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University of Glasgow | College of Medical, Veterinary & Life Sciences

Feasibility of a Surface Electromyography-based Compression Garment for Monitoring Internal Player Load in Professional Basketball

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Abstract

The psychophysiological demands placed on professional athletes nowadays is greater than ever. In fact, professional basketball players can compete up to three time per week in addition to frequent and regular training sessions. Thus, adequately prescribing and monitoring athletes' loads is important to maintain player well-being, reduce fatigue while optimising performance. Therefore, sport science research is saturated with different internal and external load monitoring approaches to help teams achieve these goals. Expansion of the global wearable technology market in sport is ever growing as practitioners seek a competitive advantage to their competitors. One such technology which has clinically and extensively been used for decades but has entered a new era into the wearable technology field in sport is surface electromyography (sEMG). However, little research reports on this technology in sport and the internal load metrics which representative companies claim it can report. The purpose of this doctoral thesis was to comprehensively examine internal load experienced by professional basketball players in the British Basketball League (BBL), while investigating a wearable sEMG technology for reporting a novel sEMG-based internal load metric ("Training Load") during controlled lab-based exercise protocols, as well as determine the feasibility of the wearable sEMG-based internal load monitoring system in the professional basketball environment.

The first observational study assessed the internal load experienced by professional basketball players during an entire season in the BBL. The research used the session-rating of perceived exertion (sRPE) method for quantifying load in professional basketball players following training sessions and competition. Results show that players experience greater Weekly Load (training only) during pre-season compared to the in-season phase. Weekly Load is greater in 1-game weeks compared to 2-game weeks, while Total Weekly Load (training and competition) is higher during 2-game weeks compared to 1-game weeks. In addition, starting players experience a moderately higher Total Weekly Load compared to bench players, yet playing status did not result in differences in Weekly Load. The results show variances in internal load depending on weekly game fixtures, training schedules and phases of the season. While the sRPE method provides a valid global measurement of the training session or competition, the nature of retrieving RPE's from players by asking a question prevents deeper investigation of internal load from specific phases of play.

The second investigative study explores the possibility of using a novel wearable sEMG garment for capturing internal load (Training Load). The research investigated the sEMG-derived Training Load during a 3-speed treadmill test and its relationship with oxygen consumption ($\dot{V}O_2$) during an exhaustive ramp incremental running treadmill test to determine maximal oxygen uptake ($\dot{V}O_{2max}$). Findings demonstrate sEMG-derived Training Load is a sensitive measure in detecting small changes in work rate during dynamic exercise, and while a moderate positive correlation between %$\dot{V}O_2$ max is shown, 80% of participants' Training Loads show a very strong positive correlation at the individual level. The findings conclude that wearable sEMG technology may provide an alternative and new approach to capturing players internal load during sport and dynamic, whole-body exercise.

The third study investigates the feasibility, practicality, and acceptability of wearable sEMG technology in the professional basketball environment. Results show a high acceptance rate (seventy-five percent) of the sEMG technology amongst professional basketball players, who report they would use the wearable sEMG technology again during team basketball training. A minority of players (twenty-five percent) report they would not use the wearable sEMG technology again due to negative experiences such as, comfortability issues and perceived negative effects on performance. While the wearable sEMG technology is relatively feasible in the environment, a few practical implications are considered important for coaches to understand before use. In particular, the time taken for downloading data to report to coaching staff or players takes longer than other load monitoring systems, such as GPS. In addition, the technology is more suited to the professional environment where a kit manager takes care of the handling procedures associated with the shorts. Lastly, the Core unit attached to the shorts can interrupt training practice.

The current thesis contributes original research to the field of wearable sEMG for monitoring internal load. Findings provide important implications for practitioners endeavouring to use wearable sEMG in a professional sport context or research to further extent. Most research in basketball is conducted internationally, within Europe and America. The thesis is one of the first studies to identify internal loads in professional male basketball players within the United Kingdom. The thesis was the first to investigate an sEMG-derived Training Load during specific running tests. Lastly, the thesis was the first to assess professional athletes’ perceptions on wearable sEMG technology, highlighting reasons for and against using the technology.

Table of Contents

List of Tables

List of Figures

List of Accompanying Material

Poster presentation: Ashcroft *et al.* (2019) **An investigation of Athos's integrated surface-electromyography biofeedback system in relation to current lower limb instability status in elite basketball players**. Presented at: Sport and Exercise Medicine Conference 2019 (Scotland, Edinburgh).

Poster presentation: Ashcroft *et al.* (2019) **An assessment of Athos's sEMG-based garments and an accelerometry-based tracking system during an incremental treadmill VO2max test.** Presented at: International and American Society of Biomechanics Conference 2019 (Canada, Calgary).

Preface

All the academic and research work presented henceforth was conducted at the University of Glasgow, Scotland. This thesis has been written to fulfil the graduation requirements of Doctor of Philosophy in Sport Science from the School of Cardiovascular and Metabolic Health in College of Medical, Veterinary and Life Sciences. I was the lead researcher for all thesis chapters, while Ross, an MSc student, helped manage chapter 5 of this study.

My supervisors Ms. Victoria Penpraze and Dr. Ole Kemi assisted me in major areas of concept formation, data collection processes and statistical analysis, as well as provide extraordinary support throughout the academic journey.

Prior to the commencement of this research, I voluntarily worked with a professional basketball team as a sport scientist. I established a gap in their athlete load management systems and decided to reach out to a wearable surface electromyography-based company (Athos™) who commercialise their product for athlete load monitoring during sport. Athos™ were in the stages of internally researching their product. Thus, I drafted a Research Collaboration proposal, which they endorsed, for supplying free of charge equipment in return for PhD research from the UoG as a third-party research body.

The wearable sEMG product piqued my interest in its potential ability to objectively capture internal Training Load, yet there was little-to-no research conducted on this metric, or product for that matter. Thus, I endeavoured to research their sEMG-based Training Load as well as the feasibility and acceptance of the product in the professional sport environment.

I would like to stress that this body of research was outside my comfort zone. Electromyography was modestly introduced in my undergraduate degree programme, "*Physiology and Sport Science*". Therefore, I had little experience or no understanding of the product, and no experience in the data processing techniques which are pivotal for extracting clean EMG data. The journey of this thesis was a steep and enjoyable learning curve.

