of GPS-derived estimates of average speed ($m \cdot s^{-1}$) and distance ($m \cdot min^{-1}$) were assessed using the typical error (TE) (Hopkins, 2000), dependent samples t-tests and 95% limits of agreement (Bland & Altman, 1986; Lamb, 1998; Atkinson & Nevill, 1998). The use of several popular reliability statistics ensured a comprehensive assessment of measurement error including approaches based upon 68% (Hopkins, 2000) and 95% of measurement error (Atkinson & Nevill, 1998). The typical error was also expressed as a CV% (Hopkins, 2000). According to previous recommendation (Roberts et al., 2006), CV% were classified as good (<5%), moderate (5 to 9.9%) or poor (≥ 10%). The typical error was also related to the 'smallest worthwhile change' (SWC%), using Cohen's (1988) standardised *d* of 0.2 x pooled standard deviation (Hopkins, 2000, 2004; Waldron et al., 2012; Batterham & Hopkins, 2006). Moderate (MWC%), large (LWC%) and very large changes (VLWC%) (or differences) were calculated as 0.6, 1.2 and 2.0 x pooled standard deviation, respectively, which corresponded to percentile changes of 8, 23, 38, and 49. Such values were then converted to percentages facilitating comparison of the CV% (i.e. the 'noise' of a measurement) with potential meaningful changes (i.e. the 'signal') in performance. All data analyses were performed using either Microsoft Excel (Version 2010, Redmond, WA) or SPSS (Version 17.0; Chicago, IL).

6.2.3.4 Validity of the original sample (chapter 4) offensive and defensive actions (Phase 3 and 4)

To examine the efficacy of the simulation protocol in replicating the external offensive and defensive demands, comparisons between the original sample data (n = 84) and those included within the BOXFIT, BOXFIT$_{W,M,R}$ and the BOXFIT$_{W,M,N}$ were made using one-sample *t*-tests. The mean differences (bias) between the frequency of each action included in the simulations and original sample data were quantified, alongside the 95% confidence intervals (Field, 2009). Such analysis revealed whether the actions of the simulation differed systematically from actual amateur boxing performance and where differences were likely to lie (i.e. 95% confidence intervals) given the range of recorded frequencies during performances (Chapter 4).

6.3 Results

6.3.1 Phase 1: Variability of GPS and video analysis estimates of movement

6.3.1.1 GPS-derived estimates of distance and speed

The average speed of the 12 boxers during the six- and nine-minute formats of sparring (see Figure 6.2) was found to vary across the three rounds ($F_{2, 20} = 4.8$, $P < 0.05$, $\eta_p^2 = 0.33$); post-hoc analysis indicated that average speed was significantly higher in round three compared to round two only ($t_{11} = -2.8$, $P < 0.017$, $ES = 0.69$). However, there was no interactive influence of round number and duration ($F_{2, 20} = 1.61$, $P > 0.05$, $\eta_p^2 = 0.14$) or main effect of round duration ($F_{1, 10} = 1.1$, $P > 0.05$, $\eta_p^2 = 0.10$).

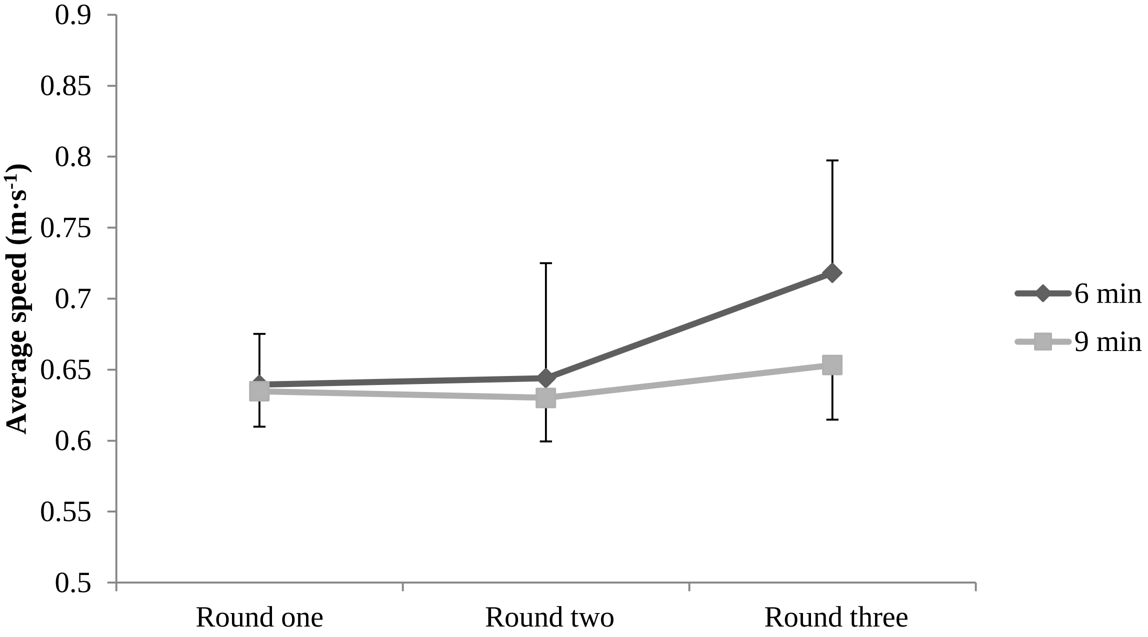

Figure 6.2. GPS-derived estimates of average speed across three rounds of sparring.

Mean total distance covered was seen not to vary across the three rounds ($F_{2, 20} = 1.0$, $P > 0.05$, $\eta^2 = 0.09$), although the group effect (round duration), as expected, was significant ($F_{1, 10} = 74.1$, $P < 0.05$, $\eta_p^2 = 0.88$) on account of the boxers engaging in the 9-minute bouts covering significantly ($P < 0.001$) greater distances in each round than those in the 6-minute bouts. The interaction of round number and duration was not significant ($F_{2, 20} = 0.6$, $P > 0.05$, $\eta_p^2 = 0.06$).

When expressed as a relative value (per minute) the distance covered neither varied significantly across the three rounds ($F_{2, 20} = 1.0$, $P > 0.05$, $\eta_p^2 = 0.01$), nor between groups ($F_{1, 10} = 0.9$, $P > 0.05$, $\eta_p^2 = 0.08$). The interaction effect was also non-significant ($F_{2, 20} = 0.7$, $P > 0.05$, $\eta_p^2 = 0.06$).

Table 6.1. GPS-derived estimates of absolute and relative distance covered during three rounds.

	Distance (m)		Distance ($m\cdot min^{-1}$)	
Round	6 minutes	9 minutes	6 minutes	9 minutes
One	78.20 ± 5.29	113.48 ± 5.24*	39.1 ± 2.64	44.15 ± 9.22
Two	79.0 ± 9.12	112.58 ± 5.75*	39.5 ± 4.59	43.75 ± 8.88
Three	82.47 ± 10.02	113.64 ± 4.44*	41.23 ± 5.01	44.23 ± 9.32

*significantly greater than the 6-minute bouts.

6.3.1.2. Video analysis of sparring

Analysis of the frequency of movements (Table 6.2) revealed a significant effect of direction ($F_{4, 20} = 28.4$, $P < 0.001$, $\eta_p^2 = 0.85$). Boxers were more frequently neutral than moving backwards (P <0.05, d = 1.8), left (P <0.05, d = 1.9) or right (P <0.05, d = 2.0). Movements in a forward direction were performed more than those to the right only (P <0.05, d = 1.7), whilst backwards movements were performed more than right-ward movements alone (P <0.05, d = 1.7). Although the sparring boxers performed an average of 8 – 9 more movements during round one (194 ± 66) compared to rounds two (185 ± 46) and three (187 ± 40), there was no significant effect of round on the number of discreet movements performed ($F_{1, 5} = 0.5$, $P > 0.05$, $\eta_p^2 = 0.09$).

Table 6.2. Video analysis-determined movement frequencies ($N \cdot \text{min}^{-1}$) in different directions.

	Neutral	**Forwards**	**Backwards**	**Left**	**Right**
Frequency	26 ± 2	17 ± 6	13 ± 4	11 ± 4	3 ± 1

6.3.2. Phase 2: Reliability of the movement template (Figure 6.1)

There were no significant differences ($P < 0.05$) between the test and retest observations for any locomotive direction (Table 6.3, below). The proportion of PA ranged between 89–95% and when the reference value was used (PA ± 1), agreement reached 95-100%. Moreover, apart from backward movements, 95% of test-retest differences were within ± 1.1 frequency counts.

Table 6.3. The intra-analyst reliability of the video analysis-determined movement frequencies.

Direction	**Median difference (Sign Test *P*)**	**95% Percentiles**	**PA (%)**	**95% CI (%)**	**PA ± 1 (%)**	**95% CI (%)**
Forward	0 (1.00)	0 to 1	92	83 to 100	100	100 to 100
Neutral	0 (1.00)	-0.1 to 1.1	92	83 to 100	97	92 to 100
Backward	0 (0.63)	-0.1 to 2.0	89	79 to 99	95	87 to 100
Left	0 (1.00)	-1.1 to 1.1	89	79 to 99	95	87 to 100
Right	0 (1.00)	-0.1 to 0.1	95	87 to 100	100	100 to 100

In Table 6.4 (below), 33 of 36 time cells were in *perfect* agreement (89.2 %, 95 % CI = 79.1 to 99.2 %) for the example of forward movements. When applying the reference value (PA ± 1), 100 % of test-retest observations satisfied the criteria. In this instance no observations fell outside of ± 1 limit. Such data is representative of the observations for each movement direction.

Table 6.4. Example of the frequency and percentage distributions of the test-retest differences for forward movements.

Difference between test-retest scores	**Frequency (N·min^{-1})**	**Percentage (%)**
-2	0	0
-1	1	2.7
0	33	91.7
1	2	5.6
2	0	0

6.3.3 Phase 2: The validity and reliability of GPS measures of sparring movements.

The table below displays the validity of the GPS-derived estimates of distance and average speed following 20 repeated trials of boxing-specific movements. One sample *t*-tests revealed significantly higher values for the GPS-derived estimates compared to the criterion values. For both measures, the bias was ≈ 15% of the criterion measure though SEE was < 3%. In addition, the 95% limits of agreement were characterised by high quantities of systematic bias (e.g. 16.9%; 7.09/42.00 $m \cdot min^{-1}$) and random variation equating to 4.3% (1.82/42) and 5.7% (0.04/0.70) of the criterion measure.

Table 6.5. The validity of GPS estimates of distance and average speed during a pilot boxing-specific movement profile.

Measure	**Criterion**	**GPS-estimate**	**95% LoA**	**%Bias ± 95% CI**	**%SEE ± 95% CI**
Distance ($m \cdot min^{-1}$)	42.00	49.09 ± 0.93*	7.09 ± 1.82	16.87 ± 2.21	2.66 ± 1.2
Average speed ($m \cdot s^{-1}$)	0.7	0.80 ± 0.02*	0.10 ± 0.04	13.69 ± 2.66	2.21 ± 0.97

* $P < 0.05$ between test-retest observations.

The absolute test-retest reliability of GPS estimates of distance covered and average speed are presented in Table 6.6. No systematic bias was evident between test-retest scores for either variable and the CV% were low. The 95% limits of agreement lay between -2.66 to 2.40 m·min^{-1} and -0.05 to 0.05 m·s^{-1} for the measures of distance and average speed, respectively. For both measures the moderate changes (0.6 x pooled SD) were larger than the CV%.

Table 6.6. The reliability of GPS estimates of distance and average speed during a pilot boxing-specific movement profile.

	Distance (m·min^{-1})	**Average speed (m·s^{-1})**
Test 1 (mean± SD)	49.02 ± 1.24	0.79 ± 0.02
Retest (mean± SD)	49.15 ± 0.53	0.80 ± 0.01
95% LoA	-0.13 ± 2.53	-0.00 ± 0.05
CV (%)	1.3 $^{\downarrow MWC}$	1.24 $^{\downarrow MWC}$

$^{\downarrow MWC}$ CV% smaller than associated moderate change in performance.

6.3.4. Phase 3: Offensive and defensive actions

Of the 13 actions used to replicate offensive competitive boxing, four were seen to have a higher frequency rate ($P < 0.05$) in the simulation than in the competition data (Table 6.7). However, such differences were typically within a single event.

Table 6.7. Comparison of *offensive* competition (mean ± SD) and BOXFIT data ($N \cdot \text{min}^{-1}$)

Action	Contest data	BOXFIT	Mean difference	95% CI of the difference	
				Lower	Upper
Attack, head	12 ± 1	13	1.02*	-1.82	-0.22
Attack, body	1 ± 0	1	0.05	-0.24	0.13
Attack, both	1 ± 0	1	-0.16	-0.09	0.41
Single punch attack	7 ± 1	7	-0.27	-0.38	0.92
Two punch attack	4 ± 1	5	-0.16	-0.19	0.51
Three punch attack	2 ± 0	3	0.35*	-0.56	-0.15
Punches	26 ± 2	26	0.28	-2.09	1.53
Jab	9 ± 1	9	-0.06	-0.88	1.00
Rear hand cross	6 ± 1	7	1.32*	-1.93	-0.71
Lead hook	6 ± 1	7	0.71	-1.41	0.00
Rear hook	3 ± 1	3	-0.48	-0.47	0.57
Lead uppercut	1 ± 0	0	0.51*	-0.68	-0.34
Rear uppercut	0 ± 0	0	0.04	-0.33	0.26

Similarly, whilst the rates of nine of the 13 defensive actions differed ($P < 0.05$) between the two data sets, only that of lean back movements approached a single frequency count; the remainder were < $0.5 \cdot \text{min}^{-1}$ (Table 6.8).

Table 6.8. Comparison of *defensive* competition (mean ± SD) and BOXFIT data ($N \cdot \text{min}^{-1}$).

Action	Contest data	BOXFIT simulation	Mean difference	95% CI of the difference	
				Lower	Upper
Defence	12 ± 1	12	0.55	-1.72	0.62
Block both arms	2 ± 0	2	-0.13	-0.24	0.50
Block right arm	2 ± 0	2	0.34	-0.72	0.03
Block left arm	0 ± 0	0	-0.45*	0.28	0.61
Clinch	1 ± 0	1	0.21*	-0.40	-0.03
Duck	1 ± 0	1	-0.08	-0.14	0.30
Foot defence	3 ± 0	3	0.50*	-0.86	-0.14
Lean back	2 ± 0	3	0.98*	-1.33	-0.63
Push	0 ± 0	0	-0.09*	0.03	0.14
Slip left	0 ± 0	0	-0.45*	0.30	0.61
Slip right	0 ± 0	0	-0.17*	0.09	0.26
Roll clockwise	0 ± 0	0	-0.07*	0.03	0.11
Roll anti-clockwise	0 ± 0	0	-0.04*	0.02	0.06

6.3.5 The boxing simulation (BOXFIT)

Owing to the absence of significant differences and interactions in GPS-determined measures of average speed, distance covered ($m \cdot min^{-1}$) and the video analysis-determined frequency of discreet direction-related movements between rounds during open sparring, a standardised movement plan (min^{-1}) was applied to all rounds of the BOXFIT. That the relative distances moved were consistent in each round for both the six- and nine-minute spars means the same movement plan could be applied to boxers engaging in either bout format (3 x 2 or 3 x 3 minutes) though the standardised movement plan should be tailored to the expected round durations.

Notwithstanding this, the validity of the GPS-derived data was questionable, consistently over-estimating the distance covered and average speed of movement during the pilot movement profile (Phase 2). However, the reliability across repeated trials of these measures was good as systematic bias represented < 0.25% of the distance covered and average speed during the simulation, and the CV% were both low (<1.3%). Accordingly, a correction factor was applied to the distance and average speed data collected during open sparring (see Table 6.9). Given the GPS-derived estimates of distance and speed consistently overestimated known values, the correction factors were an attempt to provide improved movement characteristics during the simulation.

Table 6.9. The correction factors applied to distance (m·min^{-1}) and average speed (m·s^{-1}) data and derived characteristics of the simulation protocol.

Measure	Mean difference (%)	Correction equation (GPS mean/(1+(mean diff%/100))	Resultant BOXFIT characteristics
Distance (m·min^{-1})	16.9	42.0/1.17	35.9
Average speed (m·s^{-1})	13.7	0.7/1.14	0.6

To coincide with the necessary number of attacks (*n* = 13), defences (*n* = 12) and to replicate the number of discreet movements as closely as possible (*n* = 14 forwards, *n* = 14 backwards, *n* = 10 left and *n* = 2 right), the derived movement profile of the BOXFIT utilised a marked decagon (internal radius = 160 cm; side length = 1 m; see Figure 6.3 below). The internal radius allowed for the average arm length of boxers (75 ± 4 cm, where arm length = ∑ radiale-stylion length, acromial-radiale length, mid-stylion-dactylion length (cm); *n* = 12; Hawes & Martin, 2001), ensuring the boxers cover the desired distance during forward and backward movements (85 cm). Movements left and right were 100 cm. In total, the boxers therefore complete a distance of 35.8 m·min^{-1}**.**

To complete the simulation, the boxers must move between a series of floor markings, placed at each corner and in the centre of the decagon. Beginning at any corner (marker 1; Figure 6.3) and maintaining a boxing stance throughout, they must move forward to the target and perform an attack (marker 2), before moving backwards feigning a defensive action (marker 3), and then left (*N*·min^{-1} = 10) (marker 4) or right (*N*·min^{-1} =

2) (adjusted data of Table 6.2). All movement routines are repeated over one-minute cycles and controlled via an audio cue to coincide with the mean contest demands described herein. The intensity of the protocol is regulated by the number of offensive and defensive actions, the mean corrected distance covered (m·min^{-1}) and corrected average speed (m·s^{-1}). The order of movements is presented in Table 6.10.

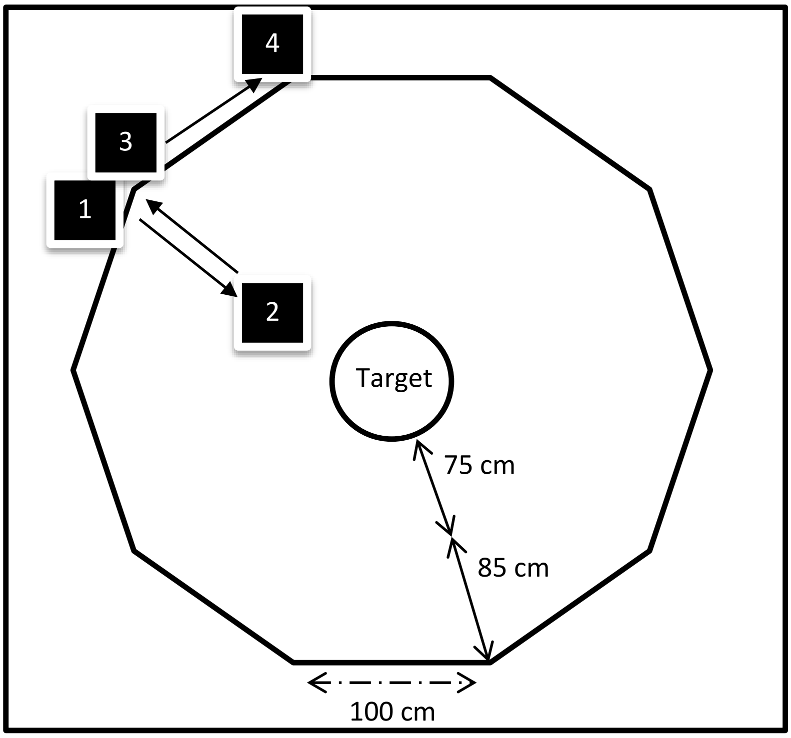

Figure 6.3. Schematic of the BOXFIT simulation protocol within a boxing ring (not to scale).

Table 6.10. The chronological order of audio cues during a one-minute of the BOXFIT.

Direction of movement	Punches to perform				Direction of movement	Defence to feign
	1st	2nd	3rd	4th		
Forward	Jab				Backwards	Block both arms
Left						
Forward	Lead hook				Backward	Block right arm
Left						
Forward	Rear cross	Lead hook			Backward	Clinch
Left						
Forward	Jab				Backward	Block both arms
Left						
Forward	Lead hook				Backward	Block right arm
Left						
Forward	Rear cross	Lead hook			Backward	Duck
Left						
Forward	Rear cross				Backward	Lean backwards
Left						
Forward	Jab	Rear hook			Backward	Lean backwards
Left						
Forward	Jab	Rear cross	Lead hook		Backward	Lean backwards
Left						
Forward	Rear cross				Backward	Foot defence
Left						
Forward	Jab	Rear hook			Backward	Foot defence
Right						
Forward	Jab	Rear cross	Lead hook		Backward	Foot defence
Right						
Forward	Jab				Backward	
Forward	Jab					
	Jab	Rear cross	Lead hook	Rear hook		
Backward						

6.3.6 The validity of the BOXFIT

When the averages of a specific group of boxers (i.e. $\text{BOXFIT}_{W,M,R}$) were used to develop a two minute round of a boxing simulation rather than those of the entire sample (n = 84) (i.e. BOXFIT), only a single significant difference emerged where the offensive actions were appraised. However, this observation likely resulted from the within-group dispersion of the $\text{BOXFIT}_{W,M,R}$ evidenced by lower and upper 95% confidence intervals. Descriptively however, there were several notable differences with fewer attacks to both the head and body, punches, jabs, lead and rear hooks.

Table 6.11. Comparison of *offensive* BOXFIT and $\text{BOXFIT}_{W,M,R}$ (mean ± SD) data for a single two minute round.

Action	BOXFIT	$\text{BOXFIT}_{W,M,R}$	Mean difference	95% CI of the difference	
				Lower	Upper
Attack, head	30	30 ± 8	-0.06	-4.53	4.41
Attack, body	2	2 ± 1	-0.13	-0.95	0.70
Attack, both	3	2 ± 2	-1.31*	-2.24	-0.39
Single punch attack	18	18 ± 6	-0.31	-3.80	3.17
Two punch attack	10	10 ± 3	-0.19	-1.84	1.47
Three punch attack	4	4 ± 1	-0.38	-1.13	0.38
Punches	65	60 ± 12	-5.23	-12.00	1.50
Jab	23	21 ± 9	-1.63	-6.50	3.25
Rear hand cross	14	15 ± 6	0.56	-2.48	3.60
Lead hook	16	14 ± 5	-2.25	-4.88	0.38
Rear hook	8	6 ± 4	-1.81	-4.10	0.47
Lead uppercut	1	1 ± 1	0.00	-0.73	0.73
Rear uppercut	2	2 ± 3	0.31	-1.15	1.78

Although there were three significant differences comparing the performances of winning, middleweight, regional ability boxers with data of the entire sample, eight actions had mean differences lower than one. However, dispersion was again evident in a number of actions as 95% confidence intervals were systematically negative and positive for the lower and upper values, respectively.

Table 6.12. Comparison of *defensive* BOXFIT and $\text{BOXFIT}_{W,M,R}$ (mean ± SD) data for a single two minute round.

Action	BOXFIT	$\text{BOXFIT}_{W,M,R}$	Mean difference	95% CI of the difference	
				Lower	Upper
Defence	26	22 ± 5	-3.94*	-6.95	-0.93
Block both arms	5	4 ± 3	-1.38	-2.97	0.22
Block right arm	4	3 ± 3	-0.63	-2.51	1.26
Block left arm	1	1 ± 1	-0.38	-1.05	0.30
Clinch	2	2 ± 2	0.13	-0.87	1.11
Duck	3	2 ± 2	-0.81	-1.88	0.26
Foot defence	6	7 ± 3	0.75	-0.95	2.45
Lean back	5	4 ± 2	-1.13*	-2.04	-0.22
Push	0	0 ± 0	-	-	-
Slip left	1	1 ± 1	-0.44*	-0.87	0.00
Slip right	0	1 ± 1	0.69	-0.13	1.50
Roll clockwise	0	0 ± 0	0.25	0.01	0.49
Roll anti-clockwise	0	0 ± 0	0.06	-0.1	0.20

Note: absence of values owing to no standard deviation in sample data

Appraising the differences between a three minute example simulation based upon winning, middleweight boxers of national standard with that of the equivalent BOXFIT, three significant differences were established for the frequency of single punch attacks, rear hooks and lead uppercuts. Moreover, there were several action frequencies that deviated markedly from the contest data despite an absence of significance. For example, the mean differences in the number of attacks to the head, punches and jabs performed exceeded three events. The 95% confidence intervals also revealed notable dispersion.

