The Physical and Physiological Demands of Taekwondo Training and International Competition

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Table of Contents

Abstract

The aim of this PhD thesis was to characterise the physical and physiological demands of taekwondo in the aftermath of an evolution of rule changes over the last 19 years. The entry of taekwondo to the Olympic games in 2000 brought a spotlight and visibility to the sport that put pressure on the governing body to refine the rules and make it more exciting for spectators. As a result, there has been an evolution in the demands of taekwondo from a technical and tactical standpoint. Anecdotally, this has also caused a shift in the physical and physiological requirements for performance optimisation but it has yet to be demonstrated in the literature. The results demonstrated an increased physical demand of and physiological response to competition, compared to previous research. This change in physical and physiological demand was not appropriately echoed in the physiological profile of the athlete suggesting that the physical preparation of athletes should focus on energy system development to optimise performance success. Furthermore, it was found that the training load actually experienced by each athlete was not sufficient to promote progressive overload due to a lack of organisation of training stress. This was influenced by a high rate of injury occurrence and a demanding competition schedule that impacted each athlete's ability to complete the scheduled training sessions. Therefore, this thesis concluded with comprehensive considerations and guidelines for designing training programmes to coordinate physical preparation with the demands and schedule of competition by optimising energy system development and individualising training programmes in order to maximise competition performance.

Declaration

I declare that the work in this thesis, which I submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own. All attempts have been made to ensure that the work is original, to the best of my knowledge does not breach any copyright laws and has not been taken from the work of others, apart from the works that have been fully acknowledged within the text.

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List Of Figures

List of Tables

Abbreviations

FM% – percentage fat mass

LM% – percentage lean mass

%HRmax – percentage of maximum heart rate

1RM – 1 repetition maximum

3RM – 3 repetition maximum

ANOVA – analysis of variance

AUs – arbitrary units

BIA – bioelectric impedance analysis

BJJ – Brazilian jiu jitsu

BLa – blood lactate

BM – body mass

cm – centimeter

CMJ – countermovement jump

CMJs – countermovement jump with arm swing

COND – taekwondo conditioning session

CP – competition phase

CPET – cardiopulmonary exercise test

cTKDet – continuous taekwondo-specific exercise test

DXA – dual x-ray absorptiometry

F – female

FM – fat mass

GB – Great Britain

GC – general conditioning

Gen – general mode of training

GP – general phase

GPS – global positioning system

HR – heart rate

HR80 – time spent above 80% of heart rate

HR90 - time spent above 90% of heart rate

HRR – heart rate recovery

iTKDet – interval taekwondo specific exercise test

kg – kilogram

L – litre

LM – lean mass

M – male

HRmax - maximum heart rate

min – minutes

MMA – mixed martial arts

mmol – millimoles

MSFT – multi stage fitness test

PCr – phosphocreatine

PSS – protector and scoring system

RPE – rating of perceived exertion

RSI – reactive strength index

RT – resistance training

s – seconds

SCR – session completion rate

SCRgen – session completion rate of general training sessions

SCRtkd – session completion rate of taekwondo training sessions

SD – standard deviation

SJ – squat jump

SJs – squat jump with arm swing

SPAR – taekwondo sparring or full contact session

sRPE – session rating of perceived exertion

T/T – technical/tactical taekwondo training session

TAC – tactical taekwondo training session

TARG – taekwondo athletes who have not yet medalled at major competitions

TECH – technical taekwondo training session

TKD – taekwondo

TL – training load

TOP – taekwondo athletes who have medalled at major competitions

VO_2 – rate of oxygen consumption

VO_{2max} – maximum rate of oxygen consumption

W – watts

WAnT – wingate anaerobic test

WT – World Taekwondo

ηL – microliters

Technical Terms

beats·min^{-1} – heart rate in beats per minute

Clinch – during combat when two athletes close the distance between each other and grapple or push

Covering – preventing an opponents kick from scoring by covering the scoring area

Dobok – white uniform athletes are required to wear during official combats

Ectomorph – somatotype of long stature with minimal fat mass and lean mass

Endomorph – somatotype of short stature with moderate lean mass and high fat mass

Fencing – when a fighter holds the front leg up, during combat, but does not try to kick with it and prevents the opponent from kicking

Gam-jeom – penalty point awarded to an opponent for a rule break during a competitive combat

Grand Prix – a circuit of WT sanctioned taekwondo competitions that are only open to higher ranking athletes and which carry a high ranking point remuneration

Judo – a Japanese martial art that involves grappling and throwing techniques

Judoka – a term for a judo athlete

Karate – a Japanese martial art which involves some or all of punching, kicking, throwing and grappling techniques

Karateka – a term for a karate athlete

Making weight – common combat sport term referring to reducing body mass in order to weigh in below a desired weight category

Mesomorph – somatotype of medium stature with high lean mass and low fat mass

ml.kg.min^{-1} – millitres of of oxygen relative to body mass per minute of exercise

mmol.L^{-1} – millimoles per litre of blood volume

Striking – a combat sport which involves any or all of kicking, punching, elbowing and kneeing

T-test – a running test of agility involving forward, backward and lateral movements

Wrestling – a form of grappling combat sport featuring clinch work, takedowns and throws

BJJ – a Brazilian grappling martial arts involving takedowns and throws but is mainly based around floor fighting

Introduction

Taekwondo is a striking-based martial art that originates in South Korea. In modern times taekwondo has developed in to an increasingly popular combat sport that is practiced all over the world. In 2000, taekwondo was introduced in to the Olympic games and since then the professionalism and competitiveness, particularly at the higher levels, has dramatically increased. The aim of taekwondo is to achieve a technical knock out or to score more points than your opponent through kicks and punches to the body and kicks to the head. Taekwondo combats generally consist of three 2-minute rounds with 1-minute breaks between rounds. Competitive tournaments usually work on a single-elimination basis and as such, during competitive taekwondo events, successful athletes can be required to compete in 3-5 combats (qualifying rounds, semi-finals and finals) in a single day (Bridge *et al.*, 2018). *World Taekwondo* (WT) is the governing body for Olympic style taekwondo and WT sanctioned events take place at national, regional and international level including continental championships, world championships and Olympic games competition (World Taekwondo, 2018).

High-level participation in any sport is a challenging and difficult task as it involves competing against the best athletes in the world. Therefore, athletes, coaches and support staff search for ways to enhance all aspects of performance. For this reason, it has become commonplace to investigate the physical and physiological demands of a sport in order to maximise the physical preparation of athletes for competition. Understanding the physical demands and physiological response of athletes to competition can direct the focus of training methodologies to enhance the physiological characteristics of athletes enabling them to withstand and thrive under maximal competitive situations (Del Vecchio and Franchini, 2013). In open-skill sports (such as taekwondo), where athletes are required to react to unpredictable and changing, externally paced environments (Coyne *et al.*, 2018), it is often thought that the physical capacities of athletes are less important than in closed-skill sports (which are relatively predictable and internally-paced). However, more recently it is becoming accepted that although optimal physical and physiological preparation may not guarantee success at an open-skill sport, sub-optimal physical preparation may contribute or even be directly causative to failure or inadequate performance (Mirzaei *et al.*, 2009).

Despite the increasing popularity of taekwondo as a combat sport and its introduction to the Olympics, its presence in the literature is relatively limited. There are some investigations into the physiological demands of competition (Bridge, Jones and Drust, 2009; Matsushigue, Hartmann and Franchini, 2009; Bridge *et al.*, 2013) of simulated combats (Butios and Tasika, 2007; Hausen *et al.*, 2017; Campos *et al.*, 2012) and the physical activity profile of competition (Santos *et al.*, 2014b; Bridge, Jones and Drust, 2011). However, the majority of this data was collected prior to a large influx of rule changes that have impacted the sport over the last 19 years and triggered an evolution of the tactical and technical demands of taekwondo. Therefore, for use in understanding the physical and physiological demands of modern-day taekwondo, the studies above may no longer offer complete ecological validity.

After entry to the Olympic Games, WT received some criticism around the transparency of scoring methods and a lack of interest of audiences during matches. In order to prevent losing Olympic membership, WT changed the rules of taekwondo significantly. A variety of alterations to scoring and rules were introduced to enhance the activity and excitability of taekwondo combats (Moenig, 2015). These included athletes being penalised for a lack of frequent fighting activity during combats, a myriad of changes to the point system to increase the number of shots to the head and most importantly, an electronic scoring system was introduced to reduce the necessity for subjective scoring. All of these rules have impacted the flow of taekwondo combats from a technical and tactical perspective and anecdotally this has led to an evolution in the physical and physiological demands of the sport. Furthermore, according to Moenig et al. (2015), many of these rule changes have been successful in increasing the action and excitability of combats and have subsequently influenced technical and tactical preparation. However, the impact on the physical and physiological demands of combats has yet to be investigated.

In order to effectively understand the full extent of the demands of a sport, researchers must not only examine the demands and implications of competition itself, but also the methods that coaches and athletes employ to prepare for competition. To this end, documenting and understanding the interplay between the physical and physiological profile of an athlete, the demands of training practices and the challenges to organising them along with the demands of competition presents an ideal way to obtain a clear view of a sport and its athletes and, as a result, gives insights into how to optimise physical preparation. There have been some attempts to profile and understand taekwondo athletes in the literature (Marković, Misigoj-Duraković and Trninić, 2005; Liao *et al.*, 2016; Ball, Nolan and Wheeler, 2011; Bridge *et al.*, 2014) but, similar to the competition studies, this data was largely collected on athletes prior to the rule changes reducing its ecological validity for present day taekwondo athletes. In contrast, to the best of this author's knowledge, there has been no literature produced with the sole aim of investigating the demands of training load over a training cycle in taekwondo athletes. As a result, the impact of taekwondo training on the physiological profiles of athletes and its ability to adequately prepare athletes for the demands of competition is absent in the literature. Given the increasing popularity and professionalism of taekwondo, there is insufficient research available to guide coaches and practitioners to optimise the physical preparation of athletes. Therefore, this doctoral work aims to provide up-to-date, relevant data to aid this process.

Aims and Objectives

The aim of the present doctoral work is to assess the physical and physiological demands of taekwondo training and competition. Determination of these demands will be achieved through the fulfillment of the following objectives:

1. To determine the physical demands of and physiological responses to an international taekwondo competition
2. To examine the physical and physiological characteristics of top level and development level taekwondo athletes in a National training programme
3. To investigate the physical and physiological demands and characteristics of a training cycle in preparation for an important selection competition
4. To assess the factors that influence taekwondo athletes' ability to complete the required training sessions during a long term training cycle

Chapter 1

Literature Review

1.0. Literature Review

1.1. The Evolution Of Taekwondo As An Olympic Sport

Taekwondo is a combat martial art that promotes self-defence by a variety of kicking, punching and blocking techniques. As the national sport of South Korea its origins are debated; some believe it originated as early as 2 millennia ago while others suggest its origins were heavily influenced by the Japanese during their occupation of Korea in the early 1900s (Park and Kim, 2016). Either way, taekwondo has flourished as a martial art and competitive sport and as of 2005, according to a survey carried out by the Korean government, is practiced by 70 million people in more than 190 countries worldwide (Kim, 2006). As a competitive sport taekwondo has rapidly progressed and in the 1988 and 1992 Olympic Games it was introduced as an exhibition sport. At the 2000 Olympic Games in Sydney, taekwondo was recognised as an Olympic sport and was also included in the first edition of the Youth Olympic Games in 2010. As an official Olympic sport, taekwondo is governed by World Taekwondo (WT) (formerly the World Taekwondo Federation), an organisation that was founded in 1973 to propagate the sport of taekwondo internationally (Moenig, 2015). WT is responsible for organising and implementing the rules and regulations at major events such as the Olympics, the World championships and the Grand Prix events as well as at regional, national and international levels according to athlete's sex, age and weight category. Athletes compete at the latter competitions in order to gain ranking points. These ranking points are important because they allow athletes to qualify for larger competitions (such as the Grand Prix series) and contribute towards their WT ranking. The top 6 WT ranked athletes in each weight category then automatically qualify a place for their country at the Olympic games while the remaining places are decided at world and continental selection competitions.

Entry to the Olympic Games has had a large impact on the sport of taekwondo in terms of popularity and visibility. However, it has also applied pressure to WT to ensure that taekwondo was appealing and exciting to a broader audience. As a traditional martial art, some aspects of taekwondo were built around displays of technique and execution that required a practiced eye to appreciate. But WT realised that this would not be sufficient to attract and entertain new audiences (Moenig, 2015). Additionally, it came to light in the early 2000s that the subjective nature of taekwondo scoring was being used to manipulate the outcomes of matches (Moenig, 2015). As a result, there has been a plethora of new rules introduced by WT aimed at increasing the activity and excitement during taekwondo combat and improving the fairness of the scoring system (Moenig, 2015).

1.2. The Rules of Taekwondo

Taekwondo combats are usually played over three 2-minute rounds separated by 1-minute breaks and competitions generally occur over a single day with athletes competing in up to 4-5 combats per day (Bridge *et al.*, 2018). The aim of taekwondo is to score more points than the opponent by the end of the match or to win by knockout. Competitors may also win by creating a points difference of 20 or more over their opponent by the end of the second round or any time during the third round. If points are equal between two opponents by the end of the third round a fourth, "golden point" round takes place during which the first person to score is awarded the match. If it is still level by the end of this round, the winner is decided based on the number of registrations (strikes that made contact with the electronic body protector but that were below the force required to score) that occurred throughout the bout.

1.3. Weight Categories

Taekwondo is a weight-modulated sport and as such there are 8 weight classes for both males and females (Table 1, p.25) for world and continental championships. 4-7kg and 3-6kg separates these categories, respectively. Athletes must weigh in below the target weight category. However, for Olympic and Grand Prix events, there are only 4 weight categories for males and females. Therefore, at these events, in order to compete athletes must make one of four weight categories separated by between 10-12kg for males and 8-10kg for females.

1.4. Rule Changes

Table 1 summarises the rule changes in taekwondo over the last 18 years.

1.4.1. Point Scoring

Points are scored by kicking the body or head protector or by punching the body protector (but not the head) of an opponent. One of the key rule changes was the re-introduction of awarding multiple points for different scoring methods. When taekwondo was originally introduced at the Olympics, there was only one point awarded by referees for a successful blow to any part of the body or head protector. In 2002, in order to increase the commercial appeal of the sport and encourage more spectacular techniques (Moenig, 2015), WT introduced a rule whereby 2 points were awarded for a successful blow to the head. This rule was amended again in 2009 and, over the last 10 years, further iterations of rule changes have awarded differing points for different types of blows. At the time of writing, one point is awarded for a punch to the body, 2 points for a straight kick to the body, 3 points for a straight kick to the head, 4 points for a spinning kick to the body and 5 points for a spinning kick to the head (WTF, 2018a; World Taekwondo, 2018). However, despite all of the changes to the points system, a consistent factor has been the increased points advantage of landing a successful kick to the head protector (otherwise known as a head shot). This initial addition made it highly beneficial for athletes who were tall for their weight class as they could more easily score a head shot on a shorter opponent (Moenig, 2015). In fact, it has been shown that the number of head shot attempts have increased (Jae-Ok and Voaklander, 2016) and subsequent concussions have increased dramatically following the initial introduction of bonus points for scoring by head kick.

1.4.2. Ring Size and Penalties

On top of the transformation of the scoring system, changes were introduced to other aspects of combat. One of most influential of these was the reduction of the ring size from 12 x 12m to an 8 x 8m in order to encourage the athletes to increase fighting activity and reduce combat avoidance. Further rules to enhance the fight activity have since also been introduced. These include penalties for avoiding combat, for falling over, for moving outside of the ring, for grabbing or pushing an opponent and for "fencing" or blocking an opponents kick with their leg (WTF, 2018a; World Taekwondo, 2018). These penalties are called *Gam-jeoms* and result in an automatic point being awarded to the opponent. The introduction of these rules aims to increase the frequency of the exchanges between opponents and thus to escalate the excitement of the combat.

1.4.3. Protector and Scoring System

Lastly, but perhaps the most revolutionary rule change, came with the introduction of the electronic protector and scoring system (PSS). Traditionally, 4 corner referees who sat on the outside of the ring judged taekwondo combats subjectively. However, after the Beijing Olympics, due to some controversy surrounding the accuracy of the subjective scoring of some combats by referees (WTF, 2018a; World Taekwondo, 2018), WT introduced an electronic PSS system which detected force from a blow and thus could enable objective, automatic scoring during combats. Initially, just the body protector contained this technology and thus headshots were still required to be scored subjectively by referees. Furthermore, there was no way for the body protector to detect what part of an opponents body had made contact with the PSS which led to the validation of scores with illegal body parts such as knees and elbows. Therefore, sensors were developed that were placed in the socks and as a result only strikes with the feet could score on an opponent’s body protector. In 2014, the PSS system was expanded to include electronic sensors in the head protectors to detect headshots. However, there are instances when an athlete may miss an opponents head protector but still make contact with the face; in this situation, the score is still valid but it is awarded subjectively by the referees. Similarly, punches to the body protector are awarded subjectively as there are no sensors in the gloves that athletes are required to wear. The development of the electronic PSS over the last 10 years has reduced the need for judges to subjectively score successful blows. As a result, athletes can score with less obvious force and power than before since they no longer have to rely on making audible contact in order to convince the judges of proper contact with their opponent (Moenig, 2015). There are currently two PSS systems in use in WT competitions: KP&P systems and Daedo systems. Both of these utilise unique and proprietary sensor and algorithms to detect and confirm a successful scoring technique.

1.4.4. Taekwondo Competitions and Weight Making

In general, WT competitions are held over the course of a single day. There are some rare exceptions to this such as the 2017 World Championships in Korea in which preliminary round combats were held on the first day and semi finals and finals were held on the second day. Athletes are required to weigh in on the day prior to the competition allowing them ~18-24 hours to re-fuel and re-hydrate after they “make weight" (weigh in below the desired category). Recently, a new rule has been introduced where athletes can be subject to spot checks 30-120 minutes before the first fight on the morning of competition. During this "random" weigh-in, athletes weight must not be more than 5% above the weight category (WTF, 2018a; World Taekwondo, 2018). All athletes must compete wearing an official taekwondo "Dobok" along with a groin guard, forearm guards, shin guards, gloves and electronic sensor socks as well as the PSS body and head protectors (World Taekwondo, 2018). Combats last for three 2-minute rounds separated by 1-minute rest periods. However, at certain competitions, the technical delegate may adjust the duration of competition to one of the following: 3x1-minute rounds, 3x1-minute 30-second rounds, 2x2-minute rounds or 1x5-minute round.

Undoubtedly taekwondo has evolved considerably with this plethora of rule changes and as a result it is possible that the demands of the sport have changed in recent times. The fact that the rule changes are largely aimed at reducing the passive part of the game and increasing the active parts suggests that this places not only a different demand on coaches and athletes from a technical and tactical point of view but may also change the demand from a fitness and physiological perspective (Kim *et al.*, 2015).

Table 1 Summary of rule changes in WT taekwondo competitions since entry to the Olympic Games in 2000

Rule Type	Previous Rule	New Rule	Year of Change
Weight Categories	8 weight categories in male and female divisions for all competitions	4 weight categories in male and female divisions for Olympic and Olympic associated events and Grand Prix events	2000 (entry to Olympic games)
Point System	1 point for any successful kick or punch to an opponent	Punch to body = 1 point Straight kick to body = 2 points Straight kick to head = 3 points Spinning kick to body = 4 points Spinning kick to head = 5 points	2018 (most recent change)
Ring Size	12 x 12m square	8 x 8m octagon or square	2015
Penalties (Gam-Jeoms)		Stepping outside the ring	2015
		Falling over	
		Fencing with your leg	
		Inactivity for >5s	
Point Scoring	Manually judged by referees	Introduction of PSS for automatic point scoring (only to the body)	2009
		Introduction of sensors into head gear to include automatic point scoring to head (only punching scored subjectively)	2014
Weigh In	No limit on weight regain between weigh in and competition	Athletes must not be >5% above weight category on the morning of competition	2018

Straight kick = kick executed using front or back leg while remaining facing opponent; Spinning kick = kick executed while spinning body to face away from opponent ; Fencing = holding leg up but not kicking and preventing opponent kicking

1.5. The Demands of Taekwondo Competition

1.5.1. The Physiological Demands of Competition

1.5.1.1. Simulated Competition

Understanding the technical, tactical, physical and physiological demands of competition in any sport is crucial to maximise preparation (Smith, 2003). Several studies have attempted to measure and quantify the physical and physiological demands of taekwondo combat in order to ensure athletes are prepared adequately. However, due to the combative nature of taekwondo competition and in line with WT rules and regulations, investigating real life competition situations can be difficult due to the necessity of wearing certain equipment (such as HR monitors and gas analysers) during a full contact combat (Butios and Tasika, 2007). Therefore, many research groups have attempted to measure the physiological demands of simulated taekwondo combats to negate this issue.

One of the first studies to investigate the physiological demands of simulated competition examined the HR and BLa response of 24 elite male Korean taekwondo athletes during three simulated combats each separated by 90 minutes (Butios and Tasika, 2007). The authors reported a mean HR of 158 beats.min^{-1} and BLa of 3.35 mmol.L^{-1} during the simulated competitions and that there was no difference in physiological responses between the weight categories (-68kg, -80kg and +80kg) suggesting that the intermittent nature of taekwondo allows sufficient time for recovery between high-intensity efforts and thus BLa accumulation does not occur. However, it is worth noting that this study was carried out over 3 x 3 minute bouts as was customary in competition at the time and this may have impacted the physiological response. Another study also investigating the physiological responses to 3 x 3 minute round taekwondo simulations reported greater mean HR and BLa values of 197 ± 2 beats.min^{-1} and 10.2 ± 1.2 mmol.L^{-1}, respectively at the end of the third round suggesting that taekwondo does in fact rely heavily on both aerobic and anaerobic energy systems (Bouhlel *et al.*, 2006). It is hard to determine why these studies report such divergent results. However, one possibility is that it is difficult to ensure maximum effort in a simulated combat due to the fact that the pressure to win may be much lower than during real competition. Therefore, it is possible that the athletes involved in the former study were not working at maximal intensity and thus had a reduced physiological response in comparison to the athletes in the latter study. Other studies have similarly reported BLa levels of 7.8-12 $mmol.L^{-1}$ (Cerda-Kohler *et al.*, 2015) and 7.4 ± 3.0 $mmol.L^{-1}$ (Bürger-Mendonça *et al.*, 2015) after the final round of combat simulations. One study investigated the energy demands of simulated taekwondo combat and found the predominant energy source to be the aerobic energy system (66 ± 6%) while the anaerobic alactic and anaerobic lactic system provided 30 ± 6% and 4 ± 2%, respectively (Campos *et al.*, 2012). Another study, investigating the effect of caffeine on response to simulated combat and performance found a similar energy system contribution from the aerobic system, anaerobic alactic and anaerobic lactic system of 63-70%, 24-33% and 3-10%, respectively (Lopes-Silva *et al.*, 2015). This suggests that taekwondo athletes should prepare for combat by increasing aerobic and anaerobic alactic capacity (Campos *et al.*, 2012). However, it is worth noting that in order to collect oxygen consumption data, athletes had to wear a portable gas analyser throughout the simulation. This may have added weight and impeded the athlete's movement and as a result it is difficult to assess how much this may have impacted energy contribution during the combats. Furthermore, due to the cumbersome nature of the gas-analyser, participants in the above studies could not wear the electronic PSS and were restricted in the combat in that their opponents could not attack them, thus further challenging the external validity of the studies (Hausen *et al.*, 2017).

To counteract this, Hausen et al. (2017) developed a gas-analyser protector that allowed athletes to safely participate in full contact combat with the electronic PSS. While this does not offset the obstructions of carrying the gas-analyser, it offers a more ecologically valid method of determining the energetics of combat simulations. Furthermore, Hausen et al. (2017) alluded to the fact that their study, in contrast to similar previous studies (Lopes-Silva *et al.*, 2015; Campos *et al.*, 2012), was conducted under updated WT rules (F, 2015; Word Taekwondo Federation, 2015) which included penalties for inactivity and increased points for head and spinning kicks and therefore had increased ecological validity for the current game. One contradiction to the ecological validity however, was the fact that this study was carried out on 6 x 6m rubber matting square in a laboratory. In this study the authors reported mean HR across the rounds as being 177 ± 10 $beats.min^{-1}$ or 93 ± 5% of maximum HR and that it increased across rounds. They also reported mean VO_2 as being 35.9 ± 3.9 $ml.kg^{-1}.min^{-1}$ or 73.1 ± 6% of VO_{2max} and peak BLa as 12.6 ± 2.8 $mmol.L^{-1}$ suggesting that this simulation, with increased ecological validity for the current version of taekwondo, elicited anaerobic and aerobic contribution at or above the highest values previously reported in other studies. This increase in physiological response is a strong indicator that updating and altering the rules may have a substantial impact on the physiological demand of combat.

Unfortunately, Hausen et al. (2017) did not use their data to estimate the energy system contribution. Those studies that did estimate energy system contribution reported low levels of anaerobic lactic contribution (2-9% of total energy) but also correspondingly low BLa values of 5-9 $mmol.L^{-1}$ (Lopes-Silva *et al.*, 2018; Campos *et al.*, 2012; Yang, Heine and Grau, 2018). Therefore, higher BLa levels as reported by Hausen et al (2017), as a result of increased ecological validity and under updated rule change conditions, may indicate that the anaerobic lactic system may have a greater contribution in the current version of the sport but further research is required to clarify this.

Another study which examined the hormonal response of elite adolescent male and female taekwondo athletes found significant increases in BLa from pre-combat to after the second round (Pilz-Burstein *et al.*, 2010). However, the authors did not report exact BLa values and did not measure BLa after the final round of each combat. Interestingly though, they report significant decreases in anabolic hormones such as IGF-1 (insulin-like growth factor-1), LH (luteinizing hormone) and FSH (follicular-stimulating hormone) and increases in catabolic hormones such as cortisol in both males and females. However, a significant reduction in testosterone and free androgen index was evident only in males. This suggests that taekwondo competition elicits a catabolic response in elite adolescent athletes and that the physiological response is moderated by sex whereby males appear to have a stronger response than females.

1.5.1.2. Live competition

According to Bridge et al. (2013) taekwondo exercise protocols designed to match the physical demand of competition do not match the physiological response of competition due to the reduced stress response. A recent study investigating the cognitive and behavior demands of simulation and competition reinforces this idea to include simulated combats as they found that the pressure, arousal and cognitive demands were decreased in a simulation setting compared with actual competition (Maloney *et al.*, 2018). However, whether the physiological response during simulated combats (and not just exercise protocols) mirrors those of competition has yet to be elucidated. Therefore, it is important that competitive combats are also investigated in order to more accurately assess the actual competition demands.

Only a few studies have measured the physiological responses to actual competition and due to rules and restrictions this has been limited to indirect measures such as HR, BLa and RPE (rating of perceived exertion) (Bridge, Jones and Drust, 2009; Chiodo *et al.*, 2011). Bridge et al. (2009) reported mean HR over 3 x 2 minute rounds to be 182 ± 6 beats.min^{-1}, peak BLa to be 11.9 ± 2.1 mmol.L^{-1} and peak RPE at the end of the final round to be 14 ± 2 on Borg's 6-20 scale. Chiodo et al. (2011) reported mean HR values as being 175±10 beats.min^{-1} over the three rounds and peak BLa values of 5.2±2 and 7.0±2.6 mmol.L^{-1} for females and males, respectively. Another study reported mean HR values and BLa post combat as being 183±9 beats.min^{-1} and 7.8±3.5 mmol.L^{-1}, respectively (Matsushigue, Hartmann and Franchini, 2009) however this was not carried out during a WT taekwondo competition but instead during a Songahm Taekwondo Federation (STF) competition which, after some technical displays, involves a single 2-minute combat and therefore reduces the relevance of this data for comparison to modern WT competition. A more recent study, investigating the physical and physiological demands of competition using BioHarness (a telemetric recording system) reported mean HR values to be 179-183 beats.min^{-1} and BLa post combat to be 12-14 mmol.L^{-1} (Janowski, Zielinski and Kusy, 2019). However, despite the authors reporting the validity and reliability of the BioHarness monitor in a laboratory setting, it has not been validated during full combat situations and therefore caution must be exercised when interpreting the data. Nonetheless, the above studies support the reports from the simulated combats in signifying a sport with a high reliance on both aerobic and anaerobic energy systems.

1.5.2. Physical Demands of Competition

1.5.2.1. Time Motion Analysis

Time motion analysis, which involves using video cameras to record combats and retrospectively analyzing the movement profile of the activity, has been used widely to assess the validity of a combat simulation as well as to quantify competitive taekwondo performance (Hausen *et al.*, 2017). Furthermore, the physiological response during taekwondo combat is directly dependent on the physical work done. Due to the intermittent nature of the sport, the intensity, duration and frequency of the exchanges along with the intensity and duration of the preparation time between exchanges will determine to what extent each energy system will contribute (Santos *et al.*, 2014b). Additionally, the amount of stoppage time that occurs during rounds will also influence this. Therefore, understanding the physical demands alongside the physiological response is important in order to adequately prepare athletes for competition.

The terminology used throughout the literature is not consistent when it comes to quantifying the time-motion analysis of the activity. Therefore, for the purpose of simplicity, the following terms will be used throughout this review. An exchange is considered any action within a combat where an athlete attempts to score or alternatively block or cover against an attack from an opponent. Exchange time (ET) will therefore imply the duration of these exchanges (the time an athlete begins to move their foot or hand toward an opponent until the attack ceases) and exchange number (EN) will be the number of exchanges that occur during each round or combat. Preparatory action will be the activity between exchanges where the clock continues to run (i.e. preparing or setting up for the following exchange) and thus preparatory time (PT) will be the duration of this non-fighting action. Rest time (RT) will be considered as stoppages within rounds; referees will pause the combat in order to re-set athletes if they have become stagnant in the clinch, if there has been an illegal action (gam-jeom) or if an injury occurs. ET:PT will be the ratio of exchange time to preparatory time while ET:NFT (non-fighting time) will be the ratio of the exchange time to the sum of the PT and RT.

Santos et al. (2014) investigated the relationship between ET and PT and RT during the 2007 World Championships and the 2008 Beijing Olympic Games. The authors reported ET of 1.3 ± 0.3s and 1.4 ± 0.5s, EN of 7.9 ± 3.3 per round and 7.4 ± 2.6 per round and an ET:PT of 1:6.3 and 1:5, respectively. Bridge et al. (2011) reported similar values at the 2005 World Championships (ET: 1.7±0.3; EN of 28±6). Since the plethora of rule changes occurred after both of these events, it is possible that these physical activity profiles are no longer indicative of current taekwondo combats. In fact, more recent studies which have reported the time-motion analysis for both simulated combat and competition have demonstrated increased ET of 1.6-2.1 and a reduced ET:PT of 1:1.7-1:3.4 (Hausen *et al.*, 2017; Bridge, Jones and Drust, 2011; Lopes-Silva *et al.*, 2018). Furthermore, the number of exchanges has increased considerably to 36-39 per combat. This suggests that the updates to the rule changes, many of which sought to increase the activity and excitement of competition, have impacted the physical demand in the desired manner. Interestingly, the time-motion analysis reported by Campos et al. (2012) in the simulated combats was noticeably different from that reported by Hausen et al. (2017). Campos et al. (2012) reported a much lower ET of 0.68-0.72s and a much greater EN of 51-54 compared with that of Hausen et al. (2017) (ET: 2±0.5s and EN: 36±7). It is possible that this is due to differences in the technique of analysis, however, it could also be due to the lack of ecological validity in the former study. Regardless, it is clear that a more detailed analysis of the time-motion data for competition is needed to better understand the demands of high-level competitive taekwondo performance.

The above data suggests that current taekwondo competition and combat simulation demand a high-level of both aerobic and anaerobic fitness. It appears that the attempt to increase the activity, excitement and action through alterations to the rules by WT is having the anticipated effect in that the frequency and duration of exchanges has increased and as a result the ET:PT ratio has reduced. However, with the continued modifications to the rules and lack of recent investigation into official competition there is a deficiency in the literature regarding both the physical demands of taekwondo and the subsequent physiological response and future research should aim to better understand this.

The rules of taekwondo have evolved dramatically since the Beijing Olympic Games. The current literature identifies taekwondo athletes as requiring moderate levels of strength, power, speed, agility and anaerobic and aerobic energy system development. Conversely, more recent competition data identifies a demand for high levels of aerobic and anaerobic development. Additionally, the data surrounding training load and periodisation in taekwondo athletes is scarce. As a result, it is difficult to assess the optimal physiological profile for taekwondo athletes under the current rule structure and what training methodologies are required to achieve this. Therefore, further research is needed to assess and optimise the physical preparation of taekwondo athletes to maximise physical performance during competition.

1.6. Physiological Profile Of Taekwondo Athletes

Taekwondo athletes are required to defend against and execute powerful kicks and punches for 3 x 2 minute rounds with 60 seconds recovery between (or an alternative as presented in Chapter 1.4.4.) in up to 6 combats over the course of a competition day making it a physically demanding sport (Bridge *et al.*, 2018). Therefore, taekwondo training is designed to develop the attributes necessary to enhance the relevant performance variables. From a physical conditioning perspective, the goal for taekwondo coaches and support staff is to prepare athletes to adequately manage the physical and physiological load experienced during combat. It is therefore important to assess and quantify the physical and physiological attributes of the athletes themselves to provide a reference framework for these attributes, to determine the effectiveness of training, to provide objective feedback to athletes and to better understand the impact of the sport on fundamental physiological variables (Bridge *et al.*, 2014).

1.6.1. Body Composition

Body composition is considered an important physical and performance variable in taekwondo and other combat sports where athletes are required to compete at a particular weight category in order to make the matches more equitable (Langan-Evans, Close and Morton, 2011). Furthermore, many taekwondo athletes attempt to lose large amounts of weight in order to fit in to a weight category lower than their natural weight and gain a competitive advantage (Franchini, Brito and Artioli, 2012) and thus understanding optimal body composition for taekwondo athletes is crucial. In a review by Bridge et al. (2014), the body composition of taekwondo athletes available in the literature at the time was reported. Bridge reported fat mass percentages (FM%) in the range of 7-14% for males and 12-19% for females and stated an apparent requirement for athletes to have low levels of fat mass (FM). The review reported a substantial difference in FM% between males and females in line with the normative data observed in other sports (Santos *et al.*, 2014a). It also reported a paucity of recent research examining the difference in body composition between different competitive levels of athletes that, if the literature was available, may start to illustrate the optimal body composition for taekwondo athletic performance. Furthermore, at the time of the review, there appeared to be no research examining the difference in body composition between different weight classes, which, given the fact that the ability to make a weight class would be largely influenced by the body composition of an athlete, seems incongruous.