Acknowledgement

I would like to express my thanks to the following individuals who have contributed to the completion of this thesis.

My supervisors Viki, Ole and Stephen, their guidance and patience throughout this process undoubtedly made it possible for me to get to this stage! A special thanks to Viki, her endless support and attention to pastoral care kept me going when times were tough and was certainly required during an unprecedented global pandemic.

A big thank you to the players and support staff within the Glasgow Rocks Basketball team. Their perseverance and ability to tolerate my research while competing professionally was second to none.

A huge thank you to Athos™, California, and their respective research team. Credit to Chris, who financially supported much of my research and helped bridge gaps in the data collection processes. In addition, thank you to Lynsey, the UoG lab technician for supporting me with equipment use throughout chapter 5.

To my friends who have endured, but also helped me with many of my struggles throughout this journey, thank you for checking on the progress of this thesis and supporting me throughout out.

Thank you Athlete Focused, most notably Andy and Stephen, as my current employers and who are ex-PhD students at the University of Glasgow, who have understood and mentored me throughout many of the unforeseen altercations during my PhD journey.

Importantly, thank you Mum and Dad, Aunt Diedre, and Uncle Paul. You have stuck by me through the whole process. You have been selfless and put up with my selfish behaviours and attitude to complete this PhD. I would not have been able to do this without your help.

Author's Declaration

"I hereby declare that all the work submitted in this thesis was carried out by myself, and that all collaborative work is defined in the acknowledgments. To the best of my knowledge and belief, it contains no material previously published or written by another person, unless stated in the acknowledgments"

Kurtis Ashcroft December 2022

Definitions/Abbreviations

95% CI	95 percent confidence interval
GPS	Global Positioning Systems
SD	Standard Deviation
ACWR	Acute:Chronic Stress Ratio
Ag/AgCl	Silver/Silver Chloride
ANOVA	Analysis of Variation
AU	Arbitrary Units
BF (%)	Body Fat Percentage
BM	Body mass
BBL	British Basketball League
CM	Centimetres
CMJ	Counter Movement Jump
EMG	Electromyography
FFM	Fat Free Mass
Kg	Kilograms
HR	Heart Rate
LPS	Local Positioning Systems

M	Metres
mV	Millivolts: SI unit of electricity
ml.kg^{-1}.min^{-1}	Millilitres Per Kilogram Per Minute
MSFT	Multi-Stage Fitness Test
N	Number of Participants
RSA	Repeated Sprint Ability
RPE	Rating of Perceived Exertion
sRPE	Session Rating of Perceived Exertion
sEMG	Surface-Electromyography
sec	Seconds
SHRZ	Summated Heart Rate Zones
TMA	Time Motion Analysis
TRIMP	Bannister’s Training Impulse
U18	Under 18 years
U20	Under 20 years
$\dot{V}O_{2max}$	Maximal Aerobic Capacity
$\%\dot{V}O_{2max}$	Percentage of Maximal Aerobic Capacity
YoYo IRT-1	YoYo Intermittent Recovery Test 1

μv	Microvolts: SI unit of electricity
V	Volts: SI unit of electricity
Ω	Omega: SI unit of electricity resistance
m Ω	Milliohm: SI unit of electrical resistance
k Ω	Kiloohm: SI unit of electrical resistance
º	Degrees of temperature

Chapter 1 Introduction

1.1 Background and research context

In basketball, every coach strives to maximise an athlete's performance for game-day success. Performance can be seen as the interaction of technical, physical, and mental qualities. A stronger performance in basketball, for instance, will result from making more successful shots, passes, and turnovers while making fewer technical mistakes. In addition, athletes with better psychological and physical qualities, such as mental toughness, confidence, self-efficacy, relative strength, cardiovascular fitness, and power, are more likely to be successful. Thus, achieving optimal basketball performance, both as a team and at the individual level, is often considered the most important goal for all competitive elite basketball squads. Basketball is a court-based team sport, which is both physically and mentally demanding, and characterised by repeated high-intensity intermittent bursts of play lasting approximately 2-5s over 40 min of game-time (Abdelkrim, el Fazaa and el Ati, 2007). A team consists of 5 players on-court at any one time which comprise of 3 general playing positions: (i) Guard, usually the smallest player in body mass and height, and requires the highest activity demands and who is considered as the tactical playmaker of the team; (ii) Forward, often taller and heavier than a guard and generally the is the most versatile player of the team; (iii) Centre, the tallest and heaviest player in the squad, the position requires a lot of rebounding and defensive style of play (Ostojic, Mazic and Dikic, 2006). Basketball involves a range of actions in all planes of movement, such as running, jumping and side shuffling at different frequency, intensity, and durations (Stojanović *et al.*, 2018a). It requires the utilisation of both aerobic and anaerobic systems. The aerobic component prevails during bouts of active recovery and low intensity movement around 60% of the time during gameplay (McInnes *et al.*, 1995; Abdelkrim, el Fazaa and el Ati, 2007). Nonetheless, a greater anaerobic capacity, and thus the ability to produce more explosive and repetitive high-intensity actions, is paramount for on-court success (Ibáñez *et al.*, 2008; Mancha-Triguero, Martín-Encinas and Ibáñez, 2020). Game duration is 40 min in live-play time, interspersed over 4 x 10 min quarters. Yet when including all stoppages, quarter and half-time breaks, games can last up to 120 min from start to finish. It is also common for professional basketball leagues to incorporate double, and even triple header game weeks, which is basketball terminology for when teams are required to compete twice, or even three times per week. With such physical and psychological stresses imposed on players, the necessity for periodising training appropriately to reduce neuromuscular and central fatigue is vital for optimising competition readiness (Pliauga *et al.*, 2018).