Table 6.13. Comparison of *offensive* BOXFIT and BOXFIT$_{W,M,N}$ (mean ± SD) data for a single three minute round.

Action	BOXFIT	BOXFIT$_{W,M,N}$	Mean difference	95% CI of the difference	
				Lower	Upper
Attack, head	30	36 ± 8	5.68	-3.45	14.78
Attack, body	2	2 ± 1	-0.50	-1.60	0.60
Attack, both	3	2 ± 2	-1.17	-2.98	0.64
Single punch attack	18	24 ± 5	6.12*	0.33	12.01
Two punch attack	10	10 ± 4	-0.17	-4.28	3.95
Three punch attack	4	4 ± 2	-0.33	-2.50	1.83
Punches	65	60 ± 15	-4.83	-22.52	12.86
Jab	23	26 ± 12	3.33	-10.54	17.20
Rear hand cross	14	14 ± 3	-0.17	-3.89	3.55
Lead hook	16	16 ± 5	-0.17	-5.66	5.32
Rear hook	8	2 ± 2	-5.83*	-7.76	-3.91
Lead uppercut	1	0 ± 0	-0.67*	-1.21	-0.12
Rear uppercut	2	1 ± 1	-0.83	-2.38	0.71

Moreover, comparing the defensive characteristics between the winning, middleweight boxers of national standard with that of the BOXFIT, only a single significant difference was established. Ninety-five percent confidence intervals were again markedly distributed across negative and positive values for lower and upper limits, respectively.

Table 6.14. Comparison of *defensive* BOXFIT and BOXFIT$_{W,M,N}$ (mean ± SD) data for a single three minute round.

Action	BOXFIT	BOXFIT$_{W,M,N}$	Mean difference	95% CI of the difference	
				Lower	Upper
Defence	26	29 ± 7	3.33	-4.08	10.74
Block both arms	5	4 ± 3	-1.17	-4.64	2.31
Block right arm	4	4 ± 3	-0.33	-3.70	3.03
Block left arm	1	2 ± 3	1.33	-1.76	4.42
Clinch	2	3 ± 2	0.83	-1.77	3.44
Duck	3	2 ± 2	-0.83	-2.76	1.09
Foot defence	6	8 ± 3	2.33	-0.96	5.63
Lean back	5	10 ± 3	4.83*	1.11	8.55
Push	0	0 ± 0	-	-	-
Slip left	1	1 ± 1	-0.33	-1.42	0.75
Slip right	0	0 ± 0	0.17	-0.26	0.60
Roll clockwise	0	0 ± 0	-	-	-
Roll anti-clockwise	0	0 ± 0	-	-	-

Note: absence of values owing to no standard deviation in sample data.

6.4 Discussion

The chapter has presented a simulation protocol (BOXFIT) based upon a comprehensive analysis of the competitive external offensive and defensive demands of amateur boxing. The frequency and composition of attacks and defensive movements closely replicate those of the average boxing contest whilst approximating those of specific subgroups (e.g. winning, middleweight boxers of regional and national standard). Additionally, a systematic examination of the external locomotive demands made of boxers ensures that the simulation provides a valid replication of the competitive environment, providing an ergonomic research tool for assessing the physiological responses to amateur boxing and the impact of specific conditioning or weight loss-related interventions. That the relative offensive, defensive and locomotive demands were somewhat comparable across rounds under a number of possible constraints (i.e. weight class, ability, contest duration and contest outcome) endorses the applicability of the simulation to a wide range of amateur boxers. Those employing the BOXFIT should however be cognisant that the demand made of boxers might under- or over-estimate the actual competitive demands experienced and so the external validity of the BOXFIT might benefit from modifications to the external demands pending the contextual constraints of competition.

This study was the first to examine the locomotive movements of boxers during competitive sparring. Such movement, referred to as ‘footwork’ within boxing, is critical to success facilitating attack and defence (Hickey, 2006) as a boxer producing submaximal ground reaction force when punching is unlikely to deliver peak force to the opponent on impact (Dyson et al., 2007; Turner, Baker, & Miller, 2011; Lenetsky et al., 2013) and footwork is also used to facilitate attacks and defences (Hickey, 2006).

The only previous attempt to quantify such movements was restricted to a measure of the frequency of VHM (Davis et al., 2013a). A variable such as this is unlikely to facilitate consistent and accurate replications of the actual external and internal demand of movements during contests as boxing-specific locomotive actions are dynamic involving steps and jumping actions (Hickey, 2006), linear and curvilinear paths as well as acute and moderate changes of direction. Moreover, boxers use ‘footwork’ to achieve horizontal displacement across the ring moving toward or away from the opponent (Hickey, 2006) and so measurements related to the vertical axis seem illogical. That only the frequency of VHM was recorded also limits the ability of such a measure to characterise the demand of boxing-specific locomotion as the mechanical work undertaken by a boxer during each VHM could have varied markedly given the diverse nature of boxing-specific movement. It therefore appears unlikely that the inclusion of VHM within a boxing simulation could accurately induce a reliable and valid physiological response. Indeed, Davis et al. (2013a) quantified 224 VHM during contests though there were 260 within the associated simulation protocol (2013b) suggesting limited experimental control of this action. Given experimental control is essential for any simulation attempting to replicate sporting demands (Drust et al., 2007; Reilly et al., 2009; Wilkinson et al., 2009a; Aanstad & Simon, 2013) or detect systematic changes in performance, alternative measures of boxing-specific movement remain necessary.

In the absence of purpose-developed technology tracking the motions of boxers, the present study has provided the most valid assessment of boxers’ movements around the ring to-date, applying GPS technology alongside video analysis to quantify boxing movement. Initially, the average speed and distance covered by boxers was assessed during open sparring. Given the extensive use of time-displacement data in previous motion analyses (Aughey, 2011), including sports characterised by short distance movements and frequent changes of direction (Duffield et al., 2009), it seemed logical to employ similar methods to appraise boxing. Moreover, for a given body mass there exists a near-linear relationship between movement speed and energy expenditure at submaximal intensities (i.e. 0.5 – 1.4 $m{\cdot}s^{-1}$; McArdle et al., 2007) and application of fixed time-displacement data (i.e. 0.6 $m{\cdot}s^{-1}$ and 35.9 $m{\cdot}min^{-1}$) to the BOXFIT movement plan therefore facilitates a valid and reliable load. However, although not confirmed during boxing-specific displacement, at higher movement speeds (i.e. > 1.4 $m{\cdot}s^{-1}$), mechanical efficiency in humans is reduced during ambulatory activities (e.g. jogging, running; Biewener, Farley, Roberts, & Temaner, 2004; McArdle et al., 2007) resulting in exponential increases in the energy cost of movement. Thus, the use of average speed within the BOXFIT will not encapsulate the additional, non-linear increase in energy cost associated with movements that were performed at higher intensities during sparring. However, the time spent at speeds > 1.4 $m{\cdot}s^{-1}$ was typically < 5% (data not presented) so average speed likely remains a useful variable in replicating the load of boxing movement.

Given the complexity of the audio cues during the BOXFIT, alongside the desire to achieve experimental control throughout, average speed also afforded a feasible dependent variable whereby auditory commands were timed to ensure participants maintained adequate speed throughout the protocol (e.g. for 1 metre movement at the desired speed of 0.6 $m{\cdot}s^{-1}$, 1.7 s separated sequential audio cues). Had various speeds and distances been used to replicate the ambulatory demands of boxing during the simulation it appears likely participants would have failed to follow instruction adequately thus reducing the accuracy and consistency of the evoked internal response.

Following the development of a pilot movement profile (see section 6.2.2.2.), the validity and reliability of the locomotive data were examined. Such analysis determined that on average, boxers covered 35.9 $m \cdot min^{-1}$ at a speed of 0.6 $m \cdot s^{-1}$ when systematic differences were accounted for. Although the validity and reliability of GPS-derived estimates have been doubted (Duffield et al., 2009; Bucheit et al., 2013), the methodical process undertaken herein established that the GPS estimates provide repeatable and accurate data. Specifically, GPS estimates of average speed and distance displayed sufficient consistency, demonstrating a CV% of <1.3% which is superior to those reported previously for movements performed within a confined playing area incorporating acute changes of direction (Duffield et al., 2009). Again, whilst the lack of research documenting the movement characteristics of amateur boxers makes the task of determining analytical goals a difficult one, Davis et al. (2013a) did note differences of ≈ 8% between winners and losers in the number of VHM performed. If this difference was characteristic of those concerning the time-displacement data, then the CV% (< 1.3%) would permit identification of the movement profiles of winners and losers separately. That the GPS revealed a systematic bias of 16.87 ± 2.21% compared to a known distance justified the application of a correction factor (Hopkins, 2000; Waldron et al., 2011). To this end, the data collected during the sparring afforded improved validity. Moreover, the low random error (Atkinson & Neill, 1998) and SEE (Hopkins, 2000) suggests corrected distances accurately reflect criterion values. As the applied GPS system did not quantify the typical directions moved by boxers, video analysis was applied to further improve the validity of the movements applied during the BOXFIT. The reliability of such analyses was also examined verifying adequate consistency of the measurements. Unfortunately, previous analyses have failed to examine the distance covered, average speed or direction of boxing movements, or indeed that of other combat sports. Such information might have facilitated a more comprehensive scrutiny of the validity of the movements associated with the BOXFIT.

Comparisons were also made between boxers engaged in six- and nine-minute spars to inform the movement of boxers during the BOXFIT. Logically, boxers participating in nine-minute spars compared to six minutes covered greater distances in each round. However, that they covered a similar distance *each minute* of performance justified a standardised movement plan that can be tailored to six- or nine-minute versions. Apart from a significant difference between rounds two and three for the average speed, there were also typically no changes in the GPS-derived estimates of movement across rounds. Moreover, that the boxers performed a similar amount of direction-related movements across rounds reinforces that a standardised movement plan *throughout* a six- or nine-minute version of the BOXFIT is appropriate.

However, as the ABAE (2007) stipulate contest rings must be 4.27 – 6.1 m^2 and data was collected within a 4.88 m^2 boxing ring, the BOXFIT movement plan might not adequately reflect the movements of boxers performing within other ring dimensions, particularly those deviating notably from 4.88 m^2 (i.e. 4.27 or 6.1 m^2). Whilst only anecdotal evidence supports this assertion, smaller dimensions could reduce the total distance covered resulting in more short movement paths and additional changes of direction compared to larger areas. Analyses of altered pitch dimensions in small-sided soccer games revealed larger relative pitch sizes (i.e. pitch area per player) were associated with an increased internal response as players had to cover greater distances (Hill-Hass, Dawson, Impellizzeri, & Coutts, 2011). In boxing, a reduced area may also increase the offensive and defensive demands given that boxers have smaller distances to move toward or away from an opponent and if boxers were to pace their efforts, the altered offensive and defensive physical and physiological load might have further reduced the impetus to move during the sparring. This would further reduce the ecological validity of the BOXFIT movement plan. However, if an inverse relationship between movement and offensive/defensive demand exists owing to contest ring size, then the physiological response to boxing may be relatively homogenous regardless of the dimensions of the ring. That is, smaller rings might be characterised by reduced movement but higher offensive/defensive demand whereas larger dimensions may result in increased movement demands but fewer offensive/defensive actions. If correct, then the movement data obtained will not have been affected by a down-regulation of exercise intensity owing to the physiological responses (Tucker & Noakes, 2009).

Clearly, altered movement demands that may accompany boxing movement within varying ring sizes requires further investigation, though the movement in the BOXFIT simulation might be limited in replicating the locomotive demands associated with all ring dimensions. Moreover, if the physical and physiological demands are modified gradually with changing contest areas, as is the case in football (Hill-Haas, Dawson, Impellizeri, & Coutts, 2011), the 4.88 m^2 ring used likely offers the most appropriate ring size to develop a generic movement pattern given boxing rings are typically available in dimensions of 4.27 (14 ft), 4.88 (16 ft), 5.49 (18 ft) or 6.1 m^2 (20 ft) only and the ABAE (2007) state the minimum contest ring size necessary for regional, inter-regional and national championships is 4.88 m^2.

Permissible systematic differences were observed between some offensive and defensive contest data and those included in the simulation given the need to amalgamate such data with GPS and video analysis data. Consequently, minor omissions were necessary. However, the exclusion of particular movements was reasonable given their replacement with alternative actions (Bridge et al., 2013). The simulation attempted to ensure equilibrium between participants' ability to respond with sufficient accuracy (Bridge et al., 2013) whilst avoiding predictable movements which may induce a lower strain (Wilkinson et al., 2009; Bridge et al., 2013). Therefore, the offensive and defensive actions of the BOXFIT appear statistically and logically justified.

Whilst previous attempts at simulation protocols have utilised boxing-specific movements (Smith et al., 2000, 2001; Davis et al., 2013), they have failed to justify statistically and examine the efficacy of the included actions. Although the simulation of Smith et al. (2000, 2001) included offensive and defensive boxing-specific actions, it was based upon a video analysis of nine-minute bouts only (three rounds, each three minutes) and owing to the 'professionalization' of amateur boxing (Jones, 2001) the demands may have altered since then. Moreover, computerised scoring was introduced in 1992 (Bianco et al., 2013) and by 1994 boxers' performances might not have fully adjusted to the tactical constraints exerted by such a novel system (Cormery, Marcil, & Bouvard, 2008), suggesting that the demands experienced by current boxers might be quite different to the 1994 performances (Smith, 2006). Even with 112 punches per three-minute round (versus 78 for a three-minute round of the BOXFIT), the protocol of Smith et al. induced peak heart rates of ≈183 $b \cdot min^{-1}$ and post contest blood lactates of 4.5-7.85 $mmol^{-1}$, both lower than those associated with competitive boxing (Smith, 2006; Ghosh et al., 2010). This was despite using novice boxers to simulate the elite demands which would likely result in a heightened physiological response assuming the novice boxers were less conditioned than elite counterparts. Thus, it is plausible other external demands (i.e. their movement profiles) did not fully replicate competitive amateur boxing, suggesting the BOXFIT might offer an improved alternative.

The simulation developed by Davis et al. (2013b) induced even lower peak heart rates of 174 ± 13 $b \cdot min^{-1}$ for the final round, though higher post-contest blood lactates of 9.5 ± 1.8 $mmol \cdot l^{-1}$ than those of Smith et al. (2000, 2001). This suggests that the protocol used may have failed to induce the physiological conditions of boxing competition (Smith, 2006; Ghosh, 2010). Importantly, it was established on novice boxers only, fewer performances than the BOXFIT, and on actions that were not clearly described or justified. Indeed, there were notable mismatches between the simulation and contest data for several offensive and defensive movements used in the protocol. For example, the number of punches performed during the simulation increased significantly between rounds two and three, in direct opposition to the contest data in which the number decreased over each round. The number of defensive actions was also significantly higher than in the contest data in all rounds (e.g. in round one, 20.1 ± 7.3 and 9.1 ± 4.9 for contest and simulation, respectively). Thus, previous attempts to simulate competitive amateur boxing have so far failed to replicate the demands with sufficient validity. The BOXFIT, however, is based upon a current and comprehensive data set, is statistically justified and so offers the best effort to-date at simulating amateur boxing.

To further evidence the external validity of the offensive and defensive actions included in the BOXFIT, two and three minute versions were compared to equivalent simulations based upon the data of specific subgroups of boxers. Specifically, the technical demands made of winning, middleweight regional and national standard boxers were contrasted to two and three minute adaptations of the BOXFIT. Whilst there were typically few significant differences established, suggesting the BOXFIT adequately approximated the performances of the respective subgroups, there were notable deviations from the BOXFIT in some behaviours and the 95% confidence intervals appraising the difference scores revealed considerable departures from the desired frequency. Consequently, those employing the BOXFIT should be aware that it might fail to replicate the external demands for a given boxer as the style of the two boxers competing acting concurrently with other situational variables (e.g. bout outcome, weight class, ability, contest format, ring dimensions) likely determine the observable characteristics of performance.

The BOXFIT is therefore the soundest protocol available *approximating* the demands of boxing given the variant nature of performance. In consort with the performance data according to contest outcome, weight class and ability (Chapter 4), those employing the BOXFIT ought to consider modifying the offensive and defensive demands and also contemplate the typical style adopted by a boxer (Hickey, 2006) during competition to enhance the external validity of the protocol. Whilst replicating the typical demands is an important feature of simulations, it might also be useful to evaluate the *range* of physiological responses following modifications to the external demand such that athletes can augment specificity during training preparing for the highest metabolic demands they are likely to experience (Amtmann, 2012). For example, if a regional standard lightweight boxer is due to progress from six to nine-minute bouts (owing to an ‘upgrade’ of ability; ABAE, 2007) such a boxer could progressively modify then perform the BOXFIT moving from a version typical of regional boxing to that of national boxing before further modifying it to replicate the worst-case demand they might experience in the contest; such an approach thus evidences its use beyond determining the typical physiological response.

Moreover, the approach taken throughout the thesis toward the development of the simulation has moved beyond the conventional approach and researchers developing simulation protocols ought to therefore consider the comprehensive, systematic approach taken within this thesis. Such an approach not only considers the independent and interactive influence of confounding variables on the external demand but the analysis of the current chapter has also highlighted the tools efficacy beyond characterising the typical demand of competition.

Based upon the external demands of amateur boxing competition, the BOXFIT offers a comprehensive and valid ergonomic research tool to examine the associated physiological responses of boxing. Whilst it is appreciated that sport-specific simulations exhibiting externally valid activity profiles do not necessarily afford valid examinations of the internal physiological responses (Bridge et al., 2013), the BOXFIT represents an improvement upon previous attempts to simulate the competitive boxing environment. Additionally, it can be justifiably adapted to six- and nine-minute versions, thus improving its applicability in the applied setting though modifications might be warranted. Owing to the limited opportunity for invasive measurements and inherent lack of control associated with the competitive environment (Roberts et al., 2010), the BOXFIT may therefore be useful for assessing the physiological demands of boxing according to a number of influencing factors, evaluating the impact of specific interventions (i.e. nutrition, hydration status, weight loss, and training) on performance and could also enhance specificity during training. Nevertheless, before it is implemented for any of these purposes, the induced physiological load and the ability of the protocol to produce valid and repeatable responses warrants investigation.

Chapter 7

The internal demand and reliability of the BOXFIT

7.1. Introduction

The quantification of the physiological and movement demands of competitive athletic performance for guiding training (in anticipation of improving sports performance) is an important endeavour in sports science (Currell & Jeukendrup, 2008; Wilkinson et al., 2009; Bridge et al., 2013). However, the collection and assessment of actual sports performance data is often met by several constraints. Firstly, high within- and between-event variances in physical and skilled parameters of performance (O'Donoghue, 2004; Gregson et al., 2010) confound the assessment of systematic changes in competitive data (Bridge et al., 2013; Sykes et al., 2013; Waldron et al., 2013). Additionally, invasive measurements (such as arterial blood sampling, muscle biopsies and expired gases) during performances are often prohibited or impractical (Waldron et al., 2012; Bridge et al., 2013; Davis et al., 2013b) and curtail a more comprehensive assessment of the physiological and metabolic responses. Instead, the quantification of such 'internal' demands during most competitive sports has typically been reliant upon manageable measures, such as heart rate, capillary blood lactate, and ratings of perceived exertion. In the popular sport of amateur boxing (Davis et al., 2013a) however, even the reported physiological loads from these measures are inconsistent owing to the diverse contexts of competition, including differing opponents, weight class, round duration, and scoring format.

Among other sports, a development in recent years has seen researchers devise sport-specific *simulations* of actual performance from detailed analyses of movement characteristics (Currell & Jeukendrup, 2008). In principle, simulation protocols provide an ergonomic framework in which to assess both the internal (physiological) responses to competitive performances, and the impact of specific interventions (e.g. environment, nutrition, hydration and conditioning). This is achieved by regulating exercise intensity, yet enabling invasive measurements of internal demand (Kingsley et al., 2006; Currell & Jeukendrup, 2008; Campos et al., 2012; Bridge et al., 2013). However, the task of simulating performance with adequate validity and reliability, particularly in sports characterised by fast, dynamic movements and actions, remains a challenge (Currell & Jeukendrup, 2008; Wilkinson et al., 2009a, 2009b; Sykes et al., 2013). Nevertheless, several sport-specific simulations do exist for team and individual sports that are not confined to replications of basic linear motions.

Despite the popularity of simulations for specific sports, including combat sports (Beneke et al., 2004; Smith, 2000, 2001, 2006; Crisafulli et al., 2009; Doria et al., 2009; Campos et al., 2012), a valid, reliable and sensitive protocol has yet to befall amateur boxing (see section 2.17). Consequently, our understanding of the physiological demands of competitive boxing is incomplete and potentially inaccurate. Such information might be useful for the organization of training, ensuring increased specificity (Bridge et al., 2009; Campos et al., 2012) whilst permitting identification of intervention-based changes in boxing-specific aspects of performance.

Although the validity, reliability and sensitivity of measurement tools are related issues, it is necessary initially to establish the test-retest consistency of movement and physiological responses to avoid undermining the validity. That is, a test cannot be valid if the induced movement and physiological loads are not repeatable (Atkinson & Nevill, 1998; Batterham & George, 2003; Currell & Jeukendrup, 2008). The ability of a test to detect small yet practically worthwhile changes in performance (i.e. its sensitivity) is also influenced by reliability (Wilkinson et al., 2009; Sykes et al., 2013; Waldron et al., 2013), such that the 'noise' of a test (random or typical error) alongside upper values of confidence intervals can be used as an estimate of the lower limit for a *meaningful* change in performance (Hopkins, 2000; Batterham & George, 2003; Impellizzeri & Marcora, 2009; Wilkinson et al., 2009; Waldron et al., 2013).

Previous attempts to simulate amateur boxing (Smith et al., 2000b, 2001; Davis et al., 2013b) have not reported the reliability of the induced performance or physiological responses and the reported external and internal loads might therefore be somewhat spurious (Wilkinson et al., 2009b; Sykes et al., 2013). Indeed, the attempt of Davis et al. (2013b) to simulate competitive boxing included over twice the quantity of expected defences and changes in offensive performance across rounds that are not typical (Davis et al., 2013a), questioning the internal validity of the protocol (Atkinson & Nevill, 2001). With the intention of offering an improved simulation, an examination of the current simulation's reliability would not only support its validity, but would highlight its likely sensitivity (Currell & Jeukendrup, 2008; Chaabene et al., 2012) and thereby its ability to detect 'real' changes in performance (Atkinson & Nevill, 1998).

7.1.1. Study aims:

(i) To quantify the physiological demands associated with BOXFIT performance.

(ii) To examine the test-retest reliability of the movement-based and physiological responses to BOXFIT performance.

7.1.2. Research questions:

(i) What are the physiological responses to BOXFIT performance?

(ii) How consistent are the induced physiological responses of the BOXFIT?

7. 2 Methods

7.2.1 Participants

Twenty-eight amateur boxers (4 novice; 12 intermediate and 12 open class) (mean ± SD; age 22.4 ± 3.5 years, body mass 67.7 ± 10.1 kg, stature 171 ± 9 cm, years of experience 6 ± 2 years, previous contests 15 ± 8; predicted $\dot{V}O_{2max} = 57 \pm 5$ $ml \cdot kg^{-1} \cdot min^{-1}$) from three amateur boxing clubs in the North West of England volunteered to participate in the study. All the boxers were tested during the competitive season and had competed within the preceding month, or were within a maximum of one month of a forthcoming contest. Participants were informed of the procedures and potential risks of participation, and subsequently provided written informed consent. Institutional ethical approval for the experimental procedures was granted by the Faculty of Applied Sciences Ethics Committee. This was supplemented with the approval of the regional ABAE governing body and respective head coaches.