More recent research that has emerged since the publication of the aforementioned review gives some insight into the body composition of taekwondo athletes (Table 2, p.35). The most recent of which is a study in youth (12-17 years old) taekwondo athletes that reported FM% as being 11-15% via bioelectrical impedance analysis (BIA) assessment (Norjali Wazir *et al.*, 2019). Another study conducted a follow up assessment of various performance measures including BIA assessment of body composition of female Korean collegiate athletes (~19 years) and found them to have a FM% of 21-25%, a FM of 12-15 kg, and a lean mass (LM) of 45-46 kg (Kim *et al.*, 2015). However, many of the available studies primarily investigate the effect of an intervention on performance variables and as a result report body composition as a secondary, dependent variable. For example, in a study measuring the effect of high-intensity interval training (HIIT) on various physical and performance measures of taekwondo athletes, dual x-ray absorptiometry (DXA) scan technology was used to assess the body composition of 33 male and female elite university taekwondo athletes. The study found LM to be between 53-54 kg, FM to be between 10-12 kg and FM% to be 16-18%. However, the authors did not report the differences between males and females making it hard to draw conclusions about the overall body composition of these athletes (Monks *et al.*, 2017). Similarly, two more studies assessed the body composition of taekwondo athletes using BIA but neglected to report the body composition of males and females separately: the first, a study on 14 elite collegiate athletes (10 males and 4 females) was carried out to examine the effects of de-training on blood lipid profiles and found athletes to have a mean body mass (BM) of 68-69 kg and a FM of 12-14 kg (Sung *et al.*, 2017) while the second study on 17 male and 5 female (21-22 years) elite level collegiate taekwondo athletes

examined the effect of prior inflammatory state on adaptation to training and found athletes to have a BM of 66-72 kg and FM% of 16-19% (Chen *et al.*, 2017).
However, some studies reported data for male athletes only such as one examining the effects of creatine on various measures of performance in 12 recreational male athletes (Manjarrez-Montes de Oca *et al.*, 2013). The authors reported a BM of 66-69 kg, a LM of 54-55 kg, a FM of 10-12 kg and a FM% of 16-18% when assessed by DXA scan. Another study reported a BM of between 60-64 kg, a LM of 52-54 kg and FM% of 10-12% for male Korean high school taekwondo athletes, when assessed by BIA, in a study examining the effects of a ketogenic diet (Rhyu, Cho and Roh, 2014).
Additionally, a study examining the effects of 8 weeks of pre-season training on body composition and other performance variables investigated 34 male and female university taekwondo athletes and reported the data separately for both males and females (Seo *et al.*, 2015). They found, via DXA scan, BM for males to be between 68-69 kg and females to be between 57-59 kg; FM% to be between 9-11% for males and 21-23% for females, FM to be between 6-8kg for males and 12-14 kg for females and LM to be 58kg for males and 43kg for females.
The above data highlights a wide variation in body composition between studies. This may be influenced by a variety of factors, mentioned by Bridge et al. (2014), such as training volumes, nutritional practices and the regularity with which they are required to make weight categories. However, the variety in the method used to collect body composition data must also be taken in to account. Bridge et al. (2014) states that the predominant tool used to measure body composition in the literature reported on was skinfold measurement, probably due to the ease with which data can be collected using this method. However, of the literature that has emerged since, the majority of body composition assessment involves either BIA or DXA scan measurements. This may reflect an increased access to these technologies in more recent times. Nonetheless, it is widely known that using difference methods to establish body composition introduces error when attempting to compare between different studies (De Lorenzo *et al.*, 2000). Therefore, it is important to be aware of the limitations of each method and how this may affect interpretation.

Table 2 Summary of the body composition data of taekwondo athletes in the most recent literature

Reference	Athlete Characteristics (n)	Sex	Method	BM (kg)	FM (kg)	LM (kg)	%FM
Manjarrez-Montes de oca et al., 2013	Recreational (12)	M	DXA	66-69	10-12	54-55	16-18
Rhyu et al., 2014	Korean highschool (20)	M	BIA	60-64		52-54	10-12
Seo et al., 2014	University (22M, 12F)	M&F	DXA	M: 68-69 F: 57-59	M: 6-8 F: 12-14		M: 9-11 F: 21-23
Kim 2015	Korean collegiate (12)	F	BIA		12-15	45-46	21-25
Monks et al., 2017	Elite university (33)	M&F	DXA		10-12	53-54	16-18
Sung et al., 2017	Elite collegiate (10M, 4F)	M&F	BIA	68-69	12-14		
Chen et al. 2017	Elite collegiate (17M,5F)	M&F	BIA	66-72			16-19
Norjali Wazir et al., 2019	Youth (52M, 46F)	M&F	BIA				11-15

M = male, F = female, DXA = dual energy x-ray absorptiometry, BIA = bioelectrical impedence analysis, %FM = body fat percentage

1.6.1.1 Somatotyping

Somatotyping is the process of categorising a body, based on both morphology and composition, into three components, namely adiposity, musculoskeletal robustness and linearity (Ryan-Stewart, Faulkner and Jobson, 2018). A three-numeral rating representing endomorphy, mesomorphy and ectomorphy, respectively, signifies these three characteristics. Skinfold, limb girth and bone breadth measurements (Heath and Carter, 1967) are utilised in predictive equations to give a somatotype rating for an individual. Although this method introduces new types of assessment tools, the opportunity for error is comparable to that of skinfold measurement. In contrast to skinfold measurements, somatotyping does not attempt to predict body composition but instead to quantify a person's body shape (Kandel, Baeyens and Clarys, 2014) and therefore has been shown to be useful in identifying talent performers and the ability of an individual to successfully perform physical activity (Ryan-Stewart, Faulkner and Jobson, 2018). There are few recent publications that document the somatotype of taekwondo athletes but Bridge et al. (2014) reports a tendency for senior male athletes to have predominance towards musculoskeletal robustness (mesomorphy) accompanied by a smaller tendency towards linearity (ectomorphy). This body shape was not seen in junior male athletes suggesting that maturation may have a role to play (Bridge *et al.*, 2014). Additionally, female athletes exhibited a similar body type to senior male athletes albeit less consistently. This data effectively illustrates the body types common to taekwondo athletes and perhaps necessary for success. However, similar to body composition data there is a paucity of research examining the difference between weight classes and levels of success.

1.6.2. Anaerobic Profile

1.6.2.1. Anaerobic Demands of Taekwondo Competition

Taekwondo is an intermittent, high-intensity sport characterised by short periods (~2 seconds) of high-intensity kicking or punching exchanges and longer periods of preparation and rest (Santos, Franchini and Lima-Silva, 2011). Taekwondo combats have been shown to elicit near maximal heart rate responses (175-183 beats.min^{-1}) and high blood lactate responses (5-11 mmol.L^{-1}) and ratings of perceived exertion in both competition (Bridge, Jones and Drust, 2009; Matsushigue, Hartmann and

Franchini, 2009) and simulated competition (Hausen *et al.*, 2017; Butios and Tasika, 2007). Furthermore, it has been demonstrated that one third of the energy required during taekwondo simulations comes from anaerobic energy systems (anaerobic alactic: 30 ± 6%; anaerobic lactic: 4 ± 2%) and that these energy systems are predominantly responsible for fuelling the high-intensity actions required to score points (Campos *et al.*, 2012). Therefore, it is important for taekwondo athletes to have a well-developed anaerobic energy system in order to meet the demands of competition.

1.6.2.2. Peak Power Output

Bridge et al. (2014) reported that male and female athletes in the literature at the time demonstrated relative peak power outputs (PPO) of between 8.4-14.7 $W.kg^{-1}$ and 6.6-10.2 $W.kg^{-1}$, respectively and that the upper strata of these scores compared favorably with those seen in other combat and power-based sports. The review also reported a potential division between higher and lower level competitors based on PPO scores described in a study comparing medalists and non-medalists in senior Polish taekwondo athletes (Sadowski *et al.*, 2012a) suggesting that the ability to generate high levels of power relative to body weight is an important component for success in the sport. Two studies independent of those reported by Bridge et al. (2014), one in recreational male athletes (Manjarrez-Montes de Oca *et al.*, 2013) and one in elite collegiate athletes (Monks *et al.*, 2017) demonstrate divergent PPO scores (6-8 $W.kg^{-1}$ and 10.2-10.9 $W.kg^{-1}$, respectively) which suggests further that PPO could be a distinguishing factor in the level of athlete in taekwondo (Table 3). This therefore indicates that PPO might be a useful variable in assessing the physiological profile of taekwondo athletes.

1.6.2.3. Anaerobic Capacity

Bridge et al. (2014) reported a reduced availability of literature concerning the anaerobic capacity, as measured by mean power output (MPO), of taekwondo athletes. Despite this, the review reports that the higher end of values for males and females (6.6-9.2 $W.kg^{-1}$ and 5.5-7.9 $W.kg^{-1}$, respectively) were comparative to those reported for athletes of other high-intensity, short-duration sports. This suggests that the ability to maintain or repeat intense actions across a combat could be an important factor for success in the sport. There has been only a small number of additional research articles in this area since the review by Bridge et al. (2014) was published (Table 3). However, one study reported MPO of Korean highschool taekwondo athletes as being 6-7 $W.kg^{-1}$ (Rhyu, Cho and Roh, 2014) while another study examining the effect creatine on Wingate Anaerobic Test (WAnT) performance in recreational taekwondo athletes reported mean MPO scores of 5-6 $W.kg^{-1}$ (Manjarrez-Montes de Oca *et al.*, 2013). A third study examining the effects of pre-season training on performance variables found MPO, in a group of 34 male and female university taekwondo athletes, to be 7.5 and 8.3 $W.kg^{-1}$ (before and after training, respectively) for males and 6.2 and 6.5 $W.kg^{-1}$ (before and after training, respectively) for females (Seo *et al.*, 2015). It is difficult to make a conclusion with such limited research however, it is likely that a greater anaerobic capacity would be beneficial for taekwondo athletes in order to sustain high-intensity actions throughout the duration of the combat (Monks *et al.*, 2017).

1.6.2.4. Fatigue Index

Fatigue Index (FI%) is a measure of the decline in anaerobic performance during the WAnT. It assesses the reduction of power throughout the test (specifically, it is calculated by subtracting minimum power output from PPO and multiplying by 100/1 to get a percentage index of fatigue) and therefore can indicate a participants ability to sustain power output. It has been found to be inversely proportionate to PPO but suggested not to indicate an athlete's anaerobic ability (Zupan *et al.*, 2009). However, a few of the studies mentioned above report FI% as being 52-59% in adolescent male taekwondo athletes (Rhyu, Cho and Roh, 2014), 27-33% in recreational male taekwondo athletes (Manjarrez-Montes de Oca *et al.*, 2013) and 43-44% and 46-47% in male and female collegiate athletes, respectively (Seo *et al.*, 2015). Interestingly, the latter study demonstrates a similar result for male and female athletes, despite PPO and MPO being markedly different between the sexes (in line with normative data for these measures). This similarity perhaps pays homage to the idea that FI% alone is not sufficient to suggest an athlete's anaerobic ability since increasing PPO, and thus improving anaerobic power, would likely lead to a higher FI% even if minimum power output by the end of the test is the same.

Table 3 Summary of the anaerobic qualities of taekwondo athletes in the most recent literature using Wingate Anaerobic Tests

Reference	Athlete Characteristics (n)	Sex	PPO ($W.kg^{-1}$)	MPO ($W.kg^{-1}$)	FI (%)
Manjarrez-Montes De Oca et al., 2013	Recreational athletes (10)	M	6-8	5-6	27-33
Monks et al., 2017	Elite collegiate athletes (33)	M+F	10.2-10.9		
Rhyu et al., 2014	Korean high school athletes (20)	M	8.4-9.6	6-7	52-59
Seo et al., 2015	University taekwondo athletes (34)	M+F		M: 7.5-8.3 F: 6.2-6.5	M: 43-44 F: 46-47

PPO = peak power output; MPO = mean power output; FI = fatigue index

1.6.2.5. Taekwondo Specific Anaerobic Tests

The data from the studies discussed previously were collected using the WAnT on a cycle ergometer, however, some authors argue that this lacks the mechanical specificity relevant to taekwondo. Therefore, various research groups have attempted to design taekwondo specific tests to measure the anaerobic capacity of taekwondo athletes. The first of these studies designed a Taekwondo Anaerobic Test (TAT) based on the WAnT. Athletes were instructed to kick a punching bag, using alternating legs, as many times as possible in a 30 second period and wore an accelerometer on their dominant leg to measure the number of kicking cycles (Sant'Ana *et al.*, 2014). The authors reported the number of kicking cycles, best kicking time and mean kicking time and found that all three were significantly correlated with lower limb muscular power, by way of countermovement jump height (CMJ), and that the number of kicking cycles was also correlated with post-test blood lactate scores (BLa). However, the authors failed to carry out a coinciding standardized test to validate the TAT against nor did they carry out test re-test reliability measures making it difficult to determine the validity or reliability of the TAT. Conversely, another study which investigated a very similar test named the Taekwondo Specific Anaerobic Test (TSAT) did carry out validity and reliability measures (Rocha *et al.*, 2016). Similarly to above, Rocha et al. (2016) found that the number of kicking cycles and the mean power (a similar variable to the mean kicking time in the above study) correlated strongly with CMJ height. Furthermore, they reported strong correlation and consistency between both the TSAT and the WAnT for all variables except anaerobic capacity (calculated as the sum of each 5 second peak power measurement in the TSAT). This may suggest that the TSAT is both a valid measure of taekwondo anaerobic qualities however, correlation does not equal causation and thus this must be considered when interpreting results. In addition, a more recent study has developed an intermittent version of the above tests, namely the Taekwondo Anaerobic Intermittent Kick Test (TAIKT), which aimed to mimic more closely the demands of actual competitive taekwondo combats which the authors claimed would increase the ecological validity of the test (Tayech *et al.*, 2018). Tayech et al. (2018) found strong correlations between the variables of the TAIKT and the corresponding variables in the Running-based Anaerobic Sprint Test (RAST) that they used as a validation tool. However, it is worth considering that attempts to exactly replicate the time-motion analysis of taekwondo combats during taekwondo specific anaerobic test may reduce the efficacy since it has been previously shown that despite the anaerobic nature of the high-intensity exchanges, the overall demand of the combat is largely aerobic (Campos *et al.*, 2012; Lopes-Silva *et al.*, 2018; Lopes-Silva *et al.*, 2015). Regardless, the TAIKT appeared to present a further alternative measure of anaerobic fitness for taekwondo athletes.

Taekwondo specific tests, while useful due to their mechanical specificity, cannot distinguish between the skill or experience level of athletes. Therefore, one of the key concerns with monitoring anaerobic capacity using this type of test is whether changes, and in particular improvements, in the test scores can be attributed to solely the development of the anaerobic energy systems of the individual or whether technical improvements and enhancement of skill level has been a factor. Researchers and practitioners must consider whether they are using these tests to assess solely the physiological function of the athlete or whether they are utilizing them to assess improvements in taekwondo from both a skill and fitness perspective. Importantly, Rocha et al. (2016) demonstrated that the WAnT does not underestimate anaerobic performance in taekwondo athletes as previously thought. Therefore, it appears that both general, mechanically unspecific tests and taekwondo specific tests appear a valid option for assessing the anaerobic performance of taekwondo athletes.

1.6.2.6. Muscular Power

During taekwondo combat, approximately 98% of points come from kicking techniques (Kazemi *et al.*, 2006). The strength and endurance of the lower limbs are important physical qualities in order for taekwondo athletes to execute a strong and accurate kick (Kim *et al.*, 2015). In order to score points, athletes must kick the electronic PSS with a minimum amount of weight-category determined force (Del Vecchio *et al.*, 2011). Athletes must also be able to produce forceful kicks quickly in order to avoid detection by their opponents (Santos, Valenzuela and Franchini, 2015). Therefore, taekwondo athletes must be able to produce force quickly to successfully execute kicking techniques and score points. Power is defined as the rate of force production (Power = Force X Velocity) and thus tests that measure muscular power may be important indicators of taekwondo performance.

Performance in jump tests, such as the squat jump and countermovement jump, with (SJa and CMJa) and without (SJ and CMJ) an arm swing, is often used to assess power in taekwondo athletes. SJ which does not include a downward movement prior to jumping can be used to assess an athlete's ability to create pretension by co-activation of the muscles of the lower limbs (Van Hooren and Zolotarjova, 2017). CMJ, in which the jump is initiated by a downward movement, takes advantage of the stretch-shortening cycle and tends to produce a greater score than the SJ (Van Hooren and Zolotarjova, 2017). Therefore, CMJ is often used as a measure of the ability of the athlete to utilise the stretch-shortening cycle.

Bridge et al. (2014) reported SJ scores for national and international taekwondo athletes of 35-45 cm for males and 23-29 cm for females whereas CMJ scores ranged from 39-43 cm for males and 26-32 cm for females. This data was lower than that reported for other combat sport athletes and other power-based sports indicating that lower limb power may be less important in taekwondo compared to these other sports. This is in stark contrast to previous findings that suggest that many of the kicking techniques require high speed and power in order to be successful (Santos, Valenzuela and Franchini, 2015; Pieter, 1995). However, this may be as a result of the paucity of research in this area. More recent research exhibits similar ranges of CMJ scores for males (37-43 cm) and females (28-30 cm) (Santos, Valenzuela and Franchini, 2015; Chiodo *et al.*, 2011) but the data is still relatively sparse. There are more studies that report CMJ and SJ scores for both males and females together, but since it is well understood that males generally outperform females in CMJ and SJ tests (Bridge *et al.*, 2014), it becomes difficult to discern any meaning regarding the distinct power profiles of male and female taekwondo athletes from this data. In order to examine the importance of muscular power for taekwondo, it would be pertinent to investigate these variables between taekwondo athletes of different competitive levels or those that are more successful and their less successful counterparts. However, this research is limited at present. Bridge et al. (2014) made reference to a study which showed a small difference in CMJ performance between female medalists and non-medalists (Marković, Misigoj-Duraković and Trninić, 2005) and one which showed a difference in SJ performance between male recreational and elite taekwondo athletes (Toskovic, Blessing and Williford, 2004). The latter study, however, did not report the same difference between female recreational and elite athletes, which may suggest that female taekwondo athletes rely less on this attribute than their male counterparts. In contrast to this, another study reported no difference in SJ or CMJ performance between male and female taekwondo athletes who were either selected or not-selected for the Italian national team (Casolino *et al.*, 2012). Furthermore, there is no research that compares lower limb muscular power of athletes of different weight classes. At present, this research is relatively confounding and further population of the literature is necessary.

1.6.2.7. Maximal Dynamic Strength

It has been suggested that the ability to produce powerful kicks may be an important component of elite taekwondo combat. Since force production is an underpinning component of power production, it follows that taekwondo athletes must possess a sufficient level of strength in order to execute powerful kicks. Muscular strength has been defined as the ability to exert force on an external object or resistance and, along with underpinning power production, has been widely demonstrated to be an important factor in enhancing both general and sport-specific skill performances and in mitigating injury risk (Suchomel, Nimphius and Stone, 2016). Strength may then be an important characteristic for taekwondo athletes. Despite this, the research investigating the strength characteristics of high-level taekwondo athletes is limited. Several studies have investigated the isokinetic strength qualities of taekwondo athletes (Seo *et al.*, 2015; Martínez Hernández *et al.*, 2014; Kim *et al.*, 2015; Fong *et al.*, 2013). However, this technique is usually utilised for rehabilitation and is thought to be inapplicable to the muscle contractions that occur during sporting events (Bridge *et al.*, 2014). Therefore, this research will not be considered in this review.

Markovic et al. (2005) reported one repetition maximum (1RM) back squat and bench press scores for elite female taekwondo athletes which have been since shown to be "average" and "elite", respectively, in comparison with the general female population of a similar age (Bridge *et al.*, 2014). This study also shows that the relative 1RM scores were significantly greater in the medalists than the non-medalists suggesting that strength is an important component of a successful athlete. Furthermore, Bridge et al. (2014) reported in his review that Toskovic et al. (2004) demonstrated significant differences in strength between male and female recreational taekwondo athletes. Another study examining four taekwondo athletes (2 male and 2 female) during the preparation for the Olympic games carried out 3RM strength testing and found mean scores to be 88 ± 3 kg for squat, 56 ± 12 kg for bench press and 61 ± 10 kg for bench pull. However, the authors did not report the scores separately for males and females thus making it difficult to deduce meaning from these results since it is well established that males have a tendency to be stronger than females (Hoffman, 2006). To the best of this author's knowledge, the only other studies that have reported the dynamic strength of taekwondo athletes examined the effect of different post-activation potentiation methods on taekwondo kicking and power performance and reported the participants (groups of 11 and 9 elite male taekwondo athletes, respectively) to have mean ½ back squat 1RM of 136.4 ± 30.7 kg and 132.8 ± 32.5 kg, respectively (Santos *et al.*, 2016; Santos, Valenzuela and Franchini, 2015). Evidently, the data indicating the maximal dynamic strength of taekwondo athletes is scarce. This may represent a reluctance of athletes and practitioners to incorporate strength training and/or testing in to taekwondo athletes' training programmes. Regardless, more research is needed to understand the role and importance of strength in taekwondo.

1.6.2.8. Speed and Agility

Speed can be defined as the shortest time it takes for one object to move along a fixed distance while agility can be defined as a rapid whole body movement with change in direction or velocity in response to a stimulus (Sheppard and Young, 2006). In taekwondo, athletes must move their leg from the ground quickly to kick an opponent in order to avoid detection. They must also be able to react quickly to defend against an attack from an opponent by covering the PSS with their upper limbs or moving quickly out of the way. Therefore, it may be beneficial for taekwondo athletes to possess a high level of both speed and agility capabilities. Speed is often measured using conventional field-based measurements such as the time taken to complete 20 metre (m) and 30 m sprints. The limited data available indicates 20 m sprint time of 3.1-3.5 seconds (s) (Chaabene *et al.*, 2018; Cetin *et al.*, 2009) and 30 m sprint time of 4.6-4.8 s (Sadowski *et al.*, 2012a) for male taekwondo athletes and 20 m sprint time of 3.6-3.8 s for females (Marković, Misigoj-Duraković and Trninić, 2005). Both Sadowski et al. (2012a) and Markovic et al. (2005) reported significantly faster scores for medalists than non-medalists suggesting that speed could be a contributing factor to success in taekwondo combat. Traditionally, agility is examined using field-based measures such as the T-test or a 50 m shuttle run. T-test scores for groups of male and female athletes have been reported as 9.9-11.4 s (Monks *et al.*, 2017; Chaabene *et al.*, 2018). Additionally, 50 m shuttle run (10 x 5m) scores have been reported for males and females as being between 16-17 s and 18-19.5 s, respectively (Seo *et al.*, 2015; Kim *et al.*, 2015). The above tests, while standardized and recognized in the literature, lack mechanical specificity in relation to taekwondo. Recently, Chaabene et al. (2018) designed a taekwondo-specific agility test in order to increase the ecological specificity to this kind of testing. They found this test to have a high level of association with the T-test and, furthermore, that it was able to distinguish between top elite and elite athletes suggesting that this may be a useful tool for investigating agility in taekwondo athletes in the future.

1.6.3. Aerobic Profile

The high-intensity actions of taekwondo combat are largely fuelled by anaerobic energy systems. However, it has been shown that the net effect of this in combination with the low-intensity activity between these actions means that the aerobic energy system is the predominant source of energy during simulated taekwondo combat (Campos *et al.*, 2012). This is likely a consequence of the aerobic energy systems involvement both in facilitating replenishment of muscle phosphocreatine stores and the shuttle of lactate, both of which are a result of the aforementioned high-intensity exchanges during taekwondo combats, and in fuelling the low-intensity activity between exchanges (Matsushigue, Hartmann and Franchini, 2009). Additionally, since taekwondo competitions occur over the course of a day and athletes can have up to 5 fights (Sant'Ana *et al.*, 2017) interspersed by varying amounts of time (Bridge *et al.*, 2018), the aerobic energy system becomes a key player in the ability to enhance recovery between combats (Bridge, Jones and Drust, 2009; Chiodo *et al.*, 2011). Therefore, a well-developed aerobic energy system, usually represented by the maximal oxygen uptake an athlete can obtain (VO_{2max}) during exercise (Araujo *et al.*, 2017b) would be important to allow taekwondo athletes to repeatedly perform optimally in competition.

Bridge et al. (2014) reported a wide range of VO_{2max} scores for both males (44-63 $ml.kg^{-1}.min^{-1}$) and females (40-51 $ml.kg^{-1}.min^{-1}$) with males having a markedly greater range of scores. The review suggested that the large variety of VO_{2max} scores could be as a result of differences in the phase, volume or structure of training but that it could also have been influenced by the method of testing. VO_{2max} can be both directly measured and indirectly estimated through a variety of modes such as treadmill running, shuttle running, cycling and sport-specific movements. Additionally, previous research has shown that there is limited agreement between different methods and modes of measurement (Keren, Magazanik and Epstein, 1980). Although cycling and running based VO_{2max} tests are widely used throughout the literature due to their validity, accuracy and reliability, they lack the mechanical specificity for taekwondo which may reduce their ability to detect a true VO_{2max} for taekwondo athletes (Sant'Ana *et al.*, 2017). In fact, a study comparing taekwondo specific tests with a treadmill continuous test reported higher cardiovascular responses with mechanically specific exercise tests (Hausen *et al.*, 2018). As a result, a number of studies are emerging in which prototypes for taekwondo specific tests are being compared with more traditional measures of VO_{2max}. One such study, which compared the VO_2 kinetics in an incremental taekwondo kicking test with those during a treadmill incremental test found there to be no significant difference in VO_{2max} between the two tests (Araujo *et al.*, 2017a). However, a key issue arises around the repeatability and reliability of this test given the subjective assessment of the effort level or power behind the kicks which may influence the intensity at which an athletes works during the test. Additionally, the need to use a portable gas analyser to assess VO_2 during the study reduces the feasibility of this test. A separate study, which compared a different prototype of taekwondo specific test with a multi stage fitness test (MSFT), resolved the above issues by measuring the force of kicks during the test and by creating an equation to predict VO_{2max} without the need for a gas analyser (Rocha *et al.*, 2016). Another study which used the same prototype as Rocha et al. (2016) but which did not include measuring the force of the kicks also found there to be no significant difference (albeit very close to significance with a p-value = 0.054) in the VO_{2max} between the taekwondo test and an incremental treadmill test (Sant'Ana *et al.*, 2017). Finally, the most recent study comparing VO_{2max} in a cardiopulmonary exercise test with both an interval- and continuous-based taekwondo test found, contrary to the studies above, a greater VO_{2max} score for the taekwondo specific tests than for the treadmill test (Hausen *et al.*, 2018). This difference may have occurred due to an increased focus on ecological validity by the authors in that they controlled power of the kicks by having athlete’s kick and score on an electronic

PSS, as they would in competition in order to ensure a minimum power throughout the tests. Nevertheless, despite this test potentially enhancing the accuracy of the measurement of VO_{2max} in taekwondo athletes, it still relies on a portable gas analyser, making it difficult to reproduce for large groups of athletes and without access to a laboratory. Additionally, similar to the issue with the anaerobic tests discussed previously, use of taekwondo specific tests may blur the ability to assess changes in VO_{2max} that are distinct from changes in taekwondo technical skills. Regardless, more research is warranted in the taekwondo community to come up with a standardised, reliable and validated method.

Bridge et al. (2014) also reported that VO_{2max} did not appear to distinguish between different levels of taekwondo athlete or between weight categories (contrary to other combat sports) and that this may be because while aerobic fitness is important to optimise the efficiency of fuelling and recovering from taekwondo bouts, by itself it does not determine success of athletes. Several more recent studies have reported VO_{2max} scores for male and female athletes together (42-60 $ml.kg^{-1}.min^{-1}$) making it difficult to establish much meaning from the results (Monks *et al.*, 2017; Liao *et al.*, 2016; Chen *et al.*, 2017). Additionally, Seo et al. (2015) reported shuttle run test scores of between 107-117 shuttles for males and 77-87 shuttles for females but neglected to report VO_{2max} scores making it difficult to compare with other studies. However, three separate studies have demonstrated elite level, male Brazilian taekwondo athletes to have VO_{2max} scores, by way of treadmill incremental test, of 49.6 ± 5, 49.6 ± 2.8 and 50.5 ± 4 $ml.kg^{-1}.min^{-1}$, respectively (Hausen *et al.*, 2017; Araujo *et al.*, 2017b; Sant'Ana *et al.*, 2017) suggesting a moderate to high level of aerobic fitness in these groups of athletes. Clearly, aerobic capacity is an important trait to manage the demands of high-level taekwondo combat, however, due to the variety in testing methods used and the lack of mechanical specificity for taekwondo, it is difficult to determine ideal levels for elite athletes and to compare across the literature.

1.6.4. Flexibility Profile

Flexibility can be defined, in sport and exercise, as the range of motion (ROM) available in a joint or group of joints (Alter, 2004). In order to score in taekwondo combat, athletes must raise their leg at least high enough to kick an opponent's trunk protector. Furthermore, it is also largely beneficial for an athlete to be able to lift their leg high enough to kick an opponents head in order to gain a greater number of points (WTF, 2018b). Therefore, having a greater ROM, particularly of the joints of the lower limbs, may be highly beneficial for taekwondo athletes. Most of the available literature has used a sit and reach (SAR) test in order to examine flexibility. The SAR test has been demonstrated to be an appropriate measure of spinal flexibility and pelvic tilt ROM (Muyor *et al.*, 2014). Bridge et al (2014) showed experienced male taekwondo athletes to have SAR scores of 36-39 cm while experienced female athletes had SAR scores ranging from 35-56 cm ranking both males and females in the top percentiles of corresponding 20-29 year olds. The latest data detailing the flexibility of taekwondo athletes suggests male athletes SAR scores to range from 20-32 cm (Seo *et al.*, 2015; Nikolaidis *et al.*, 2016) and females' to range from 18-30 cm (Nikolaidis *et al.*, 2016; Seo *et al.*, 2015; Kim *et al.*, 2015). Although the research is relatively sparse, flexibility seems to be greater in senior athletes compared to junior athletes but does not appear to discriminate between levels of success (Bridge *et al.*, 2014). In order to enhance the specificity to the mechanics of taekwondo, Sadowski et al. (2012) attempted to measure flexibility by measuring the length of front and side splits (extending the legs as far as possible in front and behind or to the left and the right, respectively, of the torso). The authors reported a mean front split distance of 90.4 ± 8.8 cm and side split distance of 77.3 ± 7.6 cm. However, there does not appear to be any other studies using this measure in the literature. Therefore, although it is probable that taekwondo athletes require adequate ROM of the lower limbs in order to execute many of the kicking techniques, a more standardized measure is necessary in order to create reference values for taekwondo athletes as well as to investigate potential differences between sexes, weight categories and athlete level of experience.

1.6.5. Summary

Taekwondo is a physically and physiologically demanding sport that appears to require athletes to have a low level of body fat while also possessing moderate to high levels of anaerobic and aerobic fitness. The literature shows that athletes also have moderate levels of strength, power, speed and agility and may also benefit from high levels of flexibility. However, it seems evident that there is a lack of conclusive agreement over the best tools and tests used to measure the relevant physiological characteristics and as a result there is ambiguity around the data in the literature at present. Furthermore, despite being a weight making sport the investigation into the differences in physiological characteristics between athletes of different weight categories is limited. There is equally limited research around the differences between athletes of varying competitive or success levels making it difficult to understand whether certain physical characteristics are more influential for success than others. In the last few years there has been a surge of interest in designing taekwondo specific tests for a variety of physiological qualities. However, while these tests certainly enhance the mechanical specificity and ecological validity, they are still some way off with respect to validity, reliability and accuracy. Therefore, at present, there is a necessity for an up-to-date, valid physiological profile of male and female taekwondo athletes across weight classes and success levels in order to better understand the physiological characteristics of taekwondo athletes today and in the future.

1.7. The Demands of Taekwondo Training

Taekwondo is a high-intensity intermittent sport that, as discussed in the previous section, requires athletes to develop aerobic and anaerobic energy systems along with strength, power, speed, agility and flexibility. It is also a highly technical and tactical sport that necessitates the proficient execution of complex skills such as kicking, punching, blocking and footwork techniques. In order for taekwondo athletes to gain the technical and physical expertise required for success, they must partake in an adequate skill-based and physical preparation training program (Chen *et al.*, 2017).

Investigations examining the routine training schedules of taekwondo athletes in the literature are relatively scarce. However, only one study reported the average session duration and frequency of specific taekwondo training of collegiate taekwondo athletes in the USA as being 2 ± 0.8 hours and 4 ± 1.2 days per week, respectively (Covarrubias *et al.*, 2015). Another study that tracked four athletes for 9 weeks in the lead up to the 2008 Beijing Olympic Games reported their training programme over this period as consisting of 3 strength sessions, 1 repeated-sprint conditioning session, 5 taekwondo skill based sessions and 3 passive recovery sessions (hydrotherapy and massage) per week (Ball, Nolan and Wheeler, 2011). They also reported that athletes participated in a periodised strength training programme in which intensity undulated between medium and high and was focused on strength and power.

Some studies have reported the training programmes of taekwondo athletes as part of investigations into training and/or nutritional interventions. Monks et al. (2017) reported a training frequency of 11 sessions per week: 5 taekwondo sessions, 3 sessions of a sit-ups programme and 3 high-intensity interval training or high-intensity continuous running sessions. Two other studies, which aimed to assess the effect of 8-weeks training cessation on a variety of factors, reported training volume as 14-15 hours per week and training frequency as 5 days and 10 sessions per week (Sung *et al.*, 2017; Liao *et al.*, 2016). Furthermore, Sung et al. (2017) described the organistion of training as involving three high-intensity days (Monday, Wednesday and Friday) that consisted of strength and conditioning training and taekwondo technical and tactical sessions and two low-intensity days (Tuesday and Thursday) that consisted of taekwondo training and video analysis of opponents. Strength and conditioning training, which totaled 6.5-7 hours per week, involved a combination of running based aerobic and anaerobic conditioning, resistance strength training, agility training and flexibility work. Taekwondo training, which totaled 7-8.5 hours per week, consisted mostly of attacking skills training (punching, kicking and set ups) combined with some match simulation and opponent video evaluation. It seems evident that taekwondo athletes engage in a relatively high volume of training that consists of taekwondo skills and tactical practice, strength training, agility training and fitness conditioning sessions. However, the extent to which this information is reported or examined in the literature is low and thus it is difficult to make assumptions as to which part or how much of the taekwondo population this information is representative of.

1.7.1. Training Load

1.7.1.1. Training Stress and Adaptation

Training, in the context of exercise and sports performance, is undertaken in order to physically and physiologically prepare athletes for the demands of the sport. In order to increase physical capacity, a stress must first be applied to the body. Seminal work in the 50's was the first to describe the stress-recovery-adaptation curve. The detailed physiology of this is beyond the scope of this thesis but can be summarised as follows: the perturbation of homeostasis brought about by the stress of exercise precedes a reduction of fitness capacity, before a period of recovery ultimately resulting in an adaptation (Selye, 1950). This adaptation, also referred to as super-compensation, represents the point at which the body, and all the relevant physiological systems, is more resistant to the initial stress imposed upon it (Le Meur et al., 2013). Therefore, successful training must involve amassed stress in the form of progressive overload for periods of time that result in fatigue and performance decrement in order to continue to promote super-compensation and adaptation and ultimately improve performance (Meeusen *et al.*, 2013). However, in order to quantify and manage training to optimise adaptations, training stress (also referred to as training load (TL)) must be measured. The following sections discuss key tools for assessing TL in taekwondo.

1.7.1.2. Markers of Internal Training Load

It is important to understand and quantify the TL athletes experience in order to assess and maximise preparation for competition. Internal TL can be described as the psychophysiological response to any exercise or training (Impellizzeri, Marcora and Coutts, 2019; Bourdon *et al.*, 2017). In combat sports, few valid and reliable methods exist to quantify TL but, according to Slimani et al. (2017), heart rate (HR) has traditionally been the most frequently used marker of internal training load. HR is a non-invasive tool that has been used as measure of the intensity of taekwondo training and combat (Haddad *et al.*, 2012; Pieter, Taaffe and Heijmans, 1990; Bridge *et al.*, 2013; Bridge, Jones and Drust, 2009; Bridge *et al.*, 2007). The use of HR to measure exercise intensity is based on the well-known linear relationship between HR and oxygen consumption during submaximal steady state exercise (Haddad *et al.*, 2011). Bridge et al. (2007) recorded HR in elite taekwondo practitioners during a 5-day training camp in order to assess the relative physiological TL and intensity of various different taekwondo training modalities. However, this study did not attempt to understand the overall TL experienced by the athletes in question and was conducted only over a short period of time. Haddad et al. (2012) used HR data to examine the TL experienced by young taekwondo athletes during a 10-week pre-competitive period. They found that two commonly used methods for determining TL by weighting time spent in different HR zones, namely Edward's TL and Bannister's training impulse (TRIMP), have good reliability and allow TL to be reduced and quantified to a single figure making it an appealing method in a practical setting.