To manage fatigue, we first must quantify the training and competition load the athlete and/or team has completed. Training Load has been defined as the input variable that is manipulated to elicit a desired training response (Impellizzeri, Marcora and Coutts, 2019). It can be sub-categorised into one of two theoretical constructs: external or internal load. External load encapsulates the accumulative physical work performed by the athlete; it is the quality and quantity of work prescribed in the training process and is captured independently of the athlete's characteristics (Bourdon *et al.*, 2017). In a systematic review which investigated training load and gameplay demands in basketball across different competitive levels, Petway et al. (2020) reported that total distance travelled, top sprint speed, total or high-intensity accelerations and decelerations are the widely stated variables used to assign the external load imposed on players in basketball training and competition. On the other hand, internal load considers an athlete's relative psychophysiological response to the training or competition stimulus (Halson, 2014; Bourdon *et al.*, 2017; Impellizzeri, Marcora and Coutts, 2019). It is the modifiable (aerobic/anaerobic capacity, strength, and power) and non-modifiable (age, height, gender, genetics) factors that make the internal response individualised, and it can be captured objectively and subjectively. The subjective response comprises a psychological element (perceived stress) and experts recommend it be used as a primary measure of Training Load (Drew and Finch, 2016; McLaren *et al.*, 2018). It could be the divergence between these two load constructs (internal and external training load) that assist in revealing an athlete's fatigue levels. For example, Manzi et al. (2010) found a strong correlation (r = 0.68) between the Yo-Yo intermittent level one recovery test scores during training and session rating of perceived exertion (sRPE) in elite European basketball players. This suggests that those with greater aerobic capacity perceive basketball practice to be less challenging than those with a lower aerobic capacity assuming the athletes achieved the same external load. It is common for sport scientists and coaches to monitor both external and internal training and competition loads simultaneously, which derives a dose-response relationship. This relationship provides practitioners with a load/fatigue measurement which ultimately helps inform athlete preparedness.

Training Load has been shown to fluctuate throughout the basketball season depending on several contextual factors such as: (i) *game congestion,* whereby one game per week is perceived as less demanding than two games per week (Conte *et al.*, 2018); (ii) *recovery cycle*, Weekly Training Load is perceived lower during short recovery cycles between two games compared to longer recovery cycles (Sansone *et al.*, 2020); (iii) *upcoming opponent*, higher weekly loads are established when the next opponent is of a lower level compared to a higher level team (Sansone *et al.*, 2021); (iv) *phase of season* (i.e pre-season, in-season and play-offs), pre-season is typically considered more demanding than in-season, and play-offs (Aoki et al., 2017; Salazar, Castellano and Svilar, 2020; Ferioli, Scanlan, et al., 2021); and (v) *type of session*, subjective load, plus indicative biomechanical markers of physiological stress are greater during official games than simulated matches and training (A Moreira *et al.*, 2012; Fox, Stanton and Scanlan, 2018; Román *et al.*, 2019). Individual characteristics also play a part in the internal and external load paradigms, such as: (i) *playing position*, guards experience greater training and competition loads than forwards and centres (Abdelkrim, el Fazaa and el Ati, 2007; Puente *et al.*, 2017; Ferioli, Rampinini, Martin, Rucco, la Torre, *et al.*, 2020; Sansone *et al.*, 2020); (ii) *playing experience*, more experienced players typically exhibit greater activity loads compared to less experienced players. Worth mentioning, is that older players (often more experienced) may take longer to recover yet possess the skill and movement efficiency to produce more frequent and higher intensity actions than less experienced players (Scanlan, Dascombe and Reaburn, 2011; Sansone *et al.*, 2020). With these contextual and individual factors in mind, it emphasises the importance of monitoring internal and external load throughout a basketball season.

Basketball training and competition loads collected from specific phases of a basketball season are reported in the scientific literature. For example, Aoki *et al.* (2017) reported 6-weeks pre-season training induced significantly greater internal and external load compared to 5-weeks in-season training in a professional male basketball team competing in the National Brazilian League. These findings were attributed to changes in weekly coaches reducing the training volume during the in-season phase to reduce fatigue (Aoki *et al.*, 2017). In addition, Manzi *et al.* (2010) observed 12-weeks in-season training in a professional male basketball team during the Italian Serie A1 Basketball Championship and reported weekly internal load to be lower in weeks with 1-game versus 2-games. They concluded that coaches naturally adopt a training tapering method in the lead up to games (Manzi *et a.,* 2010). They also report sRPE as a valid internal load monitoring tool which positively correlates with individual HR response (r=0.69 to 0.85) during training and competition.

With this knowledge, coaches periodise load to optimise mental and physiological adaptive responses, and to help prevent athletes from maladaptive responses, fatigue, and potentially soft tissue injury (Caparrós *et al.*, 2018). A handful of studies report internal and external loads from longitudinal observations (season-long) in professional male basketball across a variety of competitive leagues (Caparrós et al., 2018; Clemente, Mendes, et al., 2019; Fox, O'Grady and Scanlan, 2020; Salazar, Castellano and Svilar, 2020; Vázquez-Guerrero et al., 2020). The majority body of research explores both internal and external loads in elite European, Australian, Asian, South American, and North American (including NCAA Division 1) basketball (Petway *et al.*, 2020). To date, only one study reports external demands in elite competitive British basketball gameplay (Bishop and Wright, 2017), yet no research has been published regarding the internal training *and* competition load experienced by players. Therefore, further studies are warranted to observe and report training and competition loads in professional male basketball players competing in the British basketball league.

As previously stated, sPRE and HR are two internal load monitoring tools used in basketball, yet there are many more methods currently employed across the sport to capture a player's internal and external load. In 2017, Fox *et al* reviewed player monitoring approaches used in basketball training and competition. They indicate that time-motion analysis (TMA) is the most widely reported method for recording external loads; TMA is used for measuring time and frequency of different types of movement, such as jogging, running, sprinting, side shuffling and jumping, and which serves as a cost-effective approach for monitoring the demands of basketball when microtechnology is not feasible (Fox, Scanlan and Stanton, 2017; Stojanović et al., 2018; Petway et al., 2020). Microtechnology (global positioning systems (GPS), and microsensors (triaxial accelerometers, gyroscopes, and magnetometers)) are also common devices used for assessing the external demands of basketball, yet these are financially expensive methods. Haematological markers, HR, RPE and Training Load models, including summated-heart-rate zones (SHRZs), Banister's training impulse (TRIMP) and Lucia's TRIMP are used for internal load monitoring. In a recent review of training load and match-play demands in basketball Petway *et al.* (2020) discovered that heart rate (HR) and blood lactate concentrations ($[La^-]_b$) are the most widely used tools for quantifying internal load, while sRPE is often used as a cost-effective method. On the other hand, accelerometery, and positional tracking cameras for time motion analysis (TMA), are the favoured external monitoring approaches used for capturing training and competition demands (Petway *et al.*, 2020).