7.2.2 Experimental design

The boxers were asked to maintain a normal training load and abstain from unaccustomed exercise in the preceding 72 hours (Bryne, Twist, & Eston, 2004; Burt, Lamb, Nicholas, & Twist, 2013). All procedures took place indoors at a boxing club located in the North West of England. Participants underwent familiarisation trials

(Currell & Jeukendrup, 2008) which involved two complete attempts of the simulation protocol separated by 60 minutes, the first of which employed shadow boxing exercise and the second included all its elements (i.e. punching handheld coaching pads). The boxers returned 72 hours later to perform the first of two actual test simulations, and then 4 – 7 days later for the repeat trial. On both occasions each boxer was presented with a detailed written movement plan to read prior to the simulation. Successive trials were performed at the same time of day (± 1.5 h) in order to avoid the effects of diurnal variation (Drust, Waterhouse, Atkinson, Edwards, & Reilly, 2005). Ninety-six hours before the familiarisation, participants performed a 20 m multi-stage fitness test (MSFT) (Ramsbottom, Brewer, & Williams, 1988) in order to provide estimates of their $\dot{V}O_{2max}$ and maximal heart rate.

7.2.3 Procedures

Throughout both trials, the boxers wore a portable gas analyser (mass = 450 g; Cosmed, K4b^2, Italy) and a heart rate monitor (Polar, Electro Oy, Kempele, Finland). In addition, they wore fabric hand-wrapping (450 cm length, 5 cm width; Adidas, Germany) and boxing gloves (284 g; Adidas, Germany) as required during actual competition (ABAE, 2009). Following a 15-minute self-selected warm-up consisting of shadow boxing, jogging and punch bag exercise (Smith et al., 2000; Smith et al., 2001), the boxers performed the BOXFIT simulation protocol (see below) in a boxing ring (6.1 m^2) (temperature = 19.0 ± 3.4 °C; humidity = 41.3 ± 8.5 %). Given analysis of 2-minute amateur boxing rounds has taken place previously (Davis et al., 2013b), the analysed BOXFIT comprised three rounds of three minutes' duration, interspersed with one minute rest between rounds (50 s seated, 10 s standing). Movements during the simulation were recorded using a digital camera (Canon MV700, Japan) positioned adjacent to the boxing ring and the data files were uploaded to Dartfish TeamPro (Version 4.0, Switzerland) where the lead researcher identified deviations from the set protocol and coded them as either a *missed action* (i.e. the boxer completely failed to perform the required action) or an *incorrect action* (i.e. the boxer performed the wrong movement). Moreover, whether *missed* or *incorrect*, a note was made identifying whether the action was an offensive, defensive or motion-related error.

7.2.4 Amateur boxing simulation protocol (BOXFIT)

For a detailed discussion of the movement profile of the BOXFIT, the reader is referred to Chapter 6. Briefly, the boxers' movements were dictated by audio cue and included boxing-specific movements, offensive punches aimed towards coaching pads held by a qualified (Level 2) Amateur Boxing Association coach, and simulated defensive movements. Specifically, during each minute of the simulation, the boxers covered 35.8 m at a speed of 0.54 $m \cdot s^{-1}$, performed 26 punches (consisting of 15 individual attacks) and simulated 12 defences. To provide an assessment of punching performance, wireless accelerometers (Herman Digital Trainer, USA) were attached to the wrist-region of both coaching pads (within the 10 x 5 cm Velcro strap) used to secure it to the coach's hand. Previous analysis of the test-retest reliability of the accelerometers revealed no systematic bias and coefficient of variations of < 5 % (see Appendix 3). The concurrent validity of the accelerometer was established comparing values recorded during punching to those of a three-dimensional infrared camera system (Qualisys Track Manager, version 2.6, Qualisys Inc., Gothenburg, Sweden) (Richards, 1999). No systematic bias was established between systems, though random error (test-retest SD_{diff}

x 1.96) expressed as the 95% limits of agreement (Atkinson & Nevill, 1998) was as large as 19% of criterion measures. However, the coefficient of determination (R^2) was 0.72 and the standard error of the estimate using regression analysis represented < 10% of the criterion measure (i.e. error of 2.72 g associated with criterion mean value of 27.86 g) (Palmer & O'Connell, 2009) (see Appendix 3). Ultimately, because the criterion measure potentially introduced error to the measures also (Pyne, 2008), it was deemed that the Herman Digital Trainer (HDT) was a worthy tool to assess the acceleration generated upon punch impact, particularly given the scarcity of available tools to assess impact kinematics in combat sports (such as boxing) and the favourable cost of the equipment. The HDT receiver units were fastened to the wrist region of each handheld coaching pad, upon which boxers performed the punches of the BOXFIT. The sum acceleration delivered to coach-held pads in each round was recorded at the end of respective rounds.

7.2.5 Physiological measurements

Breath-by-breath gaseous exchange measurements of oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER) and minute ventilation ($\dot{V}_E$) were recorded throughout the BOXFIT using a portable gas analyser (Cosmed K4b^2, Italy). Before each test, the K4b^2 unit was calibrated according to the manufacturer's guidelines. That is, the gas analyser component was calibrated using ambient air (O_2: 20.93% and CO_2: 0.03%) and a gas mixture of known composition (O_2: 16.00% and CO_2: 5.00%), whilst the ventilation volume of the K4b^2 was assessed by pumping three litres of ambient air through its turbine ten times (Duffield, Dawson, Pinnington, & Wong, 2004). Peak and mean heart rates were recorded using a 1 Hz frequency throughout and subsequently expressed as raw and relative (maximum values recorded at volitional exhaustion during the MSFT) values. Expired air and heart rate data were uploaded to Quark K4b2 software (Cosmed, Italy).

Ventilatory data was used to calculate aerobic energy expenditure (EE_{aer}; expressed in $kcal \cdot min^{-1}$) using the Weir (1949) equation (Crusafulli et al., 2009):

$$EE_{aer} = 3.941 \times \dot{V}O_2 + 1.106 \times \dot{V}CO_2$$

An oxygen equivalent of 3.941 was used while the non-protein respiratory quotient (npRQ) was < 1. However, in the event npRQ became > 1, an oxygen equivalent of 5.04 $kcal \cdot min^{-1}$ was used and assumed all energy was derived from carbohydrate (Crusafulli et al., 2009). Given amateur boxing is known to rely substantially upon anaerobic metabolic pathways (Davis et al., 2013), an estimate of anaerobic glycolysis was also obtained by estimating excess CO_2 production ($CO_{2excess}$) (Crusafulli et al., 2009) as follows:

$$CO_{2excess} = \dot{V}CO_2 – (0.817 \times \dot{V}O_2)$$

where 0.817 represented the resting RER (Goedecke et al., 2000).

Such a measure estimates the magnitude of anaerobic lactic acid and hydrogen ion (H^+) accumulation since glucose is converted to pyruvate and H^+. Bicarbonate (-HCO3) subsequently buffers H^+ producing carbonic acid (H_2CO_3). The final stage in anaerobic glycolysis then involves H_2CO_3 being converted to H_2O and CO_2. Thus, increases in $\dot{V}CO_2$ above that associated with aerobic energy provision are related to lactate and H^+ accumulation during exercise and anaerobic metabolism (Yano, Horiuchi, Yunoki, & Ogata, 2002; Yano, Yunoki, Matsuura, & Arimitsu, 2009). Measures of $V\dot{C}\dot{O}_{2excess}$ have been previously employed during intermittent exercise performance (Crisafulli et al., 2002; Crisafulli et al., 2006) and the measure correlated well with the onset of blood lactate accumulation ($r = 0.914$, $P < 0.01$) (Roecker, Mayer, Striegel, & Dickhurth, 2000). Capillary blood samples were collected one minute post-exercise (Davis et al., 2013) from the ear lobe and analysed for blood lactate using a portable device (Lactate Pro, Kyoto, Japan). Ratings of perceived exertion (RPE) were recorded upon cessation of each round using the category ratio scale (CR-10) (Borg, 1990, Foster et al., 2001; Wallace, Slattery, & Coutts, 2009) and participants were asked to provide ‘global’ assessments of efforts for each round.

7.2.7 Statistical analysis

Descriptive statistics (mean ± SD) were calculated for all dependent variables and the normality of their distributions was checked using the Shapiro-Wilk test (O’Donoghue, 2012). To assess the variability of the physiological responses to the BOXFIT, along with the acceleration scores obtained during punching, 2 x 3 (trial x round number) repeated measures factorial ANOVAs were employed. Where a significant main effect or interaction was observed, Bonferroni-adjusted (i.e. alpha/number of related tests) post-hoc *t*-tests were used to identify pairwise differences. For each dependent variable, equality of variance and covariance was assessed using Mauchly’s test of sphericity. Where a significant ($P < 0.05$) Mauchly’s test was identified, in the first instance the Greenhouse Geisser ANOVA result was employed to avoid an increased type I error rate. Moreover, where sphericity was violated, and the strictest condition (Greenhouse Geisser) failed to reveal a significant finding yet the most liberal condition (sphericity assumed) indicated a difference, the Huynh-Feldt ANOVA result was used to arbitrate

(O'Donoghue, 2012). The magnitude of variance explained by main effects or interactions was quantified using partial eta squared (η_p^2) where values of 0.01 (small), 0.06 (medium) and ≥ 0.14 (large) were used (Richardson, 2011). Such values represent F-ratios corresponding to small (0.1), medium (0.25) and large (0.50) effects (Richardson, 2011). Furthermore, for each pairwise difference, accompanying effect sizes were calculated as: $d = (\bar{x}_1 - \bar{x}_2) / SD$; where $\bar{x}_1$ and $\bar{x}_2$ represent the two sample means and SD the pooled standard deviation. Standardised Cohen's d effect sizes were classified as: trivial <0.2, small 0.2-0.6, moderate 0.6–1.2, large 1.2–2.0, and very large >2.0 (Hopkins, 2004).

Absolute and relative test-retest was assessed a number of ways. Firstly, a 2 x 3 (trial x round number) repeated measures factorial ANOVA was employed to assess the null hypothesis of no difference between successive trials across rounds. That is, an absence of a significant main effect for trial number or an interaction effect between trial and round number was indicative of repeatability across trials and rounds. Where an effect was significant, Bonferroni-adjusted *t*-tests were employed to identify pairwise differences. Moreover, the typical error (TE) (Hopkins, 2000) and 95% limits of agreement were employed to provide an indication of the within-subject variability in the dependent variables between trials (Bland & Altman, 1986; Lamb, 1998; Nevill & Atkinson, 1998). Normality and homoscedasticity checks on the test-retest differences (errors) were performed using the Shapiro-Wilk and Pearson's product-moment correlation coefficient, respectively, and were found to be satisfactory. The typical error was expressed as a CV%. According to a previous recommendation (Roberts et al., 2006), CV% were classified as good (<5%), moderate (5 to 9.9%) or poor (≥ 10%). Described earlier (chapter 6), the typical error was also related to the SWC% using 0.2 x pooled standard deviation (Cohen, 1988). MWC%, LWC% and VLWC% were calculated as 0.6, 1.2 and 2.0 x pooled standard deviation, respectively. These were then converted to percentages facilitating comparison of the CV% with potential changes in performance. The reliability of the actions performed during the BOXFIT was assessed using the method proposed by Cooper et al. (2007) in which the expected number of actions was compared to those performed during the simulation.

Statistical significance was set at $P \leq 0.05$ throughout unless Bonferroni procedures were applied to a cluster of related pairwise differences. All data analyses were performed using either Microsoft Excel (Version 2010, Redmond, WA) or SPSS (Version 17.0; Chicago, IL).

7.3 Results

7.3.1 The demands of the BOXFIT across rounds

The mean heart rate response for each round and each one-minute rest period is displayed below (Figure 7.1). Heart rate responses were observed to vary due to round number ($F_{2,54}$ = 178.0, $P < 0.001$, $\eta_p^2 = 0.87$) representing 86 – 90% of HR_{max}, with values increasing significantly from one round to the next ($P < 0.001$, ES = 0.63, 0.89 and 0.34 for R1 vs. R2, R1 vs. R3 and R2 vs. R3, respectively). During the rest periods, round number again exerted a significant main effect ($F_{2,54}$ = 42.0, $P < 0.001$, η_p^2 = 0.61), albeit pairwise comparisons now revealed significant increases from rest 1 to 2 ($P < 0.001$, ES = 0.93), 1 to 3 ($P < 0.001$; ES = 0.75), but not rest 2 to 3 ($P > 0.05$; ES = 0.05).

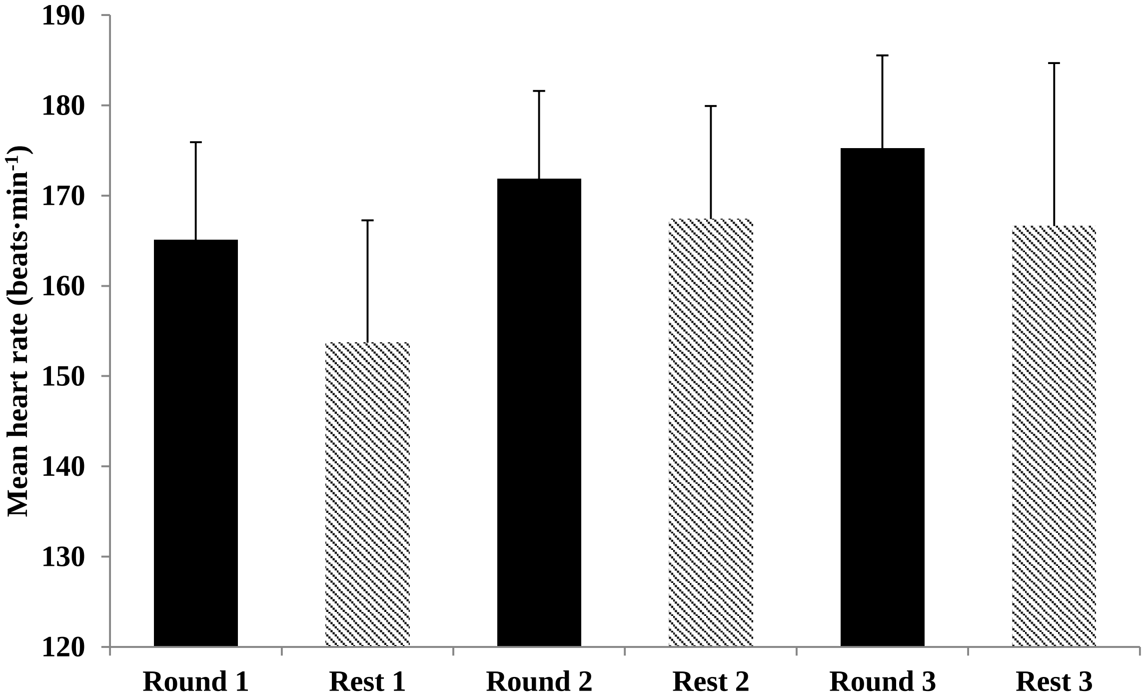

Figure 7.1. Mean heart rate during the BOXFIT simulation across round.

Peak heart rates during exercise (Figure 7.2) also varied across rounds ($F_{2,54} = 103.2$, $P < 0.001$, $\eta_p^2 = 0.79$), as did the minimum values recorded during the rest periods ($F_{2,54} = 43.2$, $P < 0.001$, $\eta_p^2 = 0.62$). Post-hoc comparisons identified a systematic increase in peak exercise heart rates across the three rounds ($P < 0.05$; $ES = 0.74$, 0.80 and 0.17, respectively) which represented 91 – 97% of HR_{max}, whereas there was a significant increase only between rest 1 and 2 ($P < 0.001$; $ES = 0.67$) and rest 1 and 3 ($P < 0.001$; $ES = 0.63$) for the minimum values.

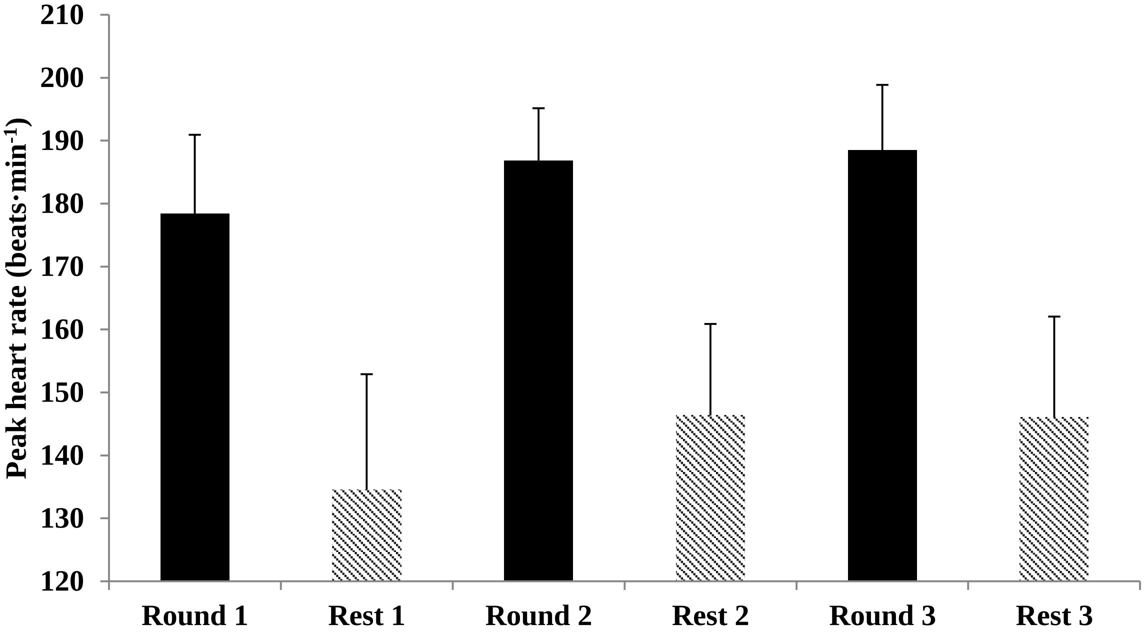

Figure 7.2. Peak and minimum heart rates obtained during BOXFIT exercise and rest periods across rounds respectively.

The RPE response was significantly influenced by the round number ($F_{2,54} = 135.0$, $P < 0.001$, $\eta_p^2 = 0.83$), with values increasing systematically across each round (all $P < 0.05$) with moderate-to-large effect sizes (Round 1 vs. Round 2 *ES* = 0.73; Round 2 vs. Round 3 *ES* = 1.04; Round 1 vs. Round 3 *ES* = 1.36) (Table 7.1).

Table 7.1. RPE and B_{lac} responses to BOXFIT performances (Mean ± SD).

	Round 1	**Round 2**	**Round 3**	**Post-simulation**
RPE	5.8 ± 1.4	6.8 ± 1.1	8.1 ± 1.1	N/A
B_{lac} (mmol·l^{-1})	N/A	N/A	N/A	4.6 ± 1.3

The total $\dot{V}O_2$ per round (Figure 7.3) varied across the three rounds ($F_{2,54} = 435.5$, $P < 0.01$, $\eta_p^2 = 0.19$), with values being significantly higher in R2 than both R1 ($P < 0.05$, $ES = 0.37$) and R3 ($P < 0.05$, $ES = 0.44$). Interestingly, the same measure did not vary across the rest periods ($F_{2,54} = 4.2$, $P > 0.05$, $\eta_p^2 = 0.13$) and the associated effects sizes were deemed trivial-to-small ($ES = 0.18 – 0.38$). Mean and peak $\dot{V}O_2$ was ≈42 and ≈55 ml·kg·min^{-1} in turn and, when expressed relative to MSFT-predicted $\dot{V}O_{2max}$ values, represented ≈69 and ≈92%, respectively.

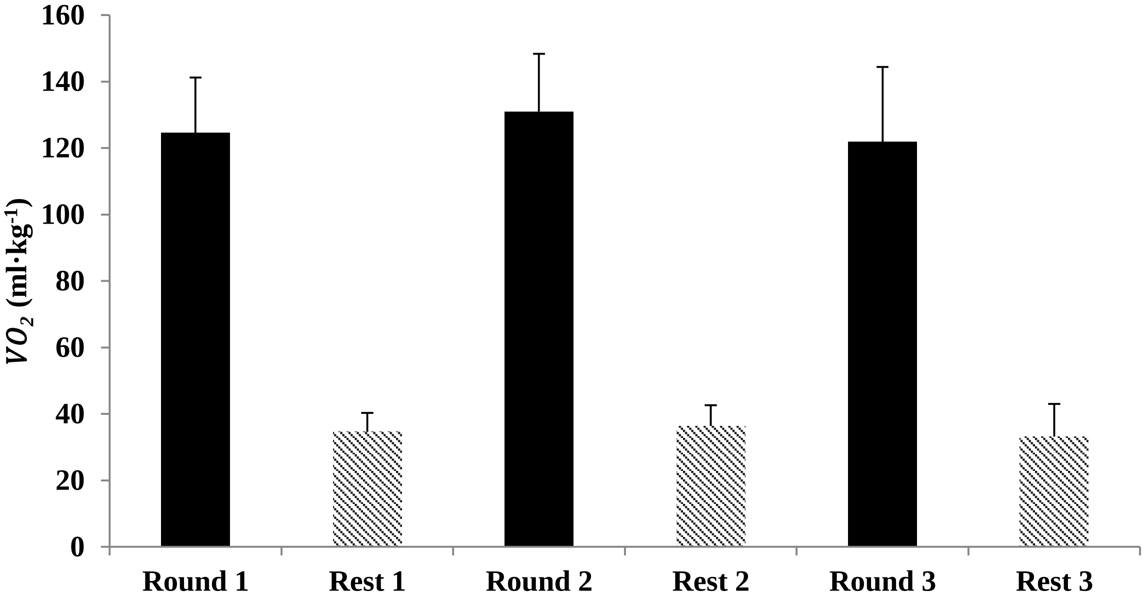

Figure 7.3. Total $\dot{V}O_2$ obtained during BOXFIT exercise and rest periods across rounds.

The EE_{aer} of the boxers (Figure 7.4) was significantly influenced by the round number ($F_{2,54} = 11.0$, $P < 0.001$, $\eta_p^2 = 0.29$), increasing positively as the simulation progressed. Post-hoc comparisons identified significant increases between the first and second ($P < 0.05$), and the first and third rounds ($P < 0.05$), albeit the accompanying effect sizes were both deemed trivial (*ES* = 0.15 and 0.08 for each comparison respectively). During the rest periods, EE_{aer} did not vary significantly across the rounds ($F_{2,54} = 3.2$, $P > 0.05$, $\eta_p^2 = 0.10$).

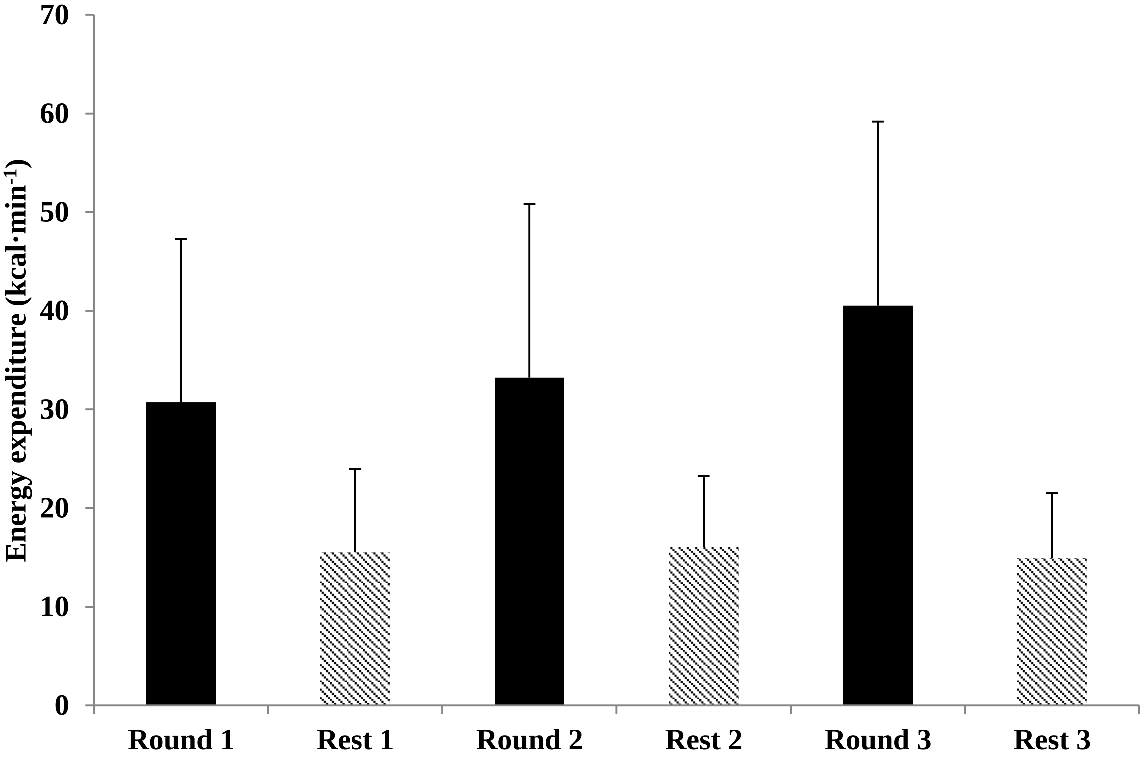

Figure 7.4. Energy expenditure (kcal·min^{-1}) during the various periods of the simulation.