Despite this, the usefulness of HR to monitor TL in taekwondo is limited due to the impact of the combative nature of taekwondo combat on the chest strap and HR monitor and the subsequent occurrence of technical failures (Slimani *et al.*, 2017). Additionally, HR is not a good indicator of intensity in training modes such as resistance training and plyometrics of which taekwondo coaches and athletes commonly make use (Haddad *et al.*, 2011; Foster *et al.*, 2001).

The session rating of perceived exertion (sRPE) is a method that is increasingly gaining popularity in the combat sport world for quantifying TL. It represents the feeling of global exertion during an entire training session and was developed to facilitate the measurement of TL (Foster *et al.*, 2001). The rating of perceived exertion (RPE) can be used to indirectly measure the level of effort and/or stress during combat sports training (Slimani *et al.*, 2017) and when combined with the duration of the session gives a measure of the physiological load experienced by the athlete (Haddad *et al.*, 2011). The sRPE method has been shown to be a valid measure of TL for both steady state and intermittent exercise (Foster *et al.*, 2001; Bourdon *et al.*, 2017) and correlates well with many measures of physiological intensity such as oxygen consumption, respiratory rate, blood lactate (BLa), HR, ventilation and electromyography (Lagally *et al.*, 2002). Haddad et al. (2011) investigated the validity of sRPE to measure taekwondo training and found a large correlation between sRPE and two HR-based methods of assessing TL (Bannisters TRIMP and Edwards TL) during a two-week intensive training camp in young taekwondo athletes. In a further study, Haddad et al. (2014) found that sRPE specifically correlated strongly with time spent in maximum HR zones and that the duration of the training session did not influence the RPE score thus making sRPE an appealing and acceptable measure of TL in taekwondo. Other studies have also evaluated sRPE in pre-pubescent taekwondo athletes (Lupo *et al.*, 2017) and to monitor training load during a selection camp to examine the difference in response to TL between those athletes selected for the Italian national team and those that were not (Casolino *et al.*, 2012). The latter study showed that non-selected athletes perceived training to be more difficult than their selected counterparts. Furthermore, sRPE is routinely being used to assess the effectiveness of taekwondo specific fitness tests (Hausen *et al.*, 2018; Tayech *et al.*, 2018) and nutritional interventions (Lopes-Silva *et al.*, 2015). sRPE appears to be an effective and simple way to measure TL in taekwondo; aside from the fact that it requires no technology and thus cannot be subject to technical failures and that it can be measured with accuracy up to 30 minutes after completion of a training session (Uchida *et al.*, 2014) it also seems to be a valid and appropriate measure of internal TL and enables coaches and athletes to understand the stimulus for physiological adaptations. However, it is worth mentioning that sRPE has a number of limitations. Due to the psychological nature of the rating, there is a level of complexity that occurs when attempts are made to interpret the data. Furthermore, care must be taken when collecting data as athletes subjective scores may be impacted if they have concerns over how the data will be used or whether it may influence their selection for competition or ability to partake in training (Bourdon *et al.*, 2017). As a result, despite the ease of use of collection, sRPE data must be collected, interpreted and used with acknowledgement and awareness of these limitations.

Adaptation to TL, or lack of, can be measured through the use of subjective wellbeing questionnaires. It is important to get a measure of how athletes are responding to training in ensure training elicits the desired effects on athletes in terms of wellbeing and performance. Saw et al. (2016) investigated the effectiveness of a variety of methods of investigating athlete response to training and found subjective wellbeing questionnaires to be effective at reflecting increases in acute and chronic training loads. Subjective wellbeing monitoring can therefore be a useful measure of fatigue and training status in athletes.

1.7.1.3. Markers of External TL

External TL can be simply defined as the actual physical work carried out during exercise and will be influenced by the organisation, quality and quantity of the exercise session (Impellizzeri, Marcora and Coutts, 2019). Recently, there is an increasing reliance and utilisation of external and objective markers of training load. In linear sports such a cycling and running, power, speed and distance can be easily measured to assess the external work done by the athlete. At present, however, there does not appear to be any valid and reliable measures of external, objective workload in taekwondo. Although these absolute measures are commonly used in other, non-combat sports and are useful for assessing work load, Haddad et al. (2012) suggested that measuring the internal load such as the acute response to training may be more useful because it takes into account the inter- and intra-individual differences that may occur in the way that individuals respond to exercise. However, it is likely that optimal understanding of TL in taekwondo will come from assessing it through a combination of both internal and external methods and therefore, efforts should be made to establish a method for quantifying the external TL of taekwondo sessions.

1.7.2. Training Periodisation

To the best of the author's knowledge, there is no literature that looks at the long term planning, organisation and periodisation of taekwondo training. Current or typical strategies have not been documented nor has there been any attempts to examine the effects of employing certain periodisation protocols or systems to taekwondo training and athletes. Therefore, this section will focus on methods of periodisation generally discussed in the literature and their applications in other combat sports.

Periodisation, as a concept in terms of the athletic preparation of high-level athletes, first came to light over 100 years ago in a book called *Olympic Sport: Guidelines for Track and Field* (Kotov, 1916). Since then, the physiological organisation of the variables needed for athletic success, in other words training periodisation, has become the prominent planning strategy for the physical preparation of athletes (Issurin, 2016). The fundamental rationale for training periodisation is the division of the entire seasonal training plan into smaller periods or training units (Cunanan *et al.*, 2018). It was characterised by a sequential transition from high to low volume, low to high-intensity and a reduction in the variety of training as competition approached (Kiely, 2012). This approach to training periodisation was designed around athletes who needed to develop singular or very closely related physical or physiological characteristics, such as track and field athletes. However, over time, it became evident that, for athletes and sports that required athletes to develop a vast array of often opposing physiological qualities, an alternative approach was needed. This was even more pressing when these athletes were required to compete multiple times over a season (Issurin, 2010). Therefore, different periodisation methods have been developed to suit the demands of a larger variety of sports and athletes. In more recent times, the idea of multi-targeted block periodisation, which involves training cycles of highly concentrated workloads aimed at developing a minimum number of targeted abilities, has been utilised to account for the demands of modern and multi-component sports (Issurin, 2010). These blocks are generally short (2-4 weeks in length) and focused around developing general fitness attributes followed by abilities more specific to the demands of the sport and ending with a short recovery or tapering block. This method, contrary to a more traditional model and due to the shorter length of blocks and thus more regular occurrence of training modalities, allows athletes to maintain both general and sport-specific qualities for the duration of the season and thus throughout all competitive events (Issurin, 2010). This concept has been further developed over time to ensure the consecutive development of physical and physiological qualities in the appropriate sequence in order to enhance the development of compatible training modalities, separate conflicting modalities and maximise the interaction and superposition between the developed physiological qualities (Issurin, 2016).

Periodisation, and in particular block periodisation, has become popular in combat sports in recent times. In the literature, this is represented by a plethora of studies that have been published in the last three years, particularly with respect to judo. The first study to emerge looked solely at the effect of linear or daily undulating strength training periodisation of elite judokas and the impact on a number of performance variables (Franchini *et al.*, 2015). The authors found that both methods of periodisation improved all measures of performance but had no impact on the response to simulated competition. This effect was also seen in a similar study in adolescent judokas (Ullrich *et al.*, 2016). However, neither of these studies made an effort to periodise the judo training alongside the strength training. On the contrary, another study examined the training load and immune response of elite judo athletes following a traditional periodisation plan (including the judo specific training) over the course of an entire season (Agostinho *et al.*, 2017). The authors found that training load and training strain varied between different mesocycles but that this had no effect on the immune responses. Despite this, they did not investigate the effect of this periodisation and the subsequent mesocycles on any performance variables making it difficult to decipher the efficacy of this training organisation on performance. Most recently, however, a study has emerged investigating the efficacy of a block periodisation model on performance of elite judokas and found that this model increased judo specific performance (by way of the *special judo fitness test*) in both international and national level athletes (Marques *et al.*, 2017). This suggests that this organisation of training could be an effective way to manage training load and elicit performance in judo athletes of different levels. Moreover, the authors suggested that this method of periodisation would benefit judo athletes with a heavy competition schedule. Taekwondo athletes, who also compete in a large number of competitions per year, then may also benefit from this periodisation model.

It is worth noting that some opposition has been presented with respect to some of the presumptions of periodisation models; namely the idea that biological adaptation to a given training stimulus is predictable and the same for everyone and thus, as a result, training can be planned and forecast to accommodate these adaptations (Kiely, 2012). It is well known that there are distinct inter-individual biological differences that result in a considerable variety in the response to the same exercise protocol. In fact, it has been shown that even in elite athletes, the same training programme can have a substantial positive effect on one group of athletes but a non-existent or even negative effect on another group (Beaven, Cook and Gill, 2008). However, what is clear is that organised variety in training plans almost exclusively has a more positive outcome than a lack of variety (in terms of efficacy and resistance to illness and injury). Whether this is due to different periodisation schemes or not is yet to be determined. Nonetheless, employing a method of variety or periodisation which complements the training of the sport and athletes in mind is, at present, still the most appropriate option for physical preparation. Additionally, an increased focus on the individual may help to alleviate and even capitalise on the individual responses to training and stimuli (Cunanan *et al.*, 2018). Despite this, as mentioned previously, the literature is largely deficient of any information into the load and/or organistion of taekwondo training at present. Therefore, the taekwondo community could benefit greatly from investigations of this nature in order to better understand training demands and whether they could benefit from the periodisation models discussed above.

Chapter 2

Sample Population and Method Justification

2.0. Sample Population and Method Justification

2.1. Overview of Sample Population

Throughout this PhD research 35 athletes (19 males and 16 females) who were members of the Great Britain Taekwondo team participated in the studies. Liverpool John Moores ethical committee and the Research Ethics Committee (REC) granted full ethical approval for all three studies. Data was collected across all Olympic weight categories and across two levels of athlete: TOP and TARG. TOP athletes were more experienced and had medaled at a major competition, TARG athletes were those that were less experienced and relatively new to the programme and who had not yet medaled at a major competition. The distribution of athletes between weight categories and experience levels can be seen in Table 4. TOP athletes were significantly older than TARG athletes ($p = 0.001$, $ES = 1.61$) but there was no difference in age between weight categories or sex (Table 5).

The data for the first study was collected at the *European Club Championships* in Istanbul, Turkey during official competition. The second study was carried out between two locations: the *National Training Centre* (NTC) where athletes completed their daily training and a physiology lab at the *Manchester Institute for Health and Performance* (MIHP). All of the data for the final study was collected at the *National Training Centre* (NTC) during athletes' scheduled training sessions (Table 6).

Table 4 Number of participants per weight class, sex and athlete level

	Total		Fly	Feather	Welter	Heavy		TOP	TARG
M	19		6	6	2	5		8	12
F	16		6	5	2	3		6	9
Total	35		12	11	4	8		14	21

Fly = -58kg male, -49kg female; Feather = -68kg male. -57kg female; Welter = -80kg male, -67kg female; Heavy = +80kg male; +67kg female;

Table 5 Age (years) of participants by sex, weight category and athlete level

	Total		Fly	Feather	Welter	Heavy		TOP	TARG
M	19.9 ± 3.4		18 ± 0.6	19.2 ± 1.2	27.0 ± 2.8	20.4 ± 4.0		22.4 ± 4.1	18.1 ± 1.0
F	19.4 ± 3.0		19.2 ± 2.2	19.4 ± 2.5	16.5 ± 0.7	21.7 ± 4.9		21.8 ± 2.9	17.7 ± 1.5
Total	19.7 ± 3.2		18.6 ± 1.7	19.3 ± 1.8	21.8 ± 6.3	20.9 ± 4.1		22.1 ± 3.5	17.9 ± 1.2

Fly = -58kg male, -49kg female; Feather = -68kg male. -57kg female; Welter = -80kg male, -67kg female; Heavy = +80kg male; +67kg female;

Table 6 Summary of methodology for three studies

Study	Location of data collection	n (M/F)	Variables Measured	Methodologies used	Duration of study
1	Live Competition	n=10 (8/2)	Internal response External demands	HR BLa RPE Hydration BM Time motion analysis	2 days
2	NTC MIHP physiology lab	n=29 (15/14)	Body composition Anaerobic profile Aerobic profile	DXA scan Wingate CMJ SJ MSFT	3 months
3a	NTC	n=25 (14/11)	Internal TL External TL Subjective response to training	sRPE HR Session frequency Session volume Activity profile Subjective wellbeing	13 weeks
3b	NTC	n=25 (14/11)	Training attendance Variables influencing attendance	SCR Injury incidence Cumulative sRPE TL Competition attendance	13 weeks

NTC = National Taekwondo Centre; MIHP = Manchester Institute of Health and Performance; n = no. of participants; TL = training load; DXA = dual x-ray absorptiometry; CMJ = countermovement jump; SJ = squat jump; MSFT = multistage fitness test; sRPE = session rating of perceived exertion; HR = heart rate; SCR = session completion rate; BLa = blood lactate; RPE = rating of perceived exertion; BM = body mass

2.2. Method Justification

This section of the general methods examines the reasoning and justification for using certain methodology. In certain instances, there were no different methodology or techniques applicable and therefore these methods will not be considered in this section but will be discussed in the methods section of the relevant study.

2.2.1. Competition

2.2.1.1. Internal Response

Heart Rate

HR has been used to determine the physiological response of taekwondo athletes to competition previously and is both non-invasive and valid for determining the intensity of competition (Bridge, 2012; Bridge, Jones and Drust, 2009; Bridge *et al.*, 2013).

Blood Lactate

Bridge et al. (2009; 2012) also used whole blood lactate concentrations (BLa) to determine the response and intensity of taekwondo athletes to competition.

Rate of Perceived Exertion

RPE has been shown to be an effective subjective measure of intensity during combat (Slimani *et al.*, 2017). RPE was taken using the Borg category ratio (CR 10) RPE scale (Borg, 1982).

Body Mass and Hydration

Measuring body mass (BM) and hydration of athletes around competition can give a good idea of the impact of making weight and how well they recover prior to the start of the competition. Taekwondo athletes often use dehydration techniques to reduce their body mass prior to competition in order to weigh in below the specified weight category (Kazemi, Rahman and De Ciantis, 2011; Aloui, Chtourou and Souissi, 2014). Extreme dehydration can have negative effects on health and on performance if not recovered before competition (Janiszewska *et al.*, 2015; Yang *et al.*, 2015). Therefore, BM and hydration status was assessed at weigh in and before and after competing to determine the extent to which they had recovered following weigh in.

2.2.1.2. External Demands

Time Motion Analysis

Time motion analysis has been used previously to determine the activity profile of competitive taekwondo bouts and thus define the physical demands of competition (Santos, Franchini and Lima-Silva, 2011; Bridge, Jones and Drust, 2011). Therefore, the activity profile of each fight was recorded in order to get a mean ratio of exchange time (determined by the initiation of either opponent of an attempted kick or punch or the subsequent defence of the former), preparatory time (determined by any part of the combat in which the clock was running but no exchange was taking place and including actions such as shifting, feinting and movement) and rest time (determined by any clock stoppage for instances such as injuries, referee stoppage, video replay or the recovery between rounds).

2.2.2. The Athlete

2.2.2.1. Body Composition

DXA Scan

DXA scanning is a 3-compartmental model which provides measures of FM, LM and bone mineral content (BMC) for both whole body and segmental areas of the body (Nana *et al.*, 2015). While DXA scanning requires a certified radiology technician, delivers a low dose of radiation, can be expensive and timely and is often only available in clinical or physiology laboratory settings, it is becoming increasingly popular in both research and practical applications due to its validity and reliability (Lemos and Gallagher, 2017; Raymond, Dengel and Bosch, 2018). However, accurate measurement of body composition by DXA scan relies on limiting both technical errors and biological variation. The former involves both technician and machine errors which can include the lack of standardization of clothing worn, the positioning and the limb placement of the participant (Nana *et al.*, 2015). The latter involves error introduced through variations in hydration status and levels of muscle glycogen (Toomey, McCormack and Jakeman, 2017). This is especially relevant in a population required to reduce body mass, often by manipulating hydration or muscle glycogen, for competition. Therefore, despite the levels of accuracy and validity of

DXA scan technology, care must be taken to limit these sources of error or variability to ensure precise measurement.

Steps can be taken to limit technical errors and these include ensuring all scans are carried out by the same technician using the same equipment and to a standardised method of limb placement and ensuring participants wear minimal clothing (boxer shorts for males and shorts and sports bra for females) and remove body jewelry. In an effort to limit biological error, participants should be weighed first thing in the morning before consuming any food or liquid. Participants should also be required not to eat or drink anything after midnight on the evening before their scan and therefore undergo an 8-10 hour over night fast. Therefore, the validity and reliability of DXA scanning technology in combination with measures taken to limit errors make this a fitting method for determining body composition in the present study.

2.2.2.2. Anaerobic Profile

Wingate Anaerobic Test

The Wingate Anaerobic Test (WAnT) was developed in the mid-1970s (Bar-Or, 1987) and since then has maintained its status as one of the most popular and effective methods to assess anaerobic performance (Hofman *et al.*, 2017). The WAnT involves participants pedaling at maximal effort on a cycle ergometer for 30 seconds at a fixed resistance relevant to body mass (usually 7.5%) (Bar-Or, 1987) or cadence (Samozino, Horvais and Hintzy, 2007). Two major energy sources are required during the WAnT: the anaerobic alactic energy system and the anaerobic lactic system (Zupan *et al.*, 2009) and as a result, the power an individual can output during this test measures how well a participant may utilise these energy systems. Since taekwondo combat, and in particular the high-intensity kicks and punches that are required to score points, is reliant on the anaerobic energy systems, the WAnT can be a useful tool in assessing the anaerobic characteristics of these athletes. Furthermore, the WAnT returns data which allows the calculation of three different measures: peak power ouput (PPO) which is the maximum power achieved over a 1-5 second consecutive period and is a measure of an athletes muscular power, mean power output (MPO) which is a measure of the capacity of an athlete to maintain anaerobic energy production and fatigue index (FI%) which is a measure of the reduction of power over the course of the 30 second test (Zupan *et al.*, 2009). Furthermore, it is important to note that both PPO and MPO can be relativised to body mass to allow comparisons to take place across a wide range of athletes. On the other hand, FI% is a less reliable measure of anaerobic fatigue (Driss and Vandewalle, 2013) however, it is reported in many taekwondo specific studies and therefore presents a useful comparative variable. Caveats to the usefulness of WAnT measurements in taekwondo athletes involve the lack of standardisation of protocols, namely variation in whether resistance or cadence is fixed, the amount of resistance or level of cadence applied, warm up and start procedures and the variation in the type of ergometer utilised, all of which could obscure the meaningfulness of the results, particularly when comparing results with other studies (Bridge *et al.*, 2014). Additionally, the WAnT is carried out on a cycle ergometer reducing the mechanical specificity of the test to the actions of taekwondo and which has been hypothesised to potentially blunt the true anaerobic profile of taekwondo athletes (Rocha *et al.*, 2016). However, the ability to go all out during an anaerobic test with a low risk of injury is of great importance when carrying out testing in elite athletes. Furthermore, the large availability of normative data for athletes, both in taekwondo and other sports, allows comparison of the anaerobic profiles of these kinds of athletes. Additionally, the lower body predominance of taekwondo and a cycle ergometer allows the inspection of the power profile of these limbs independent of the skill level of the athlete (a factor that may impact the results of taekwondo specific anaerobic tests).

SJ and CMJ

Using a force plate is considered the "gold standard" method for calculating jump height by measuring the vertical ground reaction forces exerted by the participant (Garcia-Lopez *et al.*, 2005). However, despite excellent measurement accuracy, a force plate is both expensive and immobile making it difficult to use in the field. Recently, cheaper and more easily transportable systems have been developed allowing for better ease-of-use. These systems, including Optojump (which uses photoelectric cells) and contact mats, calculate jump height by measuring flight time (Attia *et al.*, 2017). Optojump, which is easy to transport and can be used on nearly all sport surfaces, has been shown to have strong validity and reliability with force plate measurement of jump height, however, it appears to exhibit a systematic bias (Attia *et* *al.*, 2017; Glatthorn *et al.*, 2011). Therefore, it was considered a reasonable method for calculating jump height in the present studies but caution must be practiced when comparing results using different methods of calculation.

2.2.2.3. Aerobic Profile

Multi Stage Fitness Test

An incremental shuttle run test such as the multi-stage fitness test designed by Leger and Mercier can be carried out on large groups of athletes and requires minimal amounts of equipment (Léger *et al.*, 1988). The multistage fitness test (MSFT) has been shown to have relatively good agreement with VO_{2max} in adults, children (Mayorga-Vega, Aguilar-Soto and Viciana, 2015; Léger *et al.*, 1988) and in game sport athletes (Aziz, Chia and Teh, 2005) but not in squash players, runners or endurance athletes (Aziz, Chia and Teh, 2005; St Clair Gibson *et al.*, 1998). A study in taekwondo athletes demonstrated that the MSFT only gave accurate results for the participants when a novel predictive equation was used instead of the one designed by Leger et al. (1988) (Cetin *et al.*, 2005). However, this study measured VO_{2max} using a portable gas analyser during the shuttle run. While the weight of the gas analyser is not reported, carrying this during the shuttle run test is likely to have impacted the true VO_{2max} score therefore making the comparison with Leger's MSFT prediction and the new prediction equation potentially invalid. Justification for use of the MSFT in the current study lies in its efficency for use with large groups of athletes in combination with the validity and reliability.

2.2.3. Training (Part A): The Physiological Demands of High-level Taekwondo Training

2.2.3.1. Internal Training Load

Session Rating of Perceived Exertion

Session rating of perceived exertion (sRPE) has been shown to be a valid method of quantifying internal training load in Taekwondo athletes (Haddad *et al.*, 2011). sRPE is computed by multiplying the athletes' perceived exertion based off the Borg CR-10 scale (Borg, 1982) by the duration of the exercise session (in minutes) to give a single number measure of the magnitude of training load (TL) (Foster *et al.*, 2001).

Training Monotony and Strain

Mean sRPE for each test week was used to calculate training monotony and strain (Foster, 1998). Training monotony offers a useful measure of day-to-day variability of exertional effort while training strain is a measure of the general stress of exertional effort. High monotony and strain scores have been associated with increased injury risk (Foster, 1998; Foster, 2017).

Heart Rate

Heart rate (HR) has been shown to be a valid, objective and non-invasive measure of internal training load in many combat sports (Slimani *et al.*, 2017). It has been used effectively to measure the internal load of a variety of taekwondo training sessions (Bridge *et al.*, 2007). Furthermore, HR takes into account possible inter-individual responses to the same training sessions.

2.2.3.2. External Training Load

Session Type, Frequency and Volume

External training load (TL) seeks to measure the actual work completed by an athlete during training or competition. In combat sports it can be difficult to get a measure of external workload. One fundamental way to understand the work done by athletes is to measure the frequency and duration of each type of training session. Table 7 gives a breakdown of each type of training session and what it typically consisted of. The duration, in minutes, of sessions gives a measure of training volume. Session duration was captured using electronic technology on which athletes were required to check in at the start of each session (just prior to the beginning of the warm up) and check out at the end of each session (after the session debrief had been given by the lead coach). The duration of each session for each athlete was then analysed by deducting check in time from check out time. This therefore resulted in training duration and volume including the 9 ± 3 mins (Chapter 5.3.4) of stretching and debriefs which followed each training session in order to limit the disturbance to training sessions. This is a limitation to the data however it remains consistent throughout the entire data collection.

Activity Profile

It has been established that the external workload of training or competition is heavily dependent on a number variables some of which include the duration and intensity of the active and passive work periods and the duration of the rest (Buchheit and Laursen, 2013b). Examining the activity profile of taekwondo fights can give an understanding of the external work load achieved during combat (Santos, Franchini and Lima-Silva, 2011) therefore, it is reasonable to assume that examining these same variables during taekwondo training will also give an indication of external TL. While it is difficult to determine exactly the intensity of the active and passive work periods in taekwondo, this is largely dictated by the frequency and duration of these periods collectively with the rest periods (Buchheit and Laursen, 2013a) and thus an picture of the external TL can be collected in this manner. Therefore, during the test weeks, taekwondo sessions were monitored closely and the activity profile was recorded.

2.2.3.3. Subjective Response to Training

Subjective Wellbeing

Subjective wellbeing has been shown to be a valid and reliable measure of athletes response to training stress (Saw, Main and Gastin, 2016). Questions were answered on participants' personal smartphone devices to increase compliance and aid ease of use. The app on their smartphone sent out a reminder to complete their wellbeing data on awakening each morning. The app allowed them to answer 6 questions (Table 8) relating to their physical and mental wellbeing by selecting a number from 1-10 on the colour-coded sliding scale. For over a year prior to the commencement of this study, the athletes involved had been using the aforementioned questions (Table 8) to assess wellbeing as part of the high-level daily monitoring practice. This particular questionnaire is not validated or backed up in the literature, however, the decision to use these questions in this study was made to maintain continuity in the monitoring practice.

Table 7 Summary of the different types of taekwondo training sessions

Session Type	Description	Focus	Components
COND	Conditioning training	Enhance physiological conditioning of athletes with respect to individual game plans	Speed kicking on pads High-intensity pad work intervals
SPAR	Sparring and full contact training	Preparing athletes for real competitive situations and combat	Test matches Full contact situations and rounds Sparring rounds
TECH	Technical training	Enhancing technical skills and capacity	Leg holds Specific kicking techniques on pads High repetition kicking
TAC	Tactical training	Practicing typical situations and opponents and tactical options to utilise against them	Situation response Partner drills (kicking body armour) Timing drills
T/T	Technical tactical training	The application of technical kicks and movements to tactical situations	High repetition response to situations Pressure situations with partners

Table 8 Questions for subjective wellbeing

Wellbeing Questions
1. How well did you sleep last night?
2. How fatigued do you feel?
3. How is your mood?
4. How well fuelled do you feel?
5. How is your muscle soreness?
6. Do you have any injuries or illness that will affect your training?

1	2	3	4	5	6	7	8	9	10

Q. 1-5: 1 = worst ever, 10 = best ever; Q. 6: 1 = yes, severe. No training at all; 10 = none at all.

2.2.4. Training (Part B): The Factors that Affect the Organisation of High-level Taekwondo Training

In order to assess the factors affecting the periodisation and planning of training, session attendance was measured for each participant in the study. Variables that may have influenced session attendance were also measured. This will be discussed in greater detail in Chapter 5 (5.2.4.).

Chapter 3

The Physical Demands of and Physiological Response to International Taekwondo Competition

3.0. The Physical Demands of and Physiological Response to International Taekwondo Competition

3.1. Introduction

In order to maximise the chance of success in high-level sport, it is important to understand that sport in as much depth as possible. Investigation in to official competition can provide useful, practical and ecologically valid data for assessing the demands of competition from a tactical, technical, physical and physiological viewpoint. These data, and particularly the latter two, can then provide information to assist in the optimisation of the physiological profile of athletes for competition performance (Hanon, Savarino and Thomas, 2015) by focusing training methodologies around these demands. Previous studies in the literature investigated the physical and physiological demands of taekwondo competitions but these were carried out prior to the rule changes discussed in Chapter 1 therefore potentially compromising the ecological validity and appropriateness of the results to optimize physical preparation. Therefore, in order to optimise current training practices and ultimately the physiological profile of athletes, the competition demands must be investigated under the current rule set.

There are limited methods available for assessing real-time, external competition demands in sports that are held indoors. For this reason, these sports utilise methods such as HR, BLa and RPE to identify the objective physiological responses to competition. These measures have been used, with relative success, to estimate energy system contribution in basketball (Matthew and Delextrat, 2009; Scanlan *et al.*, 2012), competitive swimming (Vescovi, Falenchuk and Wells, 2011), kite-surfing (Camps, Vercruyssen and Brisswalter, 2011) and trampolining (Jensen *et al.*, 2013).

Combat sports are comparatively under-represented in the literature and could benefit from further investigations in to the demands and responses of competition (Chaabène *et al.*, 2014). Simulations of martial arts combat do not exhibit the same physiological responses as actual competition (Hanon, Savarino and Thomas, 2015; Bridge *et al.*, 2013) and thus measuring real-time variables during competitive combat is critical for understanding the authentic demands of the sport. The full contact nature of combat sports makes this problematic and as a result many studies have focused on using time motion analysis to determine physical workload and activity during competition

(Davis *et al.*, 2018; Miarka *et al.*, 2016; Bridge, Jones and Drust, 2011). Nevertheless, some studies in judo (Serrano *et al.*, 2001), boxing (Hanon, Savarino and Thomas, 2015) and karate (Chaabène *et al.*, 2014) have been able to investigate internal measures of activity such as BLa, HR and RPE and similar studies have also been done previously in taekwondo combats (Bridge, Jones and Drust, 2009; Matsushigue, Hartmann and Franchini, 2009; Bridge *et al.*, 2013).

Since the investigations by Bridge et al. (2009, 2013) and Matsushigue et al. (2009), there have been no more attempts, to the best of the author's knowledge, to determine the physiological demands of international taekwondo competition under the myriad of new rules. Therefore, the aim of this study was to measure internal and external physiological variables of international taekwondo competition under present day rules and regulations in order to characterise, with up-to-date ecological validity, the physical demands of and physiological responses to current Taekwondo so that training methodologies can be manipulated accordingly to maximise physical preparation.

3.2. Methods

3.2.1. Participants

10 elite level taekwondo athletes (8 males and 2 females) took part in the study (Table 9). All participants were regularly competing at international competitions including open tournaments, European and World Championships and Grand Prix events. Athletes represented a variety of weight classes (F: -57kg n=1, -62kg n=1; M: -58kg n=3, -63kg n=1, -74kg n=1, +80kg n=3). All participants were full time taekwondo athletes who underwent an average of 500-700 minutes of taekwondo specific training, 115-199 minutes of resistance training and 0-130 minutes of general conditioning per week and all underwent the same training schedule in the run up to the competition in question. All participants were informed of the test procedures and potential risks and gave informed consent. The project was granted full ethical approval in accordance with Liverpool John Moore's University Ethics Committee.

3.2.2. Competition Procedure

All participants competed in a WT sanctioned senior-level international competition (*European Club Taekwondo Championships*, Istanbul, Turkey, 2018). The competition was held on standard EVA foam matting and all qualifying, semi-final and final phases of the event occurred between 09:00 and 19:00 on the same day. Each fight involved 3 rounds of 90 seconds with 30 seconds rest between rounds, which is not the same as the duration of the rounds and recovery periods seen in Olympic taekwondo combats, but, as stated in Chapter 1.4.4., is an acceptable change that can be made by competition organisers. The inclusion criteria were successful collection of HR, BLa, RPE and video analysis across all rounds and data from a total of 24 fights was collected.

Table 9 Participant characteristics (body mass was recorded on morning of competition)

	Age (y)	Body Mass (kg)	Stature (cm)
Males (n=8)	18.3±1.0	78.1±18.8	186.6±7.9
Females (n=2)	18.5±0.7	60.9±2.1	169.8±2.5

3.2.3. Heart Rate

Participants were familiarised with the HR belts having worn them during multiple training sessions including test matches and sparring in the weeks preceding the competition and all competitors agreed the HR belt did not impede movements or behaviour during taekwondo activities. HR was recorded at one-second intervals during each round and recovery between rounds. HR monitors were attached to a corresponding belt and attached across a participant's chest against their skin underneath the Dobok (official competition uniform) and body protector scoring system (PSS). When participants had more than one fight they wore the same HR belt for each fight. HR was recorded using a Suunto heart rate monitor (Suunto smart sensor, Finland). Mean ± standard deviation (SD) HR was calculated for each round and the recovery between each round. Mean HR was also expressed as a percentage of each individuals maximum HR. Maximum HR for each participant was the highest recorded HR during training over four non-consecutive weeklong periods (determined during study 2, Chapter 4).

3.2.4. Blood Lactate

Whole blood lactate (BLa) concentrations were measured before each fight and at the end of each round to indicate the contribution to energy production from the anaerobic glycolytic system (Gaitanos *et al.*, 1993). Blood lactate was measured prior to the first warm up of the day in order to get a baseline measure. It was then measured no more than ten minutes prior to the start of each fight and immediately after each round (*Lactate Pro 2, Akray, KDK*). Calibration of the device was completed in accordance with the manufacturer's instructions before sampling and has been validated against blood assay criterion instruments (Bonaventura *et al.*, 2015). Competitors were familiarised with the sampling procedure at training sessions prior to the competition. A 0.3 ηL blood sample was taken from the fingertip after the first bleed was removed to reduce contamination from substances on the surface of the skin.

3.2.5. Rate of perceived exertion

RPE was taken immediately after each round by asking participants to point to or say the number representing their corresponding perceived exertion on the Borg category ratio (CR 10) RPE scale. They were instructed to rate their perceived exertion of each round independent of previous rounds. Athletes had been previously familiarised with giving an RPE score during simulated competition at least once prior to taking part in the study.

3.2.5. Time Motion Analysis

Each fight was recorded using a high definition camera (Panasonic, HC-W-580EB-K). The footage was analysed under the guidance of an experienced analyst who works within the sport of taekwondo to ensure accuracy in the determination and classification of moves and by the same researcher to avoid inter-tester error. Two combats were chosen at random and reanalysed (at least 5 days after initial analysis) by the researcher and by an experienced analyst to ensure reliability of the time motion analysis. Cohen's kappa statistic was used to measure agreement between analyses (McHugh, 2012). Kappa values of 0.81-1.0 are regarded as having very good agreement. Kappa statistics were 0.93 and 0.89 for intra-tester reliability and 0.90 and 0.86 for inter-tester reliability, therefore demonstrating "very good" agreement between trials. Fights were analysed by measuring the duration and frequency of each exchange, preparatory period and rest period (as defined in Chapter 2.2.4.2).

3.2.6. Body Mass and Hydration

BM was measured at the same time as the official weigh in (between the hours of 10:00 and 12:00 on the day prior to competition) using a digital scale (Seca 702, Seca GmbH, Hamburg, Germany). On the morning of the fight, participant's fasted BM was measured again using the same digital scales. They also supplied a urine sample from the first pass of the day and this was used to assess hydration (*Osmocheck, Vitech Scientific Ltd., United Kingdom*). Immediately after each participant's final fight of the day, BM was recorded again and a second urine sample was provided (as close as possible to the end of the last fight) for hydration assessment.

3.2.7. Statistical Analysis

Descriptive data are expressed as means ± SD unless otherwise stated. Repeated measures ANOVA were conducted across dependent variables to identify differences between rounds and recovery periods. Post hoc analysis was performed using Tukey's pairwise comparison. Effect sizes, via Cohen's d, were used to further determine the magnitude of the differences between means (Sullivan and Feinn, 2012). Effect sizes, via Cohen's d, were used to further determine the magnitude of the differences between means (Sullivan and Feinn, 2012).

$$\text{Cohen's } d = \frac{M_1 - M_2}{s}$$

$$\text{where } s = \sqrt{\frac{(s_1{}^2 - s_2{}^2)}{2}}$$

and M_1, M_2 = mean of each sample and s_1,s_2 = standard deviation of each sample. Effect sizes (ES): 0.2 = small, 0.5 = medium, 0.8 = large; 1.5 = very large.

All statistics were analysed using SPSS for Windows (*Version 24.0, SPSS Ltd., United Kingdom*).