The convergence of science and technology has swiftly progressed sport and is instrumental in providing team and individual athletes a competitive advantage (Haake, 2009; Ringuet-Riot, Hahn and James, 2013). With the rapid growth of the global sport technology industry, new devices are forever emerging while others are continuously advancing. Catapult™ GPS (Catapult Sports, Melbourne, Australia), STATSports™ GPS (STATSports Newry, Northern Ireland) and Polar HR monitors (Polar, Kempele, Finland) are three examples of wearable sport technology that improve validity and reliability year on year (Johnston *et al.*, 2012, 2014; Beato, Devereux and Stiff, 2018; Olstad and Zinner, 2020). A relative newcomer to the wearable technological field for capturing an athlete's biomechanical, or internal load is ‘surface-electromyography’ (sEMG). In 1890, Étienne-Jules Marey was the first to record muscular electrical activity during voluntary muscle contraction, which he termed ‘electromyography’ (EMG) (Reaz, Hussain and Mohd-Yasin, 2006). The EMG signal is a biomedical signal that measures electrical currents generated in muscles during voluntary muscle contraction representing neuromuscular activities (Reaz, Hussain and Mohd-Yasin, 2006). It was an invasive method that required needle or wire electrodes to be implanted directly in deep muscle tissue to assess muscle fibre action potentials. Later in the 1960s, the non-invasive method known as surface-electromyography (sEMG) was born. sEMG records the electrical signal produced by voluntary muscle contraction via electrodes placed over the skin of superficial muscles. Amid technological progress that encompasses component miniaturisation, material innovation, and refined manufacturing techniques, a recent development involves the integration of sEMG electrodes into wearable compression garments. Various techniques are used to integrate sEMG electrodes into clothing, most notably tight-fitting compression garments (detailed in Chapter 4, section *4.4.1 Textile Technologies for sEMG Electrodes*). The incorporation of sEMG electrodes into clothing is often denoted by terms such as textile electrodes, textile sensors, and textile sEMG electrodes, as highlighted by researchers including Finni et al. (2007), Colyer and McGuigan (2018), Guo et al. (2020), and Kim, Lee, and Jeong (2020). This specific terminology will be employed throughout the present thesis. This innovative approach presents a method for capturing muscle electrical activity during sports and exercise. By capturing the electrical activity of various muscle groups, there exists the potential to employ this wearable technology to objectively gauge an athlete's internal load during sports training and competitions (Colyer and McGuigan, 2018; Lynn et al., 2018).

Amidst the ongoing march of technology marked by component miniaturization, material breakthroughs, and refined manufacturing techniques, a recent advancement has emerged: the seamless integration of sEMG electrodes into wearable compression garments. Among the array of techniques used for this integration, the prominence of tight-fitting compression garments stands out (detailed in Chapter X). This method of electrode integration within clothing is commonly referred to as textile electrodes, textile sensors, and textile sEMG electrodes, as documented by researchers such as Finni et al. (2007), Colyer and McGuigan (2018), Guo et al. (2020), and Kim, Lee, and Jeong (2020). This innovative approach offers a pathway to capture the electrical activity of muscles during sports and exercise. By attaining data on various muscle groups' electrical responses, the potential arises to utilize this wearable technology to objectively assess an athlete's internal load during both training and competitive events, as highlighted by Colyer and McGuigan (2018) and Lynn et al. (2018).

Finni et al. (2007) was one of the first research groups to investigate textile sEMG electrodes in a controlled lab-based environment. They conducted a rigorous validity, repeatability, and feasibility study on textile sEMG electrodes compared to a traditional bipolar sEMG system. They explored the validity of sEMG shorts by positioning four traditional bipolar sEMG electrodes onto the exact same site of the quadriceps muscles as the textile electrodes. Participants were required to perform three 120° angle isometric bilateral knee extensions at 60% maximum voluntary contraction (MVC). This procedure was repeated twice: 1) textile electrodes recorded from the right thigh and traditional electrodes from left thigh, and 2) traditional surface electrodes recorded from the right thigh and textile electrodes from the left thigh. While in a second part, the traditional bipolar surface electrodes were placed on the individual muscles of the vastus medialis (VM), vastus lateralis (VL) and the biceps femoris (BF) on ten different participants. Participants performed knee extensions at 60% MVC, for five repetitions. Average torque and average rectified value of EMG were calculated from 1 second periods and then compared between both systems. Results showed good agreement, within 2 standard deviations (SD), demonstrating textile electrodes produce similar information on the sEMG signal amplitude compared to a traditional bipolar sEMG system. Since these findings by Finni *et al.* (2007), studies using textile sEMG electrodes (as an alternative to the conventional silver/silver chloride (Ag/AgCl) electrodes) have found similar results and good agreement with traditional sEMG signals under similar controlled conditions, and validity accepted at a recreational level (Finni et al., 2007; Bengs et al., 2017; Aquino and Roper, 2018; Colyer and McGuigan, 2018; Lynn et al., 2018; Hermann and Senner, 2020).

Furthermore, textile sEMG electrodes appears to reproduce similar results on a day-to-day and within-session basis. Finni *et al.* (2007) demonstrates good agreement between day-to-day repeatability using textile sEMG electrodes assessed over 5 consecutive days when applying three different isometric force levels during a bilateral knee-extension isometric exercise (coefficient variation (CV) 4 and 11%). Although sEMG electrodes seamlessly integrated into garments exhibit strong to excellent (<10%) repeatability across consecutive days, caution must be taken when extrapolating these findings to dynamic movements for the assessment of consistent measurements. The extent of variability during isometric circumstances becomes limited when extended to practical applications. For example, study of isometric contractions might be useful when assessing fatigue characteristics, or during rehab exercises which require limited eccentric lengthening of the muscles, as well as identifying sEMG peak amplitude thresholds for a given muscle, however, it may not be as useful under normal dynamic exercise protocols. More relevant to dynamic exercise conditions are results presented by Coyler and McGuigan (2018), who showed good within-session repeatability (CV: 13.8 and 14.1%) during run, cycle and squat exercises using textile-based electrodes for sEMG recording (Colyer and McGuigan, 2018). They concluded that textile electrodes appear capable of providing comparable muscle excitation information and reproducibility to traditionally used sEMG electrodes during dynamic tasks. A step closer to the sporting field.