Figure 7.5 depicts a significant effect of round on the $CO_{2excess}$ response during the exercise component of the BOXFIT ($F_{2,54} = 42.3$, $P < 0.001$, $\eta_p^2 = 0.611$). Post-hoc analyses identified a significant increase from the first to second round ($P < 0.001$, $ES = 0.44$), where it remained elevated during the final round ($P < 0.001$, $ES = 0.54$), though no different to the second round ($P > 0.05$, $ES = 0.11$). Levels of $CO_{2excess}$ during the rest periods were stable across the simulation ($F_{2,54} = 0.9$, $P > 0.05$, $\eta_p^2 = 0.03$; $ES = 0.01 – 0.05$).

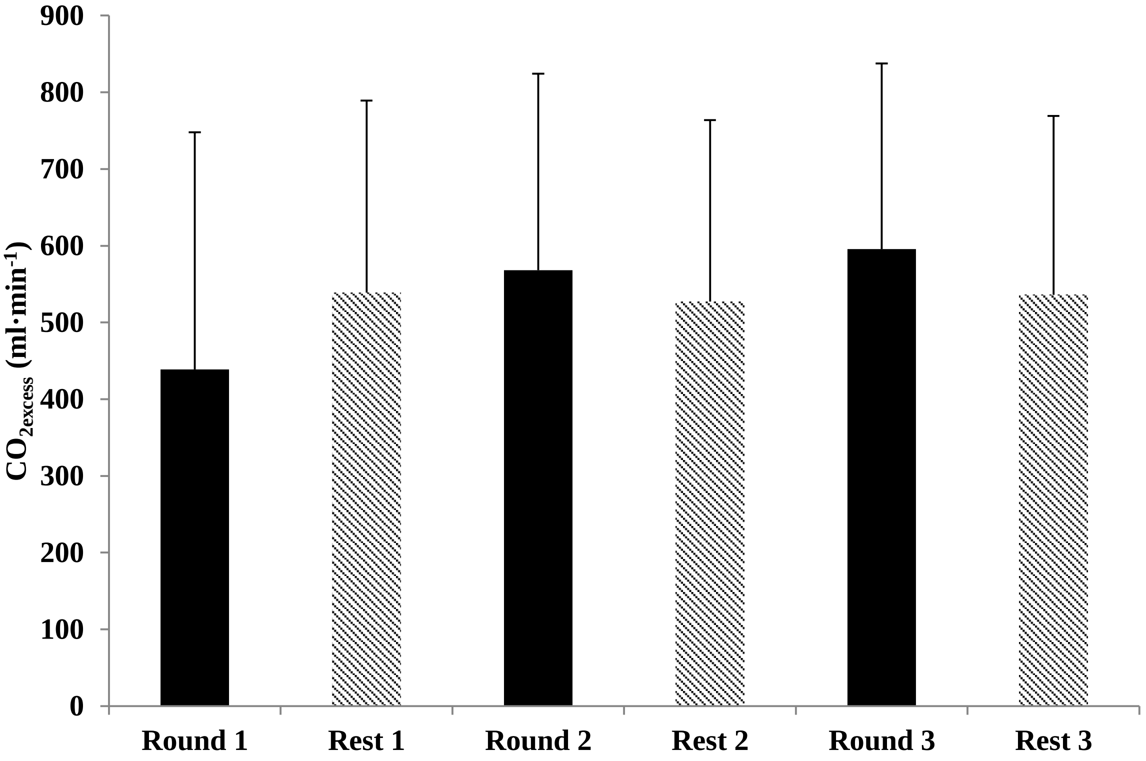

Figure 7.5. Mean $CO_{2excess}$ during the various periods of the simulation.

A main effect of round number ($F_{2,54} = 18.8$, $P < 0.001$, $\eta_p^2 = 0.41$) was observed on the acceleration produced by the boxers during the punching component of the BOXFIT (Figure 7.6). Specifically, this reflected significant increases from round one to two ($P < 0.05$; *ES* = 0.57) and round one to three ($P < 0.05$; *ES* = 0.68), but not between rounds two and three ($P < 0.05$; *ES* = 0.14).

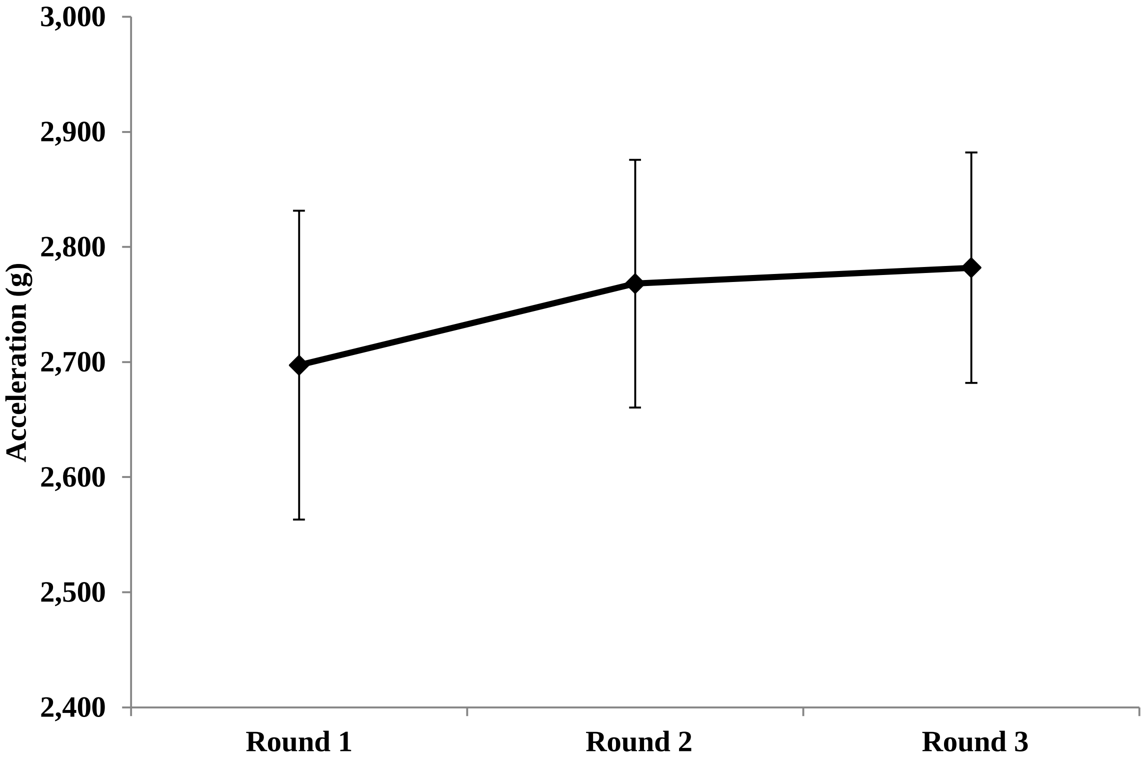

Figure 7.6. Total acceleration delivered by boxers when punching during the BOXFIT simulation in respective rounds.

7.3.2 The test-retest reliability of the BOXFIT

Across rounds, no significant main effects or interactions were observed ($P > 0.05$) for each dependent variable. Evaluating the reliability of HR_{Mean} and HR_{Peak} over the three rounds, systematic bias was -0.2 to 3 b·min^{-1} though random error (according to 95% of the sample) represented 7.9 to 19.7 b·min^{-1}, respectively. The CV% was 1.2 to 2.5% which was smaller than the MWC% in all rounds.

Mean test-retest data on the internal physiological responses during round one of the BOXFIT are presented in Tables 7.2. For round one, the CV% for mean and peak heart rate responses were both < 5% whilst those for $\dot{V}O_2$ and EE_{aer} were < 10%. Conversely, $CO_{2excess}$ was seen to vary considerably between trials (CV% > 30). Both heart rate measures and $\dot{V}O_2$ evidenced reliability smaller than the MWC% whereas the CV% for EE_{aer} and $CO_{2excess}$ were smaller than the SWC% and LWC%, respectively. The bias for each measure reflected between 0.26 and 7.88% of the respective grand means. Random error was larger, being between 7% and 11% of pooled mean scores (i.e. pooled test-retest scores; data not presented). The presented data for round one was demonstrative of that established when appraising the reliability within rounds two and three; such results can be found within appendix 8.

Table 7.2. Reliability statistics for mean HR, peak HR, $\dot{V}O_{2mean}$, EE_{aer} and $CO_{2excess}$ during round one of the BOXFIT.

	Round one				
	HR_{Mean} (b·min^{-1})	**HR_{Peak} (b·min^{-1})**	**$\dot{V}O_{2mean}$ (ml·kg^{-1})**	**EE_{aer} (kcal·min^{-1})**	**$CO_{2excess}$ (ml·min^{-1})**
Trial 1	165 ± 11	178 ± 13	126.2 ± 16.2	30.7 ± 16.8	498.2 ± 203.4
Trial 2	162 ± 11	178 ± 12	122.2 ± 16.4	30.9 ± 16.5	539.1 ± 281.3
CV%	2.4 $^{\downarrow MWC}$	2.0 $^{\downarrow MWC}$	7.5 $^{\downarrow MWC}$	8.9 $^{\downarrow SWC}$	30.1 $^{\downarrow LWC}$
95% LoA	2.4 ± 13	0.5 ± 12	5.50 ± 27.9	-0.1 ± 8.7	-40.9 ± 578.5

CV% smaller than associated small ($^{\downarrow SWC}$), moderate ($^{\downarrow MWC}$) and large ($^{\downarrow LWC}$) change in performance.

Mean post-simulation B_{lac} values did not vary significantly between trials, the bias being -0.12 (2.6%) mmol·l^{-1}. The random error (for up to 95% of comparisons) was ± 2.0 (42.8%) mmol·l^{-1} (see Figure 7.7) and the CV% for the measure was 12%; smaller than the associated MWC%).

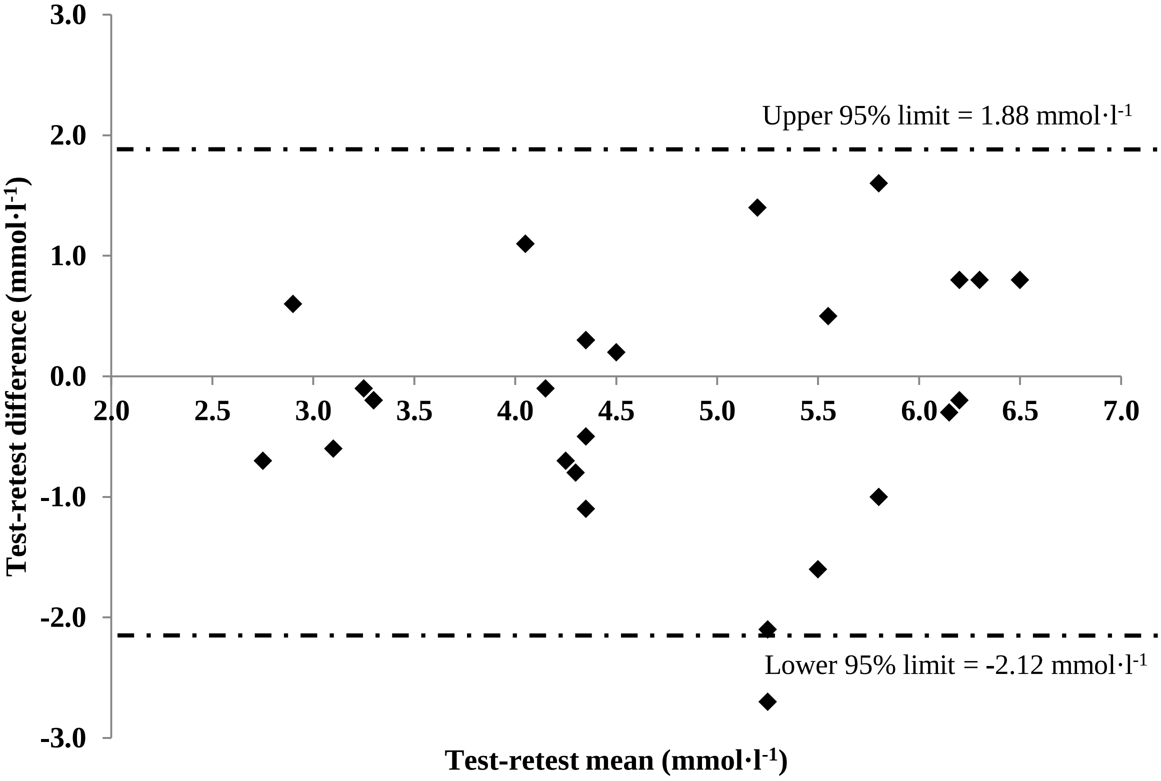

Figure 7.7. A Bland-Altman plot displaying the level of agreement and superimposed upper and lower 95% limits of agreement for the post-simulation lactate (mmol^{-1}).

The reliability of recorded RPE scores is displayed in Table 7.3. Better consistency was seen in rounds two and three compared to round one (lower CV% and narrower 95% limits of agreement).

Table 7.3. The reliability of RPE during each round over two trials of the BOXFIT.

	RPE		
	Round one	**Round two**	**Round three**
Trial 1	5.8 ± 1.4	6.8 ± 1.1	8.1 ± 1.1
Trial 2	5.8 ± 1.5	6.9 ± 1.1	8.2 ± 1.1
CV%	6.5 $^{\downarrow MWC}$	2.7 $^{\downarrow SWC}$	2.3 $^{\downarrow SWC}$
95% LoA	0.1 ± 1.5	-0.1 ± 1.1	-0.1 ± 1.0

CV% smaller than associated small ($^{\downarrow SWC}$), moderate ($^{\downarrow MWC}$) and large ($^{\downarrow LWC}$) change in performance.

Punch acceleration (Table 7.4) in each round of the BOXFIT simulation demonstrated a CV% of < 5%. Whilst the CV% was not lower than the SWC% at any point, during rounds one and three the moderate changes were larger than the CV%; during round two the CV% was lower than the LWC%.

Pairwise comparisons revealed no systematic bias between trials (all $P > 0.05$). The mean test-retest differences for rounds one and three were similar (18.6 and 18.7 g respectively) and represented less than 1% of the scores obtained (e.g. 18.6/2688.0). Random errors were, however, larger and represented 6.9%, 8.5% and 7.5% of the grand mean for rounds one, two and three, respectively. The CV% was <5% in each round and consequently smaller than moderate changes in rounds one and three but large changes in round two.

Table 7.4. The reliability of punch accelerations during respective rounds over two trials of the BOXFIT.

	Punch acceleration (g)		
	Round one	**Round two**	**Round three**
Trial 1	2697.3 ± 134.3	2768.1 ± 107.7	2782.0 ± 100.1
Trial 2	2678.7 ± 106.2	2731.2 ± 96.3	2763.3 ± 125.4
CV%	$2.1^{\downarrow MWC}$	$2.7^{\downarrow LWC}$	$2.1^{\downarrow MWC}$
95% LoA	18.6 ± 185.4	36.9 ± 232.7	18.7 ± 206.7

CV% smaller than associated small ($^{\downarrow SWC}$), moderate ($^{\downarrow MWC}$) and large ($^{\downarrow LWC}$) change in performance.

The Cooper et al. (2007) method of assessing the reliability of frequency-based performance analysis data revealed strong agreement on a test-retest basis. That is, the actions performed by the boxers during the simulation were consistent on a test-retest basis, with agreement being > 97% for offensive, defensive and locomotory actions.

Table 7.5. Summarised reliability of the actions performed during the BOXFIT simulation.

Performance indicator	Median (sign test)	PA = 0 (%)	95% CI (%)	PA ± 1 (%)	95% CI (%)
Offence	$P = 1.00$	100	100 to 100	100	100 to 100
Defence	$P = 1.00$	97	92 to 100	100	100 to 100
Locomotory	$P = 1.00$	100	100 to 100	100	100 to 100

7.4 Discussion

The present study sought to characterize the physiological responses to amateur boxing competition using the BOXFIT simulation and assess the reliability of such responses. The findings reinforce the notion that amateur boxing places a high physiological demand upon boxers (Smith, 2006; Ghosh, 2010; Arsenau et al., 2011; Davis et al., 2013b) accommodated predominantly by aerobic energy provision (Davis et al., 2013b). The reliability of the physiological measurements was largely favourable insomuch that the majority of measures were replicated with sufficient consistency to enable them to be sensitive enough to detect moderate changes in performance across all rounds. However, there were exceptions to this which will be addressed below.

Previous research has purported amateur boxing to be a high-intensity sport, though this supposition was largely based upon field-based measurements of heart rate, blood lactate and RPE (Ghosh et al., 1995; Smith, 2006; Ghosh, 2010), or measurement techniques that have lacked validity (Arsenau et al., 2011). Whilst subsequent research has used more invasive measures of internal physiological load (Davis et al., 2013b), it too lacked internal validity because the exercise intensity was not regulated (despite the intention to) and did not characterise the physiological responses to a bout of three rounds of three minutes. The present study has achieved this and revealed typical mean and peak heart rates in excess of 165 and 178 b·min^{-1}, and $\dot{V}O_2$ and EE_{aer} > 124.6 ml·kg^{-1} and > 30.7 kcal·min^{-1} during each round, respectively. That the mean blood lactate (4.6 ± 1.3 mmol·l^{-1}) and $CO_{2excess}$ (438.7 ml·min^{-1}) were raised also reflects a contribution to energy yield from anaerobic lactacid sources. Together, the data provide solid evidence to reaffirm the supposition that amateur boxing is indeed a high-intensity sport that requires aerobic and anaerobic conditioning (Smith, 2006; Ghosh, 2010;

Arsenau et al., 2011; Davis et al., 2013b). Moreover, the RPE scores (increasing across rounds from around 6 to 8) confirm a perception of effort commensurate with a high demand.

The 3 x 2-minute simulation protocol of Davis et al. (2013b) yielded lower peak heart rates (166, 173 and 174 $b \cdot min^{-1}$ across rounds) than the current study (178, 187 and 189 $b \cdot min^{-1}$). Whilst the relative intensity of the BOXFIT is likely higher, it is also plausible that its longer rounds (3 minutes) explain this difference. The heart rate responses to the BOXFIT were also higher than those recorded during taekwondo (Campos et al., 2012), Muay Thai boxing (Crisafulli et al., 2009), karate (Doria et al., 2009), and judo (Degoutte, Jouanel, & Filaire, 2003; Sbriccoli et al., 2007) simulations, suggesting amateur boxing presents a higher cardiovascular strain. For the same reasons, the energetic profile of the BOXFIT performance also indicates a higher aerobic demand than previous combat sport simulations. The total $\dot{V}O_2$ (482 $ml \cdot kg^{-1}$) and total EE_{aer} (360 kcal) are markedly higher than those recorded during the protocol of Davis et al. (2013b) (353 $ml \cdot kg^{-1}$ and 146 kcal, respectively). However, the present study did not consider the energy derived from non-aerobic sources and thus the EE_{aer} likely underestimates the *true* energy cost of BOXFIT performance. Indeed, Davis et al. (2013b) estimated the non-aerobic energy contribution to be as much as 23%, which would add considerably to the total energy cost. Despite this omission, the BOXFIT did yield a significant contribution from anaerobic metabolism given the recorded $CO_{2excess}$ values and raised lactate levels. Apart from the rest period following round one, $CO_{2excess}$ was consistently higher than the values reported for Muay Thai boxing (Crisafulli et al., 2009) and probably reflects the high-intensity acyclic efforts (e.g. punching; Davis et al., 2013b) being maintained by anaerobic metabolism (via the restoration of its substrates - creatine phosphate stores). Notwithstanding the technical proficiency necessary for successful amateur boxing performance (Chapter 4), it is therefore necessary that boxers possess both high aerobic and anaerobic capacities.

Still, given the established variance in the offensive and defensive demands of amateur boxing performance according to situational variables (Chapter 4), alongside the likely influence boxing 'styles' possess in further modifying the demands, recognizing the presented data reflects those based upon the average demand is imperative. As outlined in Chapter 6, the external demand of the BOXFIT might deviate substantially from those experienced within particular contests, even for a relatively homogenous group of boxers based upon the outcome, weight and ability (e.g. see 95% CI of the difference for BOXFIT$_{W,M,R}$; Table 6.9) and so the consequent physiological response is likely to under- or over-estimate the internal load experienced during contests pending the confounding influences. If the BOXFIT was used as part of a boxer's preparatory training it might not provide a training stimulus of sufficient magnitude if the actual demands exceeded those associated with the BOXFIT performance. In addition to the potential discrepancy in external demand, the heightened psychophysiological response of boxers during competitive bouts contrasted to those only sparring (Obminski et al., 1993) suggests the BOXFIT might also provide a lowered stress response and so even if the external did accurately reflect those of a contest, the consequent physiological response might not (Moreira et al., 2012). Indeed, Smith (2006) recorded post-contest (≈ 4 minutes) blood lactate values of 12.8 ± 3 mmol·l^{-1} far exceeding those associated with BOXFIT performance (4.6 ± 1.3 mmol·l^{-1}). Although the higher value was recorded in elite international amateur boxers who might exceed the external demands of the

BOXFIT during bouts, the large difference indicates a reduced anaerobic demand in the simulation.

The boxers of the present study possessed a predicted $\dot{V}O_{2max}$ of 57 ± 5 $ml·kg^{-1}·min^{-1}$ compared to international standard boxers whose $\dot{V}O_{2max}$ was 64 ± 5$ml·kg^{-1}·min^{-1}$ suggesting that boxers of the highest standard boxers would meet the demands of the BOXFIT with comparative ease further reducing the requirements upon the anaerobic energy systems (Gastin, 2001). Still, the sample informing the BOXFIT did not include any international performances thus differences in the physiological response are expected. Inclusion of international data in future research might further support the applicability of the BOXFIT to boxers of all abilities rather than sub-elite populations only. Moreover, the predicted $\dot{V}O_{2max}$ of the boxers herein compare favourably to those of elite international Italian boxers (58 ± 5 $ml·kg^{-1}·min^{-1}$; Guidetti et al., 2002) whilst the post-performance lactate values of the BOXFIT better approximate those evidenced in elite Indian boxers (≈ 8.1 $mmol·l^{-1}$) signifying the presented aerobic and anaerobic demands herein are indicative of those within amateur boxing.

Still, it might therefore be appropriate for individual boxers to modify the demands of the BOXFIT to better reflect the anticipated external and internal loads. Indeed, appraising the physiological demands of tailored BOXFIT simulations according to situational influences represents a fruitful area for future research such that the range of physiological responses boxers experience could be established; this could enhance the specificity of physiological assessments and training if it were used as part of a boxer's preparatory conditioning. Nevertheless, conclusions purporting the importance of well-conditioned aerobic and anaerobic (both glycolytic and adenosine triphosphate-phosphocreatine) energy systems remain relevant given athletes ought to prepare for the highest metabolic demand they might experience within competition (Dobson & Keogh, 2007).

Significant increases were observed between rounds in the markers of internal load (heart rate, $\dot{V}O_2$, and RPE) and it is likely that this observation would remain if the external demands of the BOXFIT were increased or decreased. Whilst it is likely aerobic energy sources predominate throughout all nine minutes of boxing (Davis et al., 2013b), it is plausible that phosphocreatine degradation and anaerobic glycolysis contributed to the earlier stages of energy yield (Gaitonos, Williams, Boobis, & Brooks, 1993; Bogdanis et al., 1996), before an increased reliance upon aerobic sources in rounds two and three occurred (Gastin, 2001). The intermittent high-intensity actions when exercising, alongside the brief recovery periods between rounds, may also have led to an excess post-exercise Oxygen (EPOC) uptake (Bahr, 1992; Borsheim & Bahr, 2003), progressively increasing across rounds. As high-intensity exercise contributes predominantly to the rapid component of EPOC (Bahr, 1992), the increased $\dot{V}O_2$ across rounds might therefore be due to mechanisms associated with EPOC, such as the replenishment of O_2 stores in blood and muscle, resynthesis of adenosine triphosphate and creatine phosphate, lactate removal, increased body temperature, ventilation and circulation (Borsheim & Bahr, 2003).