Table 10 HR responses to taekwondo combat (mean±SD)

	Rd 1	Rec 1	Rd 2	Rec 2	Rd 3
Mean HR (beats.min^{-1})	178 ±6*^	159 ±6	180 ±7*^	161 ±11	182 ±5*^
%HR	87.6 ±2.4*^	78.5 ±4.2	88.3 ±2.6*^	79.5 ±5.9	89.8 ±2.8*^
HR_{max} (beats.min^{-1})	189 ±5		191 ±7		195 ±6
$\%HR_{max}$	93.2 ±2.6		94.2 ±1.9		95.7 ±1.9$^{\&}$

Rd = round; Rec = recovery; HR = heart rate; %HR = percentage of maximum heart rate; HR_{max} = maximum heart rate per round; $\%HR_{max}$ = maximum heart rate per round as a percentage of maximum heart rate;
* > recovery 1, $p < 0.001$; ^ > recovery 2, $p < 0.001$; & > round 1, $p < 0.05$;

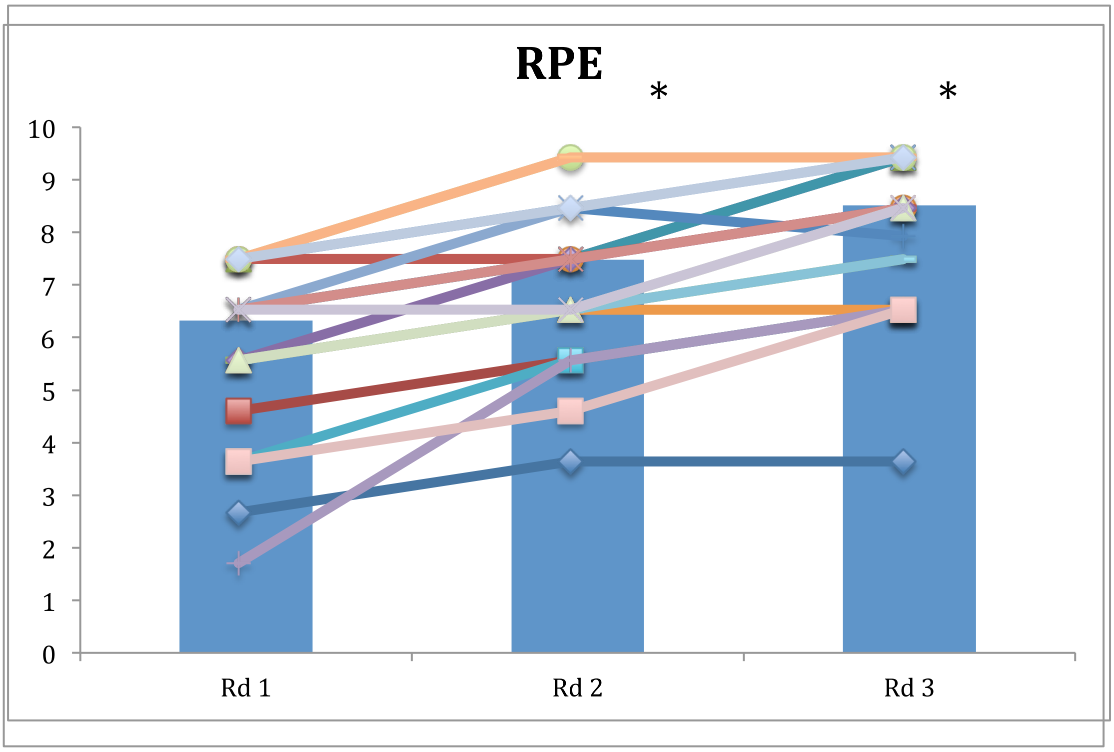

Figure 1 Mean and individual RPE scores across rounds

Rd = rounds; * > Rd 1, $p < 0.05$

3.3. Results

Athletes were tested during 24 fights in total and with performances that resulted in two quarterfinal finishes, a bronze medal and a silver medal. Participants had a varied number of fights depending on their rank and success on the day (1 fight n = 5, 3 fights n = 2, 4 fights n = 2, 5 fights n = 1).

Mean HR and %HR were significantly greater during all three rounds then they were during the breaks between rounds ($p = 0.001$, ES between 1.80 and 4.16, very large) (Table 10). HR and %HR increased across all three rounds and was not significant but showed moderate to large effect size between round 1 and 3 (MeanHR ES = 0.31 [Rd1 v Rd2], 0.72 [Rd1 v Rd3] and 0.3 [Rd2 v Rd3]); HR% ES = 0.28 [Rd1 v Rd2], 0.84 [Rd1 v Rd3] and 0.56 [Rd2 v Rd3]. Similarly, HRmax increased across all three rounds and was not significant but showed a very large effect size between the first and third rounds (ES = 0.33 [Rd1 v Rd2], 1.1 [Rd1 v Rd 3], 0.6 [Rd2 v Rd3]). $\%HR_{max}$ also increased across rounds and was significantly greater in round 3 than it was in round 1 ($p = 0.007$, ES = 1.1).

RPE scores were significantly greater after round 2 ($p = 0.04$, ES = 0.7) and round 3 ($p = 0.001$, ES = 1.3) than they were after round 1 (Figure 1).

There was a non-significant increase of 1 $mmol.L^{-1}$ in BLa between baseline and pre-combat measures. However, BLa increased across rounds with Round 1, 2 and 3 measures significantly greater than baseline and pre-combat measures ($p < 0.001$, ES = 2.0 – 4.2). BLa levels after round 2 and round 3 were significantly greater than round 1 ($p < 0.01$, ES = 0.9 and 1.3, respectively) (Figure 2).

Time motion analysis showed the mean exchange time to be 2.29 ± 0.72 s and mean preparation time to be 2.35 ± 0.75 s. The ratio of exchange to preparation time was 1:1.1 ± 0.5 and of exchange to total rest time was 1:2.2 ± 0.9. The mean number of exchanges per fight was 60 ± 15 (Table 11).

Mean BM and mean urine osmolality were also measured before and after competition. There was a significant increase of BM from weigh -in to pre-comp (2.1 ± 1.6 kg, $p = 0.003$, ES = 1.3) and from pre-comp to post-comp (1.2 ± 0.4 kg, $p = 0.022$, ES = 0.91). There was also a significant reduction in urine osmolality from pre-comp to post-comp (862 ± 166 $mOsm.kg^{-1}$ Vs. 585 ± 275 $mOsm.kg^{-1}$, $p = 0.010$, ES = 0.83).

Table 11 Physical demands, via time motion analysis, of the present study in comparison to other published studies (mean±SD)

	Present Study	Competition (Hausen et al. 2017)	Competition (Bridge et al. 2013)	Competition (Santos et al. 2011)
ET (s)	2.29 ±0.72	2.0 ± 0.5	1.7 ± 0.4	
PT (s)	2.35 ± 0.75	4.6 ± 1.2	6.4 ± 2.1	
ET:PT (1:x)	1.1 ± 0.5	2.4 ± 0.9		
ET:Rest (1:x)	2.2 + 0.9		6.3 ± 2.0	
No. of exchanges/combat	60 ± 15	36 ± 7	28 ± 6	7.6±3.0 *

ET = average exchange time; PT = average preparation time; ET:PT = exchange to preparation time ratio; ET:Rest = exchange to rest time ratio; * no. of exchanges per round

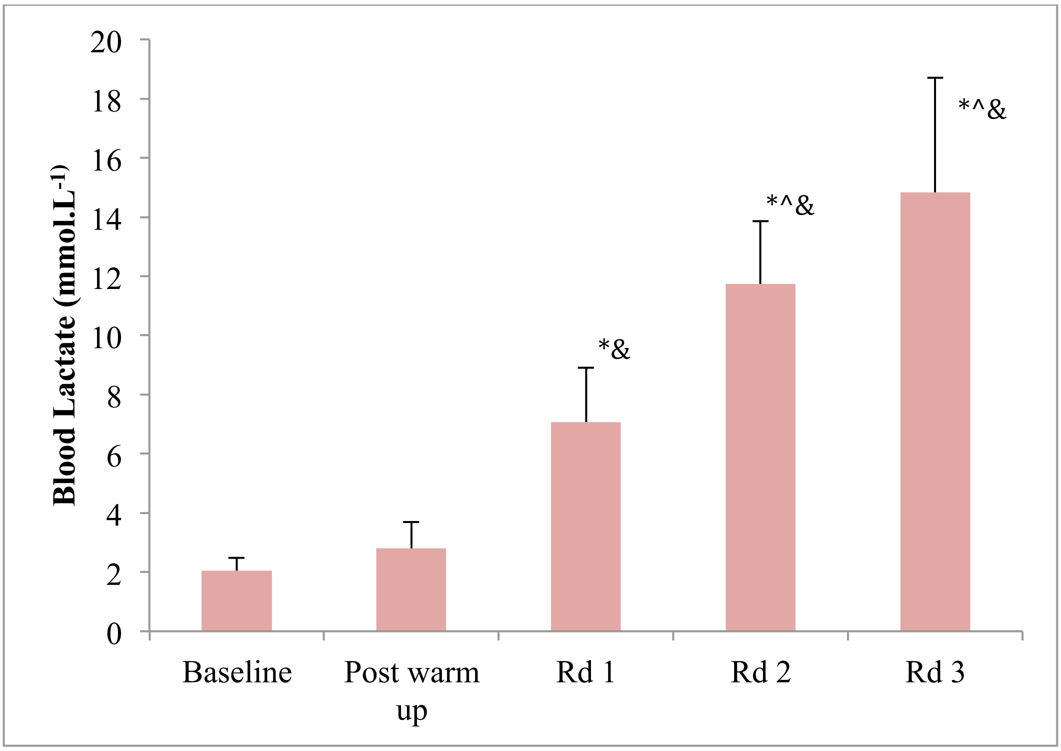

Figure 2 Mean±SD blood lactate values across rounds

& > baseline, $p = 0.000$; * > post warm up, $p = 0.000$; ^ > Rd 1, $p < 0.01$

3.4. Discussion

To the best of the author's knowledge, this is the first study to investigate the physical and physiological demands of taekwondo competition since the rule changes that followed the 2008 Beijing Olympic Games. The data collected in this study highlight that current taekwondo combats consist of a large number of short duration, high-intensity efforts interspersed by brief preparatory phases and rest. These physical demands elicit maximal anaerobic and aerobic physiological responses that correspond with a high perception of effort.

3.4.1. Physical Demands

In order to accurately depict the demands of sporting competition, it is important to not only describe the physiological responses to competition but also to illustrate the physical workload undertaken. One method to determine the physical output in striking based combat is to measure the frequency and duration of exchanges and to create an activity profile comparing the time spent involved in exchanges with the time spent in preparatory phases and at rest (Bridge, Jones and Drust, 2011; Hausen *et al.*, 2017). The relationship between these exchange and preparatory phases is indicative of the physical demands experienced by athletes (Santos, Franchini and Lima-Silva, 2011). The present study demonstrated a small increase in the duration of exchanges relative to those reported in studies prior to the rules changes (2.3 ± 0.7 s versus 1.7 ± 0.3 s (Bridge, Jones and Drust, 2011) and 1.3 ± 0.4 s (Santos, Franchini and Lima-Silva, 2011)) (Table 11). However, we report an average of 60±15 exchanges per combat which is a dramatic 2-3 fold increase in the frequency of exchanges recorded in previous studies (Santos, Franchini and Lima-Silva, 2011; Bridge *et al.*, 2013) (Table 11). There was also a dramatic increase in the mean exchange to preparation time ratio and the mean exchange to rest time ratio (Table 11) compared to previous studies (Hausen *et al.*, 2017; Bridge, Jones and Drust, 2011; Santos, Franchini and Lima-Silva, 2011).

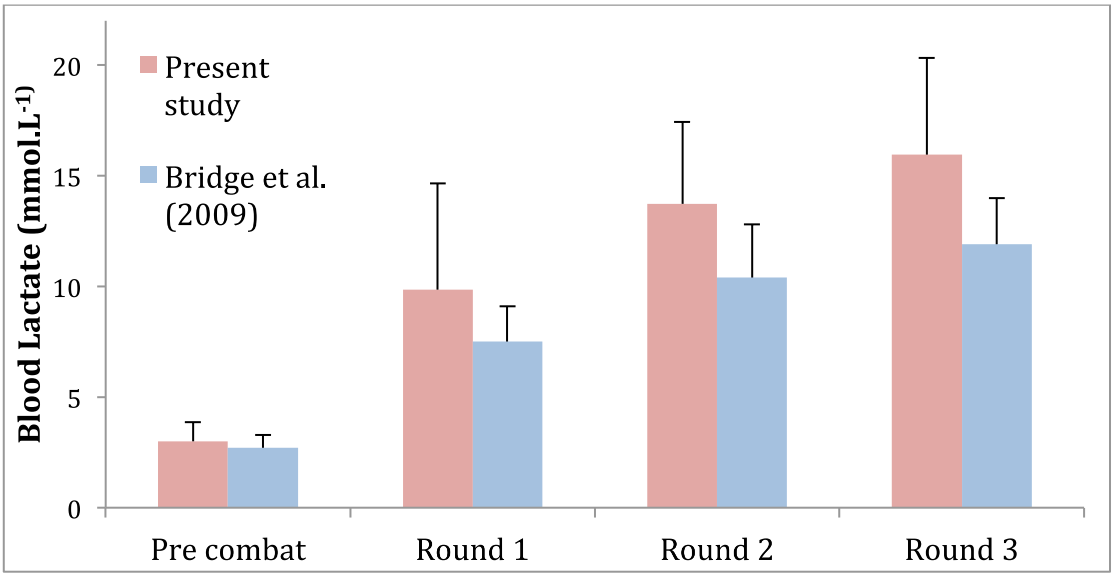

Figure 3 Mean±SD blood lactate scores across rounds in the present study compared to the 2009 study (adapted from values in Bridge et al. 2009)

3.4.2. Physiological Response

It is well understood that the physiological response to exercise is heavily dependent on a number of variables including the duration and intensity of the work periods, the duration and intensity of the active rest periods and the duration of the rest periods (Buchheit and Laursen, 2013b). The same is true of the physiological response to taekwondo combats where the frequency, duration and intensity of the exchanges and preparatory phases and the duration of the rest intervals will determine the physiological response to the combat (Santos, Franchini and Lima-Silva, 2011). Figure 4, adapted from Buchheit and Laursen (2013b), illustrates how these variables influence the physiological demands of taekwondo combats.

The present study demonstrated an increased number of exchanges, increased exchange time and decreased exchange to preparatory time ratios that corresponded with increased BLa levels compared to previous research. This finding is similar to a study in high-level boxing combats that found that there was a corresponding increase in BLa with an increase in the amount of work done, in terms of number of punches, during a boxing combat (Hanon, Savarino and Thomas, 2015). Novice boxers who only executed 15-20 punches in the final round had lower BLa post match than more senior boxers who threw >30 punches in the final round (Hanon, Savarino and Thomas, 2015; Davis, Wittekind and Beneke, 2013). This suggests that the physiological response is greater under the current rule set.

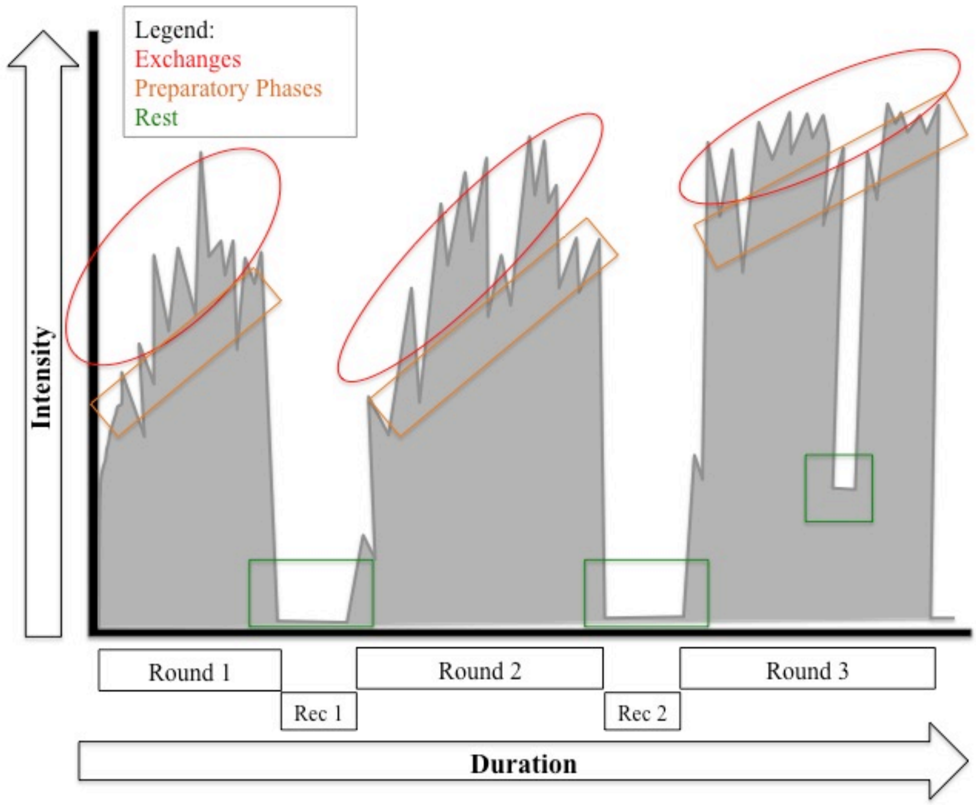

Figure 4 Schematic of the variables that influence the physiological demands of taekwondo combats (adapted from Buchheit and Laursen (2013b)). The variables include the frequency, duration and intensity of the exchanges; the duration and intensity of the preparatory phases and the duration and intensity of rest periods (including referee stoppages during rounds as seen in Round 3 above). These variables will fluctuate between rounds and combats but collectively will contribute to the physiological requirements of taekwondo competition.

Rec = Recovery

A recent study which examined kinematic and physiological demands of taekwondo combat using an advanced telemetric recording device, *Bioharness 3*, on combats in 2015 (before the introduction of some of the most recent rule changes including the introduction of a smaller ring size and penalties for lack of activity) and combats in 2017 (after the introduction of these rules) also found that these rule changes had a significant impact on BLa, HR and kinematic variables (Janowski, Zielinski and Kusy, 2019). There is ambiguity about the accuracy of the data collection using the *Bioharness 3* since it has not yet been validated in combat sports (Johnstone *et al.*, 2012) however, BLa data, which was collected independently of this system, was significantly greater post-bout in 2017 than it was in 2015 which further supports the considerable impact changing rules are having on the physiological demands of combat.

BLa values increased across rounds and were significantly higher in the second and third round than in the first round. Bridge et al. (2009) also demonstrated that BLa increased across rounds in taekwondo combats prior to the rule changes; however, the mean values described were substantially lower than in the present study (Figure 3). The mean values shown by Bridge *et al*. (2009) for the end of the third round of Taekwondo combat (11.9 ± 2.1 mmol.L^{-1}) were more comparable to those seen during single bout martial arts combats such as judo (10.4 ± 2.2 mmol.L^{-1}) (Serrano *et al.*, 2001) and karate (11.2 ± 2.2 mmol.L^{-1}) (Chaabène *et al.*, 2014). This study compared more closely with a similar study in boxing where mean BLa after the third three minute round during two, separate sets of test matches was shown to be 17±2.3 mmol.L^{-1} and 13.6±2.4 mmol.L^{-1} , respectively (Hanon, Savarino and Thomas, 2015) and a study in MMA which demonstrated BLa measures of 10.2-20.7 mmol.L^{-1} at the end of official bouts (which lasted for up to 3 x 5-minute rounds) (Amtmann, Amtmann and Spath, 2008).

Concurrently with BLa, our data also showed RPE scores to increase across rounds and to be significantly greater in the second and the third round than the first round in a similar fashion to the RPE scores seen prior to the rule changes (Bridge, Jones and Drust, 2009). It is difficult, however, to make a direct comparison between the two studies as Bridge *et al*. (2009) used the Borg 6-20 scale (Borg, 1970) and the present study, in order to maintain consistency and familiarity for the athletes participating, used the Borg CR-10 scale (Borg, 1982) due to the fact that they use this scale daily to assess internal load of training. Despite this, RPE scores in the present study of 6-10 (which correspond with perceived exertion of hard- very, very hard) versus RPE scores of 11-14 (which corresponds with fairly light - hard) indicates that the perceived effort during present day taekwondo combats is greater than those observed previously.

Studies in martial arts combats often describe a disparity between perceived intensity and actual physiological measures of intensity where levels of perceived exertion have been recorded as "moderate" and "somewhat hard" while BLa and/or HR values have been at or near maximal. This was seen in pre-rule change in taekwondo (Bridge, Jones and Drust, 2009) and in karate (Chaabène *et al.*, 2014). Further, Serrano *et al*., (2001) showed in judo that there was no significant correlation between RPE during a final judo fight and either the change in BLa levels during the fight or post-fight BLa levels. This disparity between RPE and BLa levels was not observed in the present study. In a review examining the efficacy of RPE as a quantification tool in combat sports, Slimani et al. (2017) suggested that striking sports, including MMA, appear to have a higher RPE. The review speculates that this may be as a result of increased duration of rounds and a higher percentage contribution of aerobic metabolism compared to other combat sports. Considering the former does not apply to the present study given the 90 second rounds, it could be surmised that the high RPE scores could be as a result of an increased contribution of aerobic metabolism. It has been shown previously that during a simulated taekwondo combat, 66 ± 6% of total energy contribution came from aerobic metabolism (Campos *et al.*, 2012) and that only 4 ± 2% of energy contribution came from anaerobic glycolysis. However, the physical work done (exchange time: rest ratio of 1:8) and physiological responses after the final round (BLa 7.0 ± 1.5 $mmol.L^{-1}$ and mean HR 175 ± 10 $beats.min^{-1}$) during these simulations were substantially lower than we have observed during live competition. Taken together, it could be hypothesised that modern taekwondo bouts elicit an even greater contribution from aerobic metabolism and a potential for an increased contribution from anaerobic lactic systems and that this accounts for a better association between objective (BLa) and subjective (RPE) physiological responses.

Despite the clear increase in physical load and concomitant increased physiological response in terms of BLa and RPE, the HR data in this study do not appear to be dramatically different from the data presented by Bridge *et al*. (2009). Data for both mean HR and %HR were similar between the present study and the previous study. However, it is relevant to note that there appears to be a greater difference in both mean HR and %HR during the break between rounds. The data in the present study are lower than those seen by Bridge et al. (2009 and 2013) and this suggests that the HR recovery (HRR) during breaks in rounds was more efficient in the athletes in the present study. Faster HRR in the first 30 seconds after maximal exercise is related to the aerobic fitness of the athlete (Watson *et al.*, 2017) and therefore suggests that this cohort of athletes had a greater aerobic fitness than those in the previous study.

It is clear that taekwondo has evolved considerably, both from a tactical and a physiological point of view, from taekwondo prior to the 2008 Olympic games. Current taekwondo combats involve a 2-3-fold increase in the number of exchanges and a subsequent dramatic decrease in the work to rest ratios. As a result, the physiological response of taekwondo has shifted markedly to elicit both maximal BLa levels and RPE scores indicating an enhanced reliance on both anaerobic lactic and aerobic energy system pathways. These data therefore suggest that physical preparation of taekwondo athletes should be focused around the development of aerobic and anaerobic lactic capacities in order to optimally prepare for the demands of competition.

3.5. Limitations

The most significant limitation was the reduction in the length of rounds to 90 s and the recovery to 30 s. The majority of taekwondo competitions consist of 3 x 2 minute rounds with 60 s recovery however, as discussed in Chapter 1.2, changes to the length of rounds and recovery is at the discretion of the competition organiser and occur with relative frequency. In this particular instance, the duration of rounds and recovery were reduced in order to facilitate a busy schedule of events. Variations in the duration of rounds and recovery may have an impact on the physical and physiological demands of competition however, this is also a typical occurrence at international taekwondo events and as a result is a reality of collecting data in situ.

3.6. Coordinating the Demands of Competition with the Physiological Profile of Athletes

In order to maximise physical preparation and performance success, it is imperative to understand competition from a physical and physiological standpoint. Once this is achieved, the physiological profile of athletes must then be examined in order to assess whether it is appropriate to afford sufficient physical robustness to the demands of competition. Comparison of the physiological profile of athletes with competitive demands can then illustrate the adequacy pf physical preparation or present areas for development to optimise the chances of performance success.

Chapter 4

The Physical and Physiological Profile of Taekwondo Athletes

4.0. The Physical and Physiological Profile of Taekwondo Athletes

4.1. Introduction

The previous study demonstrated that taekwondo athletes experience maximal BLa levels, maximal perceived exertion and near maximal cardiovascular strain during competition. Additionally, we demonstrated that the physical demands of competition have changed dramatically since the rule changes were introduced and that present day taekwondo combats demand a higher frequency of high-intensity exchanges with reduced chance to recover in between. Therefore, it is clear that current, competitive taekwondo combat imposes a large physiological strain on athletes and that this strain is greater than that experienced prior to the rule changes.

A significant challenge for taekwondo coaches and support staff is to optimise the the physical preparation of athletes to maximise their chances of successful performance in competition. Understanding optimal physiological profiles may enable the creation of reference values for athletes to use as a basis for training programmes (Mirzaei *et al.*, 2009; Ball, Nolan and Wheeler, 2011; Chaabène *et al.*, 2012). Considering the impact that the rule changes have had on the demands of competition, the physiological profile of taekwondo athletes must be thoroughly investigated to understand whether there are any discrepancies in these profiles with respect to the current demands of competition and thus identify areas for physical enhancement. Furthermore, this data can be compared against data prior to the rule changes to examine whether the evolution of rule changes has impacted the physical and physiological characteristics of athletes.

Taekwondo athletes compete at 4 different Olympic weight categories (-49kg to +67kg for females, -58kg to +80kg for males), which are separated by between 8-12kg. It is therefore appropriate to think that there may be some diversity in the physiology of athletes competing at different weight categories. Bridge et al. (2011) showed that there were distinct differences in the activity profile of the combats of athletes of different weight categories. It has also been shown that there is a significant effect of weight class on the scoring methods of female taekwondo athletes at the Olympic games but not on male athletes (Kazemi, Perri and Soave, 2010). This data suggests that the optimal physiological profiles may be different for athletes competing at different weight categories and between sexes. Despite this, there is very little in the literature that examines how these differences might affect the profiles and therefore provides little direction as to how to optimise training programmes accordingly. Additionally, examining the difference in performance variables between athletes of different levels of success can provide valuable information around which variables are favourable for performance (Bridge *et al.*, 2014) and can provide insights around the gaps between elite and development level taekwondo.

To the best of this author's knowledge, since the barrage of rule changes there has been no cohesive investigation in to the physiological characteristics of high-level taekwondo athletes, including Olympic, World and European medal winners, in order to better understand the needs and capacities of the sport. Therefore, the aim of this study was to comprehensively investigate the physiological characteristics of a national academy of taekwondo athletes to examine whether they are appropriate for maximising performance success under the current rule set and to compare this data with that of the data collected prior to the rule changes to gain an understanding of how the rule changes may have impacted the physiology of athletes today. Furthermore, this study seeks to investigate any differences in physiological profile between sexes, weight categories and level of success to further direct training methodology specific to the individual needs of the athlete.

4.2. Methods

4.2.1. Participants

Twenty-nine taekwondo athletes (15 males, 14 females; 19.9 ± 3.3 years old) who were members of the Great Britain (GB) National Academy took part in this study. Athletes were of two different levels of experience: TOP (n = 13; 7 males, 6 females) and TARG (n = 16; 8 males, 8 females). All participants were assessed within 3 weeks of the beginning of their competitive season during a preparatory phase and all tests were carried out on the same day (Figure 5). All participants took part voluntarily in the study, after being informed about the procedures involved, and signed a consent agreement. Parents or guardians of athletes under 18 years of age gave consent. Full ethical approval was granted by the Research Ethics Committee (REC).

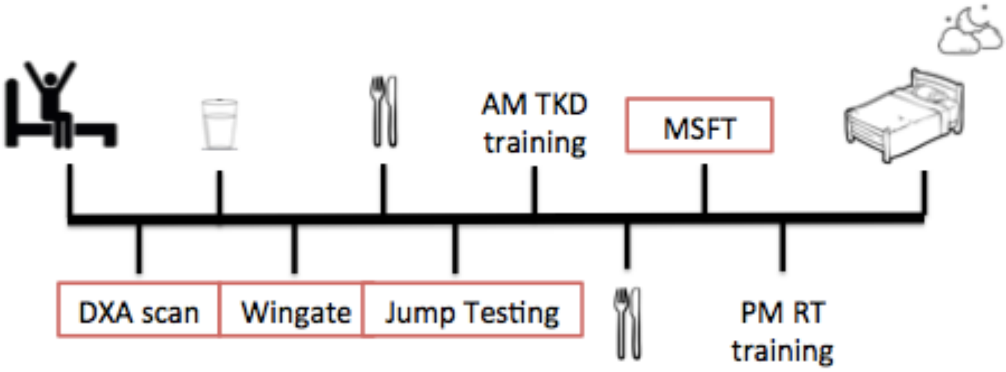

Figure 5 **Timeline of the testing procedure**

AM = morning; PM = evening; TKD = taekwondo; DXA = dual xray absorptiometry; MSFT = multi stage fitness test; RT = resistance training

4.2.2. Body Composition

Body composition was assessed via dual x-ray absorptiometry (DXA) using the *Lunar iDXA* (*GE Healthcare, United Kingdom*) and mechanincal and biological effors were limited using the steps listed in Chapter 2.2.1.1. Testing was carried out at the beginning of the season prior to preparation for competition and thus athletes were not in the process of making weight and manipulating muscle glycogen to do so. DXA scans were carried out before the first training session of each week (after two days off). Prior to scanning, participants were requested to void their bladder/bowels. Height was measured to the nearest 0.1 cm using a stadiometer; participants were instructed to maintain a neutral head position and to inhale and exhale before the sliding arm of the stadiometer was moved to the crown of the head. BM was measured to the nearest 0.01 kg using digital scales (Seca 875, Seca GmbH, Hamburg, Germany). Both height and BM were entered manually in to the DXA software system. The iDXA unit was evaluated each day prior to any scans taking place using the GE Lunar Block Calibration Phantom to ensure it was operating to the manufacturers specifications. Participants were positioned on the centre of the bed. Hands were positioned at the side of the hips and feet were turned inwards towards the centre line. Linear spinal alignment was ensured by traction of the neck and legs. Participants were instructed to remain still for the duration of the scan.

4.2.3. Wingate

Anaerobic power was assessed via Wingate using an SRM ergometer (SRM, GmbH, Germany). Data was analysed using the SRMX analysis software. Athletes were tested first thing in the morning before breakfast (and after an overnight fast; as per the DXA protocol). An experienced researcher, who ensured the protocol was the same for all athletes, carried out the Wingate tests. All athletes completed this test at least twice prior to testing to ensure familiarity since it has been shown that two days of practice is required to get valid and reliable results from non-cyclists (Martin, Diedrich and Coyle, 2000). Athletes seat and handle bar position were adjusted for limb length once seated on the bike. Athletes were instructed to pedal at 70rpm for five minutes to warm up. At the end of the 5 minutes, a countdown was given and athletes were then instructed to pedal as hard and as fast as they could for 30 seconds. The SRM ergometer was fixed at 120rpm during the 30 second Wingate. This allowed power to be measured at a revolution speed known to elicit the greatest power outputs (Martin, Diedrich and Coyle, 2000). Continued verbal support and encouragement was given throughout. At the end of the 30-second effort, athletes remained on the bike to cool down for 3 minutes at 50rpm. Power output from the 30 second effort was collected every 0.5 seconds. The greatest consecutive 1 second average was taken for peak power outputs (PPO). Fatigue index (FI) was also calculated using the following equation:

$$FI\ (\%) = \left(\frac{PPO - minPO}{PPO}\right) 100$$

Where minPO = smallest consecutive 1 second power output. Mean power output (MPO) was the average over the full 30 second test. Reliability testing was carried out on a subset of the population ($n = 10$) prior to testing. Participants were tested first thing on a Monday morning (prior to eating breakfast) and were tested again under the same conditions one week later. Test re-test correlation was $r = 0.81$, $p = 0.001$.

4.2.4. Squat Jump (SJ) and Countermovement Jump (CMJ)

SJ and CMJ were measured using the *Optojump Photocell System* (Microgate, Bolzano, Italy). Participants completed the SJ and CMJ tests without warming up and before the first training session of the day. All athletes were well familiarised with the testing procedure as it forms part of their regular training monitoring. For the CMJ, participants were asked to place their hands on their hips and in their own time to bend their knees to their desired depth and then jump as high as possible. For the SJ, participants were asked to place their hands on their hips and lower down and hold at their desired level. They were then given a countdown from three seconds after which they were instructed to jump as high as possible with no countermovement. They completed three of each kind of jump and rested at least 1 minute between jumps. The best score was taken for jump height. Reliability testing was carried out on a subset of the population ($n = 14$) prior to testing. Participants were tested before training on a Monday morning and were tested again under the same conditions one week later. Reliability testing was carried out after familiarisation. Test re-test correlation was $r = 0.78$, $p = 0.001$.

4.2.6. Multi Stage Fitness Test (MSFT)

All athletes had performed a MSFT at least once in the two years prior to testing. Before starting, athletes were instructed to run between two 20m cones on a straight running track in time with an audio signal emitted from a speaker. The warm-up procedure consisted of running the first level on the test which took one minute to complete. Athletes were then given a minute to rest before the test started. The test was carried out using protocol described by Leger et al. (1988) and began at a speed of 8.5km.h^{-1} and increased by 0.5km.h^{-1} every minute. Athletes were instructed to go until voluntary exhaustion or until they missed completing three consecutive shuttles in time with the audio signal. All tests were performed with at least three participants in order to increase motivation and encouragement was received throughout from the researcher. Athletes' scores are presented as the total number of shuttles completed. These scores were also used to compute estimated VO_{2max} score using the following equation by Leger et al. (1988):

$$Y = -27.4 + 6.0X_1$$

where Y = estimated VO_{2max} and X_1 = highest running speed (km.h^{-1}). For those athletes under 18 years old, the following equation was used:

$$Y = 31.025 + 3.238X_1 - 3.248X_2 + 0.1536X_1X_2$$

Where X_2 = age in years rounded to the lower integer.

4.2.7. Statistical Analysis

All statistical analysis was performed on *IBM SPSS Statistics 24*. Males and females were compared using independent sample t-tests. One-way ANOVAs were used to analyse the effect of weight category and group on the body composition and performance variables of males and females and Tukey's pairwise comparisons were then used to examine differences between means of weight categories and groups. Effect sizes, via Cohen's d, were used to further determine the magnitude of the differences between means (Sullivan and Feinn, 2012).

$$\text{Cohen's } d = \frac{M_1 - M_2}{s}$$

$$\text{where s} = \sqrt{\frac{(s_1{}^2 - s_2{}^2)}{2}}$$

and M_1, M_2 = mean of each sample and s_1,s_2 = standard deviation of each sample. Effect sizes (ES): 0.2 = small, 0.5 = medium, 0.8 = large; 1.5 = very large.

4.3. Results

4.3.1. Body Composition

Body composition data (Table 12) demonstrated that males have 6.8% greater LM% and 7% lower FM% than female taekwondo athletes at a significance of $p < 0.001$ (ES = 1.5 for both).

MALE: There was a significant difference in BM for all weight categories (Table 10) ($p < 0.01$). The FM of +80kg athletes was 17.6kg and 15.1kg greater than that of -58kg and -68kg athletes, respectively ($p < 0.001$, ES = 3.9 and 3.1, respectively). Furthermore, -58kg athletes had 22kg and 24.1kg less LM than -80kg and +80kg athletes ($p \leq 0.001$, ES = 4.2 and 4.0, respectively), while -68kg athletes had 16.1kg less LM than +80kg athletes ($p = 0.002$, ES = 2.6). The LM% of +80kg athletes was 10.7% and 9.7% less than -58kg ($p = 0.004$; ES = 2.3) and -68kg ($p = 0.007$; ES = 2.0) athletes, respectively while the FM% of +80kg athletes was 11.6% and 10.1% greater than -58kg ($p = 0.003$; ES = 2.4) and -68kg ($p = 0.007$; ES = 1.9) athletes, respectively. There was no effect of group on BM, LM, FM, LM% or FM%.