As mentioned, many studies investigate validity, reliability and feasibility of textile sEMG electrodes embedded into clothing in lab-based environments, while little research assesses its use in sports. Regardless, some wearable sport technology companies continue to advertise their wearable sEMG products using model athletes, commentating on athlete case studies, and claiming their products to be suitably used in a variety of open and closed skill sports for monitoring an athlete’s internal training load among other output variables. With such claims, more research is warranted surrounding this novel athlete monitoring approach to lessen the gap in knowledge for sport practitioners if they are considering using this product with their athletes.

To the researcher’s knowledge, only one study to date reports the use of wearable sEMG in open skill sport (Saucier *et al.*, 2021). Saucier *et al.* (2021) used Strive™ Sense 3© smart compression shorts, which integrates sEMG electrodes, on a NCAA D1 male basketball team during a season. They assessed both internal and external training and competition demands by sEMG response and accelerometry respectively, among three playing positions: guards, centres, and forwards. They report muscle load, or “internal load”, (the sum of muscular activation from all sEMG sensors, divided by a scaling factor) to be greater during training than competition for both guards and forwards, but not centres. While this study reports training and competition demands using the textile sEMG derived muscle load, or “internal load” variable, we intend to add to this body of research by exploring the feasibility of sEMG compression shorts in professional male basketball, taking it from the lab-based setting into the sporting field.

1.2 Purpose of thesis

The main objectives of this thesis were to explore workload trends in professional male basketball players in the British Basketball League using traditional, previously validated, internal player monitoring approaches. Secondly, to assess the internal load metric derived from compression shorts which integrates sEMG electrodes (textile sEMG electrodes) during a controlled lab-based exercise protocol, and then within a professional basketball team during training. Additionally, the author’s desire was to contribute to the scientific field of wearable sEMG in the sporting field, particularly basketball. Specific aims of the thesis were to:

1) Systematically review training and competition loads and current load monitoring systems in professional male basketball (Chapter 2).

2) Quantify training and game internal loads experienced by players, using the sRPE method, during the pre-season and in-season phases of the competitive

BBL season. To be the first study to analyse internal training and competition loads from players in the British Basketball League (Chapter 3).

3) Be the first study to investigate a novel sEMG-derived internal training load variable during controlled laboratory-based functional exercises (Chapter 5).

4) Investigate the feasibility of implementing an sEMG-based athlete monitoring system in a professional male basketball team (Chapter 6).

5) Explore the relationship of the sEMG-derived internal training load variable and the validated sRPE method in professional male basketball players during specific training drills.

1.3 Significance of thesis

The methods used in this thesis can be replicated by other researchers, strength and conditioning coaches and basketball coaches. The foundational concepts of this thesis could be applied to other basketball levels, genders, and age groups, and possibly help coaches better understand what wearable sEMG can offer their athletes. This thesis can provide insights to the versatility of the sEMG internal load variable and how it can be applied in sport. Challenging preconceived ideas surrounding the usability of sEMG in the sporting field is important for advancing the scientific field and future research in this area, which this thesis attempts. We also include some of the first feasibility-based research conducted on wearable sEMG compression shorts in the professional sporting field. In summary, this thesis is significant as it has updated and advanced the research on the use of wearable sEMG in professional sport, and for the first time identified how it might be used to monitor internal training load from specific basketball drills.

1.4 Structure of thesis

The work presented in this thesis summarises the development and pathway of the research journey and outlines the potential real-world impact of the conclusions derived from it. The central theme, the use of sEMG compression shorts (integrated sEMG electrodes (textile electrodes)) to monitor athlete internal load in professional basketball, research background information and thesis aims are presented in this introduction. Chapter two provides a review of the current approaches already deployed in basketball for monitoring players internal load, and states previously established internal and external load outputs from professional basketball players in the literature. Chapter three offers an account of player internal load in elite British basketball. Chapter four outlines the fundamental principles of sEMG as a research tool and its integration into wearable technology for capturing internal load in sport. Chapter five explores a textile sEMG system (smart compression shorts) under a controlled lab-based environment to assess its use across a variety of dynamic physical fitness tests. Chapter six introduces the smart compression shorts into an elite basketball training environment to evaluate the feasibility and potential use of the integrated sEMG for capturing internal Training Load from specific basketball drills. Chapter seven discusses the main findings of the use of wearable sEMG in basketball and prompts future research directions using the technology. Lastly, the thesis concludes with a summary of the research conclusions.

Chapter 2 Systematic review of player monitoring approaches, and internal and external player loads in professional male basketball, training and competition

2.1 Rationale

During the 2000-2015 National Basketball Association (NBA) period, Talukder *et al.* (2016) reported losses of between 10 and 50 million dollars per team each season because of player injury. When a player is unable to compete due to injury, it can negatively impact the club’s spectatorship proceeds, team sponsorship revenue, as well as inflict additional medical related costs on the club, like MRI scans and medical specialist fees, while simultaneously the club must continue to pay the injured player’s usual salary. This evidently highlights the importance for sport practitioners to embed methods within teams which could help reduce the risk of player injury. When the body is overloaded with physiological and/or psychological stress the body’s adaptive capacity is insufficient. This results in manifestations of fluctuating physical and mental performance and could lead to injury/illness (“Load, Overload, and Recovery,” 2019). One measure taken by practitioners to negate maladaptive psychophysiological responses is by appropriately managing and prescribing basketball Training Load during a season (Edwards *et al.*, 2018). This could reduce onset of early fatigue, and thereby decrease the risk of soft tissue injuries (Weiss *et al.*, 2017; Caparrós *et al.*, 2018). In addition, appropriate load management could invoke favourable tactical, technical, and physical performance outcomes for basketball competition (Gabbett, 2016; Legg *et al.*, 2017; Weiss *et al.*, 2017; Caparrós *et al.*, 2018; Cruz *et al.*, 2018; Fox, Stanton and Scanlan, 2018). For load to be administered over the annual programme, first, it must be precisely quantified. Load can be sub-categorised into one of two theoretical constructs: external or internal. External load is characterised by the physical dose the athlete performs, while internal load represents the individual psychophysiological response to training and competition (Halson, 2014; Impellizzeri, Marcora and Coutts, 2019).