The increased physiological response might, however, be explained by the concomitant increase that occurred in the amount of punch acceleration delivered by the boxers

(Figure 7.6). Despite attempts to ensure a consistent demand across rounds (i.e. number of punches, defences and distance covered) it is possible that the boxers adopted a pacing strategy to avoid fatigue and optimise performance (Abbiss & Laursen, 2008) by manipulating the force of their punches (Hall & Lane, 2001). That the recorded maximum RPE values were about 8 in round three suggests BOXFIT performance did not, in fact, result in an anticipatory pacing strategy (Tucker, 2009; de Koning et al., 2011) given maximal values were not obtained. Nevertheless, the elevated physiological load across rounds is consistent with previous attempts to simulate combat sports (Crisafulli et al., 2009; Campos et al., 2012; Davis et al., 2013b).

The present study sought to develop an amateur boxing-specific simulation protocol capable of generating repeatable internal physiological and performance-based responses such that it could detect ecologically valid intervention-based changes in a boxer's physiology and performance. Previous attempts to induce boxing-specific physiological demands have not assessed the repeatability of any component (i.e. internal physiological response or external demands) and thus their findings might be atypical. Indeed, the protocol of Davis et al. (2013b), which included 2.5 times the number of expected defences, also revealed a significant difference in the number of offensive actions between rounds two and three even though the data it aimed to replicate (Davis et al., 2013a) did not reflect this change. That the protocol they used demonstrated an increase in physiological responses across rounds might therefore reflect a low internal consistency.

Throughout the three rounds, a consistent pattern emerged where the reliability was sufficient to enable the detection of moderate changes in performance. HR_{mean}, HR_{peak} and punch acceleration presented good reliability (Roberts et al., 2006) with CV% < 2.5%, whereas CV% of 2.3 – 16% were established for measures of $\dot{V}O_2$, $EE_{aer,}$ Blac and RPE. Previous research employing mean and peak heart rate as measures of physiological strain during simulation protocols have also reported similar CV% or lower (i.e. < 2%) (Wilkinson et al., 2009b; Waldron et al., 2012; Aanstad & Simon, 2013). Likewise, the CV% for RPE and Blac scores are similar to those reported previously (Waldron et al., 2012). Employing such statistics support the BOXFIT's efficacy given the large variations often evident in match (or bout) performance (Gregson et al., 2010; Lago, Casais, Dominguez & Sampaio, 2010). However, application of the 95% LoA to even the most reliable measurement (round three, HR_{mean} ≈ 175 $b \cdot min^{-1}$) revealed a worst-case error of 4.8% (0.5 + 7.9 = 8.4 $b \cdot min^{-1}$, Table 7.4), and for a HR_{mean} of 175 $b \cdot min^{-1}$ the retest score could lie between 167 and 183 $b \cdot min^{-1}$. Despite no systematic bias, such limits could be problematic if appraising the cardiovascular responses to a BOXFIT performance. That is, these limits would fail to identify the round number of performance (i.e. round two HR_{mean} ≈ 172 $b \cdot min^{-1}$ versus round three HR_{mean} ≈ 175 $b \cdot min^{-1}$) despite the significant differences established (Figure 7.1). Thus, practitioners must make a decision regarding the reliability of the BOXFIT based upon statistics that include 68% (Hopkins, 2000) or 95% (Atkinson & Nevill, 1998) of test-retest measurement error, relating this error to analytical goals (Batterham & George, 2003).

To provide exemplary analytical goals, previous research appraising the impact of interventions (i.e. training, hypohydration or energy restriction) upon cardiovascular, glycolytic responses and the development of power during exercise was consulted. Moreover, using a recently advocated approach (Batterham & George, 2003; Hopkins, 2004; Cheuvront, Carter, Castellani, & Sawka, 2005; Bucheit & Laursen, 2013) in which the CV% of a measurement is considered ‘noise’ and the ability of a measurement to detect desirable systematic changes (the ‘signal’), analytical goals were dependent upon the reliability of the BOXFIT measurements in relation to expected percentage changes owing to intervention (Cheuvront et al., 2005). That is, the expected change (%) must exceed the BOXFIT CV% to support its reliability. Given boxers frequently undergo rapid weight loss (Smith, 2006; Franchini et al., 2012) it is plausible they might experience reductions in blood volume and hence stroke volume for a given exercise intensity, resulting in heart rates during aerobic exercise being elevated by ≈ 5 - 9% following 2.89 - 4% hypohydration (Heaps, Gonzalez-Alonso, & Coyle, 1994; Gonzalez-Alonso, Mora-Rodriguez, Below, & Coyle, 1997). The between-trial CV% for mean and peak heart rate (2.4 and 2.0%) suggest the BOXFIT could be used to identify hypo-hydration-related increases in cardiovascular demand given the expected change in heart rate exceeds 2.4%. Consequently, boxers engaged in weight loss practices could employ the BOXFIT to identify undesirable increases in heart rate (i.e. those > 2%) that suggest they ought to taper their training and consider a fluid replacement plan incorporating electrolytes and carbohydrate intake (ACSM, 2007). It might also be that a forthcoming contest is cancelled, or at least postponed, allowing the boxer to rehydrate before undergoing a more gradual approach to weight loss (Lambert & Jones, 2010).

Additionally, a meta-analysis appraising the change in VO_{2max} owing to high-intensity interval training reported increases of ≈ 6 - 9 $ml \cdot kg^{-1} \cdot min^{-1}$ (Bacon et al., 2013). The consistency of the $\dot{V}O_2$ and EE_{aer} responses during the BOXFIT resulted in CV% of 7.5% and 8.9%, respectively. Assuming increases in $\dot{V}O_{2max}$ are also reflected at the intensities associated with BOXFIT performance (≈ 42 $ml \cdot kg^{-1} \cdot min^{-1}$) owing to enhanced efficiency (increased arterio-venous difference and haemoglobin content) (Franch, Madsen, Djurhuus, & Pedersen, 1998; Jones & Carter, 2000), a ≈ 6 - 9 $ml \cdot kg^{-1} \cdot min^{-1}$ increase would exceed the noise of the measurement (i.e. 7.5% of 42 $ml \cdot kg^{-1} \cdot min^{-1}$ = 3.15 $ml \cdot kg^{-1} \cdot min^{-1}$). Still, the proposed change of ≈ 6 - 9 $ml \cdot kg^{-1} \cdot min^{-1}$ in $\dot{V}O_{2max}$ might not be consistent with those expected in amateur boxers given such a finding was based upon recreationally active participants (defined as $\dot{V}O_{2max} < 55$ $ml \cdot kg^{-1} \cdot min^{-1}$). But, knowing the sensitivity of the measurement (3.15 $ml \cdot kg^{-1} \cdot min^{-1}$) within the BOXFIT, it could remain a useful measurement for amateur boxers given the training-induced improvements in $\dot{V}O_{2max}$ recorded in elite and well-trained distance runners (>5%) possessing maximal values higher than the current sample of boxers (61-71 $ml \cdot kg^{-1} \cdot min^{-1}$ versus 57 ± 5 $ml \cdot kg^{-1} \cdot min^{-1}$). Thus, following a period of high-intensity interval training the BOXFIT could be used to identify genuine changes in markers of boxing-specific aerobic fitness.

Post-performance decrements in blood lactate associated with low carbohydrate intake, and by inference low muscle glycogen stores, have been recorded as 11 - 26% lower compared to control trials (Maughan et al., 1997; Smith et al., 2001). With a CV% of 12% associated with the BOXFIT it again appears the consistency of the measure would likely allow the identification of a boxer experiencing low muscle glycogen, hence relying on aerobic pathways of energy provision. That this situation results in lowered sustainable exercise intensities, and earlier fatigue during exercise (Maughan et al., 1997; Faude et al., 2009), identifying its occurrence pre-competition appears pertinent.

Finally, decrements of 15% in an athlete's ability to produce (peak) powerful upper-body movements are associated with 3% hypohydration (Leon, Cleary, Lopez, Zuri, & Lopez, 2008). As power in punching could be considered a function of force and velocity (Boreham, 2006) and the recorded punch accelerations within the BOXFIT are influenced by the ability of a boxer to produce force (i.e. acceleration = force/mass) and velocity (i.e. acceleration = (change in velocity)/time), the expected decrements of 15% could plausibly transfer to the punching performance during the simulation. Thus, given a sensitivity of < 6.5% and expected changes of 15% the BOXFIT could also be used to identify power-related declines in boxing-specific movements owing to hypohydration.

Therefore, using the presented results it would appear that the BOXFIT could be deemed either adequately reliable using the CV% (68% of test-retest error) or not, if using the 95% LoA (68% of test-retest error). Given the often small, yet practically beneficial changes in performance (Currell & Jeukendrup, 2008), the test-retest error using 95% LoA might be too stringent in identifying genuine changes in performance (Hopkins, 2000) and therefore employing the CV% statistics, the BOXFIT is a worthwhile means to induce consistent physiological responses.

Previous research employing the $K4b^2$ gas analyser on a test-retest basis, particularly in an applied environment, is scarce, but the findings presented herein do not compare favourably to laboratory-based assessments of respiratory gas analysis (Sealey, Leicht, Spinks, & Sinclair, 2010). That is, during a 1,000 m upper-body ergometry assessment, 95% ratio limits of agreement for $\dot{V}O_2$ data revealed systematic bias and random error of 1% and 8%, respectively; the corresponding values of systematic bias and random error for the research herein were 4 - 5 % and 23 – 45 % and estimates of EE_{aer} demonstrated lower reliability still. Such findings cast doubt on all the previous findings of the energetic demands of combat simulations as the test-retest consistency of $\dot{V}O_2$ has not been reported. Indeed, research suggests the accuracy (Howe, Matzko, Piaser, Pitsiladis, & Easton, 2013) and consistency (Duffield, Hawson, Pinnington, & Wong, 2004) of the $K4b^2$ is compromised at higher intensities. The acyclic, high-intensity nature of the BOXFIT and its reliance upon upper-body exercise might explain the degree of variability owing to a weaker locomotory-respiratory coupling during such exercise (Bateman, McGregor, Bull, Cashman, & Schroter, 2006; Sealey et al., 2010) and greater variability in the oxygen kinetics during short duration, high intensity exercise (Becque, Katch, Marks, & Dyer, 1993; Duffield et al., 2004). Finally, $CO_{2excess}$ demonstrated poor reliability independent of the statistic applied, thus questioning its relevance during high-intensity exercise. Surprisingly, the reliability of $CO_{2excess}$ has not to-date been reported despite known inter-individual variance (Roecker et al., 2000; Gaskill et al., 2001). However, the use of an estimated npRQ likely reduced the consistency of the measure as resting npRQ is known to vary considerably between athletes (Goedecke et al., 2000) owing to factors such as nutrition and training status (Bergman & Brooks, 1999; Venables, Achten & Jeukendrup, 2003). Future research should establish the reliability of $CO_{2excess}$ responses to high intensity exercise when npRQ has been quantified pre-exercise to evidence the efficacy of the measure.

Despite a regulated external demand during the BOXFIT, the repeatability of the actions performed was nonetheless assessed and the findings suggest that the simulation is highly repeatable, with perfect reliability for offensive and ambulatory actions and near perfect repeatability for defensive movements. Thus, when the boxers are fully familiarised (Currell & Jeukendrup, 2008) the BOXFIT offers a regulated means by which the external demand can be controlled, facilitating the assessment of several physiological and performance-based measures.

In characterising the internal physiological response to BOXFIT performance, it has been established that amateur boxing necessitates a well-developed aerobic capacity owing to the high cardiorespiratory demand. Accordingly, it is imperative that boxers employ high-intensity (> 90% $\dot{V}O_{2max}$) interval training given its ability to produce favourable adaptations (Bacon et al., 2013) in a number of variables that might facilitate successful boxing performance, such as an increased $\dot{V}O_{2max}$ (permitting a higher exercise intensity throughout a contest) and improved recovery (Laursen & Jenkins, 2002) between rounds. The reliability of the induced physiological responses were generally deemed acceptable as they were consistent enough to allow the detection of moderate changes in performance. As such, the BOXFIT represents a consistent means by which systematic changes in physiological changes owing to intervention can be established. Still, the BOXFIT does require an assessment of the ecological validity of the induced internal load to evidence its efficacy as a viable framework for studying the physiological responses to amateur boxing performance (Drust et al., 2007).

Chapter 8

An examination of the validity of the BOXFIT

8.1 Introduction

Whilst establishing the test-retest reliability of a simulation protocol (with respect to its internal and external loads) can be completed with relative ease, evaluating its validity is challenging as experimental control and the ability to obtain invasive measurements during the competitive performance (criterion measure) are not normally at the researcher's disposal (Svensson & Simon, 2013). For this reason, it is assumed that a simulation protocol possesses adequate validity if its external demand is representative of the competition demands (Drust et al., 2007). Although the external demand of exercise is indicative of the physiological load (Lambert & Borresen, 2010), the association is at times weak-to-moderate (Impellizzeri et al., 2005; Scott et al., 2013) and recent research suggests that simulations based upon a representative external demand do not reflect valid physiological loads owing to a reduced stress response (Bridge et al., 2013b). Accordingly, attempts have been made to improve the external demands of simulation protocols to more accurately reflect the internal loads (Thorlund et al., 2008; Waldron et al., 2013). Yet, approximating the typical external demand will (still) frequently under- or over-estimate the competitive demand owing to the substantial variability in physical exertions that occur across matches (Gregson et al., 2010; Carling, 2013).

Nevertheless, where a representative physiological load is of interest it is not always necessary to use externally valid physical movements (Drust et al., 2007). In attempting to replicate the internal demand of sports competition, validation is often been based upon how closely the physiological responses during a simulation approximate previous research that has documented the *actual* competitive demands (Bishop et al., 1999; Drust et al., 2000; Nicholas et al., 2000; Williams et al., 2010; Kingsley et al., 2006;

Roberts et al., 2010; Davis et al., 2013b; Sykes et al., 2013; Waldron et al., 2012). However, to validate the internal demands of a simulation protocol would necessitate the use of the same participants performing the simulation and *actual* sports performance (Drust et al., 2007). Unfortunately, as alluded to above, this approach is difficult to adopt and has been seldom accomplished (Thatcher & Batterham, 2004; Bridge et al., 2013).

A multitude of simulation protocols have been developed mainly for team sports such as soccer (Bishop et al., 1999; Drust et al., 2000; Nicholas et al., 2000; Williams et al., 2010) and rugby (Roberts et al., 2010; Waldron et al., 2012; Davis et al., 2013b; Sykes et al., 2013), although individual sports involving frequent technical actions have also received some scrutiny (Kingsley et al., 2006; Wilkinson et al., 2009). In particular, simulations have been devised for various *combat* sports such as Muay Thai boxing (Crisafulli et al., 2009), taekwondo (Campos et al., 2012; Bridge et al., 2013b) and karate (Beneke et al., 2004; Nunan, 2006; Doria et al., 2009). To-date, however, amateur boxing has received scant attention (Davis et al., 2013b) despite participation rates being higher than any other combat sport in England (Sport England, 2013). Previous attempts to simulate amateur boxing have lacked adequate validity as they have employed non-specific circuit training exercise (Hall & Lane, 2001) or assumed the physiological load was similar to that of competition by replicating certain aspects of the external demand (Smith et al., 2000; 2001; Davis et al., 2013a, 2013b), and have not sampled the same group of boxers in both competition and the simulation. Further confounding the validity of both previous simulations is the limited attempt to document and create a locomotive pattern representative of boxers' external loads.

To ‘capture’ the inherent variability in sports performance (Gregson et al., 2010; Carling, 2013) and confounding variables that may affect performance, a valid simulation protocol ought to be informed by performance data from a range of competitive contexts evident in amateur boxing (e.g. independent variables such as ability level, weight class and contest duration). Whilst it is also necessary to evaluate the physiological response to simulation performance and *actual* bouts in the same participants, physiological measurements during boxing competition are not permitted and therefore a viable alternative must be used. Consequently, the internal demands of the BOXFIT simulation were validated against those associated with sparring. This type of sport-specific exercise is used during training to replicate as closely as possible the internal and external demands of a competitive bout (Hickey, 2006; Smith, 2006). Whilst it might underestimate *true* demand, it has been used several times previously to replicate boxing bouts (Obminski et al., 1993; Ghosh et al., 1995; Khanna & Manna, 2006; Smith, 2006; Ghosh, 2010; Siegler & Hirscher, 2010; Stojsih et al., 2010) and the boxers were instructed to perform as if it were a contest.

8.1.1. Study aim:

(i) To examine the concurrent validity of the physiological responses to BOXFIT performance among a group of amateur boxers.

8.1.2. Research question:

(i) How accurately do the physiological responses to BOXFIT performance replicate those associated with competitive amateur boxing?

8.2 Methods

8.2.1 Participants

Ten amateur boxers (mean ± SD; age 22.9 ± 2.1 years, body mass 64.3 ± 5.2 kg, stature 168.6 ± 6.8 cm, years of experience 8 ± 3 years, previous contests 22 ± 7; predicted $\dot{V}O_{2max}$ = 59.9 ± 2.0 ml·kg·min^{-1}) who had performed the BOXFIT protocol 7 ± 2 days earlier (Chapter 6) volunteered to participate in the study. Although the procedures were typical of amateur boxing training, participants were informed of the test procedures and potential risks, and provided written informed consent. Institutional ethical approval was granted by the Faculty of Applied Sciences Ethics Committee. Permission was also granted by the head coach of the amateur boxing club where testing took place.

8.2.2 Design

All boxers took part in a BOXFIT simulation and a competitive spar. In the 72 hours preceding the BOXFIT performance, the boxers were asked monitor their training load and avoid unaccustomed exercise in the subsequent 72 hours (Byrne, Twist, & Eston, 2004; Burt et al., 2013). Seven (± 2) days later, they returned to spar against an opponent matched in weight, number of previous contests and ability (according to ABAE classifications). For each participant, the two sessions took place at the same time of day (± 2 h), avoiding the effects of diurnal variation (Drust et al., 2005), at the same boxing club located in the North West of England.

8.2.3 Procedure

The BOXFIT protocol was presented according to the procedures outlined previously (Chapter 6) and following a familiarisation trial performed 72 hours earlier. For the sparring bout, the boxers performed a 15-minute self-selected warm-up consisting of shadow boxing, jogging and punch bag exercise (Smith et al., 2000; Smith et al., 2001) prior to being fitted with a heart rate monitor (Polar, Electro Oy, Kempele, Finland) and head guard (Adidas, Germany), gum shield, fabric hand wrapping (4.5 m length, 5 cm width; Adidas, Germany) and boxing gloves (284 grams; Adidas, Germany). Participants then boxed against their matched opponent in a ring (6.1 m^2) for 3 x 3 minute rounds with one minute rest (50 s seated, 10 s standing) between rounds. They were permitted water *ad libitum* and provided with coach feedback between rounds in order that competitive bouts were replicated as closely as possible (Davis et al., 2013b).

The internal load elicited during sparring was quantified in the form of measurements of peak and mean heart rate, category-ratio ratings of perceived exertion (RPE) and blood lactate accumulation, replicating those obtained during the BOXFIT. Heart rate was recorded throughout sparring using a 1 Hz frequency and expressed as raw values, whereas RPE (Borg, 1990; Foster et al., 2001) was recorded immediately after each round and lactate was measured with a Lactate Pro analyser (Lactate Pro, Kyoto, Japan) one minute post-exercise (Davis et al., 2013b) via an ear lobe capillary sample.

To verify that the spars were reflective of competitive performance, a *performance analysis* of their external offensive and defensive demands was conducted post-spar for a subsequent comparison with the data generated previously from real fights (Chapter 4). Each spar was recorded using two digital cameras placed at adjacent sides of the ring (Canon MV700, Japan) and the footage uploaded to Dartfish TeamPro (Version 4.0, Switzerland) in which the researcher identified the number of punches and defences performed, thereby characterising the *overall* offensive and defensive demands.

8.2.3 Statistical analysis

Descriptive statistics (mean ± SD) were calculated for all dependent variables and the normality of their distributions was checked using the Shapiro-Wilk test (O'Donoghue, 2012). Independent samples *t*-tests were used to compare the frequency of punches, defences and post-exercise blood lactates in the sparring bouts to those recorded in actual (3 x 3-minute) amateur boxing bouts (Chapter 4). The assumption of equality of variance (Levene test) was satisfied for the number of defences and lactate levels, but not the number of punches ($P < 0.05$), and the corresponding statistics ('Equal variances *not* assumed') were therefore used instead.

The variability of the heart rate and RPE values across the boxing conditions (spar and BOXFIT) and rounds (one, two and three) was examined via a two-way repeated measures ANOVA. Where necessary, significant effects were followed-up with Bonferroni-corrected paired samples *t*-tests. Post-exercise blood lactate levels were compared using a paired *t*-test. For all pair-wise comparisons, accompanying Cohen's effect sizes (*ES*) were calculated as: $d = (\bar{x}_1 - \bar{x}_2) / \mathrm{SD}$; where $\bar{x}_1$ and $\bar{x}_2$ represent the two sample means and SD the pooled standard deviation (Richardson, 2011). Effect sizes were deemed trivial (< 0.20), small (0.20–0.49), moderate (0.50–0.79) and large (≥ 0.80) in accordance with Cohen's guidelines (1988).

Systematic and random error between sparring and BOXFIT measures was then characterised using the 95% limits of agreement technique (Bland & Altman, 1986; Nevill & Atkinson, 1998). Normality and homoscedasticity checks on the test-retest differences (errors) were performed using the Shapiro-Wilk and Pearson's product-moment correlation coefficient, respectively, and were found to be satisfactory. To further characterise bias, the agreement between the sparring and BOXFIT-derived measures was also assessed by expressing the percentage difference between them as: %bias (± 95 confidence intervals, CI) = [(sparring – BOXFIT) /criterion)*100] (Jennings et al., 2010a, 2010b). To provide an assessment of random variation based upon 68% of measurement error (Hopkins, 2000), the standard error of the estimate expressed as a percentage was employed (SEE ± 95% CIs) (Peterson et al., 2009; Portas et al., 2010). The standard deviation of the mean percentage error between the spar data and the BOXFIT provided the SEE. Data analyses were performed using Microsoft Excel (Version 2010, Redmond, WA) and SPSS (Version 17.0; Chicago, IL). Statistical significance in all tests was set at $P \leq 0.05$.

8.3 Results

8.3.1 The validity of the external demands of open sparring

The average and peak heart rates during sparring represented 92 ± 4% and 100 ± 3% of maximum values determined during the MSFT, respectively. Contrasting the sparring and competitive data, analysis revealed no systematic bias between conditions for the number of punches (spar: 219.3 ± 32.7 versus competitive data: 218.3 ± 88.7; $P > 0.05$; $ES = 0.02$) and defences (spar: 94.1 ± 10.8 versus competitive data: 94.0 ± 28.9; $P > 0.05$; $ES = 0.01$) performed (Figure 8.1). However, post-sparring blood lactate values were significantly lower than post-competitive boxing values; spar ($n = 10$): 10.4 ± 1.9 $\text{mmol}\cdot\text{l}^{-1}$ versus competitive data ($n = 27$): 13.0 ± 1.9 $\text{mmol}\cdot\text{l}^{-1}$; $P < 0.05$; $ES = 1.4$).