FEMALE: -49kg athletes had significantly lower BM by 12.3kg, 15.7kg and 23.9kg than -57kg, -67kg and +67kg athletes, respectively ($p < 0.001$; ES = 6.4, 6.2 and 13.6, respectively). -57kg athletes had significantly lower BM by 11.6kg than +67kg athletes ($p < 0.001$; ES = 5.6) and -67kg athletes had a significantly lower BM than +67kg athletes by 8.2kg ($p = 0.007$; ES = 3.1). -49kg athletes also had significantly less LM than all other weight category athletes by 5.9kg (ES = 1.2), 9.9kg (ES = 2.1) and 16.5kg (ES = 8.4) versus -57kg, -67kg and +67kg athletes, respectively ($p < 0.05$;) while -57kg athletes had significantly lower LM than +67kg athletes by 10.6kg ($p = 0.001$, ES = 2.1). -49kg athletes had significantly less FM than -57kg athletes by 5.9kg ($p < 0.05$; ES = 2.4) and +67kg athletes by 6.5kg ($p < 0.05$; ES = 2.8). There were no differences in LM% and FM% between weight categories. There was no effect of group on any of the body composition variables.

Table 12 Body composition characteristics by sex, weight category and athlete level

		n	BM (kg)	FM (kg)	FM%	LM (kg)	LM%
Male	-58	5	60.9±1.8	8.0±0.7*	13.1±1.4**	49.9±2.0*§	81.9±1.5+
	-68	6	71.6±4.0	10.5±2.3*	14.6±2.9**	57.9±3.3**	80.9±2.9+
	-80	2	91.3±2.7	15.2±1.2	16.8±2.5	71.9±7.1	78.7±2.7
	+80	3	103.8±2.7	25.6±6.4	24.7±6.6	74.0±8.2	71.2±6.2
	TOP	7	81.2±15.9	12.3±4.1	14.9±2.6	65.1±11.7	80.3±2.3
	TARG	9	73.3±17.4	13.8±9.0	17.4±6.7	56.4±8.2	78.2±6.4
	Total	16	76.8±16.7	13.1±7.1	16.3±5.3&	60.2±10.5	79.1±5.0&
Female	-49kg	4	52.4±1.6	10.8±1.2	20.6±1.7	39.3±0.6	75.0±1.6
	-57kg	5	64.7±2.2^$	16.7±3.2++	25.7±4.1	45.2±6.7^^	69.9±3.7
	-67kg	2	68.1±3.2^$	15.9±3.6	23.6±6.4	49.2±6.7^^$	72.1±6.4
	+67kg	3	76.3±1.9^	17.3±3.1++	22.7±3.8	55.8±2.7^^	73.1±3.4
	TOP	7	67.0±7.9	14.9±2.0	22.4±3.0	49.1±6.9	73.2±3.0
	TARG	7	61.4±9.8	15.2±5.1	24.2±4.8	43.6±5.2	71.5±4.5
	Total	14	64.2±9.1	15.0±3.7	23.3±4.0	46.3±6.5	72.3±3.8

FM = fat mass; FM% = percentage body fat; LM = lean mass; LM% = percentage lean mass; & > female, p < 0.001; MALE: * < +80kg, p < 0.001; § < -80kg, p ≤ 0.001; ** < +80kg, p < 0.01; + > +80kg, p < 0.01;; FEMALE: ^ > -49kg, p < 0.001; $ < +67kg, p < 0.01; ^^ > -49kg, p < 0.05; ++ > -49kg, p ≤ 0.05

4.3.2. Anaerobic Profile

The anaerobic profile characteristics are summarised in Table 13.

4.3.2.1. Wingate

For both male and female athletes, there was no significant effect of weight category or group or no significant interaction effect on relative PPO, relative mean power output or FI%. Male athletes demonstrated both a greater relative PPO than female athletes in the 30-second Wingate test (M: 10.1 ± 1.4 $W.kg^{-1}$; F: 9.0 ± 1.2 $W.kg^{-1}$, p = 0.03; ES = 0.8) and a greater relative mean power output (M: 7.9 ± 0.9 $W.kg^{-1}$, F: 6.7 ± 0.8 $W.kg^{-1}$; p = 0.001; ES = 1.4). However, there was no significant difference in FI% between males (46.4 ±10%) and females (43.2 ± 11.7%) (ES = 0.3).

4.3.2.2. Jump Testing

For both male and female athletes, there was no significant effect of weight category or group or no significant interaction effect on either CMJ or SJ. Male athletes had a significantly greater mean CMJ and SJ height than females (CMJ: 35.5 ± 6.0cm versus 29.9 ± 4.4, p = 0.01, ES =1.1; SJ: 31.9 ± 5.5cm versus 28.0 ± 4.1cm, p = 0.044, ES = 0.8).

4.3.3. Aerobic Profile

4.3.3.1. MSFT

The aerobic characteristics of taekwondo athletes are summarised in Table 14. In male athletes, there was a significant effect of group on both MSFT score and VO_{2max} with TOP athletes outperforming TARG athletes by a score of 8 and 1.9 $ml.kg^{-1}.min^{-1}$ ($p < 0.05$, ES = 0.6 and 0.8), respectively. -58kg athletes significantly outperformed +80kg athletes in the MSFT by a score of 40 (p = 0.02; ES = 5.0) leading to a significantly greater VO_{2max} (55.4 ± 2.7 $ml.kg^{-1}.min^{-1}$ versus 44.6 ± 0.0 $ml.kg^{-1}.min^{-1}$, p = 0.001; ES = 5.7) Similarly, -68kg athletes outperformed +80kg athletes by a score of 43 (p = 0.004; ES = 2.9) a had a significantly greater VO_{2max} score (56.1 ± 5.5 $ml.kg^{-1}.min^{-1}$, p = 0.003; ES = 3.0). There was no significant effect of weight category or group on the MSFT score or VO_{2max} score in females. Male athletes had a significantly greater mean MSFT score (103 ± 20) than females (78 ± 20) (p = 0.006; ES = 1.3). Males also had a significantly greater VO_{2max} score than females (M: 54.0 ± 5.5 $ml.kg^{-1}.min^{-1}$, F: 47.3 ± 5.4 $ml.kg^{-1}.min^{-1}$; p = 0.05; ES = 1.2).

Table 13 Anaerobic characteristics of taekwondo athletes by sex, weight category and athlete level

		n	PPO (W/kg)	MPO (W/kg)	FI (%)	SJ (cm)	CMJ (cm)
Male	-58	5	9.9 ±1.6	7.9 ±0.8	40.1 ±11.1	30.0 ±2.6	34.4 ±4.5
	-68	6	10.8 ±1.6	8.2 ±1.1	52.3 ±8.4	31.7 ±6.3	35.9 ±7.0
	-80	1	9.9	7.9	44.7	38.2	40.8
	+80	2	9.0 ±0.1	7.2 ±0.2	43.9 ±1.5	34.1 ±10.5	34.4 ±9.9
	TOP	6	10.0 ±1.3	8.0 ±1.0	43.8 ±6.0	33.6 ±7.3	36.6 ±7.3
	TARG	8	10.2 ±1.5	7.9± 0.8	48.3± 12.2	30.6± 3.8	34.7± 5.2
	Total	14	10.1± 1.4*	7.9± 0.9**	46.4± 10.0	31.9 ±5.5*	35.5± 6.0*
Female	-49kg	4	8.9± 1.3	6.9± 0.8	38.3± 17.5	25.3± 2.1	27.3± 2.6
	-57kg	5	9.0 ±1.4	6.6 ±1.0	46.4 ±9.4	29.4 ±5.7	31.3 ±6.0
	-67kg	2	9.3 ±1.0	6.8 ±1.0	47.3 ±5.8	29.6 ±4.8	31.6 ±5.7
	+67kg	3	9.2 ±1.4	6.6 ±0.7	41.7 ±12.3	28.1 ±2.1	30.0 ±2.4
	TOP	7	9.2 ±1.2	6.8 ±0.7	41.0 ±12.1	29.8 ±3.7	31.8 ±4.4
	TARG	7	8.8 ±1.2	6.5 ±0.9	45.4 ±11.8	26.1 ±3.8	28.1 ±3.8
	Total	14	9.0 ±1.2	6.7 ±0.8	43.2 ±11.7	28.0 ±4.1	29.9 ±4.4

PPO = peak power output; MPO = mean power output; FI = fatigue index; SJ = squat jump; CMJ = countermovement jump; * > female, $p < 0.05$; ** > female, $p = 0.001$;

Table 14 Aerobic characteristics of taekwondo athletes by sex, weight category and athlete level

		n	MSFT score (no. of shuttles)	Estimated $VO2_{max}$ ($ml.kg^{-1}.min^{-1}$)
Male	-58	5	107±9 $^{\&\&}$	55.4±2.7 $^{\&}$
	-68	6	110±20 $^{\&}$	56.1±5.5 $^{\&}$
	-80	1	106	53.6
	+80	2	67±7	44.6±0.0
	TOP	6	107±26^{+}	55.1±7.3^{+}
	TARGET	8	99±17	53.2±4.1
	Total	14	103±20*	54.0±5.5**
Female	-49kg	4	85±22	49.1±5.7
	-57kg	4	71±18	45.4±5.7
	-67kg	2	90±19	50.6±4.2
	+67kg	1	57	41.6
	TOP	4	85±18	49.9±4.5
	TARGET	7	74±21	45.9±5.7
	Total	11	78±20	47.3±5.4

MSFT = multistage fitness test; $VO2_{max}$ = maximum oxygen uptake, * > female, $p < 0.01$; ** > female, $p = 0.05$; $^{+}$ > TARG, $p < 0.05$; $^{\&}$ > +80kg, $p < 0.005$; $^{\&\&}$ > +80kg, $p < 0.05$

4.4. Discussion

The aim of this study was to 1) to create an up-to-date profile of the physical and physiological characteristics of taekwondo athletes under the current rule set, 2) to compare this data with previous literature prior to the rule changes to assess the impact of these changes on physiological characteristics and 3) to determine any differences in physiological characteristics between sexes, weight categories and athletes of two levels of performance success. The data collected in this study indicated males outperformed females in all variables except FI%. There were significant differences in BM, LM and FM between weight categories for both males and females but only male athletes demonstrated differences in weight classes for FM% and LM%. Similarly, only males demonstrated a difference in MSFT and VO_{2max} score between weight categories and performance levels.

4.4.1. Body Composition

The majority of competitive taekwondo athletes fight at a weight class below their natural weight with the belief that this will provide a competitive advantage over their opponent (Kazemi, Rahman and De Ciantis, 2011). In order to optimise this process and increase their power-to-weight ratio, combat athletes favourably reduce their fat mass when making weight for competition (Langan-Evans, Close and Morton, 2011). For that reason, body composition is a defining and important characteristic for taekwondo athletes. This study provides a profile of body composition for both male and female taekwondo athletes across all of the Olympic weight classes. The data in the present study, measured by DXA scan, demonstrated a significant difference between male and female athletes in both LM% and FM% which is consistent with normative data reported across a wide range of sports and athletes (Santos *et al.*, 2014a). It also showed higher FM% for male athletes (16.3 ± 5.3%) than that reported in two other studies in the literature that measured body composition via DXA scan.

It is difficult to make direct comparisons between our data and the majority of data available in the literature because of the error introduced by using prediction equations to estimate body fat (Santos *et al.*, 2014a; Fonseca-Junior *et al.*, 2017). Unpublished data from our lab has found large discrepancies between typical body composition prediction equations and DXA derived body composition data in taekwondo athletes. Therefore, it is challenging to assess whether there are changes in the body composition profiles of taekwondo athletes since the introduction of rule

changes after the 2008 Olympics. However, there are some studies that have utilised DXA scans for measuring body composition. Table 15 demonstrates a comparison of the data in the present study with that in the literature prior to the rule changes.
One study reported median FM% of 9.5% for elite Spanish male athletes (Ubeda *et al.*, 2010) which is substantially less than the median FM% reported in this study (15.1%). Similarly, another study reported mean FM% of 11.4±2.4% for elite collegiate male athletes prior to an 8-week pre-season training period (Seo *et al.*, 2015). However, the BM range of the athletes reported in these studies was significantly smaller (67.8-90.6kg and 60-79kg, respectively) than that of the athletes reported in the present study (58.3-106.82 kg). Since we demonstrated that heavyweights have a significantly greater FM% than lower weight categories this may account for the difference seen between the data in the present study and those reported above. On the other hand, Seo et al. (2015) reported FM% of elite female collegiate athletes to be 23.2±3.6%, which is very similar to the data reported for the females in this study despite the fact that there is also large difference in the range of BM values seen between that reported by Seo et al. (2015) (53-66kg) and our data (51.0-78.1kg). However, this is likely explained by the lack of significant difference between heavyweight and lighter weight females for FM%. Since data in the present study demonstrated a difference in body composition between weight categories it is therefore difficult to identify meaning when comparing mean body composition variables of taekwondo athletes from mixed weight categories between studies, particulalrly in males. For that reason, the present study provides the first weight category specific body composition physiological profile, using DXA scan technology, for international taekwondo athletes.

Table 15 Comparison of body composition, via DXA, of data from the present study versus that carried out prior to the rule changes

Reference	Athlete Characteristics (n)	Sex	BM (kg)	FM (kg)	LM (kg)	%FM
Present Study	**British International (15M, 14F)**	**M&F**	**M: 76.8 ±16.7 F: 64.2 ± 9.1**	**M: 13.1 ± 7.1 F: 15 ± 3.7**	**M: 60.2 ± 10.5 F: 46.3 ± 6.5**	**M: 16.3 ± 5.3 F: 23.3 ± 4**
Manjarrez-Montes de oca et al., 2013	Recreational (12)	M	66-69	10-12	54-55	16-18
Ubeda et al., 2010	Spanish International	M	78			9.5
Seo et al., 2014	University (22M, 12F)	M&F	M:68-69 F:57-59	M:6-8 F:12-14		M:9-11 F: 21-23
Monks et al., 2017	Elite university (33)	M&F		10-12	53-54	16-18
Kim et al., 2011	Recreational adolescents (21)	F	53			29-31

M = male, F = female, BM = body mass, FM = fat mass, LM = lean mass, %FM = body fat percentage, DXA = dual energy x-ray absorptiometry

There was no significant effect of the level of success (TOP vs. TARG) on the body composition of either the male or female athletes investigated in the present study. Bridge et al. (2014) states that differences in body composition between experience levels may be attributed to different training regimen, nutritional practices and/or requirements to make certain weight categories. However, since all of the athletes in the present study were subject to the same training schedule, given the same nutritional advice and required to compete at Olympic weight categories, this might explain why no differences were seen. Therefore, it is possible that once training and nutritional guidelines are sufficient for athletes, body composition is not a distinguishing factor between success levels of athletes at the beginning of a season. However, further research would be required to examine whether this changes as athletes get closer to competition.

Table 16 Comparison of Wingate anaerobic test data between the present study and that seen in the literature prior to the rule changes

Reference	Athlete Characteristics (n)	Sex	PPO ($W.kg^{-1}$)	MPO ($W.kg^{-1}$)	FI (%)
Present Study	**British International (15M, 14F)**	**M&F**	**M: 10.1 ± 1.4 F: 9.0 ± 1.2**	**M:7.9 ± 0.9 F:6.7 ± 0.8**	**M:46.4 ± 10.0 F:43.2 ± 11.7**
Monks et al., 2017	Elite collegiate (33)	M+F	10.2-10.9		
Seo et al., 2015	University (34)	M+F		M:7.5-8.3 F:6.2-6.5	M:43-44 F:46-47
Rhyu et al., 2014	Korean highschool (20)	M		6-7	52-59
Manjarrez-Montes De Oca et al., 2013	Recreational (10)	M	6-8	5-6	27-33
Sadowski et al., 2012	Polish National and International (28 medallists, 36 non-medallists)	M	Medallists: 9.9 ± 1.0 Non-medallists: 9.1 ± 1.5		
Lin et al., 2006	Taiwanese International (11M, 7F)	M&F	M: 8.4 ± 0.9 F: 6.6 ± 0.6	M: 6.6 ± 0.6 F: 5.5 ± 0.9	
Bercades et al., 1995	US post-pubertal junior olympic athletes (76 M, 54 F)	M&F	M: 11.3 ± 0.2 F: 9.0 ± 0.2	M:8.2 ± 0.1 F:6.6 ± 0.1	
Taaffe and Pieter, 1991	US junior olynpic athletes (27M, 24 F)	M&F	M: 10.7 ± 0.3 F: 8.4 ± 0.3	M:8.4 ± 0.2 F:6.6 ± 0.2	
Taaffe and Pieter, 1990	US International (12M, 8F)	M&F	M: 11.8 ± 2.0 F: 10.2 ± 2.5	M: 9.2 ± 1.2 F: 7.9 ± 1.2	

M = male, F = female, PPO = peak power output, MPO = mean power output, FI = fatigue index

Table 17 Comparison of vertical jump performances using optical acquisition systems* in present study versus the literature prior to the rule changes

Reference	Athlete Characteristics (n)	Sex	SJ (cm)	CMJ (cm)
Present Study	**British International (15M, 14F)**	**M&F**	**M: 31.9 ± 5.5** **F: 28.0 ± 4.1**	**M: 35.5 ± 6.0** **F: 29.9 ± 4.4**
Casolino et al., 2012	Italian National (NR)	M&F	M: 35-40 F: 23-28	M: 39-42 F: 26-29
Chiodo et al., 2011	Italian International (11M, 4F)	M&F		Pre match M: 40.8 ± 4.9 F: 28.2 ± 2.5 Post match M: 43.9 ± 5.2 F: 30.8 ± 2.3
Markovic et al., 2005*	Croatian International (6 medallists, 7 non-medallists)	F	Medallists: 29.8 ± 2.9 Non-medallists: 27.7 ± 2.4	Medallists: 32.8 ± 3.9 Non-medallists: 28.7 ± 1.9

M = male, F = female SJ = squat jump, CMJ = countermovement jump, NR = not recorded. * used jumpmat technology

Table 18 Comparison of estimated maximal oxygen uptake of athletes in current study compared with the data in the literature from shuttle run tests prior to the change in rules

Reference	Athlete Characteristics (n)	Sex	Predicted $V02_{max}$
Present Study	**British International**	**M&F**	**M: 54.0 ± 5.5** **F: 47.3 ± 5.4**
Perandini et al., 2010	Brazilian International (7M, 4F)	M&F	M: 51.9 ± 2.9 F: 41.6 ± 2.4
Butios and Tasika, 2007	Korean International (8 <68kg, 8 < 80kg, 8 > 80kg)	M	< 68kg: 53.9 ± 4.1 < 80kg: 54.7 ± 4.1 > 80kg: 52.6 ± 3.9
Bouhlel et al., 2006	Tunisian International (8)	M	56.2 ± 2.6

M = male, F = female

4.4.2. Anaerobic Profile

The muscular power of taekwondo athletes' lower limbs is important in order to generate kicks, the delivery of which require the rapid application of force under unloaded conditions (James, Kelly and Beckman, 2013). A common way to measure the muscular power of the lower limbs is through countermovement (CMJ) and squat jumps (SJ) (Suchomel *et al.*, 2015). CMJ and SJ performance differed between males and females as is commonly seen in the literature in combat sports (Bridge *et al.*, 2014; Chaabène *et al.*, 2015; Chaabène *et al.*, 2012; Franchini *et al.*, 2011). Despite these differences, the CMJ and SJ performances of the male athletes only in the present study (Table 17) are substantially lower than those reported in previous studies using similar technology (CMJ: 39-43cm; SJ: 35-40cm) (Chiodo *et al.*, 2011; Casolino *et al.*, 2012). On the contrary, the performances of the female athletes in the present study (Table 17) fall well within the ranges previously reported (CMJ: 26-32cm; SJ: 27-29cm) (Casolino *et al.*, 2012; Marković, Misigoj-Duraković and Trninić, 2005). Given that previous literature has shown taekwondo athletes to score lower in these variables than other combat sports such as karate and judo (Bridge *et al.*, 2014; Chaabène *et al.*, 2012; Franchini *et al.*, 2011), it is pertinent to question why the male athletes, and not the female athletes, in the present study have an even more reduced power profile. It is possible that this is representative of different training methodologies between the male and female athletes. However, it may also be influenced by a change in the dynamics of taekwondo with the introduction of the new rule set. For example, the increased frequency of high-intensity exchanges within combats will reduce the overall intensity of these exchanges due to the inverse intensity-duration relationship of energy system contribution (Chapter 3.4). As a result, it may not be necessary, at least in males, to be able to produce maximal power outputs in modern day taekwondo combats.

Taekwondo combats are high-intensity and intermittent in nature with exchanges that last an average of 2 seconds (Hausen *et al.*, 2017; Bridge, Jones and Drust, 2011). Anaerobic pathways, such as ATP-PCr and anaerobic glycolysis, are predominantly responsible for fuelling these high-intensity exchanges (Campos *et al.*, 2012; Bridge *et al.*, 2014). For this reason, taekwondo athletes must have well-developed anaerobic energy systems. Table 16 compares the anaerobic Wingate test relative PPO and MPO scores for the present study versus the data in the literature prior to the rule changes. Both PPO and MPO scores are similar across all studies. This suggests that the anaerobic power and capacity of taekwondo athletes has not changed substantially with the introduction of a myriad of rule changes. However, as discussed previously, the current physical demands of taekwondo combats require athletes to repeatedly engage in up to 60 high-intensity exchanges over the course of three rounds. This indicates that a high level of anaerobic capacity would be advantageous for taekwondo athletes to resist fatigue during combat. Therefore, increased MPO may be an area to enhance the physical preparation of athletes for competition.

There were no differences between weight categories or success level in either males or females, the former of which is in agreement with a study in Taiwanese athletes which showed no differences in PPO between weight classes, albeit with small sample sizes (Lin *et al.*, 2006). The latter, however, is contrary to previous literature which has recorded a tendency for more successful male athletes to have a greater relative PPO (Sadowski *et al.*, 2012b) than their less successful counterparts (Table 16). This observation, which suggests that PPO no longer distinguishes between athlete success levels, lends further support to a reduction in the requirement of absolute power for success in modern taekwondo. This data, along with the CMJ and SJ data, may indicate a reduced necessity for, at least in males, modern day taekwondo athletes to exhibit high levels of lower limb muscular power which is in line with the demands of taekwondo combat under the current rule set (Chapter 3). Since the degree of difference between modern and past taekwondo athletes, in terms of power output, is greater in males, it stands to reason that there might be a superior physiological influence and component to taekwondo performance in male athletes than in female athletes.

4.4.3. Aerobic Profile

The importance and predominance of the aerobic energy system to taekwondo combat was discussed in chapter 1.5.3. Aerobic energy systems are crucial for sustaining lower intensity actions during taekwondo as well as for assisting recovery from high intensity actions during and between taekwondo bouts. It has also been shown that repeated exposure to taekwondo combats, such as that experienced during a competition day, modulates the physiological demand in successive bouts with a reduced plasma noradrenaline and blood lactate response and an increased HR response (Bridge *et al.*, 2018). Furthermore, a reduced work:rest ratio in the current iteration of taekwondo combats may enhance the reliance on aerobic energy (Chapter 3). This study showed a significant but expected difference in the MSFT scores between male and female athletes ($p < 0.01$; ES = 1.3). The mean estimated values of VO_{2max} for the athletes in the present study (M: 54.0±5.5 $ml.kg^{-1}.min^{-1}$, F: 47.3±5.4 $ml.kg^{-1}.min^{-1}$) are compared to the shuttle run test data in the literature for taekwondo athletes prior to the rule changes in Table 18. The data for both males and females are comparable to what was observed in the present study. Similarly, this data is at the lower end of that recorded for male boxers (49-65 $ml.kg^{-1}.min^{-1}$) (Chaabène *et al.*, 2015) and karatekas (57-61 $ml.kg^{-1}.min^{-1}$) (Chaabène *et al.*, 2012) but within the ranges recorded for female boxers (44-52 $ml.kg^{-1}.min^{-1}$) (Chaabène *et al.*, 2015). Karate combat (Beneke *et al.*, 2004) and boxing combat (Davis, Leithäuser and Beneke, 2014) have both been shown to have a greater contribution of aerobic energy (77.8 ± 5.8% and 77%, respectively) than simulated taekwondo combats prior to the rule changes (66 ± 6%) (Campos *et al.*, 2012). Since the demand for aerobic energy supply increases as a competition day unfolds thus potentially rendering finals as requiring more aerobic contribution than matches earlier in the day (Bridge *et al.*, 2018) and the rule changes may have further increased the aerobic cost of combat, this warrants increased focus on the development of the aerobic capacity of high-level taekwondo athletes.

The data in the present study showed that there was a significant effect of weight category on aerobic capacity in males but not in females (Table 14). The only other taekwondo study which compares the differences between weight categories (Butios and Tasika, 2007) of males showed no significant differences (Table 18). However, literature in other combat sports such as that in female wrestlers, junior male boxers and male and female judo players demonstrated a propensity for heavyweight athletes to have lower aerobic capacities than that of the lighter weight categories (Franchini *et al.*, 2011; Zi-Hong *et al.*, 2013; Khanna and Manna, 2006) which is similar to the data for the male athletes in the present study. This finding adds weight to the implication that the physiological demands of current taekwondo combats are greater in male athletes than in female athletes.

Our data also showed no effect of athlete's level of success on aerobic capacity in female athletes which is similar to data seen in studies in judo (Franchini *et al.*, 2005) and karate athletes (Imamura *et al.*, 1998). However, male TOP athletes in the present study significantly outscored TARG athletes ($p < 0.05$; ES = 0.6) further adding weight to case for an increased physiological demand for male taekwondo combat compared to females. This is similar to differences in aerobic capacity have been reported between junior and senior male Indian boxers although these athletes were divided by age (Senior:20-25 years; Junior: < 19 years) rather than success level which may have been the determining factor in these differences (Khanna and Manna, 2006). It is worth noting that the small sample sizes in the heavier weight categories (welterweight and heavyweight) for both males and females in the present study may not allow possible differences to be detected. It is also possible that the lack of differences between weight categories may indicate that all taekwondo athletes must possess a certain level of aerobic fitness in order to manage the demands of both training and competition. Furthermore, this consistency in aerobic capacity in the female cohort may also be influenced by the enhanced ability of females to resist fatigue in comparison to males (Hicks, Kent-Braun and Ditor, 2001). This ability, via mechanisms such as substrate utilisation, muscle mass and muscle morphology, may impact the affect of competition demands and/or training on female physiology meaning that there are less differences between weight categories and athletes of different levels due to overall increased ability to resist fatigue.

Athletes in the present study were examined at the beginning of the season after having some time off which may impact the results and comparisons being made above. However, by its very nature, profiling of combat athletes provides only a snapshot of the physiology and physical characteristics which will be influenced by phase of the training cycle (Ball, Nolan and Wheeler, 2011) and the training methodologies employed. The lack of distinctions that can be made between weight categories but particularly between experience level suggest that these characteristics are influenced heavily by the training methodologies of athletes but also that these traits are subjective to the changing demands of competition. Despite this, it seems that present day taekwondo athletes, and in particular the males, are athletes with moderate aerobic and anaerobic capacities and reduced abilities to produce maximal power outputs. Therefore, under the current set of rules, which increase the frequency of exchanges and reduce the rest during combats leading to an increase in the physiological response, importance should be placed on developing these capacities in order to enhance physical preparation and increase the chances of success.

4.5. Limitations

The predominant limitation in this study arises as a result of limited participant demographics and a subsequent impact on the statistical meaningfulness of comparison between groups. For example, there were limited numbers of athletes available in the higher weight categories for both males and females meaning comparisons of variables between weight categories was difficult. For some variables such as MSFT score, there were as few as n = 1 athletes in some of the categories (-80kg males). As alluded to in the study, this makes it difficult to discern whether there are real differences in the physiological profiles between weight categories. Additionally, data collection was restricted to the beginning of the taekwondo season to reduce the impact on the training and preparation for competition. The resultant physiological profile therefore, does not take into account the changes that may occur as athletes prepare for competition, particularly with respect to body composition and making weight.

4.6. Influencing the Physiological Profile through Training

This study compared the physiological profile of taekwondo athletes under the current rule set with the data in the literature prior to the rule changes and found most physical and physiological characteristics were largely consistent with those reported previously. Given that the previous study demonstrated an increased physiological response to competition with the current rule set, this suggests that optimal preparation of taekwondo athletes would benefit from increasing aspects of their physiological profile such as anaerobic and aerobic capacity. The physiological profile showed a limited difference between athletes of distinct success levels and variations only in body composition and aerobic capacity between weight classes and athlete level in males. It also showed divergent values between male and female athletes in line with normative data and interestingly, indicated that male taekwondo athletes may be more heavily influenced by the physiological demands of combat than female athletes.

Creating a physical and physiological profile can serve as the basis on which to structure and plan training programmes to optimise taekwondo athletes' physical preparation for the demands of combat. However, physiological profiles are influenced by the training phase and training methodologies in place at the time of data collection. In order to understand how to achieve and optimise these profiles, the causative training practices must also be examined. Training methodologies can then be manipulated with optimisation of the physiological profiles in mind. Therefore, the next study aims to investigate the current training strategies being employed by high-level taekwondo athletes and the factors that effect the optimisation of the physiological profile.

Chapter 5

The Demands High-level Taekwondo Training and the Factors that Influence Training Organisation

5.0. The Demands of High-level Taekwondo Training and the Factors that Influence Training Organisation

5.1. Introduction

The previous studies in this thesis examined both the physiological demands of international taekwondo competition under the current rule set and the physiological profiles of present day international taekwondo athletes and indicated that there may be some discrepancies between them, particularly for male athletes. The aim of physical preparation is to appropriately develop the physiological characteristics of athletes for the demands of competition and this is achieved through adequate training methodologies and organisation. However, in order to optimise these processes, current training practices must first be assessed. Investigation of these training practices may then allow an understanding of the factors that affect the optimisation of the physiological profiles of athletes and therefore can offer areas to develop and enhance physical preparation for competition.

Taekwondo training represents the time athletes spend on physical, technical and tactical preparation for competitive performance. The aim of training is to expose the body to stressful stimuli in order to adapt and increase fitness and skill acquisition. This training stress is quantified using a variety of tools that were discussed in Chapter 1.6.1 and include both external and internal measures of TL in order to get a cohesive picture of the stress imposed through the physical work completed and the physiological response to that work, respectively. For athletes that train at a high frequency and/or volume, an accumulation of stress occurs from training sessions with inadequate recovery periods between them (Le Meur *et al.*, 2013). Therefore, the organisation of training must also be assessed in order to understand whether it is appropriate to maximise adaptations and performance success and to mitigate the risk of injury and over training (García-Pallarés *et al.*, 2009).

The organisational efficacy of training can be assessed by examining the factors that may affect the ability of an athlete to complete the required training load for optimal physical preparation. In combat sports, one of the key factors that may impact training organisation is the competition schedule and subsequent weight making process. Athletes focused on competing regularly and having to manipulate body mass to do so may impact their ability to undergo and recover from the training stress required to optimise physical preparedness. Additionally, the occurrence of injury can also have an impact on the ability to complete scheduled training sessions. Therefore, it is important to assess the impact these factors may have on the training load experienced by athletes.

A physically demanding sport like taekwondo requires athletes to maximise physical preparation, and thus their physiological profile, through adequate and efficient training stimuli. However, in order to correctly plan and implement a well-structured and relevant periodised training plan, the physical and physiological demands of training, along with its organisation, must first be well documented and understood. A number of studies are emerging examining the training stresses and needs of judo athletes (Agostinho *et al.*, 2017; Franchini, Panissa and Julio, 2013; Bromley *et al.*, 2018; Baudry and Roux, 2009). These studies have then enabled subsequent work examining the implementation of periodisation strategies and the optimal methods to maximise physical preparation of judo athletes (Franchini *et al.*, 2015; Ullrich *et al.*, 2016; Marques *et al.*, 2017). However, the literature surrounding the long term training load or demands of taekwondo athletes is scarce and as a result of this it is difficult to plan and implement training periodisation strategies to optimise the physical preparation of these athletes and align it with the technical and tactical preparation. Therefore, the aims of this study were: 1) to investigate and define the training load and demands of high-level taekwondo athletes and 2) to assess the factors affecting the efficient organisation and understanding of the training load experienced by athletes in a taekwondo training programme.

5.2. Methods

5.2.1. Participants

Participants included male (n = 14) and female (n = 11) members of the Great Britain National Academy. Participants were informed of what the study involved and all gave prior consent to take part. The study was conducted with the full approval of the Liverpool John Moore's research ethics committee. Only a subset of the entire participant collection was included during each test week due to injuries, competitions and scheduled time off training. On a session-by-session basis, participants who were available to train during the test week were included in the data collection for that week in order to be representative of the typical training population.

5.2.2. Experimental Approach

All data collection for this study was carried out at the National Training Centre (NTC). Participants were tested during 4 non-successive, equally spaced weeks over the course a 13-week macrocycle in the lead up to an international competition. The macrocycle consisted of two mesocycles; a general phase (GP) designed to prepare athletes physically for the demands of training and combat and a competition phase (CP) focused on preparing athletes more specifically for the technical, tactical and specific demands of combat. The first two testing weeks (week 2 and week 5) were during the GP and the second two testing weeks (week 8 and week 12) were during the CP. For the purposes of the current study, all group-training sessions were considered. This refers to scheduled training sessions where athletes trained as part of a group. Therefore, certain types of training sessions were excluded from analysis; these included individual sessions, rehabilitation sessions and sessions added in to promote weight loss.

The aim of the first part of this study was to characterise the training load of elite taekwondo athletes. For this, session frequency and type along with subjective wellbeing data was measured on every training day throughout the entire macrocycle. During the four test weeks (2, 5, 8 and 12) the activity profile and the heart rate (HR) of all taekwondo sessions and the session rating of perceived exertion (sRPE) of both taekwondo and non-taekwondo sessions (resistance training and general conditioning) were measured.

The aim of the second part of this study was to examine the factors that affect the organisation of long term training plans. For this, the above data were assessed with respect to: 1) injury data that was recorded in conjunction with medical professionals for the duration of the macrocycle, 2) competition schedule data during the macrocycle, 3) session attendance data and 4) the difference between athlete level and experience (TOP v TARG).

5.2.3. Part 1

5.2.3.1. Session Type and Frequency

The type and the frequency of each training session were recorded throughout the macrocycle. At the end of each training session, a conversation took place with the lead coach and they were asked to recount what training methods and tasks had taken place throughout the sesssion. This information was used to determine the training session type based on the requirements detailed in Table 7 (Chapter 2.2.2.). Taekwondo training sessions were grouped in to five main categories: conditioning sessions (COND), sparring and test match sessions (SPAR) technical/tactical sessions (T/T), tactical sessions (TAC) and technical sessions (TECH) (Table 7). General training sessions were grouped in to resistance training (RT), which was composed of strength, power, mobility and pre-habilitation training and general conditioning (GC), which consisted of training in a wide range of modes (such as bikes, treadmills, circuits, sleds, cross-trainers, ski ergs, rowers etc). All of the general training sessions (RT and GC) were individualised to athlete's specific needs based on injury status, objective performance requirements utilising data from the physiological profile of each athlete (study 2, Chapter 4), gym training age and body composition/weight making requirements.

5.2.3.2. Session Volume

Session volume was the duration, in minutes, of each training session. Athletes were required to check in and out of training sessions on a computer screen situated in the training hall. This then calculated the duration of each athletes training session. Cumulative session volume was calculated by summing the session volume for each athlete for all sessions during a test week. The mean cumulative session volume for the whole group was calculated by getting the average of this number.

5.3.2.3. Subjective Wellbeing

Each athlete recorded wellbeing data first thing in the morning every day of the training week during the macrocycle. Questions were answered on participants' personal smartphone devices to increase compliance and aid ease of use. The app on their smartphone sent out a reminder to complete their wellbeing data on awakening each morning. The app allowed them to answer 6 questions relating to their physical and mental wellbeing by selecting a number from 1-10 on the colour-coded sliding scale within the app (Table 8). This ensured athletes reported their daily wellbeing before they started their day and without any influence from their peers.