Congested game and training schedules are often experienced by professional basketball players. As previously described in Chapter 1, some leagues incorporate double and even triple-header game weeks (Manzi *et al.*, 2010; Conte *et al.*, 2018a; Fox, O'Grady and Scanlan, 2020). Therefore, it is no surprise that in recent years a considerable amount of research focuses on reporting basketball player loads and player load monitoring approaches used in training and competition (O'Grady *et al.*, 2020; Petway *et al.*, 2020). Noteworthy, Petway *et al.* (2020) published a thorough systematic literature review which reveals internal and external loads experienced by players from practice and gameplay in elite, sub-elite, and youth basketball. *"Their review was published following the commencement of this PhD"*. However, the current review aims to provide an in-depth, up-to-date analysis and interpretation of research corresponding to professional senior male basketball loads from training and competition only. The review by Petway *et al.* (2020) reports on many external load variables, including accelerations (ACC) and decelerations (DEC), change of directions (COD), and frequency, duration, and distance of time motion analysis (TMA) variables, such as stand/walk, jog, run, sprint, jump and all movements combined. Yet, they fail to discuss external loads presented in the literature which microsensor technology can quantify, commonly reported as the square root of the sum of the instantaneous rates of change in acceleration from the vertical, horizontal, and medio-lateral planes divided by a scaling factor, such as PlayerLoad™ (Catapult™ Sports) and Total Load (StatSports™) which are given in arbitrary units (AU). Therefore, the current review will add to the body of research conducted by Petway *et al.* (2020) by extracting external and internal player loads from the literature conducted in professional male basketball training and competition.

A separate review by Fox *et al.* (2017) provides an account of internal and external load monitoring approaches used in basketball training and competition across all playing levels (amateur to professional) and age groups (junior to senior). Upon reviewing twenty-three articles, Fox *et al.* (2017) reports that TMA and HR were the most widely used internal and external load monitoring approaches applied in basketball, respectively. However, TMA is susceptible to human error when processing video footage, and is also time-intensive (Barris and Button, 2008), therefore using microsensors as a faster and more efficient way to obtain objective load data immediately following basketball training and competition has more recently augmented the confidence in practitioners for adopting this technology in the sport (Schelling and Torres, 2016; Caparrós et al., 2018; Svilar, Castellano and Jukic, 2018, 2019; Svilar et al., 2018; Vazquez-Guerrero et al., 2018; Vázquez-Guerrero et al., 2018; Salazar and Castellano Paulis, 2020; Salazar, Castellano and Svilar, 2020; Salazar et al., 2020). Interestingly, they found that RPE was the least reported internal load measure during competition, irrespective of its ease of use and cost-effectiveness. Moreover, they report that microsensors were used in only two studies based on basketball competition. Given the speed and extent of which player load monitoring technology advances in quantification methodology and technological validity, especially microsensors (Beato, Devereux and Stiff, 2018; Luteberget, Spencer and Gilgien, 2018; Luteberget and Gilgien, 2020; Olstad and Zinner, 2020), further analysis of the research surrounding player load monitoring approaches used in professional male basketball is warranted.

Manzi *et al.* (2010) examines the in-season internal training load profiles of professional basketball players 12 weeks before the play-off phase. Alternatively, Aoki *et al.* (2017) reports internal and external training load from 6-week preseason and 5 week in-season periods. On the other hand, weekly training load has been reported over one full season (Ferreira *et al.*, 2021), and even 2 full seasons (Salazar, Svilar, *et al.*, 2020), while research investigates the differences in internal load between the in-season and play-off phases (Ferioli *et al.*, 2021). Many of these studies are conducted across different leagues and phases of the season. There is an important gap in the available research that does not permit concluding why there are such variances in basketball training loads amongst different professional basketball teams. Thus, further discussion is warranted to help interpret these variances, and why caution must be taken when generically applying these results to another team. Lastly, understanding how players respond to training during different parts of a season will assist with implementing a training-dose during specific times of the year, as well as identifying if training closely mimics the demands of competition.

The aim of the current systematic literature review is two-fold i) to thoroughly examine the current literature and identify existing internal and external loads in professional senior male basketball; ii) distinguish workload monitoring approaches which are currently used in professional male basketball. The review intends to set a precedent for future research based on player loads and load monitoring in professional, male basketball.

2.2 Methods

2.2.1 Study design

The current study is a systematic review which aims were two-fold: Firstly, to investigate internal and external loads in professional senior male basketball training and competition. Secondly, to explore the current internal and external load monitoring approaches used in elite male senior basketball. The review was conducted by researchers from the University of Glasgow and did not require Institutional Ethics Committee approval. The review was undertaken in accordance with the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) statement (Moher et al., 2009).

2.2.2 Search Strategy

The current systematic review was performed from 1st December 2017 until the 09th August 2021. Online databases used for researching were Web of Science, PubMed and Google Scholar. All electronic database searching was set within the time range of 1946 to August 2021.

Advance Search Key Words were linked with Boolean operators ('AND', 'OR'). Words which were incorporated in the search: Basketball, Load*, Elite, Professional, Colleg*. Specific words were truncated* to allow for greater scope of literature searching. Load*, Demand*, Workload* and Colleg* were truncated following characters to broaden the term, for example, loading or loads, demands or demanding.

The Web of Science and PubMed database searching examples are shown below. The following procedure was identical for both database searches.

1. TS=Basketball

2. TS=Load* OR Demand* OR Workload*

3. 1 AND 2

4. TS= Elite OR Professional OR Colleg*

5. 3 and 4

After completion of electronic database searching, the article titles were reviewed and organised systematically. Titles which were deemed relevant to the current review led to abstract analysis. Titles and abstracts were cross-referenced to recognise duplicates. Depending on abstract content, full text articles were extracted and read for inclusion. Figure.1 illustrates the systematic review process. The search procedure was performed by one researcher (KA) and cross-checked by another (VP).

First, the literature was searched only for professional basketball training and competition loads. Secondly reviewed, was the current workload monitoring approaches and methods used in basketball.