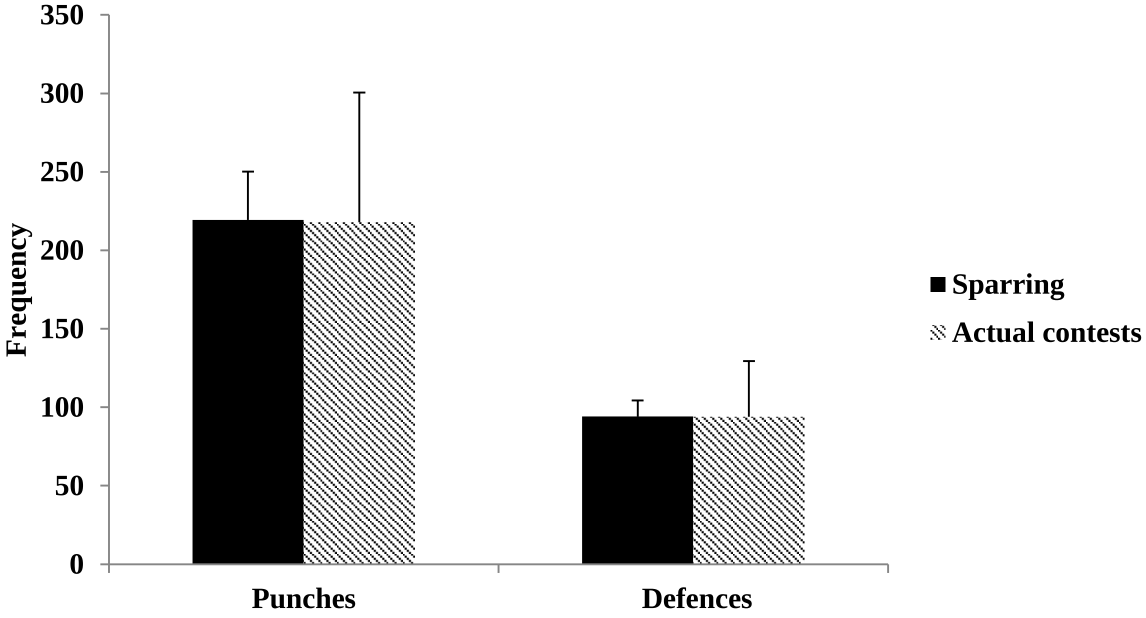

Figure 8.1. A comparison of the external demands of the sparring with actual competitive data.

8.3.2 The validity of the BOXFIT's internal load

The boxing condition (i.e. spar versus BOXFIT) exerted a notable influence on the markers of internal load (Table 8.1) with three variables (mean HR, $F_{1,9} = 10.1$, $P < 0.001$; peak HR, $F_{1,9} = 5.5$, $P < 0.05$; RPE, $F_{1,9} = 5.7$, $P < 0.05$) being significantly higher in the sparring bout. The effect of round was also significant on each (mean HR, $F_{2,18} = 87.4$, $P < 0.001$; peak HR, $F_{2,18} = 42.2$, $P < 0.001$; RPE, $F_{2,18} = 75.8$, $P < 0.001$), with values increasing across successive rounds. However, the condition did not produce a significant main effect where mean HR ($F_{2,18} = 3.25$, $P > 0.05$) and peak HR ($F_{2,18} = 0.71$, $P > 0.05$) were expressed relative to maximum values. The effect of round was also significant on each (mean HR, $F_{2,18} = 87.4$, $P < 0.001$; peak HR, $F_{2,18} = 42.2$, $P < 0.001$; RPE, $F_{2,18} = 75.8$, $P < 0.001$; mean %$HR_{max,}$ $F_{2,18} = 89.78$, $P < 0.001$; peak %$HR_{max,}$ $F_{2,18} = 40.6$, $P < 0.001$), with values increasing across successive rounds. Moreover, the interaction of condition and round number was only significant for RPE scores ($F_{2,18} = 8.0$, $P < 0.05$). More specifically, mean HR and RPE was lower during the BOXFIT in rounds two and three (both $P < 0.05$; *ES* = both 1.3), whereas peak heart rate was lower in round one only ($P < 0.05$; *ES = 0.6*).

The 95% LoA revealed systematic biases of 4.9 – 10.0 $b{\cdot}min^{-1}$ and random errors in the range 14.0 – 22.6 $b{\cdot}min^{-1}$ for mean HR, and likewise, 4.7 - 7.2 $b{\cdot}min^{-1}$ (bias) and < 18.6 $b{\cdot}min^{-1}$ (random error) for peak HR. Where heart rate was expressed relative to maximum values, 95% LoA were again associated with systematic differences for mean HR though bias was <3.5% and random error 4.5 – 12.1%. Moreover, no systematic differences were observed in the relative peak HR response with bias and random error <2% and <10.6%, respectively. For RPE, the bias was ≤ 1.4 units and 95% of the differences were ≤ 3.0 units across the three rounds. For mean and peak HR (both absolute [b·min^{-1}] and relative [% HR_{max}] values), %Bias was < 6.4% in all rounds, and the %SEE typically < 2.8% of the criterion; the corresponding values for RPE were considerably larger for all rounds (Table 8.1).

Table 8.1. The validity of the physiological response to BOXFIT performance during respective rounds.

		Sparring	**BOXFIT**	**95% LoA**	**%Bias ± 95% CI**	**%SEE ± 95% CI**
Round one	**Mean HR (b·min^{-1})**	169 ± 1	164 ± 7	-4.9 ± 22.6	6.1 ± 2.7	2.7 ± 1.2
	Mean HR (% HR_{max})	86 ± 6	84 ± 3	-1.0 ± 12.1	6.4 ± 2.8	2.8 ± 1.2
	Peak HR (b·min^{-1})	185 ± 8	177 ± 8*	-7.2 ± 18.6	4.7 ± 2.1	2.1 ± 0.9
	Peak HR (% HR_{max})	94 ± 4	90 ± 4	-2.0 ± 10.6	5.3 ± 2.3	2.3 ± 1.0
	RPE	5.7 ± 1.0	5.8 ± 1.6	0.1 ± 3.0	18.2 ± 8.0	11.8 ± 5.2
Round two	**Mean HR (b·min^{-1})**	183 ± 7	174 ± 6*	-10.0 ± 15.4	3.9 ± 1.7	1.7 ± 0.7
	Mean HR (% HR_{max})	93 ± 4	89 ± 3*	-3.5 ± 4.5	4.4 ± 1.9	1.9 ± 0.8
	Peak HR (b·min^{-1})	191 ± 6	186 ± 6	-4.7± 14.9	3.7 ± 1.6	1.6 ± 0.7
	Peak HR (% HR_{max})	97 ± 3	95 ± 3	-0.7 ± 9.0	4.5 ± 2.0	2.0 ± 0.9
	RPE	8.0 ± 0.7	6.9 ± 1.0*	-1.1 ± 2.4	12.8 ± 5.6	5.6 ± 2.5
Round three	**Mean HR (b·min^{-1})**	188 ± 6	179 ± 7*	-9.5 ± 14.0	3.5 ± 1.5	1.5 ± 0.7
	Mean HR (% HR_{max})	96 ± 3	91 ± 3*	-3.2 ± 8.0	3.9 ± 1.7	1.7 ± 0.8
	Peak HR (b·min^{-1})	196 ± 6	190 ± 6	-5.2 ± 15.4	3.8 ± 1.7	1.7 ± 0.7
	Peak HR (% HR_{max})	100 ± 3	97 ± 3	-0.9 ± 9.2	4.5 ± 2.0	2.0 ± 0.9
	RPE	9.3 ± 0.7	7.9 ± 0.9*	-1.4 ± 1.0	10.0 ± 4.4	4.4 ± 1.9

* Denotes a significant difference ($P < 0.05$).

The mean blood lactate recorded across BOXFIT (5.1 ± 1.0 mmol·l^{-1}) and sparring (10.4 ± 1.8 mmol·l^{-1}) conditions and associated difference score for the ten boxers is displayed in Figure 8.2. A pairwise comparison revealed a systematic bias of 5.4 mmol·l^{-1} between values obtained during the BOXFIT and open sparring ($P < 0.001$). Random error between conditions was 3.5 mmol·l^{-1}. Consequently, 95% of the difference between conditions lay within 1.9 to 8.8 mmol·l^{-1}. %Bias was 9.8 ± 4.3% and %SEE represented 4.3 ± 1.9%.

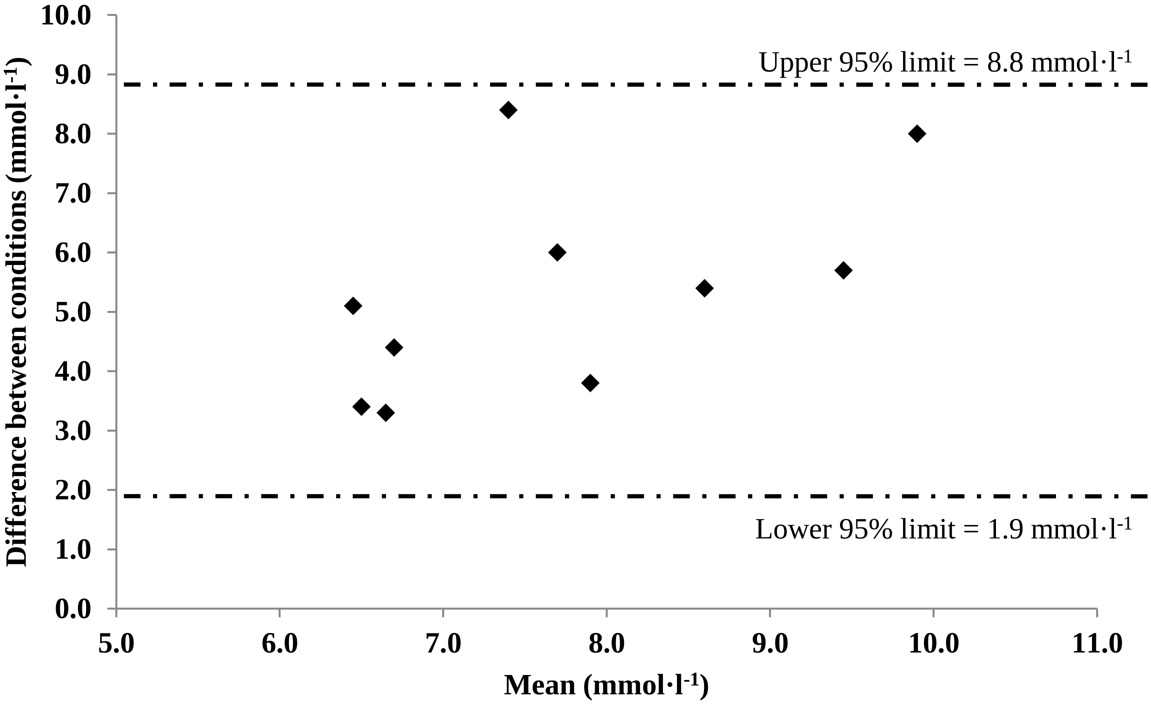

Figure 8.2. A Bland-Altman plot displaying the agreement (superimposed upper and lower 95% limits) between the post-BOXFIT and post-sparring bout blood lactates.

8.4 Discussion

Whilst it was established earlier in this thesis that the BOXFIT accurately replicates the average external demands of competitive amateur boxing (Chapter 6), the current study has highlighted that its resultant internal demand is typically lower than that evidenced during competitive sparring. Such a finding is consistent with previous research in combat sports in which valid external actions have failed to reproduce the physiological load of competition (Bridge et al., 2013b; Davis et al., 2013b). Likewise, whilst open sparring was shown to offer a valid external demand, its post-contest blood lactate levels indicate it may underestimate the physiological load of *actual* competition. That the BOXFIT failed to replicate the internal demand of sparring therefore suggests it is unlikely to recreate the physiological load of amateur boxing performance. Nevertheless, the BOXFIT simulation presently affords the most valid simulation of amateur boxing given it is the first simulation to quantify its reliability (Chapter 6) and also replicate the external demand of *actual* boxing contests with improved validity. Moreover, several markers of physiological load were characteristic of those recorded during sparring suggesting it approximates some aspects of internal load associated with amateur boxing. Still, such a conclusion is based upon a version of the BOXFIT employing the average external demand and a movement plan developed from sparring within a 4.88 m^2 boxing ring. Consequently, modified external demands based upon a comparatively specific analysis of boxers employing particular tactics during a bout, across numerous independent and interactive influences not considered within chapter 4, could further improve the validity of the physiological response recorded herein.

Previous attempts to validate boxing-specific simulations have failed to assess the validity of the physiological responses induced (Smith et al., 2000; 2001; Davis et al., 2013b), basing validation upon notational analysis of some of the external demands (Davis et al., 2013a) and assuming the physiological responses must therefore also be representative of boxing (Drust et al., 2007). However, in comparison to previously analysed bouts (Davis et al., 2013a) the simulation of Davis et al. (2013b) included 2.5 times the number of defences ($P < 0.05$) and offensive performance uncharacteristic of that evidenced during the contests used to inform the protocol (Davis et al., 2013a) questioning the validity of the external demand in the simulation employed. Had the movements adequately replicated contests, research has nevertheless demonstrated that valid external demands performed during simulations can fail to induce the desired physiological response (Bridge et al., 2013a, 2013b). Indeed, the heart rate response during the Davis et al. (2013b) simulation was on average 9, 10 and 12 $b{\cdot}min^{-1}$ lower than values recorded during sparring in rounds one, two and three, respectively (de Lira et al., 2013), confirming the failure of the simulation to induce a representative internal demand. Comparison of the heart rate response during the BOXFIT to those of *actual* bouts (Ghosh et al., 1995) revealed a lower mean heart rate of 9, 5 and 3 $b{\cdot}min^{-1}$ across respective rounds of the BOXFIT, suggesting it better approximates the cardiovascular strain of boxing performance than the attempt of Davis et al. (2013b). Indeed, heart rate data expressed relative to maximum values alongside the %bias and %SEE statistics suggest the cardiovascular responses to BOXFIT performance closely approximate those of sparring and it could therefore be a worthwhile protocol to be used during athlete conditioning and to assess systematic changes in the heart rate response associated with boxing performance. However, that it consistently underestimates the cardiovascular demand, even if only by ≈ 5%, means it might not adequately condition a boxer for a contest in its current form.

Nevertheless, given amateur boxers at times are not engaged in competition, or indeed training (e.g. during off-season, injury-enforced cessation of training), the BOXFIT could be used to evidence a boxer's 'readiness' to compete by providing baseline measurements of a boxer's physiology during the simulation pre-competition. For example, if the BOXFIT peak heart rate in round three was 190 $b{\cdot}min^{-1}$ and the subsequent performance was characterised by fatigue (owing to a decrease in offensive and defensive movements) then following a period of training, upon reappraisal of BOXFIT performance the boxer would either hope to evidence a heart rate of <190 $b{\cdot}min^{-1}$ or deliver higher punch accelerations for the equivalent cardiovascular strain to evidence an improvement in boxing-specific fitness.

Interestingly, the HR_{mean} over the duration of the BOXFIT protocol (172 ± 6 $b{\cdot}min^{-1}$) represented 96% of those values recorded during sparring (180 ± 7 $b{\cdot}min^{-1}$) and relative (% HR_{max}) peak heart rates were near-maximal, though post-exercise B_{lac} measurements were 49% of those recorded during sparring. This suggests the external demand induced a similar cardiovascular strain but an unrepresentative glycolytic response. Thus, attempts to improve the physiological response to a BOXFIT performance should firstly focus on the anaerobic component of boxing. Indeed, the attempts of Davis et al. (2013b) and Smith et al. (2000, 2001) all induced higher lactate values than the BOXFIT. Though this observation was unexpected given the more extensive approach to simulation development used in the current research, the higher frequency of punches within the Smith et al. (2000; 2001) procedures (112 versus 73 of the BOXFIT), alongside the observation novice boxers were used to simulate elite movement patterns, might explain such disparity. Yet, it was the protocol of Davis et al. (2013a) involving ≈ 22 punches each minute (compared to 23 of the BOXFIT) that yielded markedly higher lactate values (9.5 ± 1.8 mmol·l^{-1} versus 5.1 ± 1.0 mmol·l^{-1}). Regardless of the explanation, it is an important limitation of using the BOXFIT in its current form because of the known importance of glycolytic energy provision, as is the ability to prevent the associated deleterious effects of accumulated blood lactate (Smith, 2006; Davis et al., 2013b; Hanon et al., 2015). If used to prepare a boxer for a bout then, the anaerobic demand of the BOXFIT requires re-appraisal.

Moreover, RPE scores were lower during rounds two and three suggesting boxers did not find the BOXFIT as arduous a task compared to sparring and despite instructions for maximal effort throughout the simulation, it appears this was not the case, so an improved adherence to the instructions for maximal effort throughout the BOXFIT might also improve its validity. It is also plausible that RPE was reduced during the BOXFIT due to the absence of ‘contacts’. Previous research in rugby league training revealed the number of impacts was predictive of the RPE (Lovell, Sirotic, Impellizzeri, & Coutts, 2013) and it is therefore plausible that self-reported measures of exertion might be influenced by the number and severity of punches received during competitive amateur boxing, questioning the applicability of the RPE in quantifying internal load. That HR_{mean} reflected between 88 and 101% of corresponding values during sparring suggests in *some* boxers the simulation actually induced a valid heart rate response throughout the exercise. This is an intriguing finding which supports earlier criticisms of the BOXFIT that the external load, and subsequent physiological response is, in its current form, unlikely to reflect the demands of contests in *all* individuals. Those employing the BOXFIT should thus tailor the external demands ensuring an improved reflection of the physiological responses of actual contests. Indeed, the amalgamation of individualised physiological and competition-based appraisals of performance results in enhanced sensitivity (Abt & Lovell, 2009; Lovell & Abt, 2013). Future research could therefore explore the benefit of customising the BOXFIT to individual boxers, provided an adequate number of performances are available for a boxer, to identify whether the physiological responses can be better characterised.

Although the external demand and reliability of the BOXFIT have been established, the present study sought to assess the validity of the physiological responses using the same group of boxers under simulation and sparring conditions. Such an approach is atypical as validation of the induced internal load during simulation performance is usually based upon the proximity of the recorded values to previous research findings documenting the demand of *actual* competition (Drust et al., 2007). Sparring was employed to validate the BOXFIT responses since, with the exception of post-contest measures such as blood lactate, it is not possible to obtain physiological measures during competitive bouts. Initially, it was confirmed that the spars were reflective of competitive performances insofar that the external demand was similar (Figure 8.1) and the heart rate response was typically higher than those previously observed during competition (Ghosh et al., 1995; Smith, 2006; Ghosh, 2010), although post-contest B_{lac} values were significantly lower following sparring than those recorded after *actual* contests. Thus, whilst the external demands of the spars may not have induced the expected glycolytic demand, the attainment of heart rates higher than previously recorded during boxing contests (Ghosh et al., 1995; Smith, 2006) and near-maximal

RPE scores during sparring ensured that valid data had been gathered, against which the BOXFIT could be validated. Moreover, reliance on a post-contest blood lactate value (between spars and competitive data [Chapter 4]) to validate the internal load of sparring could be erroneous as nutritional state was not controlled in the hours before either condition; responses might therefore have been influenced by pre-exercise consumption of carbohydrates (Billat, 1996).

A direct comparison of the two boxing conditions revealed notable differences in the markers of internal load. More specifically, the BOXFIT failed to adequately induce the desired HR_{mean} (rounds two and three), HR_{peak} (round one), RPE (rounds two and three) responses and post-contest B_{lac} observed during sparring. Nevertheless, at certain times the HR (absolute and relative observations) and RPE responses to the BOXFIT performance were typical of those evidenced during sparring, and when expressed via %bias and %SEE, the heart rates do suggest that the BOXFIT approximates the internal demands of boxing. However, contrary to this, 95% LoA fail to support the validity of all the measures in any round since the worst-case limits could reflect responses that are uncharacteristic. For example, the data indicate that a boxer with a spar HR_{mean} of 188 $b{\cdot}min^{-1}$ in round three could be as low as 165 $b{\cdot}min^{-1}$ in the corresponding BOXFIT, which would be more reflective of a round one value (≈ 169 $b{\cdot}min^{-1}$). Despite RPE increasing in a similar manner across rounds, there were significant differences between conditions for rounds two and three (Table 8.1). Indeed, for a RPE of 8 during round two, 95% LoA indicate the BOXFIT-equivalent score could be lie between 4.5 and 9.3; values lower and higher even than round one and three ratings, respectively. Considering therefore that the spars might not quite reflect the internal physiological load of actual boxing (i.e. similar external demand but significantly lower B_{lac} compared to competition; Figure 8.1), the current protocol of the BOXFIT is unlikely to induce a physiological response characteristic of the internal demand experienced during *actual* competitive amateur boxing.

That said, in combat sports simulation protocols based upon external demands have failed to replicate the internal physiological response owing to a reduced stress response (combined physical and psychological stressors, and resulting hormonal responses) (Moreira et al., 2012; Bridge et al., 2013b; Davis et al., 2013b). In the competition setting, contestants experience negative psychological affective states (e.g. increased anxiety, lower self-confidence) which, in response to external stressors, stimulate the HPA axis (Filaire, Maso, Degoutte, Jouanel, & Lac, 2001; Moreira et al., 2012). This results in an increased physiological response to exercise for a given external load (Kudielka, Schommer, Hellhammer, & Kirschbaum, 2004). That increased negative affective states and resultant adrenocortical responses have been recorded in combat sport environments with increased importance (i.e. contest versus sparring; Obminski et al., 1993; national versus regional competition; Filaire et al., 2001) suggests simulation protocols will never truly represent the internal physiological state of competition unless psychological stress similar to that of competitive boxing is induced. Moreover, a stronger desire to win in combat sports has been shown to induce increased cortisol levels, thus simulations again might not induce the anticipated physiological state unless possessing a competitive element (Suay et al., 1999; Salvador, Suay, Gonzalez-Bono, & Serrano, 2003). That combat sports simulations occasionally fail to induce the desired internal load might be due to an absence of aggressive behaviour (Salvador, Suay, Martinez-Sanchis, Simon, & Brain, 1999) and dyadic confrontation with injurious exchanges (Moreira et al., 2012) as they are known to increase the psychophysiological response to exercise. Thus, combat simulations void of these characteristics would therefore be expected to produce invalid internal loads. Indeed, Arsenau et al. (2011) recorded increased physiological responses when comparing a lab-based simulation of sparring to actual competitive sparring despite a consistent external demand suggesting the confrontational element in actual boxing heightens the internal demand. Boxers might also have manipulated properties of their punches (i.e. force, velocity, power) between the conditions (Hall & Lane, 2001) accounting for some of the variance evidenced. Indeed, the RPE support this possibility as they were typically lower during the BOXFIT despite a similar external demand (Bridge et al., 2013). Furthermore, the BOXFIT did not employ unanticipated movements, which might further explain its inability to fully replicate the physiological load of amateur boxing (Girard et al., 2005; Wilkinson et al., 2009a; Bridge et al., 2013).

In the manner of previous simulations, if the intention is to replicate the physiological load it might therefore be prudent to increase the external demand made of boxers during the BOXFIT in order to more closely approximate the *actual* demands of boxing performance (Thorlund et al., 2008; Waldron et al., 2012). To overcome the probable reduced psychological stress experienced by boxers when performing the BOXFIT, the external demand could be increased to evoke a higher internal demand that more closely replicates that experienced during real contests.

The BOXFIT protocol has undergone a comprehensive assessment of its reliability (Chapter 7), sensitivity (Chapter 7) and validity that together offers a well-informed evaluation of its potential use as an ergonomic tool for assessing the internal physiological responses and intervention-based systematic changes in amateur boxing. The simulation currently produces the most accurate physiological responses to amateur boxing, approximating those of previous research (Ghosh, 2010), though it still underestimates selected aspects of internal load at different time-points. This underestimation is likely mediated through reduced HPA axis stimulation because of lower psychological stress (Obminski et al., 1993; Suay et al., 1999; Flaire et al., 2001; Salvador et al., 2003; Moreira et al., 2012). Future research might seek to improve the validity of the internal physiological responses by increasing the external demand (Thorlund et al., 2008; Waldron et al., 2012) or inducing a negative affective psychological state.

Chapter 9

Conclusions

9.1 Main findings

9.1.1 The development of the BOXFIT

In order to develop a sport-specific simulation, a detailed description of the competitive environment should be undertaken and this ought to include quantifications of both the external and internal metabolic demands made of athletes (Drust et al., 2007; Bishop, 2008). Whilst there have been several studies documenting the internal physiological response to boxing-specific exercise (Chapter 2), there have been only two previous attempts to quantify the external demand of amateur boxing (El-Ashker, 2011; Davis et al., 2013a), and such attempts were beset by inadequate assessments of reliability (of the analysis tools) and considered only the performances of winning and losing boxers. Moreover, in both studies there was a failure to align the outcome data with that of the judges' real-time decisions, rendering the profiles presented possibly inaccurate.