5.3.2.4. Activity Profile

Taekwondo training sessions were monitored closely during the test weeks and the activity profile was recorded. A researcher, familiar and experienced with the sport and the training process, used a hand held stopwatch to record the time participants spent working actively (ACTIVE), passively (PASSIVE) and at rest (REST). These were defined as follows:

- ACTIVE was defined as the time per training session that participants spent kicking or punching pads or body armour, the time spent between these actions setting up for the next action and the repeated repetitions of these actions
- PASSIVE was defined as the time spent holding pads for partners or taking kicks on the body armour and the movement in between
- REST was defined as the time spent having breaks between active and passive work, either standing or seated on the ground

A description of the type of activity was also recorded to give an activity profile for each aspect of the training session. Warm ups and the pre- and post-training stretch were recorded but not included in the analysis.

5.3.2.5. Session RPE

Athletes were asked "how was your training session?" and instructed to score it between 1 and 10 as per the Borg CR-10 scale to record a global, uncomplicated impression of the entire training session (Haddad *et al.*, 2011). As stated above, athletes started each training session by checking in on a computer screen at the training hall. On completion of each training session, athletes spent 10-15 minutes stretching off and then completed their RPE score by checking out of the session and inputting their RPE score by sliding scale on a computer screen using the Borg CR-10 scale for reference. This was then automatically saved under the player's profile. Athletes were unable to see the scores left by other athletes and only one athlete could input at a time which helped to minimise factors that could affect athletes' scores such as peer pressure and repeating others' ratings (Malone *et al.*, 2015). Logging check out time and subtracting the check in time recorded session duration. sRPE was completed for all taekwondo and general training sessions including resistance training (RT) and general conditioning (GC) and RPE scores were collected between 10 and 30 minutes after the cessation of the training session (Uchida *et al.*, 2014).

5.3.2.6. Training Monotony and Strain

The sRPE data for each test week was then used to calculate training monotony and strain. Training monotony (Foster, 1998) was calculated as the average weekly sRPE TL for each athlete divided by the standard deviation of sRPE training load for that week (mean sRPE/SD). This was then used to calculate the training strain by multiplying training monotony for each week by the average sRPE training load for that week (mean sRPE * training monotony).

5.3.2.7. Heart Rate

Heart rate was recorded using the Firstbeat team system (*Firstbeat Sports, Jyväskylä, Finland)*. Participants placed the chest strap underneath their clothing before the commencement of the training session and it remained on throughout the entire session. Data was transmitted from the belt to a receiver connected to a portable laptop and analysed using the Firstbeat software (*Firstbeat Sports, Jyväskylä, Finland*). Participants indicated that the HR belt did not impede their movements or behaviour during any of the training sessions. Participants wore the same HR belt throughout all 4 training weeks to minimise inter-device differences. Raw heart rate data were collected for each session and computed to extract mean HR per session as a percentage of each individual's HR_{max} and time spent at different percentages of HR_{max}. HR_{max} was computed as the highest HR recorded for each individual over the course of 4 weeks of data collection (197 ± 7 beats.min^{-1}). Since it has been shown that in taekwondo athletes, standard aerobic capacity measures, such as a maximal treadmill test, elicit smaller cardiopulmonary responses than taekwondo specific tests (Hausen *et al.*, 2018), this was deemed a more appropriate method to determine peak HR values.

5.2.4. Part 2

5.2.4.1. Injury Data

The injury data was collected with the guidance of medical professionals that worked within the Great Britain National Academy. The injury profile of each athlete was updated for each day of the macrocycle to include the status of any on-going injuries or the occurrence of any new ones. Any existing or previous injuries that had impacted each day's training was also recorded. If an athlete could not do the taekwondo training session due to an injury, it was recorded as a day lost to injury. If they could only take part in some of the training or it was modified as a result of an injury (meaning they could not take part in the full session), it was counted as a day affected by injury. Injury data were compiled to include the number of new injuries and the number of existing injuries that affected training during the macrocycle and the number of days lost and affected by injuries. The nature of the occurrence of each injury, the location on the body and whether it was contact or non-contact were also recorded.

5.2.4.2. Session Completion Rate

Before the beginning of each training session, athletes were required to check-in to the training session to confirm their attendance and whether they were taking part or to give a reason as to why they were not taking part. Check-in was done on a computer screen in the training hall and athletes did this as standard before all training sessions. Athletes classed as in "rehab" at the beginning of the testing period (those whom the medical team deemed unfit to participate in any taekwondo training sessions for period of time equal to or greater than four weeks due to long term injury) were not included in the session completion rate (SCR). Scheduled training sessions were those sessions scheduled for the training group. SCR was classed as the percentage of scheduled training sessions completed by each individual during each test week.

5.2.4.3. Competition Data

Data were collected on the competitions attended by the athletes taking part in the study. Athletes weight category, number of combats and final result were collected for each competition. The total number of competitions attended by each athlete and the competition location were also recorded.

5.2.4.4. Athlete Level

Variables were analysed with respect to the athlete level (TOP v TARGET) in order to investigate distinctions in training load and participation between these two groups of athletes. Weekly cumulative sRPE TL and training volume (minutes) was calculated for each athlete and the average over the four test weeks was compared between levels. Average session completion rate for all training sessions, taekwondo session completion rate and general session completion rate were compared between levels. Finally, the percentage of total training days affected by injury and the percentage of test week training days affected by injury were computed for each athlete and this was compared between levels.

5.2.5. Statistical Analysis

Activity profile, HR, wellbeing and mean sRPE data are presented as the mean (±SD) for training sessions during each test week. Total sRPE data were calculated by summing the sRPE scores for each athlete per test week and getting the mean (±SD) of total sRPE scores of those athletes who completed 70% or more of the training sessions that week. Differences between phases were assessed using student's t-test (session frequency) or paired t-tests (session volume and cumulative sRPE). Repeated measures ANOVA was used to assess changes across test weeks (session volume, subjective wellbeing, mean sRPE, HR data) and during microcycles (subjective wellbeing, sRPE, HR data). A 2-way ANOVA was used to assess the effect of test week and session type on the activity profile. Bonferroni adjustment was used where relevant to further compare differences between means. A Pearson product-moment correlation was used to examine the relationship between cumulative weekly training load, SCR and the percentage of training days affected by injury. Effect sizes, via Cohen's d, were used to further determine the magnitude of the differences between means (Sullivan and Feinn, 2012). Effect sizes, via Cohen's d, were used to further determine the magnitude of the differences between means (Sullivan and Feinn, 2012).

$$\text{Cohen's } d = \frac{M_1 - M_2}{s}$$

$$\text{where s} = \sqrt{\frac{(s_1{}^2 - s_2{}^2)}{2}}$$

and M_1, M_2 = mean of each sample and s_1,s_2 = standard deviation of each sample. Effect sizes (ES): 0.2 = small, 0.5 = medium, 0.8 = large; 1.5 = very large.
All data were analysed using *IBM SPSS Statistics 24*.

5.3. Results: Part 1

5.3.1. Session Frequency and Type

The session frequency and type across the 13-week macrocycle can be seen in Figure 6. This is further broken down in to microcycle session frequency and type over the four test weeks in figure 7. There was an average of 7.7 ± 1.7 training sessions per week over the course of the 13 week macrocycle; 4.7 ± 1.3 of these were taekwondo sessions and 3 ± 1.3 were general sessions. There were a total of 52 scheduled sessions during the first mesocycle, the general phase (GP) (28 taekwondo and 24 general training) and 48 during the second mesocycle, the competition phase (CP) (33 taekwondo and 15 general). Table 19 shows the distribution of the session frequency and volume across the test weeks and mesocycles. There was no significant difference between number of sessions per week in the GP (8.7 ± 0.8) and the CP (7.3 ± 1.8) but the effect size of the difference was very large (p = 0.06, ES = 1.0).

The GP consistently contained 2 resistance training (RT) sessions, 2 general conditioning (GC) sessions, 1 sparring/contact taekwondo session and 2 (week 1, 2 and 5) or 4 (week 2, 3 and 6) technical/tactical sessions and 2 tactical sessions (week 2 and 5). In contrast, CP was less consistent; there were generally 2-3 RT sessions per week with the exception of week 9 and 13 (as many of the participants travelled to a competition during these weeks). Tactical specific training sessions replaced the technical/tactical and technical session seen during GP and on week 8, 11 and 12 there was an increase to two sparring/contact and/or test match sessions. During the CP, taekwondo specific conditioning sessions replaced GC sessions.

Training sessions generally took place in the morning and afternoons on Monday, Tuesday, Thursday and Friday with a single session on Wednesday mornings. Morning sessions typically commenced at 9 or 10am and lasted for 116 ± 37 minutes. Afternoon sessions lasted for 103 ± 29 minutes and started between 2.30pm and 4pm. In between sessions, athletes typically refuelled, had physiotherapy treatment and engaged in recovery modalities such as manual therapy, cold-water immersion, compression garments and naps. They also spent time doing schoolwork and having meetings with coaches, nutrition or psychological support.

5.3.2. Session Volume

Total training volume (minutes) was assessed for all athletes that completed 70% or more of the scheduled training sessions (Table 19). Week 2 and week 8 had non-significant greater training volumes than week 12 and week 5 and as such there was no significant effect of week on training volume (p = 0.08). However, there was a large effect size difference between week 5 and week 2 (ES = 1.35) and week 8 (ES = 1.41). Furthermore, there was no significant difference between training volume during the CP and the GP (p = 0.4, ES = 0.13).

Table 19 Summary of session volume and frequency during test weeks and phases

	Week 2	Week 5	Week 8	Week 12	GP	CP
No. of participants	18	15	20	20		
Session Frequency	9	9	9	9	8.7±0.8	7.3±1.8
TKD session frequency	5	5	6	6	4.7±0.8	4.7±1.7
General session frequency	4	4	3	3	4.0±0.0	2.1±1.2
Cumulative weekly volume (mins)	800±113	650±109	815±125	733±177	750±131	769±160
Training Monotony (AUs)	2.3±0.8	6.9±1.0	2.8±0.9	2.8±0.7		
Training Strain (AUs)	1157 ±882	3310 ±4708	1999 ±839	2063 ±1617		

TKD = taekwondo, GP = general phase, CP = competition phase

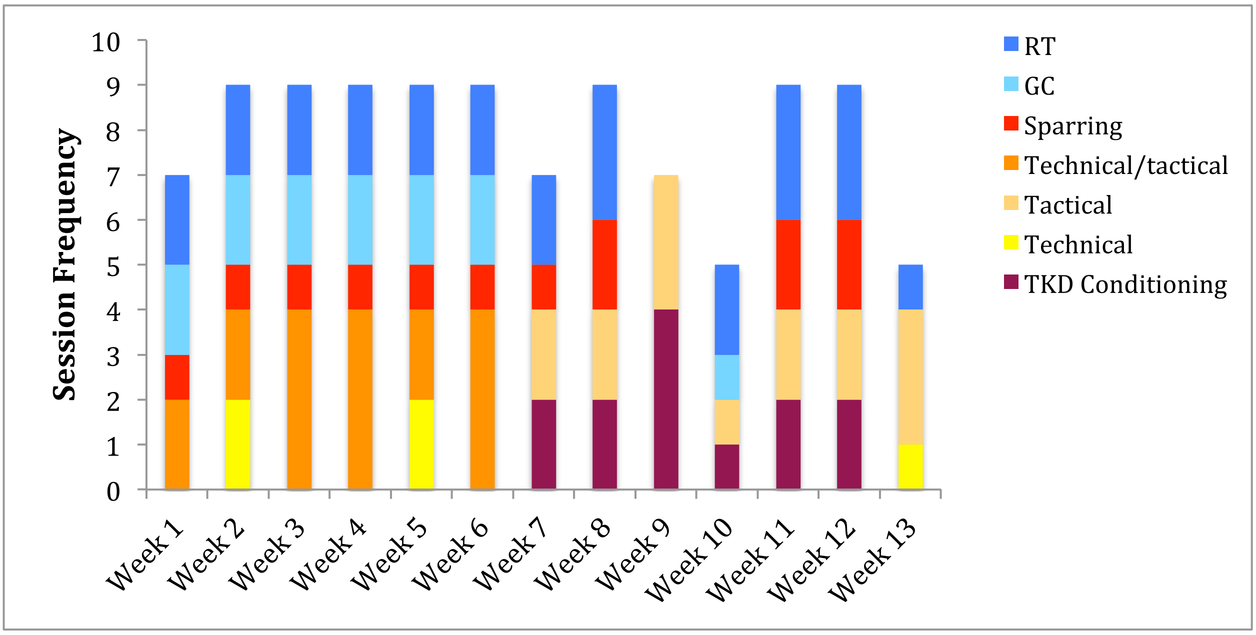

Figure 6 Structure of the session frequency over the macrocycle

Test Week	Session	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
2	**AM**	T/T	Tech	T/T	Tech	Spar
	PM	RT	GC		GC	RT
5	**AM**	T/T	Tech	T/T	Tech	Spar
	PM	RT	GC		GC	RT
8	**AM**	Tac	Cond	RT	Tac	Spar
	PM	RT	Spar		Cond	RT
12	**AM**	Tac	Cond	RT	Tac	Spar
	PM	RT	Spar		Cond	RT

Figure 5 Session frequency and layout of the microcycles throughout the macrocycle

5.3.3. Subjective Wellbeing

Subjective wellbeing data was analysed over the 13-week macrocycle. There was no significant effect of week on wellbeing score. However, there was a significant effect of day of the training week on wellbeing score ($p < 0.001$). Wellbeing scores on Mondays (48 ± 8) were significantly greater than those on Wednesdays (45 ± 8, $p = 0.007$, ES = 0.38), Thursdays (44 ± 8, $p < 0.001$, ES = 0.5) and Fridays (43 ± 8, $p < 0.001$, ES = 0.63). Furthermore, wellbeing scores on Tuesdays (46 ± 7) were significantly greater than those on Thursdays ($p = 0.041$, ES = 0.27) and Fridays ($p < 0.001$, ES = 0.40) and wellbeing scores on Wednesdays being significantly greater than those on Fridays ($p = 0.039$, ES = 0.25).

5.3.4. Activity Profile

The mean warm up time for taekwondo sessions was 12.2 ± 6.5 min. This was generally followed by a period of 9.1 ± 3.0 min to stretch. There was no significant difference between time spent active, passive or at rest between test weeks or between session types. Furthermore, there was no significant effect of test week or session type on the ratios of: Work (active + passive):Rest (W:R), Active Work:Rest (A:R) and Active:Passive (A:P). W:R and A:R was greater during week 8 (W:R 1:1.9 ± 0.9, A:R 1:3.3 ± 1.3) than during week 2 (W:R 1:1.2 ± 0.04, A:R 1:2.5 ± 0.1), week 5 (W:R 1:1.5 ± 0.6. A:R 1:2.7 ± 0.8) and week 12 (W:R 1:1.3 ± 0.4, A:R 1:2.4 ± 0.7) but none of these differences were significant ($p \geq 0.4$). However, effect size calculations indicated that week 8 had a both a greater W:R and A:R by a large to very large difference than week 2 (W:R ES = 1.1, A:R ES = 0.87) and week 12 (W:R ES = 0.86, A:R ES = 0.80).

5.3.5. Session Rating of Perceived Exertion (sRPE)

Figure 8 shows the daily training loads, via sRPE, associated with the specific session types during the four test week microcycles. Cumulative sRPE TL was calculated by getting the mean of athletes' total sRPE TL during each of the test weeks. Only athletes that had completed 70% or more of scheduled sessions were included for analysis. There was no significant effect of test week ($p = 0.09$) or of training phase ($p = 0.2$) on cumulative sRPE TL. Week 5 demonstrated a reduced training load compared with the rest of the test weeks, which was not significant (Table 20) ($p \geq 0.2$ for all except for week 8 which was close to significance at $p = 0.06$, ES = 1.3, 1.5 and 0.9 for week 2, 8 and 12, respectively). Further, once relevant data points had been excluded there was no significant difference between the numbers of sessions completed by the included athletes per test week demonstrating that this factor was not dictating total sRPE training load.

Training monotony was highest on week 5 but was greater than the proposed limit of 2 AUs on all four test weeks (Table 19). Training strain was also highest on week 5 but increased across the other three test weeks.

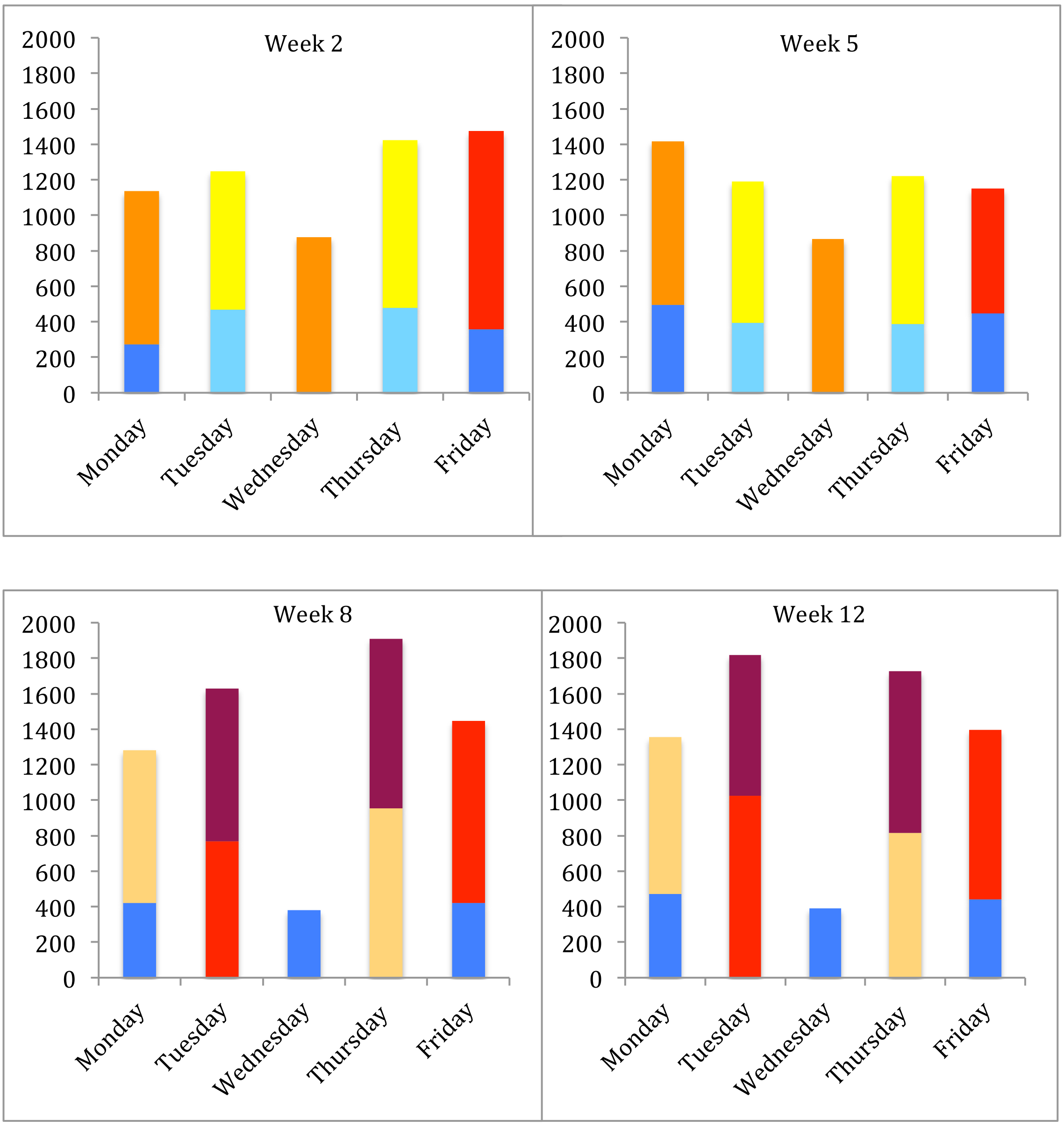

Figure 6 Mean sRPE values of training sessions during the test week macrocycles

5.3.6. Taekwondo Training (TKD) sRPE

There was a significant effect of test week on the mean sRPE TL for taekwondo training sessions (p = 0.009) (Table 20). Further analysis showed that this was down to the mean sRPE of week 5 (819 ± 130 AUs) being significantly lower than that of week 2 (911 ± 178 AUs, p = 0.02, ES = 0.6), week 8 (911 ± 173 AUs, p = 0.01, ES = 0.6) and week 12 (896 ± 193 AUs, p = 0.04, ES = 0.5). There was a significant effect of session type on mean sRPE TL (p = 0.019) (Table 21) but this difference was seen only in a greater mean TL in sparring sessions (939 ± 243 AUs) compared with technical sessions (833 ± 142 AUs, p = 0.013, ES = 0.6). Finally, there was a significant effect of day of the week on mean sRPE TL (p = 0.008) (Table 22) due to a greater mean sRPE TL being experienced on Fridays (953 ± 235 AUs) compared with Tuesdays (843 ± 199 AUs, p = 0.002, ES = 0.5).

5.3.7. General Training sRPE

There was no significant effect of test week, training day or training type (GC versus RT) on the mean sRPE TL of general training sessions (p ≥ 0.1).

5.3.8. Heart Rate

5.3.8.1. Mean HR as a percentage of HR_{max} (%HR)

There was a significant effect of test week on %HR (p = 0.003) (Table 20). This was seen in a significantly greater %HR during sessions in week 2 (69.5 ± 4.5%) versus those in week 5 (66.1 ± 5.9%, p = 0.029, ES = 0.61) and week 12 (65.5 ± 6.8%, p = 0.003, ES = 0.68). There was also a significant effect of day of the training week on %HR (p = 0.020) (Table 22). %HR during training sessions on Mondays (69.7 ± 5.1%) were significantly greater than those on Tuesdays (66.2 ± 6.2%, p = 0.031, ES = 0.59) and Thursdays (66.2 ± 5.8%, p = 0.020, ES = 0.6). Furthermore, there was a significant effect of training session type on %HR (p = 0.02) (Table 21). Tactical training sessions had a greater %HR (70.1 ± 5.7%) than did conditioning sessions (65.5 ± 5.2%, p = 0.006, ES = 0.81) and sparring sessions (66.1 ± 6.1%, p = 0.004, ES = 0.67).

5.3.8.2. Time (s) spent above 80% HR_{max} (HR80)

There was a significant effect of test week on HR80 (p= 0.000) (Table 20). HR80 during week 2 (35.7 ± 13.7 min) was significantly greater than HR80 during training sessions in week 5 (23.0 ± 13.4 min, p = 0.000, ES = 0.91), week 8 (26.4 ± 11.5 min, p = 0.000, ES = 0.7) and week 12 (23.5 ± 13.2 min, p = 0.000, ES = 0.91) (Table 20). There was also a significant effect of training day on HR80 (p = 0.005) (Table 22) with training sessions on Mondays having a significantly greater HR80 (33.4 ± 12.7 min) than sessions on Tuesdays (25 ± 11.5 min, p = 0.014, ES = 0.69) and Thursdays (24.3 ± 12.7 min, p = 0.004, ES = 0.72). Furthermore, there was a significant effect of session type on HR80 (p = 0.002) (Table 21) with conditioning/individual training sessions having significantly lower HR80 (20.5 ± 9.8 min) than technical/tactical sessions (30.9 ± 14.3 min, p = 0.006, ES = 0.85) and tactical sessions (30.9 ± 13.5 min, p = 0.005, ES = 0.89).

5.3.8.3. Time (s) spent above 90% HR_{max} (HR90)

There was a significant effect of test week on HR90 (p = 0.000) (Table 20). HR90 was significantly greater during sessions in week 2 (11.5 ± 9.8 min) than in week 5 (4.7 ± 5.7 min, p =0.000, ES = 0.84), week 8 (6.1 ± 6.0 min, p = 0.000, ES = 0.66) and week 12 (6.1 ± 6.6, p = 0.001, ES = 0.64). There was no significant effect of session type or training day on HR90 (Table 21 and 22, respectively).

Table 20 Training load variable by test week (mean±SD)

	Week 2	Week 5	Week 8	Week 12
Cumulative sRPE (AUs)	5511±759	4460±832	5884±1052	5447±1409
n > 70%	12	6	14	18
Mean sRPE TKD (AUs)	911±178	819±130*	911±173	895±193
Mean sRPE Gen (AUs)	393±142	424±131	405±137	434±133
%HR	69.5±4.5	66.1±5.9**	67.6±5.6	65.5±6.8***
HR80 (min)	35.7±13.7	23.0±13.4***	26.4±11.5***	23.5±13.2***
HR90 (min)	11.5±9.8	4.7±5.7***	6.1±6.0***	6.2±6.5***

sRPE = session rating of perceived exertion; TKD = taekwondo training sessions; Gen = general training sessions; %HR = percentage of max heart rate; HR80 = time spent above 80% of max heart rate; HR90 = time spent above 90% of max heart rate; * significantly less than week 2,8,12, $p < 0.05$; ** significantly less than week 2, $p < 0.05$; *** significantly less than week 2, $p < 0.001$)

Table 21 Training load variable by session type (mean±SD)

	COND	SPAR	T/T	TAC	TECH
Mean sRPE (AUs)	874±146	939±243*	882±146	878±114	833±142
%HR	65.5±5.2**	66.1±6.1**	68.1±5.5	70.1±5.7	66.8±5.6
HR80 (min)	20.5±9.8	25.8±12.6	30.9±14.3***	30.9±13.5***	28.4±13.4
HR90 (min)	5.0±4.9	8.2±9.0	7.5±7.4	7.5±6.9	6.3±7.6

sRPE = session rating of perceived exertion; %HR = percentage of maximum heart rate; HR80 = time spent above 80% of maximum heart rate; HR90 = time spent above 90% of maximum heart rate; COND = conditioning session; SPAR = sparring or full contact session; T/T = technical and tactical session; TAC = tactical session; TECH = technical session; * significantly greater than TECH, $p < 0.05$; ** significantly less than TAC, $p < 0.01$; *** significantly greater than COND, $p < 0.01$

Table 22 Training load variables by day of the week (mean±SD)

	Mon	Tue	Wed	Thu	Fri
Mean sRPE TKD (AUs)	888±130	843±199	873±163	897±115	953±235*
Mean sRPE Gen (AUs)	405±148	443±142	387±134	436±93	419±138
%HR	69.7±5.1	66.2±6.2**	67.8±6.6	66.2±5.8**	67.0±5.8
HR80 (min)	33.4±12.7	25.0±11.5**	28.8±17.5	24.3±12.7**	26.6±13.4
HR90 (min)	7.8±7.1	8.4±7.6	7.6±7.7	4.8±6.9	7.8±9.4

sRPE = session rating of perceived exertion; TKD = taekwondo training sessions; Gen = general training sessions; %HR = percentage of maximum heart rate; HR80 = time spent above 80% of maximum heart rate; HR90 = time spent above 90% of maximum heart rate; * significantly greater than TUE, $p < 0.05$; ** significantly less than MON, $p < 0.05$

5.4. Discussion: Part 1

The aim of the first part of this study was to characterise the training load experienced by elite taekwondo athletes during a 13-week macrocycle in the lead up to a competition. The TL variables demonstrated limited variety of training stress throughout the 13-week macrocycle despite the culmination in an important competitive event. This was represented by a decline in the physiological strain of training sessions as the macrocycle progressed resulting in plateaued physical preparation. The data also demonstrated that training periodisation within this training cycle was limited to the microcycle organisation with the highest training strain at the beginning of the week, resulting in reduced subjective wellbeing that was rescued after 2 weekend rest days. Finally, the data provide evidence that the greatest physiological load comes from tactical based sessions indicating a bias for training load to be largely determined by the skill acquisition and application characteristics of the sport.

The macrocycle investigated in the present study, composed of two mesocycles, culminated in an important competition that was the basis on which athletes were to be selected for the European Championships in the same year. The present study showed that the session frequency of taekwondo athletes in this programme did not change between two distinct training phases. This is consistent with a finding in a study on the training periodisation of elite nordic combined athletes which found that session frequency remained the same throughout the general preparation and the competition phase although the volume changed in order to manipulate the training stress (Tønnessen *et al.*, 2016). On the contrary, despite a change in the training schedule and an increased frequency of taekwondo training sessions, there was no significant change in training volume between the two phases in the present study.

Furthermore, given that Saw et al. (2016) showed that subjective wellbeing was sensitive to acute and chronic changes in TL the absence of TL variety is mirrored in the limited change in wellbeing across the macrocycle. This finding is in contrast with data from a study investigating training load during a 33 week rugby-7s season which showed that subjective wellbeing responded accordingly to changes in TL and was lower during the in-season than during the high volume pre-season period (Marrier *et al.*, 2018). It is also in contrast with a study in football players which showed that specific measures of wellbeing (fatigue, muscle soreness and sleep quality) were sensitive to changes in workload during a 17 day in-season competition phase (Thorpe *et al.*, 2015). This therefore suggests that the training stress imposed on the taekwondo athletes in this study was not sufficient to elicit a decrement in subjective wellbeing.

To further investigate the TL of elite taekwondo athletes, data was collected during four non-consecutive training microcycles (test weeks), two within each of the mesocycles. This allowed characterisation of changes in training stress at the beginning and end of each mesocycle in order to better understand the variation of TL across the macrocycle. Cumulative sRPE TL, a variable representative of both the volume and perceived intensity of training, was not significantly different between each of the test weeks. This is in contrast to the data seen in a season long study examining the training load of national judo athletes whose weekly total sRPE varied between training phases in line with the periodised plan that they followed (Agostinho *et al.*, 2017). Additionally, the activity profile, as a measure of both external training volume and intensity, despite showing a trend to increase towards week 8, did not vary significantly across the test weeks. According to James et al. (2013), successive mesocycles within a macrocycle should have a greater overall training stress in order to continue to promote training adaptations. In fact, in a study examining super-compensation kinetics in rubgy-7s athletes, it was shown that after three weeks of training at the same volume and intensity, measures of performance such as speed, strength and mean power output (as a measure of power endurance) actually began to diminish (Marrier et al., 2017). Therefore, the apparent absence of variation in either external or internal training load, also demonstrated by a high training monotony and strain score, across the macrocycle suggests that the training stress organisation needed to elicit optimal physiological preparation was not present in this cohort of athletes during this training cycle.

Conversely to the sRPE and activity profile data, the HR data demonstrated that %HR, HR80 and HR90 decreased from week 2 to week 12. While HR data are generally regarded as a means to measure the internal intensity of training (Saw, Main and Gastin, 2016), it is so only in terms of a response to the actual volume and intensity of the work done. As such, the HR data in this study is an internal response of taekwondo athletes to a volume and intensity of training stress that does not appear to vary across the test weeks. Therefore, the decline of both the average HR of athletes during training sessions and the time spent in maximal training zones (HR80 and HR90) suggests that initially, the training load stimulus is sufficient to cause a certain degree of physiological response but that the lack of variation of this training stress as the macrocycle develops results in the absence of a sufficient progressive overload and a subsequent plateau in the training response.

It is well established that high-intensity interval training at or near VO_{2max} is an efficient way of eliciting improvements in aerobic fitness (Buchheit and Laursen, 2013a; Buchheit and Laursen, 2013b) and various studies have documented that time spent above 90% HR_{max} (Thomas, Adeniran and Etheridge, 1984; Helgerud *et al.*, 2007) is closely associated with time spent at or near VO_{2max}. Studies in football (Ferrari Bravo *et al.*, 2008; Impellizzeri *et al.*, 2006) have shown the efficacy of increasing the time spent at intensities at or above 90% of HR_{max} during training to induce significant improvements in measures of aerobic fitness. It has also been demonstrated in basketball athletes that there is a relationship between HR and VO_2 in sport specific conditioning drills (Castagna *et al.*, 2011). Since the predominant energy source during taekwondo combats is the aerobic system (Campos *et al.*, 2012), it is reasonable to deduct that the more time spent in maximal HR zones, and subsequently at or near VO_{2max}, may lead to improvements in the aerobic fitness qualities necessary for optimal taekwondo performance. Therefore, the uniformity in workload (by way of sRPE TL scores and activity profiles) across the test weeks and the corresponding reduction in time spent at intensities necessary for eliciting fitness improvements indicate not only a plateau but also a potential decrement in the physiological capacities of elite taekwondo athletes in the lead up to competition. Suggestions for avoiding training plateaus will be discussed in the second part of this study.

When the data were further broken down with respect to the days of the training week, there was a significant trend for subjective wellbeing to decrease throughout the week. Both %HR and HR80 were greater on Mondays than on Tuesdays and Thursdays which indicates that the higher training stress accumulated at the beginning of the training week substantially impacted subjective wellbeing that did not recover despite a reduced training volume in the middle of the week (Wednesdays). Mean sRPE, in contrast, was greatest on Fridays and demonstrated a trend to increase across the training week. Friday sessions consistently involved sparring which had a greater sRPE TL than did the technical training sessions that tended to occur earlier in the week. sRPE takes into account residual and external stress and is increasingly recognised as relevant for monitoring combat sport athletes' performance recovery (Slimani *et al.*, 2017). This trend, therefore, indicates that the accumulated fatigue experienced throughout the week may have influenced the perceived training stress as the week progressed. As a result, similar to findings in a study of the season-wide TL of a premiership football club (Malone *et al.*, 2015), these data suggest that there is a periodisation to the training stress within a microcycle but that this does not extend out to the wider training cycle.

Paradoxically, TAC sessions and T/T sessions induced a greater physiological strain, as demonstrated by increased %HR and/or HR80, than did COND sessions and/or SPAR sessions. This seems contradictory given the goal of conditioning and sparring sessions are to specifically prepare athletes for the physical and physiological strain of taekwondo competition. Despite this, SPAR sessions had a higher sRPE TL than all other session types (albeit only significantly higher than T/T sessions). The mismatch in subjective internal (sRPE) and objective internal (HR) TL measures may in part be due to the increased psychophysiological load that occurs during full contact sparring. Similarly the nature of TAC and T/T sessions are geared towards executing technical skills and tactical options in a manner representative of competition. However, they differ from SPAR sessions in that they involve carrying out these actions repeatedly in order that they become second nature and can thus be executed under the stress of a real combat situation. Therefore, the volume of these repetitions, executed at combative intensity, may elicit a high physiological load without the psychophysiological response that occurs during combative situations. This should be taken into consideration when attempting to quantify and understand the training load of individual athletes.

The data demonstrates that while the taekwondo athletes in the current study experience microcycle training periodisation, they forego long term, macrocycle periodisation of training stress in preparation for competition. As a result, athletes are not exposed to the premise of training periodisation; namely periods of progressive overload and subsequent recovery to allow supercompensation, and athletes may therefore undergo a physiological plateau or even a de-training effect as a result. This may be in part due to an emphasis on technical and tactical preparation but also as a result of factors that will be discussed in the second part of this discussion. Regardless, the deficiency of meso and macrocycle organisation of training from a physiological perspective may impact the physiological profile of athletes. Understanding the physiological demands of competition and profiles of taekwondo athletes along with the training methodologies employed, including the deficiencies and areas for development, provides an insight in to the optimal way to physically prepare athletes for competition. However, in order to maximise this process, the factors that affect organisation of training in this cohort of athletes must be taken in to consideration. Therefore, the second part of this discussion aims to investigate this in the context of maximising the physiological profile of taekwondo athletes to increase the chance of performance success.