2.2.3 Inclusion and exclusion criteria

This systematic review included longitudinal and cross-sectional studies investigating professional/elite senior male basketball players. Participants played in a variety of teams competing in: Euro League and Europe Top Divisions, FIBA Competition and Australia. Studies which were conducted on participants playing in the NBA, NBA G-League, South America, and Asia were excluded from the study. This was deemed appropriate due to the fact NBA league game schedule is highly game based compared to European leagues. NBA teams frequently play up to 4-games per week, unlike 2-games per week maximum in European teams. Moreover, studies which were published in journals with a poor impact factor (typically lower than 1), and which did not report common methodological terminology or protocols when reporting methods for monitoring player loads were not included. Lastly, each study had to include the phase of season in which they monitored player loads to be considered for inclusion. Additionally, National Collegiate Athletic Association Division 1 (NCAA-D1) was also considered for analysis, but as training volumes and student-athlete abilities vary greatly between colleges it was considered inappropriate for inclusion.

Inclusion criterion:

1) The study was written in English language and published in a peer-reviewed journal with an impact factor >1 (average or above).

2) The study declares that players are professional/elite level, senior male basketball players, only. Studies which include both professional and sub-elite (one league below the top tier league, but whereby players still play full-time), were also included.

3) The study reports training and/or competition internal and/or external load variables.

4) The study reports physiological or metabolic demands of training and/or competition.

Exclusion criterion:

1) The study includes semi-professional male basketball players, female basketball players, wheelchair basketball players, college basketball players, youth basketball players, and junior elite basketball players characterised as under 19 yrs old.

2) The study fails to report training and/or competition loads.

3) The study does not include training and/or competition metabolic or physiological demands.

2.3 Results

2.3.1 Study selection

A total of six-hundred and fifty-two records were identified through database searching using the advance search protocol. After all titles were screened and duplicates removed, a total of one hundred and ninety-seven records were assessed for eligibility. Of these, one hundred and sixty studies were excluded for lack of load monitoring and inclusion of participants at the professional senior male level. This left thirty-seven remaining studies which were deemed appropriate for full text analysis and inclusion in this review. Figure 1 below depicts the review process.

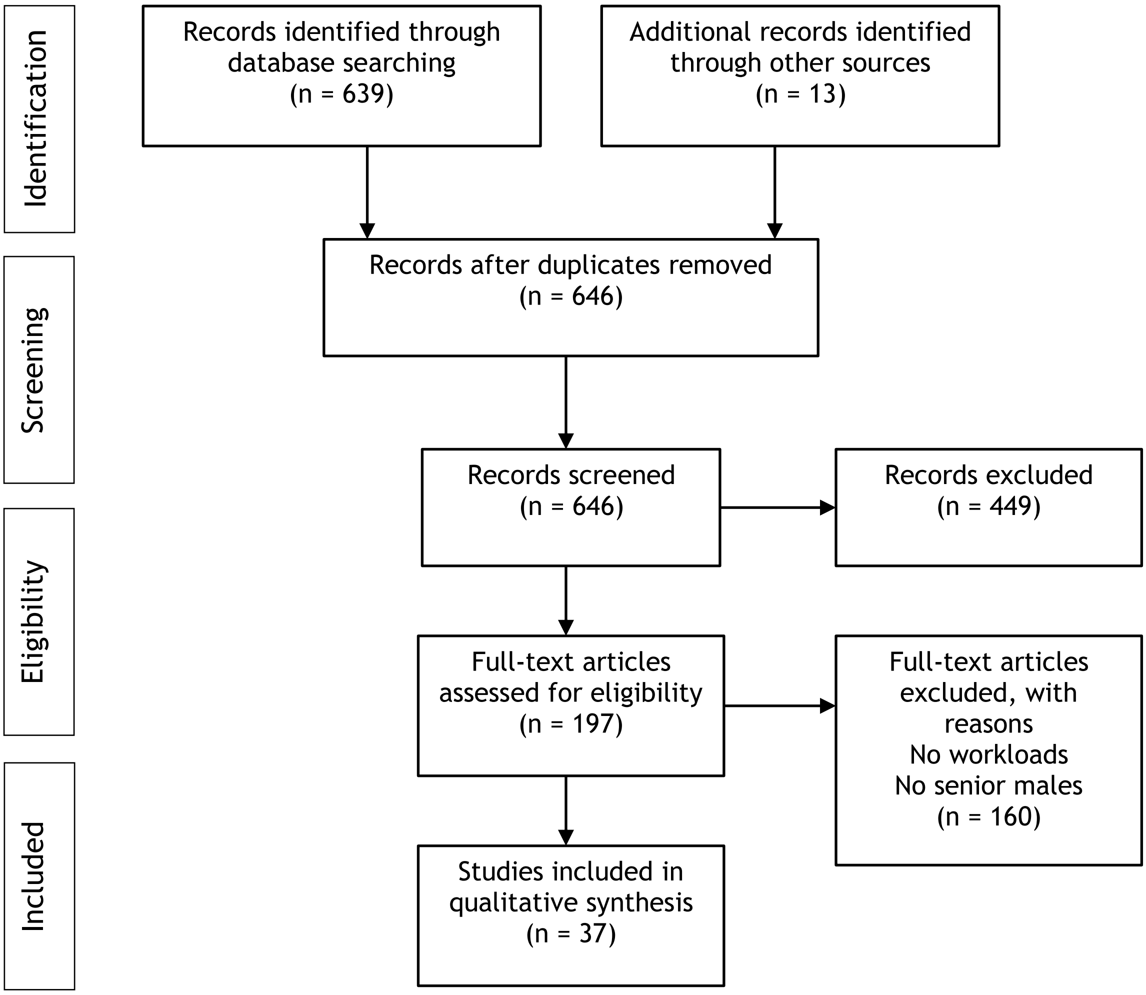


Figure 2.1 Systematic review article identification flow chart

Journal articles included are from the years 1946-2021. Studies incorporated were experimental and observational cohort studies. Overall, thirty-seven studies were included for review. No studies incorporated were carried out within the UK. Whilst some studies do not directly aim to explore player load directly, all studies exemplify a form of load.