Accordingly, a performance analysis informed by a reliable, objective and valid selection of key performance indicators (Chapter 3) was undertaken to establish the external demands of competitive amateur boxing and assess the influence of particular confounding variables (weight class, ability, contest duration, and contest outcome) on performance (Chapter 4). Moreover, instead of considering only the individual effect of an independent variable, the interaction between confounding influences was also appraised. Collectively, the findings reinforced the assertion the sport involves a high external demand and indicated that many offensive and defensive actions, and their subsequent outcomes, were significantly influenced by independent and interactive effects. Of particular note was the influence of *ability* of the boxers, likely a result of the different contest durations when comparing regional to national boxers (i.e. six minute vs nine minute bouts). Still, the c*ontest outcome* and *weight class* exerted independent influences also and there were several two- and three-way interactions established suggesting boxing performance is a complex and dynamic environment. Consequently, boxers should prepare to experience a range of demands within competitive boxing, particularly if the conditions of their boxing are likely to alter (i.e. progression from regional to national contests), consequently tailoring their conditioning and tactical approach to the expected external demands.

Nevertheless, analyses revealed substantial within-group variation so anticipating the typical the demands might not adequately characterise those experienced within a contest. That is, for a given contest outcome, weight class and ability, the demands varied markedly. Whilst difficult to make definitive conclusions, it appears that the ‘style’ of the boxers and the interactions between them (McGarry, 2009) determine the nature of a bout more so than any individual situational variable. Thus, not only should boxers and coaches approach and interpret a performance affording due cognizance to the outcome, weight class and ability of the boxer, but they should also anticipate a range of demands pending the style of the boxer and their opponent.

Despite the dispersion, and in the manner of protocols developed in many other sports, the findings were subsequently used to inform the offensive and defensive elements of a simulation. Given the intention to develop initially a protocol that could best approximate the demands of amateur boxing *per se*, the protocol utilised the average demand. Nonetheless, since the impact of ability (and thus contest duration) upon the total demand of a bout was fundamental when appraising boxing performance, the relative frequencies (i.e. actions per minute) were utilised in an attempt to standardise the demands between contest formats. Generally, there were fewer differences between groups in the *relative* demand (Appendix 2) suggested such an approach, given the intention to approximate demands, was justified. Consequently, a relative technical demand was identified meaning the duration of the simulation could be tailored to the ability, and associated contest durations, of a boxer. In the current research, the nine-minute version of the BOXFIT was employed to assess the physiological response to simulated performance.

In attempting to develop a boxing-specific simulation of performance that characterised the *total* external demand, a quantification of the locomotive movements of boxers (i.e. boxing-specific steps, strides and jumps moving a boxer around the boxing ring) was necessary. For this purpose, GPS technology was employed given its documented efficacy in providing reliable and accurate estimates of time-displacement data. Following the quantification of its reliability and validity in assessing boxing-specific movements (Chapter 5), a standardised movement plan was established which regulated the intensity, and by inference the physiological load (McArdle et al., 2007), of the ambulatory movements of the simulation. Again, analysis of the typical movements expressed relative to the exercise duration suggested the approach would approximate the locomotory demands if applied to six or nine minute contests. Consequently, the BOXFIT simulation protocol was developed (Chapter 6) following amalgamation of the average technical of competition (Chapter 4) and ambulatory (Chapter 6) demands recorded during sparring. Its development adds to the growing number of sport-specific simulation protocols which permit invasive measurements of internal load and can be used to track systematic changes in aspects of fitness and performance.

9.1.2 The internal demands of the BOXFIT

Simulation protocols are often used to replicate the metabolic responses to the characteristic actions of the competitive environment (Drust et al., 2007). Employing such an approach (Chapter 7), the BOXFIT yielded a high cardiorespiratory response evidenced via peak heart rate and $\dot{V}O_2$ in excess of 188 b·min^{-1} and 40 ml·kg^{-1}·min^{-1}, respectively. In addition, a significant recruitment of anaerobic sources was indicated via elevated $CO_{2excess}$ during performance and post-simulation blood lactates exceeding 4.5 mmol·l^{-1}. Such findings add considerably to previous attempts to quantify internal load (Smith et al., 2000, 2001; Davis et al., 2013b) and provide valuable data that should inform the metabolic conditioning of amateur boxers. Indeed, given the noteworthy reliance upon aerobic energy provision, it seems pertinent that boxers should adopt high-intensity (> 90% $\dot{V}O_{2max}$) interval training (Bacon et al., 2013) that would be of benefit both during the active rounds and recovery between rounds (Tomlin & Wenger, 2001).

Importantly, the reliability of the BOXFIT was deemed acceptable given its ability to detect physiological markers of enhanced cardiorespiratory fitness, hypohydration and glycogen depletion. Moreover, the test-retest variation typically resulted in an ability to detect moderate changes in physiological responses, and reliability was comparable to other sport-specific simulations (e.g. Wilkinson et al., 2009b; Waldron et al., 2012; Aanstad & Simon, 2013). In terms of validity, the physiological response to BOXFIT performance was seen to differ somewhat compared to that exhibited during sparring, suggesting that the internal load of the simulation did not fully replicate that of the competitive environment. With adequate consistency in the induced internal load however, the BOXFIT affords the most valid replication of amateur boxing performance to-date and given some modifications, could better approximate the demands of competition thus providing a useful ergonomic tool for quantifying the demands of amateur boxing performance. The research has also presented a framework which should underpin the development of simulation protocols in any sport. Such an approach warrants a reliable and comprehensive quantification of the external ambulatory and technical demands of competitive performance considering the role of confounding variables, followed by an appraisal of the simulations reliability and validity.

9.2 Limitations

9.2.1 Situational variables in performance analysis

Whilst the sub-discipline of performance analysis has been rightly criticised for affording only a rudimentary examination of the competitive environment, generating outcome-oriented data (Glazier, 2010) and failing to adequately consider the context within which performance takes place (Mackenzie & Cushion, 2012), the consideration afforded in the development of the BOXFIT to specific independent factors (such as contest outcome, weight and ability), and their interactions, was a concerted attempt to appreciate the processes underpinning the outcome-based key performance indicators (Carling, Wright, Nelson, & Bradley, 2013). Although not all-embracing, the analyses reported in Chapter 4 endeavoured to consider the context of performance by comparing the external demand and technical efficiency of boxers according to the round, weight class, and ability, and highlighted some key performance indicators that distinguished successful aspects of competitive boxing (e.g. enhanced offensive performance alongside reduced defensive demand). Furthermore, the analysis satisfied the needs of the simulation protocol where, albeit in conjunction with motion analysis (Chapters 6), it was necessary only to approximate the offensive and defensive external demand.

9.2.2 Performance variation and simulation development

Known as a characteristic feature of sports performance (Gregson et al., 2010; Kempton et al., 2015), substantial between- and within-group variability was established when appraising amateur boxing performance despite establishing specific groups based upon the outcome, weight class and ability. Whilst the considered situational variables explain to some extent the dispersion, the within-group variation remained noteworthy. This suggests therefore that the tactical approach of a boxer (i.e. their 'style'), and the subsequent dyadic interaction with the opponent and their style (McGarry, 2009) influence, substantially, the demands of amateur boxing.

Whilst the analyses of Chapter 4 revealed the significant influence of bout outcome, weight and ability and the extent of dispersion, the developed simulation used a standardised demand which was largely independent of the confounding influences and did not account for variability. It instead attempted to approximate the performance of all boxers utilising the average relative demand. Indeed, comparison of the technical demands of the BOXFIT with data of specific sub-groups (i.e. $\text{BOXFIT}_{W,M,R}$ and $\text{BOXFIT}_{W,M,N}$) revealed notable deviations indicating the external demands of the BOXFIT did not replicate the competitive demand for all boxers. Moreover, where the motions of boxers were considered, the movement plan was based upon sparring within a contest ring of $4.88m^2$ which might further reduce the validity of the protocol. Given such observations, it appears pertinent that the developed simulation is modified to better replicate the demands experienced by boxers. It thus appears unlikely that the

BOXFIT in its current form, characterises the external demands of performance for *all* boxers.

9.2.3 The physiological response to the BOXFIT

The simulation protocol was developed to replicate the typical demands of competitive amateur boxing performance. Whilst the external demands incorporated did replicate the *physical performance* of the average amateur boxing bout, the *physiological response* was seen to underestimate that of amateur boxing. That the validation process relied upon sparring as the source of comparison naturally questions the ability of the BOXFIT to induce representative metabolic conditions as sparring is known to induce a lower stress hormone response than *actual* bouts of amateur boxing (Obminski et al., 1993), despite a similar external demand. Indeed, there is a growing body of research suggesting the psycho-physiological response is a key determinant of internal load (Suay et al., 1999; Salvador et al., 2003; Moreira et al., 2012; Bridge et al., 2013) and it is unlikely that the simulation replicated the conditions necessary to generate such responses with adequate validity.

The methods employed did not establish the contribution of the lactate- and phosphocreatine-derived energy and, given their significant contributions to total energy expenditure during an amateur boxing simulation of six minutes (4% and 19% for lactate and phosphocreatine sources, respectively), the findings of Chapter 7 likely underestimate the *true* energetic demand. Despite this, it seems plausible that the anaerobic demand of the BOXFIT performance over nine minutes (three rounds, each three minutes in duration) is relatively reduced (percent contribution) owing to the increased reliance upon aerobic sources of energy provision (Gastin, 2001). This statement is supported by comparatively higher heart rates recorded throughout the BOXFIT and lower lactate levels contrasted to a previous six-minute simulation of amateur boxing (Davis et al., 2013b); indeed the longer duration of the BOXFIT likely accounts for the increased reliance upon aerobic sources.

9.3 Future directions

9.3.1 Situational variables in performance analysis

Owing to the aforementioned limitations of the performance analysis in Chapter 2, future analyses should strive to more fully account for the diverse contextual and situational variables impacting boxing performance. Notwithstanding the variables considered (see above), and also that of sample size (which was relatively large), there are other confounding variables that might affect performance. Variables that are known to influence sporting performance in other sports include match status (i.e. score), location and opposition type and quality (O’Donoghue, 2009; Lago et al., 2010; Sampaio, Lago, Casais, & Leite, 2010). Each of these contextual influences could impact boxing performance as the boxers are usually made aware of the ‘score’ of the contest between rounds, and compete at venues considered to be ‘home’ and ‘away’ against various opponents. Moreover, the style and strategy of individual boxers, and the dyadic interaction with the opposing boxer (and their style and strategy), appears an important feature of boxing performance that likely produced large within-group dispersion. Accounting for such confounding influences would facilitate a systematic and comprehensive understanding of the competitive environment of amateur boxing.

A possible means of achieving the above goal, and in particular recognising the processes underpinning successful performance, could be the use of using temporal pattern analysis (Borrie & Jones, 1998; Borrie, Jonsson, & Magnusson, 2002; Lapresa, Alvarez, Arana, Garzon, & Caballero, 2013) or the application of dynamic systems theory (Glazier, 2010) to consider the interactive, complex nature of sports performance (McGarry, 2009). However, temporal pattern analysis would only supplement the research herein by identifying particular patterns that emerge using the *same* performance indicators, whilst the application of dynamic systems theory to sports performance relies on the identification of 'control' and 'order' parameters, which are not easily identified and quantified in sports. Moreover, objectively classifying boxing styles and tactical strategies requires investigation given the current subjective, coaching-based definitions presently available.

9.3.2 The validity of the physiological response to BOXFIT performance

That the BOXFIT was found to underestimate the physiological responses to sparring means that future research should consider a protocol that produces a higher internal load, more representative of the *actual* competitive performance. This would require modifications that increase the external demand (Thorlund et al., 2008; Waldron et al., 2012), or artificially induce an elevated stress hormone response through psychological intervention (Kirschbaum, Pirke, & Hellhammer, 1993) to increase the physiological response to the prescribed exercise intensity. Though unlikely owing to governing body restrictions preventing physiological measurements during competition and practicality (i.e. face mask of gas analyser inhibiting performance), further research might also attempt to quantify the *actual* demands of competitive amateur boxing as such data would provide a 'gold standard' measure of internal load, against which the concurrent validity of a simulation could be assessed (Drust et al., 2007).

To this end, recent research (de Lira et al., 2013) has quantified the linear heart rate-$\dot{V}O_2$ (HR-$\dot{V}O_2$) and heart rate-ventilatory thresholds relationships using maximal graded exercise to exhaustion and estimated the physiological response (i.e. $\dot{V}O_2$, time above ventilatory threshold) during sparring. Whilst this approach has been successfully applied in other sports, such as soccer (Esposito et al., 2004) and rugby league (Coutts, Reaburn, & Abt, 2003) and likely reflects a representative internal load (i.e. elevated cortisol response; Obminski et al., 1993), the HR-$\dot{V}O_2$ relationship is diminished during intermittent exercise and is not necessarily accurate for individuals (Achten & Jeukendrup, 2003). Moreover, it fails to document the significant anaerobic energy contribution in amateur boxing (Davis et al., 2013b) and it is unlikely that a heart rate monitor would be permitted during actual contests given its location within the target area. Future research might therefore consider the merit of either applying increasingly invasive measurements (i.e. $\dot{V}O_2$, blood sampling) during a simulation at the expense of its ecological validity.

9.3.3 Specific simulations

The attempt to derive an ecologically valid sport-specific simulation protocol in amateur boxing was based upon the body of evidence suggesting specificity during physiological assessment facilitates an accurate reflection of sports performance (St Clair Gibson et al., 1998; Muller et al., 2000; Drust et al., 2007; Reilly et al., 2009). Indeed, the amalgamation of performance and motion analysis data has provided the most valid simulation of amateur boxing to-date. However, amateur boxing is constrained by a number of variables and future work might seek to develop and apply ‘scenario-specific’ versions of the BOXFIT simulation (e.g. $\text{BOXFIT}_{\text{W,M,R}}$) in order to identify the physiological requirements of performance with improved accuracy. Thus, considerable scope exists to quantify the demands of competition and subsequently develop and apply adapted versions of the BOXFIT to different contest formats (i.e. three rounds, two minutes duration and four rounds, two minutes duration), age (i.e. junior [11 – 17 y] and senior [18 – 35 y] age groups) and ability (novice, intermediate, open national and elite international standards) groups and sexes, given such variables have received scant research attention and may influence performance. Having identified the importance of ability (and contest duration), weight class and contest outcome within the thesis, it seems logical that the BOXFIT is initially modified according to these variables, with subsequent appraisals of the physiological responses enhancing the validity of findings.

Moreover, the BOXFIT is currently based upon the mean demands recorded per minute of competition, and it might therefore be of benefit to develop multiple adjusted BOXFIT simulation protocols that include the *range* of values recorded (given the established variability in external demand observed among boxers). Given the potential influence of many confounding variables, research attempting to appraise the physiological responses of boxing might benefit from tailoring the simulation to individual boxers such that the external demands of all boxers have been considered. This seems particularly pertinent if the BOXFIT is to be used as part of a conditioning program preparing athletes for the *worst-case* metabolic demand (Amtmann et al., 2008; Amtmann, 2012). This would be an arduous task requiring multiple performances per boxer (O'Donoghue, 2005) before developing individual protocols so those employing such an approach ought to consider its feasibility.

9.3.4 Application of the BOXFIT to research

In the manner of other sport-specific simulations, the BOXFIT has been developed to facilitate the identification of systematic changes in aspects of performance owing to intervention or possibly the use of ergogenic aids. Whilst the assessment of training-induced systematic changes in the physiological response to BOXFIT performance seems intuitive, the sport is also classified by weight, and with knowledge of its reliability and sensitivity, the BOXFIT could be applied to establish the effect of rapid and gradual weight loss upon the physiological response to boxing performance. Athletes competing in combat sports aim to enter a weight classification below their natural body mass whilst maintaining strength, power and endurance (Fogelholm, Koskinen, Laakso, Rankinen, & Ruokonen, 1993; Fogelholm, 1994; American College of Sports Medicine, 1996, 2007; Oppliger, Steen & Scott, 2003; Alderman, Landers, Carlson, & Scott, 2004; Degoutte et al., 2006; Udelson et al., 2007; Artioli et al., 2010) to gain a physiological advantage over the opponent. However, the methods used to achieve such weight loss can result in dehydration, glycogen depletion, compromised health and decreased performance (Steen & Brownwell, 1990; Scott, Horswill, & Dick, 1994; Roemnich & Sinning, 1997a, 1997b; Hall & Lane, 2000; Smith et al., 2000b; Smith et al., 2001; Ransone & Hughes, 2004; Dickson et al., 2005; Schmidt, Piencikowski, & Vandervest, 2005; Buford, Rossi, Smitth, O’Brien, & Pickering, 2006; Smith, 2006; Judelson et al., 2007; Murray, 2007; Sawka & Noakes, 2007; Kempton et al., 2010; Lingor & Olson, 2010; Morton et al., 2010). Indeed, this area of research has already been the subject of scientific investigation in amateur boxing (Hall & Lane, 2000; Smith et al., 2000; Smith et al., 2001; Smith, 2006), though the application of the BOXFIT, or adapted versions with enhanced validity, would likely improve the accuracy of future assessments of weight loss and boxing-specific physiology. That research has typically failed to establish any negative effects of dehydration and glycogen depletion might be due to the invalid modes of assessment (e.g. arm cranking exercise; Mendes et al., 2013) and the BOXFIT, with its established reliability and sensitivity, would improve the validity of the appraisal.

The findings also contribute to the developing body of research suggesting simulation protocols do not recreate the physiology of competitive performance, despite the use of a representative external demand. Given the purported role of psycho-physiological stressors in accounting for this discrepancy, research ought to appraise the causes of this phenomenon (e.g. heightened motivation, aggression, cognitive demand) thus enhancing the validity of simulations. Moreover, if simulations are to be useful ergonomic tools then other mediating factors should be examined (e.g. unanticipated movements, number of contacts) to further enhance the accuracy of the competitive replication.

9.3.5 Application of the BOXFIT to applied scenarios

Specificity has been described as a necessary component of physical and physiological conditioning (Muller et al., 2000) thus a fundamental application of any simulation is its use as a conditioning tool (Drust et al., 2007). The BOXFIT then, particularly if modified to better replicate the physiological demands of amateur boxing, could be used as part of a boxer’s metabolic conditioning, providing a sport-specific means of training. Indeed, it is by replicating or even exceeding the metabolic profile of competition (Dobson & Keogh, 2007; Amtmann et al., 2012) that favourable adaptation takes place and therefore the BOXFIT could prove beneficial to boxers and coaches preparing for competition. Moreover, the design and intensities of training should ideally be determined by prior physiological examinations possessing adequate specificity, validity and reliability. Again, following adjustment, the BOXFIT could provide sufficient training stimulus owing to overload, and also be used to monitor progression. For example, if a boxer were to progress from regional to national standard contests, and thus from six- to nine-minute contests, the BOXFIT could be gradually amended to continually provide sufficient physiological adaptation. On this note, the BOXFIT could provide benchmarks identifying boxers likely to transition successfully between contest formats.

Where baseline measurements are considered further, if the simulation was used in the preceding period (< 7 days) before a contest, the BOXFIT could identify physiological markers of boxing-specific fitness following intervention (e.g. high intensity interval training) or a period of inactivity (e.g. injury, off-season). For example, following injury performance of the simulation upon a boxer’s return to training could establish the magnitude of the associated decrements. If it were habitually used as part of a boxer’s conditioning, boxing-specific fitness could be continually monitored and only when fitness no longer deviated markedly from ‘baseline’ values would a boxer be ‘passed’ to compete. Likewise, and as alluded to above, the BOXFIT given its reliability and sensitivity could also be used to evidence a notable decline in aspects of performance that are associated with weight loss. Given its prevalence in boxing, a tool that could identify permissible weight loss would seem useful.

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Appendix 1

Table 10.1. Details of group sub-divisions within chapter 4.

							n^4
Light flyweight >45-48kg	2 (2.4%)	Three, 2min rounds	2 (2.4%)	4.9		Regional	
						National	
				5.5	2 (2.4%)	Regional	2 (2.4%)
						National	
				6.1		Regional	
						National	
		Three, 3min rounds		4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1		Regional	
						National	
Flyweight >48-51kg	2 (2.4%)	Three, 2min rounds		4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1		Regional	
						National	
		Three, 3min rounds	2 (2.4%)	4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1	2 (2.4%)	Regional	
						National	2 (2.4%)
Bantamweight >51-54kg	6 (7.1%)	Three, 2min rounds	2 (2.4%)	4.9		Regional	
						National	
				5.5	2 (2.4%)	Regional	2 (2.4%)
						National	
				6.1		Regional	
						National	
		Three, 3min rounds	4 (4.8%)	4.9	2 (2.4%)	Regional	
						National	2 (2.4%)
				5.5		Regional	
						National	
				6.1	2 (2.4%)	Regional	
						National	2 (2.4%)

							n^4
Featherweight >54-57kg	8 (9.5%)	Three, 2min rounds		4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1		Regional	
						National	
		Three, 3min rounds	8 (9.5%)	4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1	8 (9.5%)	Regional	
						National	8 (9.5%)
Lightweight >57-60kg	8 (9.5%)	Three, 2min rounds	6 (7.1%)	4.9	2 (2.4%)	Regional	2 (2.4%)
						National	
				5.5	4 (4.8%)	Regional	4 (4.8%)
						National	
				6.1		Regional	
						National	
		Three, 3min rounds	2 (2.4%)	4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1	2 (2.4%)	Regional	
						National	2 (2.4%)
Light welterweight >60-64kg	12 (14.3%)	Three, 2min rounds	12 (14.3%)	4.9	6 (7.1%)	Regional	6 (7.1%)
						National	
				5.5	6 (7.1%)	Regional	6 (7.1%)
						National	
				6.1		Regional	
						National	
		Three, 3min rounds		4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1		Regional	
						National	

							n[4]
Welterweight >64-69kg	12 (14.3%)	Three, 2min rounds	6 (7.1%)	4.9	2 (2.4%)	Regional	2 (2.4%)
						National	
				5.5	4 (4.8%)	Regional	4 (4.8%)
						National	
				6.1		Regional	
						National	
		Three, 3min rounds	6 (7.1%)	4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1	6 (7.1%)	Regional	
						National	6 (7.1%)
Middleweight >69-75kg	16 (19%)	Three, 2min rounds	10 (11.9%)	4.9	4 (4.8%)	Regional	4 (4.8%)
						National	
				5.5	4 (4.8%)	Regional	4 (4.8%)
						National	
				6.1	2 (2.4%)	Regional	
						National	2 (2.4%)
		Three, 3min rounds	6 (7.1%)	4.9		Regional	
						National	
				5.5	2 (2.4%)	Regional	2 (2.4%)
						National	
				6.1	4 (4.8%)	Regional	
						National	4 (4.8%)
Light heavyweight >75-81kg	6 (7.1%)	Three, 2min rounds	2 (2.4%)	4.9		Regional	
						National	
				5.5	2 (2.4%)	Regional	2 (2.4%)
						National	
				6.1		Regional	
						National	
		Three, 3min rounds	4 (4.8%)	4.9		Regional	
						National	
				5.5	2 (2.4%)	Regional	2 (2.4%)
						National	
				6.1	2 (2.4%)	Regional	
						National	2 (2.4%)

							n^4
Heavyweight >81-91kg	10 (11.9%)	Three, 2min rounds	6 (7.1%)	4.9		Regional	
						National	
				5.5	6 (7.1%)	Regional	6 (7.1%)
						National	
				6.1		Regional	
						National	
		Three, 3min rounds	4 (4.8%)	4.9		Regional	
						National	
				5.5	2 (2.4%)	Regional	2 (2.4%)
						National	
				6.1	2 (2.4%)	Regional	
						National	2 (2.4%)
Super heavyweight >91kg	2 (2.4%)	Three, 2min rounds	2 (2.4%)	4.9		Regional	
						National	
				5.5	2 (2.4%)	Regional	2 (2.4%)
						National	
				6.1		Regional	
						National	
		Three, 3min rounds		4.9		Regional	
						National	
				5.5		Regional	
						National	
				6.1		Regional	
						National	

‘n’ = performances within each weight class; ‘n^2’ = performances within given contest format (values previously filtered according to weight class); ‘n^3’ = performances within various ring sizes (values previously filtered according to weight class and contest format); ‘n^4’ = performances within regional and national competition (values previously filtered according to weight class, contest format and ring size). ‘%’ = percentage of sample within respective conditions.