5.5. Results: Part 2

5.5.1. Session Completion Rate (SCR)

During the four test weeks, athletes completed a mean of 5.5 ± 3.0 training sessions per week. This equates to a mean session completion rate of 60.7 ± 33.4%. The median SCR was 66.7% (IQR: 44.4%-88.9%). The mean SCR was 64.0 ± 36.5% for taekwondo training sessions (SCRtkd) and 56.5 ± 40.5% for general training sessions (SCRgen). There was no significant difference between the SCRtkd and SCRgen for each athlete. There was a significant effect of test week on the SCR ($p = 0.020$) (Table 23) with the SCR being significantly lower in week 5 (43.4 ± 31.6%) than it was in week 8 (69.3 ± 28.3%; $p = 0.050$, ES = 0.86) and week 12 (72.0 ± 28.2%, $p = 0.025$, ES = 0.95). There was also a significant effect of test week on SCRgen ($p = 0.020$) with the session completion rate being significantly lower in week 5 (30.9 ± 41.8%) than it was in week 8 (63.5 ± 39.3%; $p = 0.033$, ES = 0.85) and week 12 (74.6 ± 29.6%, $p = 0.002$, ES = 1.21). The same effect was not seen SCRtkd.

Table 23 Session completion rate and training load/volume during the test weeks

	Week 2	Week 5	Week 8	Week 12	Total
TKD SCR (%)	59.1±40.7	53.3±40.7	73.0±32.3	70.6±29.8	64.0±36.5
Gen SCR (%)	57.1±39.6	31.0±41.8	63.5±39.3*	75.6±29.6*	56.6±40.5
Total SCR (%)	58.2±38.8	43.4±31.6	69.3±28.3*	72.0±28.2*	60.7±33.4
Session Frequency	5.2±3.5	3.9±2.8	6.2±2.5	6.5±2.5*	5.5±3.0
Cumulative sRPE	4468±1898	3793±1102	4930±1825	5227±1560	4659±1696
Cumulative Volume (mins)	652±273	552±139	688±236	711±192	657±221

* significantly greater than week 5, $p < 0.05$

5.5.2. Injury Incidence

During the 13-week macrocycle, there were 26 new injuries sustained and 2 new illnesses. However, there were 34 injuries and 3 illnesses that affected training days throughout the macrocycle (newly sustained and pre-existing). Of the 25 athletes who commenced the study, 3 athletes were removed from the analysis due to leaving the programme or sustaining a long-term injury before the second test week (week 5) that put them out of training for the duration of the macrocycle. Therefore, of the 22 athletes who were considered for analysis, 18 were affected by at least one injury and 4 did not incur any injuries or have any pre-existing injuries that affected training during this macrocycle.

There was an average of 2 ± 1.4 injuries and illnesses per athlete that affected training during this macrocycle. The macrocycle lasted for 90 days and included 64 training days. The mean number of days affected by injury or illness for each athlete was 25 ± 27 (Range: 0-83; IQR:0-44). The mean percentage of days affected by injury during the macrocycle was 27.7 ± 30.3% (Range: 0-92%; IQR:0-48.9%).

Of the 34 injuries that affected training during this macrocycle 56% were lower limb injuries, 23% were hip injuries, 12% were neck/back/head injuries and 9% were upper limb injuries. Contact injuries made up 60% while non-contact injuries made up the other 40% of all relevant injuries to affect training during this period. Contact injuries were responsible for 56% of days affected by injury while non-contact injuries and illness were responsible for the remaining 44%.

5.5.3. Correlation Analysis

There was a significant correlation between the cumulative sRPE weekly training load (total sRPE TL) for each test week and the corresponding session completion rate: Week 2 $r = 0.991$, $p < 0.001$; Week 5 $r = 0.957$, $p = 0.001$; Week 8 $r = 0.918$, $p = 0.001$; Week 12 $r = 0.942$, $p = 0.001$. However, there was significant negative correlation between the amount of days affected by injury (%) over the whole macrocycle and the average session completion rate of taekwondo training sessions ($r = -0.438$, $p = 0.047$) as well as a significant negative correlation between each athlete's average session completion rate for taekwondo sessions and the average of their injury days for the test weeks (%) ($r = -0.446$, $p = 0.043$). There was no significant correlation between the average session completion rate for general training sessions or for all training sessions and the number of days affected by injury over the whole macrocycle or the test weeks.

5.5.4. Competition Attendance

All athletes attended at least one competition (1.8 ± 0.8; Range: 1-3) independent of the selection competition that concluded the macrocycle. There were 5 possible competitions athletes attended outside of the selection competition of which 2 were classed as Category C (long distance travel >10 hours and across >6 time zones) and thus were likely to cause significant jet lag and travel fatigue.

5.5.5. Athlete Level

There was a significant difference between the average weekly cumulative (total) sRPE training load between TOP (3151 ± 547 aus) and TARG (4803 ± 1414 aus) athletes ($p = 0.005$, ES = 1.54) and the average weekly cumulative training volume between TOP (462 ± 122 mins) and TARG (657 ± 189 mins) athletes ($p = 0.01$, ES = 1.23). Furthermore, TARGET athletes had a greater mean sRPE than TOP athletes for week 5 (TARGET: 849 ± 116, TOP: 729 ± 131; $p = 0.006$, ES = 0.97) and week 8 (TARGET: 997 ± 127, TOP: 833 ± 173; $p = 0.000$, ES = 1.08) (Figure 9). Total SCR differed significantly between TOP (51.8 ± 12.9%) and TARGET (71.9 ± 16.6%) athletes ($p = 0.005$, ES = 1.35), as did the SCRtkd between TOP (51.4 ± 14.0%) and TARGET (77.8 ± 21.0%) athletes ($p = 0.003$, ES = 1.48). There was no significant difference between TOP and TARGET athletes for the total number of injuries and illnesses or for the number of contact injuries, non-contact injuries and illnesses separately. Furthermore, there was no significant difference for the percentage of total or test week training days affected by injury or for the SCR of general training sessions.

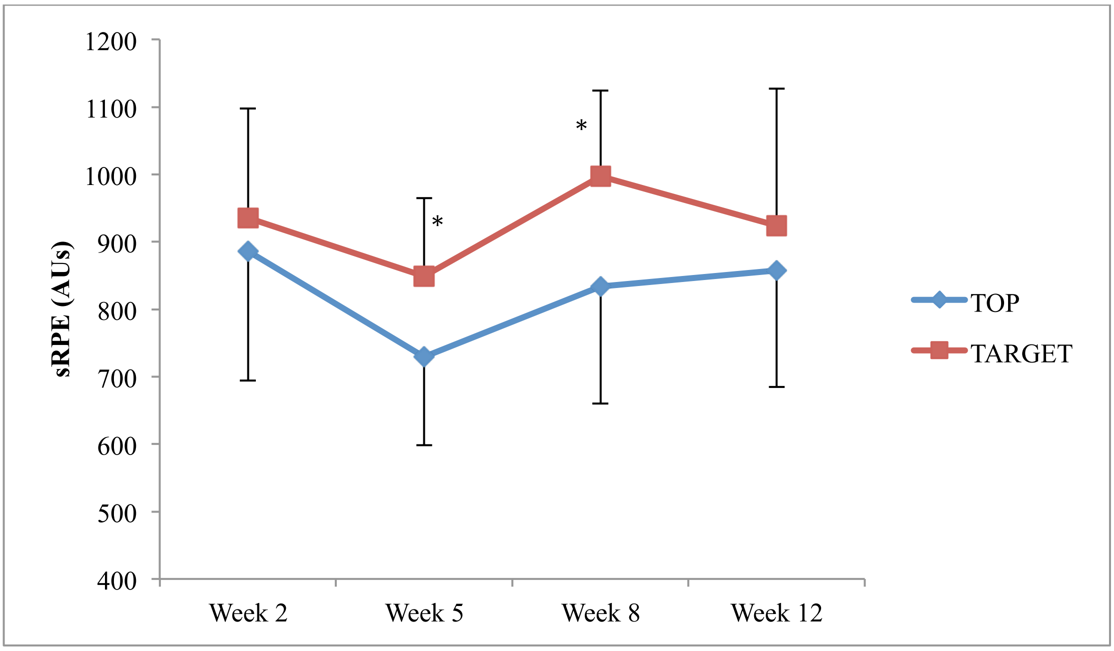

Figure 7 Mean sRPE values for TOP and TARG athletes over the test weeks

sRPE = session rating of perceived exertion; TOP = taekwondo athletes that have medalled at a major competition; TARG (TARGET) = taekwondo athletes that have not yet medalled at a major competition; * significantly greater than TOP athletes, $p < 0.01$

5.6. Discussion: Part 2

Part 1 of this study demonstrated a lack of variety and organisation of training load variables over the course of a training macrocycle. It is established that a lack of organisation of training load results in sub-optimal physical preparation along with an increased risk of injury, illness (Gabbett *et al.*, 2016) and reduced performance success. As a result, the data collected for this study suggests the elite taekwondo athletes in question may be both enhancing their risk for non-contact injuries and reducing their ability to maximise performance capacities. Therefore, the aim of the second part of this study was to investigate the factors that influence taekwondo athletes' ability to undergo an organised and periodised training load and to suggest a practical solution to combat this.

The results demonstrated that individual athletes in the same program are unsystematically experiencing diverse amounts of training stress within a training macrocycle despite following the same training plan. The session completion rate (SCR) of each individual implies that this unintentional divergence in training load among athletes may be as a result of the effect of new and pre-existing injuries and competition attendance. These variables show no evidence of being considered in the training schedule. As a result, the ability of athletes to complete all scheduled training sessions is limited leading to disorganised exposure of training load over time.

Investigation into the attendance of scheduled training sessions by athletes indicated not only that athletes are, on average, completing just 60% of scheduled training sessions but also that there is a wide variation in the session completion rate between athletes (IQR: 44.4%-88.9%). This variation suggests that athletes, unbeknownst to their coach or other support staff, may deviate from the session frequency planned in the group schedule. As a result, there is uncertainty surrounding the frequency and volume of training being undertaken by each individual athlete making it difficult to manage and organise the training stress experienced. This lack of consistency in session completion and the subsequent ambiguity around training load is likely to present a problem for optimising the periodisation of training load for the athletes in question.

It is important to establish an understanding for the erratic completion of scheduled training sessions in order to investigate solutions to better manage the training load. Investigation of the injury data suggests a high rate of injuries and illnesses (2 ± 1.4) during the examined macrocycle. Furthermore, the number of training days affected by injury represents a substantial proportion of the macrocycle (30%). The significant negative correlation between an individuals session completion rate for taekwondo sessions (SCRtkd) and the number of days affected by injury suggests that this is a large contributor to the inconsistent completion of training sessions and as a result a contributing factor to the disorganised training load undergone by the athletes in question. The lack of correlation between session completion rate of general training sessions (SCRgen) and days affected by injury suggests that it is taekwondo training sessions which are predominantly impacted by injuries and illness. Experience from the environment indicates that this may be partly due to the individual nature of the general training sessions and the subsequent ease with which training sessions could be modified to enable athletes to complete them despite injuries. Conversely, the group-focused nature of taekwondo training sessions does not allow for this in the same way. However, it should be stated that correlation, or lack thereof, does not necessarily imply causation and injury occurrence in athletes is highly complex (Bittencourt *et al.*, 2016). However, from the perspective of a cohesive completion of organised training cycles, these findings make an argument for a more individualized approach to training planning and organisation that would allow athletes to complete a high percentage of scheduled training sessions even in the event of minor injuries.

There is evidence that non-contact injuries can be caused by inappropriate training plans with excessive or rapid changes (both increases and decreases) in training load (Gabbett *et al.*, 2016). Non-contact injuries made up 40% of the injuries that affected training during this macrocycle. Furthermore, non-contact injuries were responsible for affecting 43% of the injury affected training days. Therefore, disorganised training load may not only result in suboptimal physical preparation but may also itself be contributing to an increased incidence of subsequent injuries.

It is also likely that competition attendance had a significant effect on session completion rate. This is indicated in a significantly reduced session completion rate in week 5 during which 5 of the 25 (20%) of the athletes participating in the study attended a competition that required long haul travel. Athletes participated in at least one and up to three competitions throughout the 13-week macrocycle, independent of the competition that concluded the macrocycle. The combination of travel (including long haul travel in 4 out of 7 possible competitions), making weight, tapering periods prior to competing and recovery periods after competing can all impact how much of the set training schedule an athlete completes. This then poses the further question of whether an athlete should recover from a mid-cycle competition and then re-build fitness or whether they should capitalise on the competitive stimulus and maintain intensive training load (Le Meur *et al.*, 2013). As Le Meur et al. (2013) discussed, both options are valid but the decision must depend on the level of accumulated fatigue and the time frame before the next competition. In other words, consideration must be given to the competition schedule as a whole and to each individual's specific goals for each competition. Therefore, proper organisation and planning of the training stresses must incorporate these variables in to the periodisation model.

It is has been shown previously in judo (Marques *et al.*, 2017) and taekwondo (Casolino *et al.*, 2012) that the experience level of an athlete influences their response to training. TARG athletes in the present study had greater mean sRPE for taekwondo training sessions than did TOP athletes. Furthermore, the less advanced (TARG) taekwondo athletes in the present study had a greater SCR and SCRtkd than did their more advanced counterparts and as a result had a significantly greater weekly average cumulative sRPE TL and volume. Despite the differences in SCR and cumulative TL and volume, there were no differences in the number of injuries and illnesses and in the number of days affected by injury or illness between the two groups of athletes. This indicates that TARG athlete's injuries were less severe and impacted training less than those of TOP athletes. Marques et al. (2017) demonstrated that less advanced judo players showed greater improvements in a judo specific performance test than their more advanced counterparts after a 13-week block periodised training cycle. This therefore highlights a further need to individualise training plans with consideration given to the level of the athlete in question.

It is evident that a demanding competition schedule and a high incidence of injuries contribute largely to an unsystematic completion of training sessions and thus a disordered training load. Taekwondo is well understood to be a physically and physiologically taxing sport with a high reliance on muscular strength, speed and power (Seo *et al.*, 2015; Bridge *et al.*, 2014; Casolino *et al.*, 2012; Ke-tien, 2012) as well as requiring highly developed anaerobic and aerobic capacities (Bridge, Jones and Drust, 2011; Bridge *et al.*, 2014; Hausen *et al.*, 2017; Chiodo *et al.*, 2011; Bürger-Mendonça *et al.*, 2015; Butios and Tasika, 2007; Campos *et al.*, 2012; Matsushigue, Hartmann and Franchini, 2009). However, in order to maximise the physiological adaptations and avoid overtraining or detraining, efficient organisation of training variables is required (García-Pallarés *et al.*, 2009). Therefore, if elite taekwondo athletes are experiencing disorganised training stress during training macrocycles, this is likely to impact their ability to maximise performance through both a reduced physical and physiological preparation and an increased risk of sustaining non-contact injuries.

5.7. Practical Solutions

5.7.1. Individual Plans

At present, variables such as competition attendance and injury incidence of individuals are not being taken in to account when planning training macrocycles due to an emphasis on designing a training plan with a group first perspective. While it is crucial to have adequate training partners within training sessions in order to increase competitiveness and match the demands of competition as closely as possible, taekwondo is ultimately an individual sport in which athletes of different weight category, sex and experience ultimately have different needs with respect to their physiological profile optimisation (Chapter 4) and training load and organisation requirements (Chapter 5.5.5). Therefore, a simple way to enhance the effectiveness of training plans and increase the SCR would be to design training plans around each individual that take into account their competition attendance, current and recent injury status and experience level. Further injuries or last minute changes to the competition schedule could then be catered for on a case-to-case basis by making small modifications to the individual's plan.

Session frequency has been shown to be a useful way to manipulate training stress (Marrier *et al.*, 2017; Mujika, 2010) and therefore provides an ideal, straightforward approach to constructing individual training plans that can be easily modified when necessary. While session frequency is a relatively crude way to manipulate training load and it is certainly not the only way to periodise and progress training stress, it does offer a convenient simplicity in that it only relies upon changing the number of training sessions an athlete completes per week. Given the difficulty of coordinating and understanding the training stress each individual in a large programme of athletes experiences during a training macrocycle, effortlessness of implementation is of paramount importance. Therefore, utilising session frequency to individualise the TL for each athlete in the group is highly practical can be easily adapted in the case of unexpected interruptions to the training plan. Further, depending on whether the load from competition attendance is to be utilised as an addition to the training schedule or needs to be recovered from, the training plan can be easily modified to reflect this by adjusting the session frequency preceding or following the competition. Finally, it can be easily designed to suit the needs of each individual athlete dependent on their experience. For example, less experienced athletes, who are likely to perceive TL as higher than their more experienced counterparts and to have a greater adaptation to the training (Marques et al, 2017), could have a reduced session frequency than more experienced athletes (Figure 10). This would allow them to experience a TL unique to their individual needs while still taking part in group training sessions.

Chapter 5.4 indicated that a lack of training periodisation might have resulted in training plateaus or even de-training effects despite the culmination of the training cycle in an important competition. Meso- and macro-cycle periodisation was missing due to a lack of individualisation and organisation of training as discussed above largely due to an inability to keep track of the training loads experienced by each athlete. Therefore, individualisation of training load using session frequency would further provide a simple method with which coaches and support staff could easily keep track of the training loads completed by athletes. This would help to minimise the likelihood of unintentional lack of progressive overload.

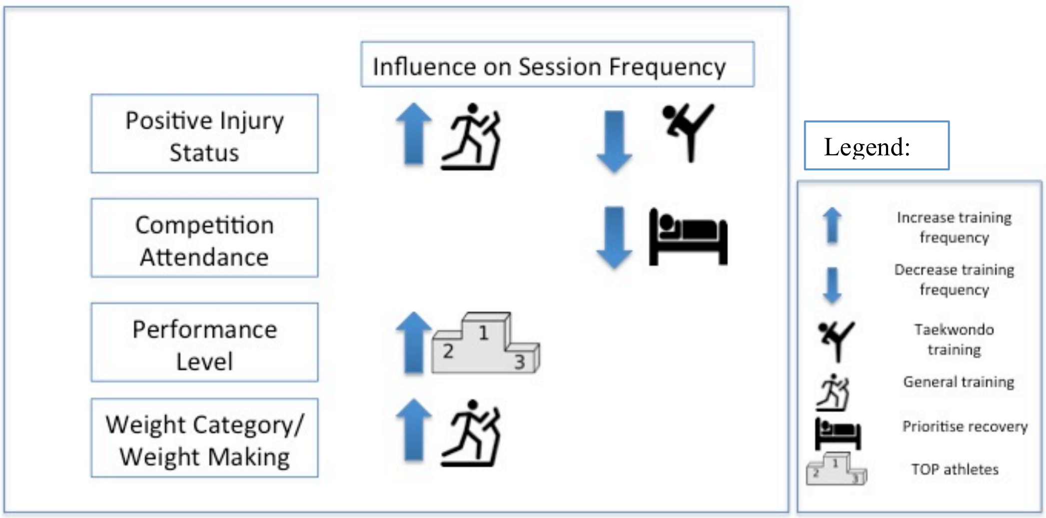

Figure 10 **Summary of the factors to consider when implementing individualised training plans and how these factors should affect training load in terms of session frequency**

5.7.2. Content

Multi-targeted block periodisation has been suggested to be an effective approach to organising training for sports that require the development of multiple, opposing physiological adaptations (Issurin, 2016; Marques *et al.*, 2017; James, Kelly and Beckman, 2013; García-Pallarés *et al.*, 2009). This type of periodisation aims to consecutively develop physiological qualities in blocks in such a way that each block sequentially benefits the following block but also separates opposing physiological mechanisms to limit interference. The cycle begins with general training and tends towards more sport specific training allowing different qualities to be emphasised at different stages of the training cycle while also taking into account the individual needs of each athlete (James, Kelly and Beckman, 2013). Importantly, this type of periodisation incorporates recovery periods at the end of each block to allow super-compensation to occur and a taper period at the end of the macrocycle in order to encourage peak performance.

Figure 11 depicts an example of the proposed individualised periodisation framework of a macrocycle culminating in an important competition at the end of the final week (week 13). It is a multi-targeted block periodisation design, the utilisation of which has been demonstrated to be effective in other combat sports such as judo and MMA (James, Kelly and Beckman, 2013; Marques *et al.*, 2017). There are three 4-week mesocycles and a final taper week leading into the competition. Each of the 4-week mesocycles work on the 3:1 method based on increasing the load (in this case in terms of session frequency) for the first three weeks of each mesocycle and finishing with a de-load week (of reduced training frequency) to allow supercompensation to occur prior to the beginning of the subsequent mesocycle (James, Kelly and Beckman, 2013). Each of the mesocycles involve highly concentrated workloads directed at a small number of training modalities. These workloads aim to directly support the following mesocycle but limit the potential for negative interaction effects which can be seen when attempting to develop opposing physiological qualities (Issurin, 2016). Testing sessions could be included in the first week of each mesocycle to determine the effectiveness of each mesocycle and inform the progress of each athlete. Furthermore, these testing sessions would provide check in points during the macrocycle in which to assess the training status of individuals. This would help to reduce the likelihood of training plateaus or de-training effects as it would allow any lack of progress to be identified within the macrocycle and thus addressed in the following mesocycle.

The blocks are divided into three phases: an accumulation phase, a transmutation phase (which consists of two mesocycles: a general-specific mesocycle and a specific mesocycle) and a realisation phase. The accumulation phase aims to develop more general fitness components such as aerobic and muscular endurance. This phase has a reduced frequency of taekwondo sessions that focus predominantly on technical development. The general-specific transmutation phase aims to develop qualities specific to the sport such as high-intensity anaerobic conditioning at work:rest intervals that complement competition demands and the inclusion of strength and power work to supplement the increasing intensity (James, Kelly and Beckman, 2013). It also involves an increase in taekwondo training with the incorporation of tactical sessions and sparring. The specific transmutation phase then emphasises taekwondo specific training including the shift of conditioning work to taekwondo modalities, an increase in the frequency of taekwondo training with a special focus on tactical and sparring sessions and low-volume, high-intensity resistance training to focus on power and speed development and maintaining muscle recruitment abilities. For those athletes who are susceptible to large reductions in body mass, it may be pertinent to focus on maintaining intensity and frequency of training during this process while reducing volume to reduce the negative effects associated with reducing body mass (Langan-Evans, Close and Morton, 2011). Finally, the taper week or the realisation phase reduces training volume by 40-60% with the aim of enhancing recovery and maximising an athletes “sharpness” to ensure they are ready to compete.

The previous section demonstrated how high-level taekwondo athletes in a full time programme were not being exposed to organised, progressively overloaded training stress and as a result may have been subject to physiological plateaus or even de-training during training cycles culminating in an important competition. The factors that effect implementing periodised training stress was shown to be largely influenced by not taking into account the individual needs of each athlete, in particular with respect to their injury status and competition attendance. Therefore, implementing this individualised approach to training periodisation may allow coaches to prescribe and manage the training load of athletes over a macrocycle enhancing their ability to coordinate technical and tactical preparation with physical preparation and ultimately maximising their potential for performance success during competition.

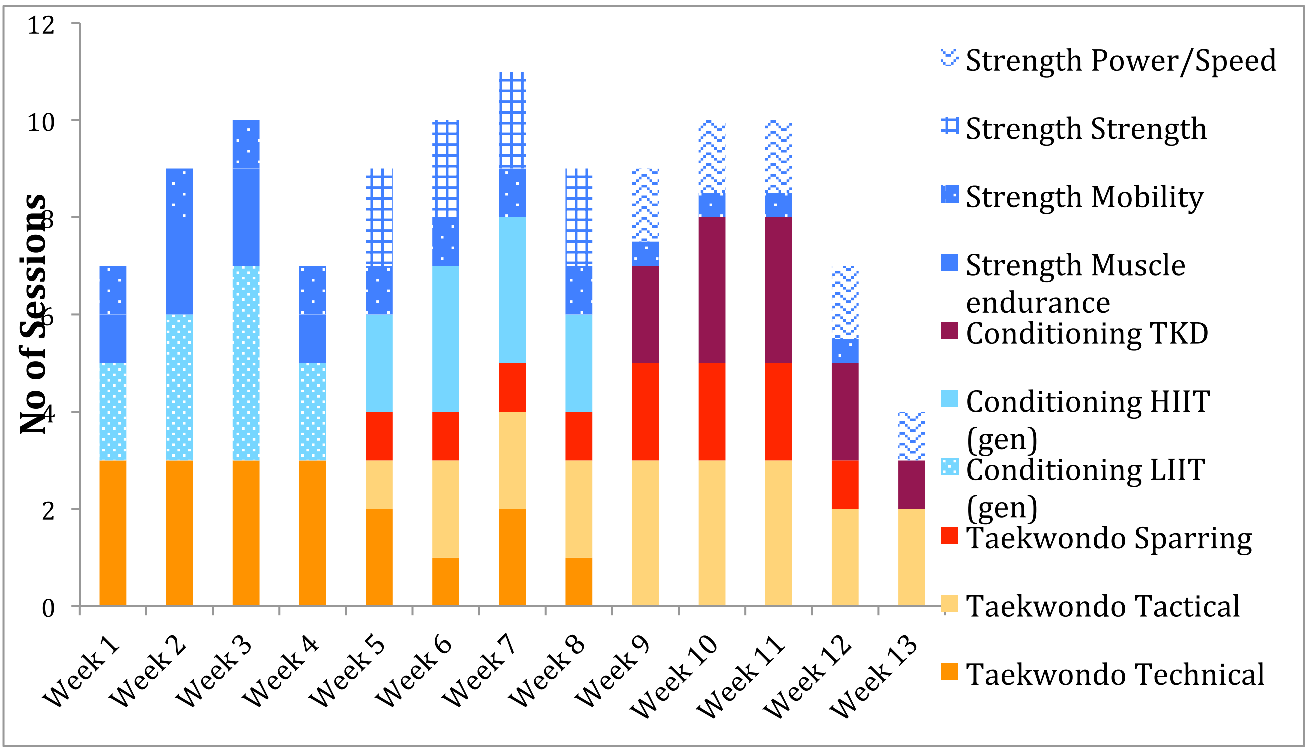

Figure 11 Example of training frequency and distribution of proposed individualised framework

Gen = general mode of training; TKD = taekwondo specific mode of training

5.8. Limitations

The key limitation in this study was the inability to collect data consecutively over the course of the 13-week macrocycle. Data collection took place during preparation for an important competition, which allowed maximisation of ecological validity for training demands. However, it also meant that limited interruptions to training sessions and for athletes were required in order to ensure preparation was not affected. Therefore, data collection was restricted to four non-consecutive weeks throughout the macrocycle. However, a longer and more cohesive data set may have illustrated more detail in terms of training load experienced by athletes and the periodisation of this load. Further, there was no testing battery at various points in the macrocycle to examine the changes in fitness capacities of athletes throughout. Since this study reported a possible plateau or de-training effect as the macrocycle progressed, a testing battery would have allowed further investigation of this. However, in order to limit the disturbance to physical preparation this was not included in the study.

5.9. Summary

Chapter 3 demonstrated that taekwondo competition under the current rule set has an increased physiological demand compared to previous literature and thus may require athletes to have a high level of aerobic and anaerobic lactic capacities. However, Chapter 4 indicated that the physiological profile has not changed in tandem with the changing demands of competition and as a result, presents areas for improving the physical preparation of athletes for competition. Physical preparation is determined by the training experienced by athletes and this study demonstrated that taekwondo athletes do not experience organised, progressive training loads in preparation for competition. This is influenced by the competition schedule, injuries and the resulting ability to complete training sessions and a lack of individualised approach to training. Therefore, implementing an effective training periodisation programme with the aim of maximising the physiological profile of athletes offers a valuable path for optimal physical preparation.

Chapter 6

Synthesis of Findings

Chapter 6. Synthesis of Findings

6.1. Realisation of Aims and Objectives

The aim of this PhD thesis was to investigate the physiological demands of elite taekwondo training and competition. This was achieved through the realisation of the research objectives set out in Chapter 1. An investigation in to the demands of competition was carried out in order to provide an up-to-date, ecologically valid assessment of the physical and physiological demands of international competitive taekwondo combat (Objective 1). The physical and physiological characteristics of taekwondo athletes were then examined in order to create an ecologically valid physiological profile of taekwondo athletes in the current iteration of the sport and compare it with that of athletes prior to the rule changes (Objective 2). Training inputs largely influence physiological profiles and therefore an investigation in to the physiological demands and characteristics of a training cycle in a full-time taekwondo programme (Objective 3) were completed. Finally, further examination of the factors that effect organising and planning training over a cycle for optimisation of physical preparation was then conducted (Objective 4).

The realisations of the above aims and objectives have created a cohesive blue print on which the physical preparation of taekwondo athletes may be optimised. Adequately preparing an athlete for the demands of competition with the optimisation of their physiological profile will be achieved through efficient and optimal training loads and subsequent adaptations. In turn, these adaptations over the course of different training cycles within a competitive taekwondo season will rely heavily on the organisation and periodisation of training stresses. For this reason, this discussion will focus on utilising the information gained from examining the demands of competition under the current rules along with the evolution of the physiological profile to suggest implications and practical considerations for optimising the training process for taekwondo athletes.

6.2. The Effects of Rule Changes on Energy System Demands

The findings in this thesis (Chapter 4) suggest that the physiological profile of taekwondo athletes has not changed, particularly with respect to the energy system development and capacity, despite the multitude of rule changes in the last decade.

However, investigation in to the demands of competition (Chapter 3) demonstrates a shift in the physical demand of and physiological response to competitive taekwondo. Chapter 3.4 demonstrated a 2-3 fold increase in the number of exchanges per taekwondo combat than was reported in the literature prior to the rule changes. This was accompanied by reduced work:rest and active:passive ratios and a resultant decreased duration of the rest or active rest periods during combats. It is well understood that during intermittent exercise the duration of both the work and rest interval influence the intensity of the exercise (Buchheit and Laursen, 2013b) and specifically, that increased duration or frequency of work periods coupled with reduced duration or frequency of rest periods will result in reduced work intensity. This therefore suggests that the exchanges during current taekwondo combats may be reduced in overall intensity.

The physiological response to taekwondo combat demonstrates further the relationship between intensity and duration (Figure 4, p. 81). The increased volume of work is echoed with a near maximal exhibit of BLa response. This indicates that athletes were maximizing the extent of their anaerobic energy supplies resulting in a very high level of blood lactate accumulation. Previously, studies in the literature have suggested that a very small proportion (<5%) of energy during taekwondo combats is supplied by the anaerobic lactic system (Lopes-Silva *et al.*, 2018; Lopes-Silva *et al.*, 2015; Campos *et al.*, 2012). However, as discussed in Chapter 1.4 of this thesis, the authors of the aforementioned studies reported relatively low to moderate BLa levels during and after these combats. This is in contrast to the data reported in this thesis (Chapter 3.3) and suggests that taekwondo combats elicit a greater anaerobic lactic response under the current rule set. As a result, this provides an avenue for enhancing the physiological robustness of athletes for competition through training. This will be discussed further in following sections.

Additionally, it is understood that a reduction of intensity due to an increase in the duration of work (or the frequency of intermittent work intervals) leads to an increase on the reliance of aerobic energy supply due to the limited resources of the anaerobic energy systems as the duration progresses (Buchheit and Laursen, 2013b; MacLaren and Morton, 2011). As discussed in chapter 3.3, athletes of high-intensity, striking combat sports such as karate, boxing and MMA exhibit high VO_{2max} scores to cope with the demand of combats which elicit maximal BLa and RPE scores and which have a high contribution of energy from the aerobic system (Beneke *et al.*, 2004; Davis, Leithäuser and Beneke, 2014; Amtmann, Amtmann and Spath, 2008). Therefore, given the increase in frequency of exchanges, the high BLa levels and RPE scores of taekwondo combats (Chapter 3.3, 3.4) taekwondo athletes may also benefit from maximising their aerobic capacity to remain robust to the demands of competition.

The current rule set in taekwondo appears to have changed the physical demand and the subsequent physiological response of combats. Present day taekwondo athletes need to be able to engage in high-intensity exchanges up to 60 ± 15 times (Table 11) per combat in up to 5 combats per day. The current physiological response is in contrast to that documented in the literature prior to the rule changes and is more similar to that seen in other striking combat sports such as karate, boxing and MMA suggesting that the energy contribution distribution to combats may have changed from that reported by Campos et al. (2012). However, the physiological profile does not appear to have changed to appropriately match the demands of competition and therefore, this highlights both an important direction for future research as well as an opportunity to enhance the physiological profile of athletes for competition. Development of optimal energy system capacities, including the ability to produce and manage high BLa levels along with an efficient aerobic system, may be critical for maximising taekwondo athletes' chance of performance success and should be the predominant focus of physical preparation.

6.3. Implications for Training

6.3.1. Anaerobic Capacities

Given the high physiological load of taekwondo competition, and in particular the increased demand placed on anaerobic glycolysis, it follows that taekwondo athletes should aspire to possess high levels of anaerobic abilities. Since taekwondo athletes accumulate a high level of BLa during competitive bouts, developing an ability to tolerate this accumulation is likely to provide fatigue resistance and thus be beneficial for sustaining performance. Typically, BLa accumulation occurs as a result of prolonged high-intensity exercise where the rate at which energy is required by the working muscles is greater than can be supplied by the aerobic energy system alone (Ferguson *et al.*, 2018). The kinetics of anaerobic glycolysis and how to manipulate them are beyond the scope of this thesis. However, understanding that anaerobic glycolysis plays an important role in taekwondo provides an opportunity to enhance the efficiency of the energy supply during combats by increasing an athlete's ability to produce and shuttle lactate. This can be achieved by a variety of different high-intensity interval designs (Buchheit and Laursen, 2013b; Buchheit and Laursen, 2013a).

Another key factor in anaerobic energy system development for the modern day taekwondo athlete lies in enhancing the mechanical efficiency with which athletes execute movements, kicks and punches during combat (Helgerud *et al.*, 2007; Tønnessen *et al.*, 2016). The mechanical efficiency of an athlete, which is often called exercise economy, has been shown to enhance endurance performance (García-Pallarés *et al.*, 2009). In middle-distance runners, the ability to apply forces of the correct magnitude and direction and with the correct timing is associated with optimal running economy (Thompson, 2017). These characteristics are largely developed by strength and power training (García-Pallarés *et al.*, 2009). In the same sense, taekwondo athletes could benefit from strength and power training in order to enhance the mechanical efficiency of kicks, punches and the necessary rapid changes of direction during combats. It is largely thought that in order to execute a kick one must exert a certain level of force at a high velocity (James, Kelly and Beckman, 2013). Therefore, an emphasis on strength and power training could help reduce the energetic demand and relative intensity of each kick for athletes and as a result, enhance the endurance capacity for exchanges.

High-intensity interval training (HIIT) has been popular in recent decades in a large variety of sports to promote efficient anaerobic adaptations but more recently has become popular in combat sports to complement sport-specific training and maximise physical preparedness (Franchini, Cormack and Takito, 2019). HIIT methodologies can provide a way to increase the anaerobic power and capacity of combat athletes (specifically to manage the high frequency and intensity of exchanges as demonstrated in Figure 4, p.81) using general modes of exercise such as running and cycling. In fact, it has been shown that just 11 running HIIT sessions in 4 weeks of training can increase the anaerobic power and capacity of taekwondo athletes (Monks *et al.*, 2017) more than continuous running training. Furthermore, HIIT training also increased the vertical jump scores of athletes suggesting it can be useful for increasing mechanical power output as well. This may be as a result of an increased recruitment of fast twitch muscle fibres (Monks *et al.*, 2017) and thus can be used alongside strength training to maximise the exercise economy of taekwondo athletes. HIIT training therefore provides an appropriate tool to enhance anaerobic abilities of taekwondo athletes and thus maximise their physical preparedness for the large anaerobic demands of current taekwondo compeititon.

Chapter 3 demonstrated an exchange time to preparation time ratio, also called a high-intensity to low-intensity ratio (Hi:Lo ratio) of 1:1 during present day taekwondo combats. This can be used to provide a basis on which anaerobic conditioning can be prescribed. Both general and taekwondo specific anaerobic conditioning can be planned to prepare athletes for these work intervals during competition. Table 24 illustrates some examples of conditioning modes using these work:rest and Hi:Lo ratios.