Appendix 2

Table 10.2. The overall offensive and defensive demands of competition by outcome, weight class and ability ($N \cdot \text{min}^{-1}$) (mean ± SD).

			Attacks launched	**Punches**	**Defences**
Win	**Light**	**Regional**	14 ± 0	26 ± 5	9 ± 2
		National	16 ± 5	30 ± 12	10 ± 2
	Middle	**Regional**	16 ± 4	29 ± 10	10 ± 2
		National	16 ± 4	29 ± 6	11 ± 2
	Heavy	**Regional**	15 ± 1	22 ± 4	11 ± 1
		National	16 ± 3	27 ± 6	11 ± 2
	Total	**Regional**	13 ± 1	25 ± 7	10 ± 4
		National	15 ± 4	32 ± 12	8 ± 2
Lose	**Light**	**Regional**	14 ± 2	26 ± 8	9 ± 3
		National	15 ± 3	28 ± 6	10 ± 3
	Middle	**Regional**	15 ± 3	27 ± 10	10 ± 2
		National	15 ± 3	28 ± 8	10 ± 2
	Heavy	**Regional**	11 ± 1	17 ± 3	11 ± 3
		National	13 ± 4	23 ± 7	12 ± 3

Table 10.3. The frequency of attacks across rounds according to the outcome, weight class and ability ($N{\cdot}\mathrm{min}^{-1}$) (mean ± SD).

			Round one	**Round two**	**Round three**
Win	**Light**	**Regional**	12 ± 3	12 ± 3	12 ± 4
		National	16 ± 5	16 ± 5	17 ± 4
	Middle	**Regional**	17 ± 4	16 ± 3	16 ± 4
		National	15 ± 1	16 ± 2	13 ± 2
	Heavy	**Regional**	14 ± 2	14 ± 2	12 ± 3
		National	15 ± 4	16 ± 3	14 ± 5
Lose	**Light**	**Regional**	9 ± 3	8 ± 3 $^{L,L,N\ L,M,R}$	10 ± 5
		National	14 ± 5	15 ± 7	15 ± 8
	Middle	**Regional**	15 ± 4	15 ± 3	15 ± 3
		National	14 ± 1	14 ± 2	14 ± 3
	Heavy	**Regional**	15 ± 4	14 ± 5	12 ± 5
		National	13 ± 8	11 ± 5	11 ± 5

Table 10.4. The frequency of punches across rounds according to the outcome, weight class and ability ($N \cdot \mathrm{min}^{-1}$) (mean ± SD).

			Round one	**Round two**	**Round three**
Win	**Light**	**Regional**	22 ± 3	21 ± 2	20 ± 1
		National	29 ± 12	29 ± 12	33 ± 14
	Middle	**Regional**	30 ± 9	29 ± 7	29 ± 6
		National	23 ± 4	24 ± 4	23 ± 4
	Heavy	**Regional**	26 ± 8	24 ± 7	23 ± 9
		National	36 ± 15	31 ± 11	31 ± 10
Lose	**Light**	**Regional**	16 ± 1	13 ± 2 $^{\mathrm{L,M,R}\ \mathrm{L,H,R}}$	13 ± 7
		National	23 ± 9	25 ± 12	28 ± 17
	Middle	**Regional**	27 ± 8	29 ± 7	28 ± 6
		National	24 ± 4	24 ± 9	27 ± 11
	Heavy	**Regional**	29 ± 11	27 ± 11	28 ± 11
		National	27 ± 15	22 ± 8	22 ± 13

* Significantly different to lose, middle, regional & lose, heavy, regional boxers.

Table 10.5. The frequency of defences across rounds according to the outcome, weight class and ability ($N \cdot min^{-1}$) (mean ± SD).

			Round one	Round two	Round three
Win	**Light**	**Regional**	7 ± 3	$6 \pm 3^{W,M,R}$	9 ± 6
		National	10 ± 3	10 ± 3	10 ± 3
	Middle	**Regional**	11 ± 3	11 ± 2	11 ± 2
		National	11 ± 2	11 ± 2	11 ± 3
	Heavy	**Regional**	10 ± 4	10 ± 3	10 ± 5
		National	9 ± 3	8 ± 1	8 ± 2
Lose	**Light**	**Regional**	10 ± 8	9 ± 5	9 ± 3
		National	12 ± 3	13 ± 3	12 ± 3
	Middle	**Regional**	$12 \pm 3^{L,H,R}$	$12 \pm 4^{L,H,R}$	11 ± 3
		National	11 ± 3	10 ± 2	9 ± 2
	Heavy	**Regional**	9 ± 2	$8 \pm 2^{\#}$	9 ± 3
		National	12 ± 5	13 ± 1	11 ± 0

* Significantly different to win, middle, regional; #

Appendix 3

Table 10.6. Reliability of the HDT and the Qualisys ProFlex 3D motion capture system (filtered data) for assessing acceleration, displaying measures of absolute reliability.

Drop height	**System**	**Test (g)**	**Retest (g)**	**95% LoA (g)**	**TE (g)**	**CV (%)**
Full	HDT	16.83 ± 0.59	16.57 ± 0.68	0.27 ± 1.77	0.64	3.12
Mid	HDT	12.27 ± 0.37	12.57 ± 0.50	-0.30 ± 1.38	0.50	2.58
Quarter	HDT	10.1 ± 0.28	10.3 ± 0.25	-0.20 ± 0.81	0.29	1.55

Table 10.7: Overall parameters of the prediction model using the HDT acceleration (g) to estimate Qualisys Proflex 3D motion capture acceleration (g) for all punches (n = 180).

	Coefficients	**Standard Error**	**t-value**	***P*-value**
Intercept **(α)**	-0.45	1.32	-0.34	0.73
HDT pooled punch data **(β)**	1.01	0.05	21.63	0.001

R^2 = 0.72 (adjusted R^2 = 0.71), SEE = 2.72, SEE% = 9.76%.

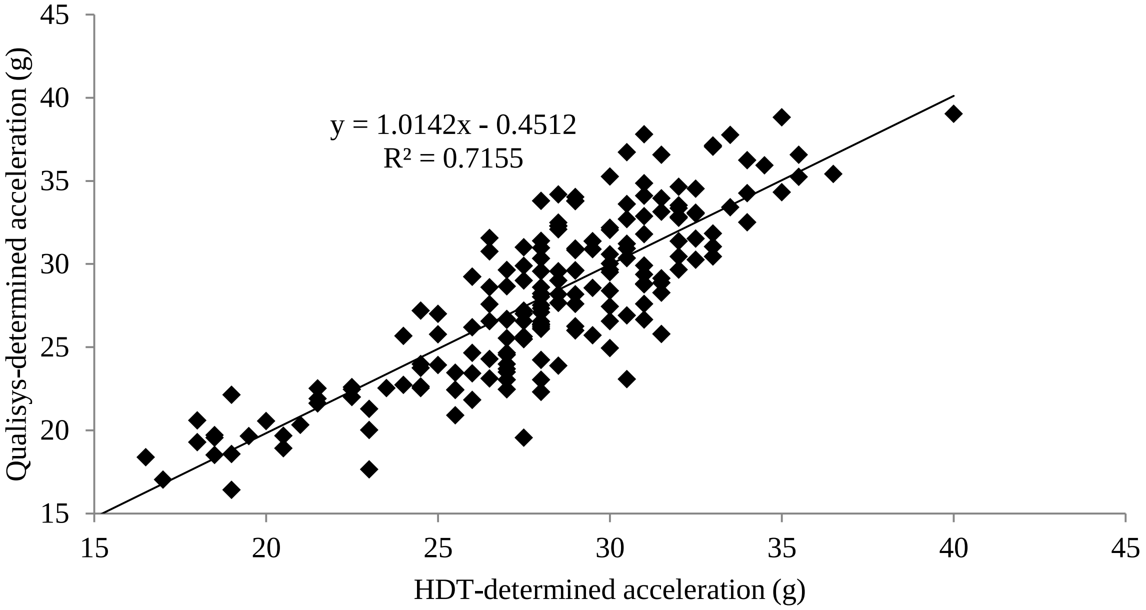

Figure 10.1: Correlation plot between the HDT and the 3D determined acceleration for all punches.

Appendix 4

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Edward Thomson

2nd August 2012

Dear Edd,

Study title: **An examination of the physiological and punching kinematic responses during an amateur boxing simulation protocol.**

FREC reference: **716/12/ET/SES**
Version number: **1**

Thank you for sending your application to the Faculty of Applied Sciences Research Ethics Committee for review.

I am pleased to confirm ethical approval for the above research, provided that you comply with the conditions set out in the attached document, and adhere to the processes described in your application form and supporting documentation.

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Application Form	1	July 2012
Appendix 1 – List of References	1	July 2012
Appendix 2 – C.V. for Lead Researcher	1	July 2012
Appendix 3 – Participant Information Sheet	1	July 2012
Appendix 4 – Participant Consent Form	1	July 2012
Appendix 5 – Pre-test Health Questionnaire	1	July 2012
Appendix 6 – Pre-participation Health Questionnaire	1	July 2012
Appendix 7 – Risk Assessment Form	1	July 2012
Appendix 8 – Written Permission – Merseyside &	1	July 2012

Cheshire Amateur Boxing Association		
Appendix 9 – Email correspondence from Regional Secretary – Merseyside & Cheshire Amateur Boxing Association	1	July 2012
Appendix 10 – Protocol outline	1	July 2012

With the Committee’s best wishes for the success of this project.

Yours sincerely,

Cynthia V Burek

Prof. Cynthia Burek
Chair, Faculty Research Ethics Committee

Enclosures: Standard conditions of approval.

Cc. Supervisor/FREC Representative

Appendix 5

Participant information sheet

An examination of the physiological and punching kinematic responses during an amateur boxing simulation protocol.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

What is the purpose of this study?
The purpose of this research is to measure how you respond physiologically during a boxing simulation protocol designed by myself. In addition, the research is concerned with measuring your punching force throughout the boxing protocol.

Why have I been chosen?
You have been chosen to take part as you are a registered senior amateur boxer who is regularly competing in amateur boxing bouts.

Do I have to take part?
It is up to you whether or not you take part. If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you do take part you are still free to withdraw at any time and without reason or fear of reprisal.

What will happen to me if I take part?
You will be required to be tested on 3 separate occasions, with a minimum of 3 days separating the first and second, and a minimum of 7 days between the second and third. On each occasion, you will be asked to perform a 20-min warm-up, consisting of stretching, jogging, ‘shadow boxing’ and striking hand-held coaching pads before the performance test.

On the first occasion, you will be talked through the demands of the exercise and listen to the audio cues that are provided throughout the 3 x 3 minute exercise. Following this, you will perform a single 3 minute round of the protocol using shadow boxing exercise. After adequate recovery time (> 10 mins), you will then be required to exercise for 3 x 3 minute rounds with a 1 minute rest interval between each round. The exercise will involve you punching hand-held coaching pads in a pre-determined manner as well as performing standardized defensive manoeuvres and movements around the ring. All movements required will be familiar to you as a competitive amateur boxer. More specifically, it will involve you moving in a boxing stance 45 metres per minute, simulating 11 defensive manoeuvres per minute and throwing 26 punches per minute of exercise. In total, you will travel 405 metres, simulate 99 defensive movements and throw 234 punches. On the second and third occasions, you will perform only the 3 x 3 minute exercise protocol with 1 minute rest intervals.

You will also be asked to wear a heart rate monitor throughout the exercise, give a simple rating of how hard the exercise feels (your ‘perceived exertion’) and a fingertip blood sample at the end of the test, all of which will help appraise the intensity of the boxing exercise.

What are the possible disadvantages and risks of taking part?
The fingertip blood sample at the end of the contest might be a bit uncomfortable for a few seconds. Furthermore, it is anticipated that the exercise intensity may cause some discomfort. However, it is unlikely to be more physically stressing than much of the training you undertake in preparation for a contest.

What are the possible benefits of taking part?
By performing a test that replicates the demands of a contest (i.e. the amount of punches thrown, defences performed and movements around the ring) you will be adding to the preparation for potential upcoming contests. Furthermore, the test may provide information regarding your performance/fitness over the course of a simulated contest and it is possible that it could be used to address any weaknesses you have and improve your training.

What if something goes wrong?
If you wish to complain or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact Professor Sarah Andrew, Dean of the Faculty of Applied Sciences, University of Chester, Parkgate Road, Chester, CH1 4BJ, or 01244 513055.

Will my taking part in the study be kept confidential?
All information which is collected about you during the course of the research will be kept strictly confidential so that only the researcher carrying out the research will have access to such information.

What will happen to the results of the research study?
The results will be written up into a report as part of a PhD thesis. Your identity will not be revealed in any subsequent report or publication.

Who is organising and funding the research?
The research is funded by the Department of Sport and Exercise Sciences. Edd Thomson, a PhD student in the Department of Sport and Exercise Sciences at the University of Chester will be carrying out the study.

Who may I contact for further information?

If you would like more information about the research before you decide whether or not you would be willing to take part, please contact:

Edd Thomson at:
e.thomson@chester.ac.uk
01244 511189 (ext. 1988)

Appendix 6

PRE-TEST HEALTH QUESTIONNAIRE

(PLEASE NOTE THAT THIS INFORMATION WILL BE CONFIDENTIAL)

Name:……………………………. DOB:…………….. Age:…………

Practical/Project Title: An examination of the physiological and punching kinematic responses during an amateur boxing simulation protocol.

Please answer these questions truthfully and completely. The purpose of this questionnaire is to ensure that you are fit and healthy enough to participate in this laboratory practical/research project. Please circle appropriate answer.

1. Are you currently engaged in weight loss practices as part of your training or preparation for a forthcoming contest **Yes** **No**

2. Have you in the past suffered from a serious illness or accident. **Yes** **No**
   If Yes, please provide details

   ………

3. Have you consulted your doctor the last 6 months **Yes** **No**
   If Yes, please provide details

……

4. Do you suffer, or have you suffered from

Asthma	**Yes**	**No**
Diabetes	**Yes**	**No**
Bronchitis	**Yes**	**No**
Epilepsy	**Yes**	**No**
High blood pressure	**Yes**	**No**

5. Is there any history of heart disease in your family **Yes** **No**

6. Are you suffering from any infectious skin diseases, sores, blood wounds, or infections i.e., Hepatitis B, HIV, etc.? **Yes** **No**
   If Yes, please provide brief details
   ………

7. Are you currently taking any medication **Yes** **No**
   If Yes, please provide details

…………………………………………………………………………………………………
…………………………………………………………………………………………………
………………

8. Are you suffering from a disease that inhibits the sweating process **Yes** **No**

9. Is there anything to your knowledge that may prevent you from participating in the testing that has been outlined to you? **Yes** **No**
   If Yes, please provide details

…………………………………………………………………………………………………
…………………………………………………………………………………………………

Your Recent Condition

- Have you eaten in the last 2 hours? **Yes** **No**
  If Yes, please provide details
  …………………………………………………………………………………………………
  ………………………………………………………………………………………
- Have you consumed alcohol in the last 24hr **Yes** **No**
- Evaluate your diet over the last two days. **Poor** **Average** **Good** **Excellent**
- Have you had any kind of illness or infection in the last 2 weeks **Yes** **No**
- Have you exercised in the last 2 days? **Yes** **No**

  If Yes, please describe below

…………………………………………………………………………………………………
…………………………………………………………………………………………………
………………

Persons will not be permitted to take part in any experimental testing if they:

- have a known history of medical disorders (i.e. hypertension, heart or lung disease)
- have a fever, suffer from fainting or dizzy spells
- are currently unable to train because of a joint or muscle injury
- have had any thermoregulatory disorder
- have gastrointestinal disorder
- have a history of infectious diseases (i.e. HIV or Hepatitis B)
- have, if pertinent to the study, a known history of rectal bleeding, anal fissures, haemorrhoids or any other similar rectal disorder.

My responses to the above questions are true to the best of my knowledge and I am assured that they will be held in the strictest confidence.

Name: (Participant)………………………………………… Date:………………….

Signed (Participant): ……………………………………….

Name: (Researcher)………………………………………… Date:………………….

Signed (Researcher): ……………………………………….

Appendix 7

University of Chester

Title of Project: An examination of the physiological and punching kinematic responses during an amateur boxing simulation protocol.

Name of Researcher: Edd Thomson

Please initial box

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason and without my legal rights being affected. ☐
3. I agree to take part in the above study. ☐

Name of Participant ____________________ Date ____________________ Signature ____________________

Researcher ____________________ Date ____________________ Signature ____________________

1 for participant; 1 for researcher

Appendix 8

Chapter 3 additional results

The table below illustrates the reliability of a frequent (attack) and an infrequent (lead uppercut) performance indicator (Table 3.6). For attacks, perfect reliability was established as evidenced by the total (71 instances) and recordings in all time cells. For lead uppercuts, four actions were recorded during the initial analysis and five during the retest. However, perfect agreement was still established within 36/37 time cells.

Table 3.6. Intra-observer reliability data for a frequent (attack) and infrequent action (lead uppercut) recorded by the expert analyst into the 36 ten-second time cells. Data represents boxer A only.

Cell number	Attack	Attack retest	Attack: same data in test retest	Lead uppercut	Lead uppercut retest	Lead uppercut: same data in test retest
1	1	1	Yes	0	0	Yes
2	2	2	Yes	1	1	Yes
3	2	2	Yes	0	0	Yes
4	1	1	Yes	0	0	Yes
5	3	3	Yes	1	1	Yes
6	3	3	Yes	0	0	Yes
7	1	1	Yes	0	0	Yes
8	1	1	Yes	0	0	Yes
9	2	2	Yes	0	0	Yes
10	2	2	Yes	0	0	Yes
11	3	3	Yes	0	0	Yes
12	1	1	Yes	0	0	Yes
13	3	3	Yes	0	0	Yes
14	2	2	Yes	1	1	Yes
15	1	1	Yes	0	0	Yes
16	4	4	Yes	0	0	Yes
17	2	2	Yes	0	0	Yes
18	2	2	Yes	0	0	Yes
19	1	1	Yes	0	0	Yes
20	2	2	Yes	0	0	Yes
21	2	2	Yes	0	1	No
22	1	1	Yes	0	0	Yes
23	2	2	Yes	0	0	Yes
24	3	3	Yes	0	0	Yes
25	1	1	Yes	0	0	Yes
26	2	2	Yes	0	0	Yes
27	2	2	Yes	0	0	Yes
28	3	3	Yes	0	0	Yes
29	2	2	Yes	0	0	Yes
30	2	2	Yes	0	0	Yes
31	2	2	Yes	0	0	Yes
32	0	0	Yes	0	0	Yes
33	2	2	Yes	1	1	Yes
34	2	2	Yes	0	0	Yes
35	3	3	Yes	0	0	Yes
36	2	2	Yes	0	0	Yes
37	1	1	Yes	0	0	Yes
Total	**71**	**71**	**Yes = 71** **No = 0**	**4**	**5**	**Yes = 36** **No = 1**

Table 3.8. Summarised intra-observer test-retest values for the defensive actions of the amateur boxer using 10 second time cells – boxer A.

Performance indicator	**Median (sign test)**	**PA = 0 (%)**	**95% Confidence Interval (%)**	**PA ± 1 (%)**	**95% Confidence Interval (%)**
Defence	$P = 1.00$	97	92 to 100	100	100 to 100
Block both arms	$P = 1.00$	100	100 to 100	100	100 to 100
Block right arm	$P = 1.00$	97	92 to 100	100	100 to 100
Block left arm	$P = 1.00$	100	100 to 100	100	100 to 100
Clinch	$P = 1.00$	100	100 to 100	100	100 to 100
Duck	$P = 1.00$	100	100 to 100	100	100 to 100
Foot defence	$P = 1.00$	97	92 to 100	100	100 to 100
Lean back	$P = 1.00$	97	92 to 100	100	100 to 100
Push	$P = 1.00$	100	100 to 100	100	100 to 100
Slip left	$P = 1.00$	100	100 to 100	100	100 to 100
Slip right	$P = 1.00$	100	100 to 100	100	100 to 100
Roll clock	$P = 1.00$	100	100 to 100	100	100 to 100
Roll anti-clockwise	$P = 1.00$	100	100 to 100	100	100 to 100

Key: PA = proportion of total agreement; PA ± 1 = proportion of agreement within the reference value of ± 1; N/A = not applicable.

Chapter 7 additional results.

During round two, the CV% for mean and peak heart rate responses were again < 5%. Both measures were consequently smaller than the MWC%. Limits of agreement revealed 95% of the differences could lie < 10 $b\cdot min^{-1}$ and 23 $b\cdot min^{-1}$ on a test-retest basis for mean and peak heart rate measures, respectively. Whilst $\dot{V}O_2$ and EE_{aer} recorded CV% larger than heart rate measurements, both measures of reliability were smaller than the MWC%. Limits of agreement however, represented worst-case differences representing 25% and 65% of respective pooled mean scores. $CO_{2excess}$ again evidenced the poorest reliability with a CV% of 30.2% able to detect only large changes in performance, in addition to limits of agreement representing a worst-case difference of 110%.

Table 7.3. Reliability statistics for mean HR, peak HR, $\dot{V}O_2$ ($ml\cdot kg^{-1}$), EE_{aer} and $CO_{2excess}$ during round two of the BOXFIT.

	Round two				
	Mean HR ($b\cdot min^{-1}$)	**Peak HR ($b\cdot min^{-1}$)**	**$\dot{V}O_2$ ($ml\cdot kg^{-1}$)**	**EE_{aer} ($kcal\cdot min^{-1}$)**	**$CO_{2excess}$ ($ml\cdot min^{-1}$)**
Trial 1	172 ± 10	187 ± 8	131.0 ± 17.7	33.23 ± 17.9	584.4 ± 220.3
Trial 2	172 ± 11	184 ± 13	126.1 ± 15.0	30.20 ± 17.1	672.5 ± 242.8
CV%	1.8	2.5	6.2	13.3	30.2
SWC%	1.2	1.2	2.5	10.9	7.4
MWC%	3.6↓	3.6↓	7.6↓	32.6↓	22.1
LWC%	7.2	7.2	15.2	65.3	44.3↓
VLWC%	12.0	12.0	25.3	108.8	73.8
95% LoA	-0.2 ± 9.8	2.7 ± 19.7	4.9 ± 26.5	3.0 ± 17.5	-88.1 ± 587.1

↓ CV% smaller than associated change.

During round three, the CV% for mean and peak heart rate responses were < 1.5%. All remaining measures displayed CV% >10%. Both heart rate measures and EE_{aer} possessed CV%s smaller than the MWC% whereas the same statistic for $\dot{V}O_2$ and $CO_{2excess}$ was lower than the LWC%. With the exception of $CO_{2excess}$, systematic differences between test-retest scores were all < 3.3%; however, random error was as large as 54% of pooled mean values. Considering $CO_{2excess}$, bias and random error constituted 9% and 94% of the test-retest mean, respectively.

Table 7.4. Reliability statistics for mean HR, peak HR, $\dot{V}O_2$ ($ml \cdot kg^{-1}$), EE_{aer} and $CO_{2excess}$ during round three of the BOXFIT.

	Round three				
	Mean HR ($b \cdot min^{-1}$)	**Peak HR ($b \cdot min^{-1}$)**	**$\dot{V}O_2$ ($ml \cdot kg^{-1}$)**	**EE_{aer} ($kcal \cdot min^{-1}$)**	**$CO_{2excess}$ ($ml \cdot min^{-1}$)**
Trial 1	175 ± 10	189 ± 11	122.0 ± 22.8	32.1 ± 19.0	625.2 ± 218.4
Trial 2	175 ± 9	188 ± 10	126.1 ± 15.2	32.1 ± 16.5	686.3 ± 237.6
CV%	1.2	1.5	13.0	16.5	29.5
SWC%	1.06	1.08	3.09	10.88	6.90
MWC%	3.17↓	3.25↓	9.26	32.63↓	20.70
LWC%	6.33	6.5	18.5↓	65.3	41.4↓
VLWC%	10.6	10.8	30.9	108.8	70.0
95% LoA	0.5 ± 7.9	0.8 ± 10.1	-4.1 ± 54.4	0.03 ± 17.4	-61.1 ± 613.1

↓ CV% smaller than associated change.