Table 24 Example of anaerobic conditioning utilising the 1:1 Hi:Lo ratio

HIIT Mode	Hi:Lo (1:1)	Reps/Set	No. of sets	Rest between sets
General	30s @ RPE 8-9: 30s @ RPE 4-5	3 (3 mins)	3-6 (increase no of sets as mesocycle progresses)	1 min
Circuit	15s high intensity exercise (jump squats, MB slams, broad jumps, MB/cable rotations, MB throws etc.) : 15s low intensity exercise (BW squat, jog, carry etc.)	6 (3 mins)	3-6	1 min
TKD	5-10s of a high intensity kicking combination : 5-10s of a preparatory combination	9-18 (3 min sets)	3-6	1 min

Table 25 Summary of thesis key findings and implications for training

Thesis Key Findings	Study	Implications for Training
The physiological profile of athletes appears not to have shifted appropriately in line with the demands of competition due to rule changes	2	Aerobic and anaerobic lactic energy system development should form the basis of the physical preparation of athletes
Continuity and progressive overload of training was impacted negatively by injury occurrence and competition schedule	3	Individualisation of periodised training plans are necessary to avoid training plateaus or detraining effect
Tactical and tactical/technical training are the most physiologically demanding	3	This should be taken into account when planning and considering the total training stress
Increased number of exchanges per combat and subsequent A:P ratio A+P:R ratios leading to reduced intensity of exchanges	1	Priority for athlete to be able to sustain repeated higher intensity efforts over maximizing the intensity of the effort
Increased physiological demand in terms of BLa and subjective scores	1	Increase development of aerobic capacity and lactate tolerance. Strength and power training to enhance exercise economy.
The findings of the three studies taken together provide a blueprint on which training aims and periodised plans can be based	1,2,3	Coaches, support staff and athletes should consider utilizing the blueprint to optimise and coordinate physical preparation with technical and tactical preparation

A:P = active to passive ratio; A+P:R = active + passive to work ratio; BLa = blood lactate

6.3.2. Aerobic Capacities

While having a well-developed anaerobic energy system is important to allow taekwondo athletes to be both efficient within and sustain the intensity of the exchanges, enhancing the function of the aerobic system will increase the efficiency with which the anaerobic energy system can function. Oxidative metabolism is the predominant energy source during combats not only due to fuelling the low-intensity activity between exchanges and during the brief respites within rounds but also due to its requirement for the replenishment of ATP-PCr and for its involvement in the shuttle and oxidation of lactate substrates from the working muscle to its desired location (Gaitanos *et al.*, 1993; Brooks, 1986). Therefore, aerobic metabolism plays a key role in enabling athletes to resist fatigue and aid in recovery during and between the three rounds of a combat (see Figure 4, p.81). It also assists in the recovery between combats allowing athletes to continue to execute technical and tactical skills all the way through to the final rounds of the final combat. The aerobic energy system can be developed in a multitude of ways including methods to develop it centrally and peripherally. Traditional, low-intensity steady state (LISS) training can offer a low physiological and/or mechanical stress way to enhance aerobic fitness which may be beneficial during the general phase of training (see following section 6.4.1.1). Additionally, a variety of general and specific low and high-intensity interval training (LIIT and HIIT) methods can be used to improve aerobic capacity (Buchheit and Laursen, 2013a; Buchheit and Laursen, 2013b; Helgerud *et al.*, 2007). Monks et al. (2017) demonstrated an increase in the $V0_{2max}$ of taekwondo athletes after 11 HIIT running sessions. Therefore, aerobic capacity can be increased in a variety of ways that will be influenced by the desired adaptation in the current phase of training (Table 26).

Table 26 Example of conditioning methods that could be used to develop aerobic conditioning

Mode	Interval Type	Duration
General (cycling, rowing, running etc.)	LISS	30-60 mins
General (cycling, rowing, running etc.	LIIT (1:1 Hi:Lo ratio)	30-60 mins
Circuit	LISS (6-10 exercises, keep RPE @ 4-6 and/or HR @ 50-70% $HR_{max)}$)	30-40 mins
TKD	LIIT (1:1 Hi:Lo ratio of low intensity kicking combinations (20-30s) and preparation periods (20-30s) for 3-5 minutes followed by 1 min rest.)	30-40 mins (5-10 rounds)

6.4. Considerations for Designing Training Plans

As discussed above, taekwondo athletes would benefit from having a proficiency to produce and utilise lactate during exercise, efficient movement and biomechanics to execute all of the movements necessary to engage in combat with minimised effect on fatigue and a well-developed aerobic system to support and recover from the exchanges during combat. Therefore, this provides a blueprint on which training can be constructed. However, as shown in Chapter 5, in order to understand the stimuli each athlete is experiencing over the course of a training cycle and thus to maximise their adaptations and overall physical preparation, there are a number of training considerations to take into account. These considerations can be broken down in to two key areas based on the findings surrounding the challenges of training in this thesis (Chapter 5.6, 5.7): 1) the periodisation of taekwondo training during a competitive season and 2) the factors affecting the individualisation of training programmes for athletes. These considerations will be discussed below with respect to the training implications above.

6.4.1. Training Periodisation

Chapter 5 demonstrated that in order to adequately develop the relevant physiological qualities and avoid plateaus, de-training and training monotony (Mujika and Padilla, 2000b; Mujika and Padilla, 2000a) and reduce the risk of injury (Issurin, 2010), training must be planned and deliberated with respect to longer blocks of time such as mesocycles and macrocycles. Furthermore, regard must be given to the stimulus athletes experience during each training session, even when the focus of that training is independent of the physical and physiological preparation of the athlete. For example, it was shown in this thesis that the most physiologically taxing taekwondo training sessions were the ones that focused on the development of technical and tactical abilities (Chapter 5.3, 5.4). An understanding of the training stress and stimulus of all training sessions should therefore be considered when approaching medium and long term planning of training cycles.

Given the physiological demands of taekwondo competition at present, it is clear that maximising energy system development is of critical importance. However, there is a large gap between understanding this and incorporating the necessary stimulus at a frequency, volume and intensity that creates, and continues to create, the adaptations necessary for this development over the course of an entire training cycle. Furthermore, it is also important to develop strength and power qualities in order to enhance the mechanical efficiency of athletes. Therefore, the periodisation of training must consider how to maximise both opposing and complimentary qualities along with the technical and tactical demands of training.

6.4.1.1. Training Organisation

Once consideration has been given to the stimulus provided by each training session type and the way in which to maximise the development of opposing physical qualities, one of the biggest challenges in taekwondo is training organisation around the competition schedule. Athletes often compete from early January through to mid December with no scheduled off-season. Therefore, coaches and support staff must design the organisation of the competitive season and attempt to schedule in periods free of competition in order to incorporate rest and recovery and general preparation.

Given the scarcity in the literature surrounding long term organisation and planning of training for taekwondo athletes, it is difficult to know how much time is necessary for adequate recovery between competitions or how much time will allow adequate general physical preparation. One way to overcome this would be to take guidance from the training periodisation plans of other combat sports. Research in judo and

MMA suggests that training blocks of 3-5 weeks within a cycle is sufficient to develop the relevant physical and physiological capacities (Marques *et al.*, 2017; James, Kelly and Beckman, 2013). Furthermore, both of these authors suggest that block periodisation, a method where general training adaptations are the focus in the beginning with a consequential drive towards specificity as the cycle progresses, is beneficial. This allows a reduction in the training monotony and an increase in training variety due to having a general block that has a reduced volume of sport specific work.

Additionally, a general block would allow a short term shift in focus away from the arduous and taxing nature of taekwondo tactical and combat training towards the general development of some of the fundamental physiological capacities discussed above, namely aerobic development, lactate threshold and mechanical efficiency, which would help reduce training monotony and enhance injury mitigation (Mujika and Padilla, 2000b; Mujika and Padilla, 2000a; Ziaee, Rahmani and Rostami, 2010). For example, it may be beneficial to develop baseline aerobic conditioning using an exercise bike or other off-feet modality in combination with weight-bearing modalities such as running. Due to the low mechanical load of the former, the volume and frequency can be increased drastically and central improvements in aerobic abilities can be obtained efficiently while incorporating the latter could maintain some exposure to mechanical load to maintain or develop robustness. Additionally, it has been suggested previously that the optimal way to specifically develop energy systems for combat in taekwondo (Bridge, 2012) and MMA (James, Kelly and Beckman, 2013) is to replicate the work to rest ratios and the duration of exchanges seen in combat during conditioning protocols (Figure 10). Therefore, during a general phase, this can provide a level of specificity while utilising a non-specific exercise mode to maximise training volume and frequency during this short training block. This method of high-intensity training has also been suggested to be effective for use during specific conditioning training. For example, recreating the work:rest ratios recorded in study 1 (Chapter 3) during taekwondo pad work may be an effective way of developing the anaerobic energy systems necessary to sustain these repetitive high-intensity actions during competition (Figure 9).

Furthermore, considering the impact of non-contact injuries on the ability of athletes to complete training cycles (Chapter 5.5), performing this kind of training during regularly scheduled general blocks may help athletes to increase their overall training load while reducing the mechanical load experienced during taekwondo specific activities to reduce the occurrence of these kinds of injuries (Gabbett, 2016). This may also elicit a greater stimulus of the central and peripheral systems independent of the mechanical and neuromuscular fatigue that occurs during taekwondo specific drills.

6.4.1.2. Training Load Management

Chapter 5.6 discussed the importance of utilising a simple method for managing and manipulating TL throughout the periodised cycle. Session frequency has been shown to be a very straightforward and yet effective way to manipulate training stress (Mujika, 2010). However, despite these benefits, session frequency does not take into account the intensity or the specific physiological adaptations within each training session. Therefore, the planning process becomes critical in setting out the objectives in terms of the desired physiological adaptations for each block.

For example, aerobic capacity is a valuable trait for taekwondo athletes (Chapter 3.4). There are myriad of way that coaches may develop the aerobic capacity of taekwondo athletes including low-intensity steady state work and higher intensity intervals in both a general and a taekwondo specific manner. However, if the development of this capacity is not a specific priority within a training block, then using session frequency alone it may be difficult to determine whether and to what extent this system is being developed just by managing the number of training sessions per week. Conversely, specifying this capacity as a focus in a general training block, for example, would ensure that the increase in volume would involve training sessions that emphasised enhancing aerobic capacity. Subsequent blocks that seek to develop lactate threshold and tolerance and/or enhance strength and power characteristics would follow a similar fashion. The correct order for these blocks also becomes important and should be structured in such a way that the interference effect is avoided; each subsequent block should allow maintenance of previously developed capacities as a secondary outcome and/or the previously developed capacities should enhance the development of the subsequent capacities (James, Kelly and Beckman, 2013; Issurin, 2010; García-Pallarés *et al.*, 2009).

6.4.2. Individualisation

Taekwondo is an individual sport but, unlike some other individual sports, training requires interaction with training partners. Therefore, taekwondo coaches and support staff often have to plan training with a larger group of athletes in mind. It was suggested in this thesis that the by-product of this group-focused approach is a factor that contributes to a lack of continuity of training stress experienced by each individual athlete (Chapter 5.6, 5.7). However, it may be beneficial to plan the general training structure around the group as a whole and to develop broad themes and organisation as discussed previously and then use these as a framework for each individual plan. In this way, there is some coordination between training plans and phases allowing them to have and be training partners.

6.4.2.1. Training Adaptation Rate

Once the group themes have been established, the individualisation of plans must take into account a variety of factors to optimise the physical preparation of each athlete specific to their individual needs. There are large inter- and intra-individual variations in the response to training and the subsequent adaptations (Chapter 1.6.2) (Kiely, 2012). For this reason, the optimal duration and composition of a training block will vary between individuals. One way to attempt to understand these variances is to schedule testing specific to the relevant physiological capacity within cycles. For example, following a training block aimed at enhancing general aerobic capacity, it may be pertinent to carry out a measure of aerobic fitness (such as the MSFT). If improvements in these scores for an individual are below what is expected then adjustments can be made to prolong the current block or for the following block to include some additional aerobic conditioning. Furthermore, this can then be utilised as a learning opportunity for the next cycle whereby an athlete may need a longer or more intense block of general conditioning than other athletes.

6.4.2.2. Athlete Success Level

It is also of importance to consider the training history, experience levels and goals of each individual athlete. More experienced athletes lose more training days from injuries than less experienced athletes (Chapter 5.6). While these athletes may be more subject to the effects of injury due to a longer training history they may also have a reduced requirement for technical and/or tactical training volume. Therefore, this could be an important consideration when constructing their training plans in that they could participate in a reduced frequency or volume of technical/tactical training but could rely on more general modes of training to enhance the physiological conditioning, particularly during general phases of training. On the other hand, less experienced athletes may need to do a higher volume of fundamental technical and tactical training and therefore they may need to incorporate this throughout the entire training cycle. Furthermore, since we know non-contact injury is more of an issue for TOP athletes (who tended to have an older training age), including preventative measures in the form of adequate strength, power and mobility training could offset this.

The level of experience of an athlete will also play an important part in their competitive goals for the season. The highest level athletes, who already have a high number of ranking points and who have won major medals in previous seasons, will have different competitive goals to athletes who are new to the programme and whose main priority will be to get experience fighting on the international stage and begin to collect ranking points. In that sense, high-level athletes' competition schedule may be relatively quiet in the first quarter of a year with their first main priority being the major in the summer (Europeans, Worlds, Olympic Games). They will then have a busy second half of the year (excluding Olympic years) competing in the Grand Prix circuit. For these athletes, it is then appropriate to have a longer general preparatory phase at the beginning of the year and again after the major championships in the summer and prior to the beginning of the Grand Prix circuit. On the other hand, a newer athlete who needs competitive experience and ranking points may need to compete in a large array of lower level tournaments throughout the first half of the year but would have a quieter second half of the year when there are less of these competitions available. For these athletes, the large body of preparatory work could be done towards the end of the calendar year to prepare them for the demands of the competition schedule early in the following year. Throughout this time, it is possible that these athletes can continue to train together and have overlap in their training schedules so that there are plenty of training partners available however, the focus of the overall schedule may be different.

6.4.2.3. Body Composition and Making Weight

In weight making sports, an important physical preparation characteristic surrounds the process of "making the weight". This thesis has profiled the body composition of taekwondo athletes at the beginning of a season using DXA scan technology (Chapter 3.3). The research is conflicting regarding the effects of making weight for combat sports. Both acute and long-term weight loss strategies have been shown to affect performance variables negatively (Kazemi, Rahman and De Ciantis, 2011; da Silva Santos *et al.*, 2016; Franchini, Brito and Artioli, 2012) but also that the 18-24 hour period between weigh in and competition is sufficient to re-establish hydration and performance measures to baseline (Yang, Heine and Grau, 2018). However, it is thought that long-term body re-composition to prioritise maintenance of lean mass while reducing fat mass is the most effective method of making weight due to the positive effect on power-to-mass ratio as well as the ability to maintain exercise capacity (Yang *et al.*, 2015). Additionally, new WT rules require taekwondo athletes to be within 5% of the weight category on the morning of competition (WTF, 2018b). Therefore, taekwondo athletes that sit above 5% of their weight category must make some effort to effect change in their body composition in order to make weight rather than relying solely on acute weight loss methods such as dehydration. Chapter 5.5 demonstrated the frequency with which high-level taekwondo athletes can compete throughout a training phase (2-4 times per 12 week cycle) and therefore, the implications of manipulating body composition repeatedly throughout a year long taekwondo season should be considered as part of the individualised preparation of taekwondo athletes. Although the detail surrounding the process and effect of making weight is beyond the scope of this thesis, athletes who have to reduce a lot of body mass may need to specifically focus on maintaining performance variables so that they do not diminish as a consequence of reducing body mass.

6.4.2.4. Implementation of Periodised and Individualised Plans

Figures 12, 13, 14 and 15 give examples of microcycle training schedules for each mesocycle in the proposed macrocycle. For each of the 4-week mesocycles (1-3), the third week is presented. Since the mesocycles are organised in a 3:1 format (3 weeks of loading and a de-load week) with an increasing training load over the three weeks, this allows depiction of the heaviest training week within each mesocycle. This provides a framework for training organisation within the mesocycle. The considerations required for each individual athlete are then discussed below. Implementation of training load utilising this framework and considerations will allow a structured, approproate and progressively overloaded training stress to be experienced by each individual athlete which may increase the effectiveness of physical preparation and coordinate peak technical and tactical performance with physical performance to provide the greatest chance of success at competition.

Mesocycle 1: Accumulation Phase

Week 3		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	Session	Technical	LIIT	Technical	LIIT	Technical	Rest	Rest
	Priority	3	1	3	1	3		
PM	Session	LIIT	Strength	Mobility	Strength	LIIT		
	Priority	1	2	2	2	1		

Figure 12 **Example of a microcycle training schedule during mesocycle 1 (accumulation phase) with the considerations for each athlete discussed below**

Phase Focus: Aerobic Conditioning and Muscle Endurance

Considerations for the individual

Injury Status: given the lower priority of taekwondo during this phase, athletes with injuries could afford to sacrifice some taekwondo sessions and instead include extra conditioning/strength.

Performance level: it may be necessary for TARG athletes to place a higher priority on taekwondo training at this stage, they may replace LIIT for taekwondo sessions to enhance skill preparation . Further, since TOP athletes are more likely to miss training to injury, conditioning sessions should be used maximise general conditioning and introduce variety in to training to reduce training monotony.

Weight making: Athletes making weight may further prioritise general LIIT session to increase energy expenditure and assist with this process. Strength training should be maintained to assist in maintaining lean mass.

Competition Status: If an athlete is attending a competition during this microcycle, strength and general LIIT may need to be modified accordingly and or replaced with taekwondo specific sessions

Adaptation Rate: some athletes may do better with LISS over LIIT. Previous macrocycles or preference may help to determine this.

Mesocycle 2: Transmutation Phase (General-Specific)

Week 7		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	Session	Technical	Tactical	Technical	Tactical	Sparring	HIIT	Rest
	Priority	1	4	1	4	4	2	
PM	Session	Strength	HIIT	Mobility	HIIT	Strength		
	Priority	3	2	3	2	3		

Figure 13 **Example of a microcycle training schedule during mesocycle 2 (general-specific transmutation phase) with the considerations for each individual athlete discussed below**

Phase Focus: Technical Preparation and Anaerobic Conditioning

Considerations for the individual

Injury Status: Priority in this phase is technical TKD sessions so where possible these should be attended even if they need to be modified. Anaerobic conditioning is also prioritised but as it is a general transmutation phase these can be modified to suit any injury concerns. Lower priority taekwondo sessions could be replaced with appropriate conditioning sessions if necessary.

Performance level: TARG athletes may consider replacing conditioning sessions with TKD if additional skill training is necessary however a conditioning focus could be tagged to the end to ensure physical preparation demands are met and progressive overload is still occurring. TOP athletes may continue to reduce training monotony by maintaining general modes for conditioning sessions.

Weight making: The high frequency of training in this microcycle should be sufficient from an energy expenditure point of view but low-intensity steady state work could be tagged on to some session to increase this if necessary. If energy deficit is large, HIIT training could be largely low impact to reduce injury risk (increase in frequency of taekwondo sessions should offer sufficient impact stimulus). Strength sessions could be adjusted to focus on maintaining lean mass.

Competition Status: Competition attendance during this microcycle may warrant a reduction or removal of strength sessions. Competition day could be a good training stimulus (if desired) and may be sufficient to replace Friday and Saturdays sessions (if athlete has an appropriate number of fights).

Adaptation Rate: Based on testing session at the beginning of this mesoycle, insufficient improvements in aerobic capacity after the previous mesocycle may warrant exchanging some HIIT conditioning for LIIT conditioning to continue to make aerobic capacity improvements during this phase.

Mesocycle 3: Transmutation Phase (Specific)

Week 10		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	Session	Tactical	Strength/ mobility	Tactical	Tactical	Sparring	HIIT (TKD)	Rest
	Priority	1	3	1	1	1	2	
PM	Session	HIIT (TKD)	Sparring		Strength/ mobility	HIIT (TKD)		
	Priority	2	1		3	2		

Figure 14 Example of a microcycle training schedule during mesocycle 3 (specific transmutation phase) with the considerations for each individual athlete discussed below

Phase Focus: Tactical Preparation and Sparring

Considerations for the individual

Injury Status: With the focus now on tactical and sparring preparation, these sessions must be prioritised. If athletes suffer an acute injury appropriate conditioning sessions could replace tactical/sparring sessions on a short term basis. The two phases prior to this ideally should have allowed athletes who were managing longer term injuries space/time to appropriately rehabilitate so that they could maximise the Taekwondo focus of this phase. HIIT sessions could still be off feet/general modes if impact/load needs to be managed.

Performance level: TOP athletes may still prioritise the frequency/volume of TKD sessions if they need to manage load but ideally this phase would be focused on TKD tactical preparation group wide with the subsequent availability of a large group of training partners

Weight making: Athletes focused on making weight may need to manage load/impact/recovery if energy deficit is large. HIIT conditioning could be altered to general modes if required and book ended with steady state to increase energy expenditure if need be.

Competition Status: If competing during this microcycle then tactical sessions could still be prioritised but sparring replaced with competition day. Depending on athlete and importance of the competition, HIIT/strength training frequency/volume could be adjusted accordingly

Adaptation Rate: Based on testing session at the beginning of the mesocycle, anaerobic conditioning could be increased by tagging some HIIT at the end of tactical sessions. However, the high volume of tactical sessions (especially given their high physiological load) and sparring along with TKD conditioning should lead to continued anaerobic conditioning stimulus. Therefore, low scoring anaerobic capacity athletes could be re-tested mid cycle to ensure they are improving (especially given the brief and off-foot nature of the Wingate Anaerobic Test).

Mesocycle 4: Realisation

Week 13		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	Session	Tactical	HIIT	Tactical	Optional low level TKD/ conditioning	Optional low level TKD/ conditioning	Competition Day	
	Priority	n/a	n/a	n/a				
PM	Session	Strength						
	Priority	n/a						

Figure 15 Example of a microcyle training schedule during mesocycle 4 (taper/realisation phase) with the considerations for each individual athlete discussed below

Phase Focus: Taper

Considerations for the individual

Injury Status: Ideally injury status is good and athletes are ready to compete. If not, medical and coaching team to make a call whether athlete can compete or not

Performance level: This may dictate what/how many sessions athlete takes part in. TOP athletes are more likely to have a competition week routine that they like to stick to. TARG athletes could follow the above plan with input from coach and following their own preference

Weight making: It is likely most athletes will be involved in some sort of weight making by this stage. This may warrant some extra low-intensity conditioning early in the week but the key considerations will be effective management of rest and recovery especially if there is significant dehydration and/or glycogen depletion

Competition Status: n/a

Adaptation Rate: n/a

6.5. Summary

The findings and practical outcomes of this thesis for maximising physical preparedness for competition are summarised in Figure 16. This thesis demonstrated a shift in the demands of elite taekwondo competition towards a high volume of action under the new rule changes. As a result, the physical load and subsequent physiological response to competitive taekwondo bouts involves a high anaerobic (particularly anaerobic glycolysis) and aerobic load. This shift in competitive demand was not echoed in the physiological profile of taekwondo athletes. As such, optimising the ability of taekwondo athletes to resist fatigue under these competitive conditions should be the priority of physical preparation in coordination with the technical and tactical training. However, as seen in Chapter 5 of this thesis, there are a variety of factors that affect the ability of taekwondo athletes to experience cohesive and progressive training loads and stresses over the course of a competitive season. Therefore, this discussion aimed to utilise the realisations of this thesis by presenting the training considerations taekwondo practitioners could consider in order to optimise physical preparation for competitive success.

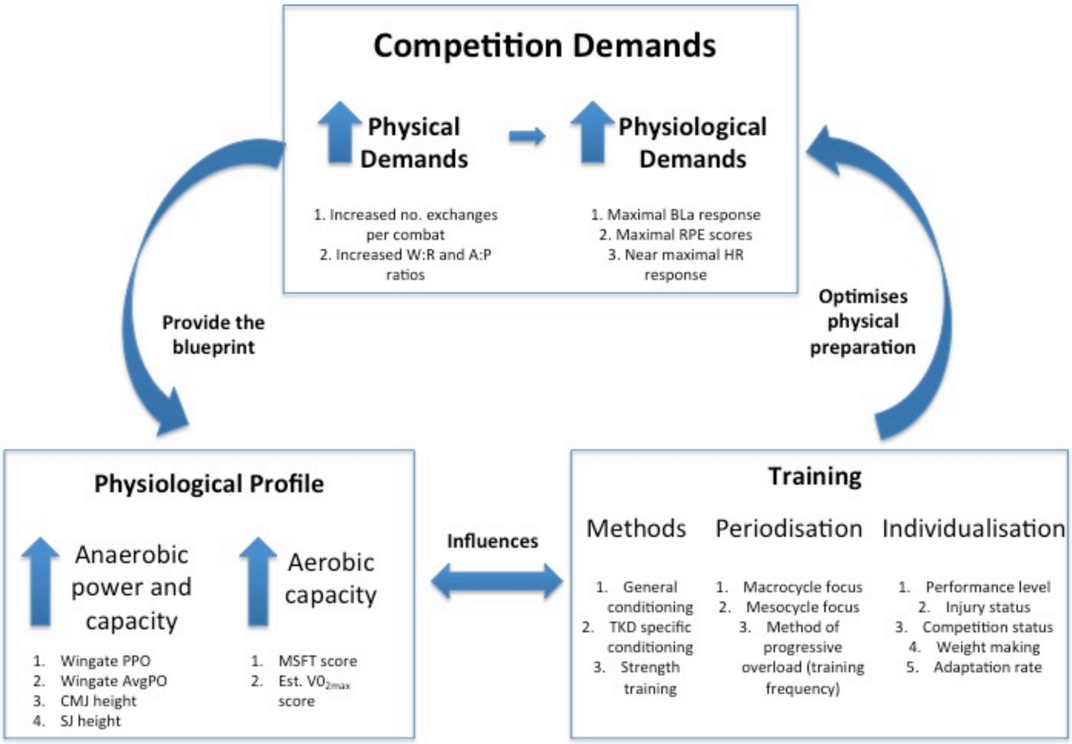

Figure 16 Summary of finding from this thesis and considerations for maximising physical preparedness for competiton

Competition demands provide the blueprint on which the physiological profile can be based. A focus on anaerobic power and capacity along with aerobic capacity may optimise the phsyiological profile of athletes. These can be measured using the WAnT, jump testing and the MSFT. The optimisation of the physiological profile can then be achieved through appropriate training methodologies. Training methodologies should be considered in terms of:

1) methods and modes used to enhance the appropriate physiological capacities

2) the periodisation strategies used to ensure optimal physical preparedness for important competitions and to reduce training monotony and injury risk

3) individualisation systems to maximise the training experience and streamline the training load and stress for each individual athlete based on their level of performance/experience, injury status, adaptation rate, competition attendance and weight making status

6.6 Reflections from Working in a High Performance Sporting Environment

Ecological validity is an important concept for research in high performance sporting environments in order to maximise the relevance of findings for the population. However, collecting data in these environments presents a specific set of challenges that must be managed appropriately.

Conditions for data collection for this thesis were set out prior to commencement and included a directive that minimal disruptions to training and competition were required throughout. Participating athletes were training for and competing in important competitions throughout the data collection periods and coaches and directors requested that their day to day routines be disturbed as little as possible. As a result, data collection was required to be organised around training and competition schedules. For example, physiological profile variables had to be chosen and carried out with respect to what would cause least disturbance to training sessions. Furthermore, organising data collection around set training schedules means the windows for this to occur are relatively small. Therefore, data collection can be greatly impacted by injuries and dropouts of participants because there may not be alternative windows in which to re-arrange data collection. Additionally, in high-level sport (and as illustrated in Chapter 5.2) the incidence of injury and illness is commonplace. This had a large impact on the available participants and subsequent participant numbers in all studies for this thesis.

Collecting data in a high performance environment allows data to be accurate and reflective of the real world. However, as a result, it means that the environment cannot be controlled and researchers must be reactive to changes in the environment. This can be problematic with respect to the cohesiveness of the data collected. For example, a last minute change in the duration of rounds in international taekwondo competitions is a relatively common-place occurrence and thus data collection for the first study (Chapter 3) is reflective of the this type of event. However, when analysing the resultant data and comparing with other data in the literature this presents a challenge.

Finally, but not without significant importance, is the reality that collecting data in a high performance environment means managing the emotions and behaviours of athletes and coaches who are under a large amount of pressure to get results and perform. Asking exhausted athletes to get up 60 minutes early to complete testing sessions can be met with a lot of resistance and requires a lot of empathy and coercion. Furthermore, coaches who are under pressure to ensure they prepare athletes adequately often change their mind about and struggle to see the long term usefulness of research that impacts their training sessions and athletes when things are not going to plan. As a result, researchers in this environment must be mindful of these things and be able to adapt plans when necessary. This can therefore impact the quality of the data collected.

6.7. Limitations

The present thesis has contributed to and advanced the research surrounding the physical and physiological attributes of taekwondo athletes as well as the demands of taekwondo training and competition. The research from the three studies that make up this thesis has culminated in a series of recommendations and guidelines that may assist in optimising the physical preparation and thus the performance success of taekwondo athletes. Furthermore, these studies may also contribute to the wider body of current literature once the embargo on submission for publication has been lifted (after the 2020 Olympic Games). The research also recruited a wide selection of full time taekwondo athletes including Olympic Games, World Championship and European Championship medalists. Despite this, there were a number of limitations with respect to the data collection, principally due to restrictions collecting data in situ, ecological validity and limited participant numbers. These limitations were considered following the discussion of each study.

6.8. Recommendations for Future Research

The three studies depicted in this thesis provide a framework for the physiological demands and requirements of elite taekwondo athletes during training and competition in the modern evolution of the sport. However, the relative scarcity of the literature in taekwondo, particularly in light of the last decade of rule changes, necessitated that the studies in this thesis largely be investigations in to the sport and athletes as they are in the present state. Further research could seek to investigate the efficacy and usefulness of the suggested training approaches for optimising the physical preparation of taekwondo athletes.

There are many factors that contribute to success during competitive taekwondo combats, of which physical preparation plays just one part. As a result, it is difficult to accurately assess the impact of a physical preparation intervention on performance. However, this could be negated by designing a taekwondo specific performance fitness test similar to the one created for judo (Sterkowicz, 1995; Franchini *et al.*, 2009). While there have been a multitude of studies that have aimed to create taekwondo specific measures of different physiological variables (Sant'Ana *et al.*, 2017; Santos and Franchini, 2018; Hausen *et al.*, 2018; Hausen *et al.*, 2017; Rocha *et al.*, 2016; Araujo *et al.*, 2017b; Chaabene *et al.*, 2018; Tayech *et al.*, 2018), there is no one test which reflects the overall fitness capacity of an athlete. For example, the cTKDet and the iTKDet are taekwondo specific tests for determining the cardiorespiratory capacities of taekwondo athletes (Hausen *et al.*, 2018). While these tests were shown to be valid for determining the aerobic qualities of taekwondo athletes, they may not account for improvements in anaerobic qualities or exercise economy and therefore may not accurately depict whether an intervention has improved the overall taekwondo-specific fitness capacity of an athlete. For this reason, establishing a reliable, accurate and valid measure of taekwondo fitness performance would pave the way for an onslaught of research to determine optimal methods for physical preparation.

One way to determine optimal methods of physical preparation would be to assess the efficacy of different modes of training for enhancing taekwondo specific fitness. For example, it was discussed previously (Chapter 6.4.2.) that it may be beneficial to include general modes of training for developing fundamental physiological variables such as aerobic capacity and lactate threshold as it would help to reduce training monotony, may be important for reducing injury incidence and would allow athletes a different stimulus and reduced mechanical load. There is a presumption that general training modes would be less advantageous than specific training modes for improving physical preparation for combat but this has not yet been determined. Therefore, since reducing non-contact injury is of primary concern as athletes become more experienced, understanding the impact of general conditioning modes (such as cycling or running) versus taekwondo-specific conditioning (such as pad work) on physical preparation would be highly advantageous and would provide important detail on the optimisation of individual physical preparation.

The implementation of a periodised training plan for individual taekwondo athletes has been discussed in this thesis (Chapter 4.7.1). Block periodised training progressing from general to more specific physiological qualities similar to that of judo and MMA has been proposed as an efficient and optimal way to enhance the physical preparation of taekwondo athletes. However, the effectiveness of this for taekwondo athletes requires investigation. Comparison of a block periodised plan with a non-periodised training plan could measure changes in physical and physiological variables, including performance in a taekwondo specific fitness test, in order to assess the efficacy of the periodised structure. This would allow a better understanding of the potential benefits and limitations of this method of training organisation. Furthermore, follow on studies could also look at the long term impact of training periodisation on injury incidence, type and severity to assess the impact of periodisation on maintaining and maximising the health of athletes.

It was discussed previously (Chapter 5.4) that is it possible that the energy contribution of taekwondo combat has changed since the introduction of the new rules. Similar to the study by Campos et al. (2012), it would be valuable to confirm the energy system contribution of simulated taekwondo combat but in an ecologically valid setting that replicates both the modern taekwondo rule set but also the updated physical and physiological demands (Chapter 5.3). Furthermore, it has been demonstrated that the physiological demands of taekwondo combat changes over the course of a competition day (Bridge *et al.*, 2018). Successive ecologically valid simulated combats could therefore be held to mimic a competition day and further investigate the predominant energy systems during combat and how this may change as athlete progresses from the preliminary rounds to the finals. This would allow energy system development and overall physical preparation to be optimised with respect to the specifics of competition day demands.

Finally, it is apparent in many combat sports that there are stark differences in the physiological profiles (Neha, Ajita and Kaur, 2010; Ohya *et al.*, 2015) and the demands of competition (Miarka *et al.*, 2015) between different weight classes. In taekwondo combats, it has been shown previously, albeit under the previous rule set, that the activity profiles differ between weight classes (Bridge, 2012; Bridge, Jones and Drust, 2011). Since the difference between Olympic weight classes in taekwondo athletes is so large (8-12kg), it is probable that there are also significant differences in the physiological demands of competition. Larger scale investigations in to the physiological demands of competition would help to establish any differences between weight categories. This research would then help direct and further individualise the focus of the physical preparation of taekwondo athletes.

6.9. Conclusions

The primary aim of this thesis was to examine the physiological demands of high-level taekwondo training and competition. The objectives outlined in Chapter 1 were realised through the studies that followed and collectively contribute to novel research and information regarding the physiological demands of elite, modern-day taekwondo. This was achieved through firstly examining the physical and physiological demands of international competition, followed by an analysis of the characteristics of present day taekwondo athletes and subsequent comparison with the characteristics reported in the literature prior to the rule changes and finished by investigating the training load and and factors that affect appropriate training organisation in a full time taekwondo programme. The thesis found that the physical and physiological demands of taekwondo competition under the current rule set have changed significantly since the introduction of a vast array of rule changes intened to increase the excitement and activity of taekwondo combats. However, examination of the physiological profile did not demonstrate the same evolution suggesting that taekwondo athletes are not maximising their physical preparation for competition. Furthermore, investigation into training demands, adaptations and organisation showed that current taekwondo training practices may fall short on adequately organising progressive training loads in order that athletes can physically peak for important competitions.

Taken together, this thesis has demonstrated a clear area for enhancing and maximising the physical and physiological development and preparation of athletes for competition. Subsequently, it has culminated in the development of considerations for optimising the physical preparation of taekwondo athletes for competitive success. These considerations have utilised findings based on the evolution of the demands of competition and comparison with the physiological profile of athletes and the training undertaken to achieve these characteristics. Therefore, this thesis provides a blue print on which training can be structured according to the considerations provided above in order to maximise performance at critical competitive events. It can serve as a basis for coordinating both the physiological adaptations over time in a structured, practical and periodised fashion (and thus optimising the physiological profile of athletes) with the technical and tactical development enabling a synchronous realisation of these critical components of performance success. It is hoped that this research will not only inform both the direction and methodology of future investigations but also that it will provide scientifically supported practical applications and advice for the taekwondo community.

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