2.4 Findings

Percentage of studies which report external load monitoring approaches used in basketball competition and training was 32.4% and 21.6%, respectively. Methods used to quantify internal load from basketball competition, only and training, only was 8.1% and 18.9%, respectively. Finally, the percentage of studies which includes internal load monitoring approaches in both training and competition was 29.7%, and external load monitoring approaches in both training and competition was 13.5%.

Based on the methodologies employed to report training or competition loads (internal or external), the studies are summarised in the following tables and discussed in the relevant subsections. Table 2.1 lists the internal load monitoring techniques employed in professional male basketball, while Table 2.2 lists the external load monitoring techniques. The internal training and competition load of professional male basketball players, as documented in the literature, are shown in Tables 2.3, 2.4, and 2.5.

2.5 Internal load monitoring approaches

In total 22 studies included in this review employ at least one method of internal load monitoring (Table 2.1). Internal load captures the psychophysiological response from the external stimulus (training and competition) applied to the players (Impellizzeri, Marcora and Coutts, 2019). sRPE (n=18) and HR (n=5) were the two most frequently reported internal load methods in this review. Self-adjusted chest straps with small electrode pads which sit on top of the surface of the skin were used by all studies reporting HR data, irrespective of the manufacturer. Studies which include the sRPE method in this review calculates the internal load by multiplying the rating of perceived exertion (RPE) by the duration of the training or competition session (Foster et al., 2001). A few differences are cited in the relevant sub-section regarding differences in quantifying the sRPE. Several studies are highlighted in Table 2.1 which use an alternative RPE scale to the CR 0-10 scale used by Foster *et al.* (2001) to quantify sRPE (Doven *et al.*, 2017, 2020). When exploring the existing literature, different methods used to quantify load will result in a lack of cohesiveness in reporting the load outcomes. The diverse methodologies contribute to a lack of uniformity in report internal load outcomes (Tables 2.3, 2.4 and 2.5).

Nonetheless, these studies were deemed integral to the systematic literature review as they provided insights from a Dutch sample, which helps to illustrate the spectrum of load monitoring approaches and preferred quantification methodologies to capture player internal loads.

To add, Table 2.1 illustrates that a significant portion of research is conducted within mainland Europe, specifically Spain and Italy. Upon closer inspection, 3 studies in Spain are produced by the same research group (Svilar *et al*), while 4 studies in Italy are constructed by Ferioli *et al*. It must be highlighted that this would bias the results and reduces the level of confidence when contrasting internal loads across studies which reported in the literature, especially if much of the research is emanates from the same participant pool. These findings highlight the need for broader research inclusion encompassing diverse countries and professional leagues. An expansion in research would help coaches and researchers understand the different types of load monitoring approaches which other teams adopt and make it possible to compare load prescription and periodisation strategies if the research discloses the internal loads.

The forthcoming subsections provide an account of the different types of internal load monitoring techniques, all of which are reported in Table 2.1.

Table 2.1 Study summary: internal player load monitoring approaches in professional, male basketball.

Study Reference	Participants (n=)	Age (years)	Country/ League	Duration/ Phase of season	Internal load method	Technology/Equipment used
Training						
Aoki et al. (2017)	9	27.8 ± 6.8	Brazilian	Preseason (6-weeks) and in-season phase (5-weeks)	HR, sRPE	CR-10 RPE scale
Ferioli *et al.* (2018a)	12 16	26.2 ± 6.5 23.6 ± 4.9	Elite Italian Sub-Elite Italian	Preparatory phase (7-weeks)	sRPE	CR-10 RPE scale
Ferioli *et al.* (2018b)	14 18	25.6 ± 6 23.7 ± 4.7	Elite Italian Sub-Elite Italian	Preparatory phase (7-weeks)	sRPE	CR-10 RPE scale
Freitas *et al.* (2013)	20	22 ± 5	Brazilian	Preparatory (1-7 weeks) and competitive phase (8-19 weeks)	sRPE	CR-10 RPE scale,
Svilar, Castellano and Jukic (2018)	13	25.7 ± 3.3	Spanish	In-season phase (16-weeks)	sRPE	CR-10 RPE scale
Svilar *et al.* (2018)	13	25.7 ± 3.3	Spanish	In-season phase (16-weeks)	sRPE	CR-10 RPE scale
Torres-Ronda *et al.* (2016)	14	25.5 ± 4.7	Spanish	In-season phase (8-weeks)	HR	Suunto HR monitors, Lince sport analysis software
Competition						
Daniel *et al.* (2017)	10	27.6 ± 5.5	Brazilian	Regular season (6-games)	HR	Polar HR, JVC HD Everio GZ-HM690 model camcorder
McInnes *et al.* (1995)	8	23.5 ± 3.2	Australian	State competition and practice games	HR, Haematological markers [Lac^{-1}]	Sports Tester PE-3000 (Polar Electro), Analox PL-M4 lactate monitor

Table 2.1 (continued)

Vaquera *et al.* (2008)	8	27.5 ± 11.6	Spanish	Preseason phase (5-games)	HR	Polar HR
Training + Competition						
Clemente *et al.* (2019)	15	27.1 ± 5.2	Elite European	42 weeks (16 regular, 26 congested)	sRPE	CR-10 RPE Scale
Clemente *et al.* (2020)	15	27.1 ± 5.2	Elite European	Regular season (42-weeks)	sRPE	CR-10 RPE Scale
Doeven *et al.* (2017)	14	26.7 ± 3.8	Dutch	In-season phase (6-weeks)	sRPE	CR 6-20 RPE Scale
Doeven *et al.* (2020)	16	24.8 ± 2	Dutch	34 weeks	sRPE	CR 6-20 RPE Scale
Ferioli and Torre *et al.* (2021)	35	24 ± 6	Italian Division I (n=10) Division II (n=11) Division III (n=14)	2-consecutive competitive seasons	sRPE	CR-10 RPE Scale
Ferioli & Scanlan *et al.* (2021)	35	28.3 ± 5.7	Italian	Regular season phase (6-weeks), Playoff phase (6-weeks)	sRPE	CR-10 RPE Scale
Manzi *et al.* (2010)	8	28 ± 3.6	Italian	Regular season (12-weeks)	sRPE	CR-10 RPE Scale
Moreira *et al.* (2012)	10	26.4 ± 3.8	Brazilian	Regular season (4-weeks)	RPE, Haematological markers (salivary cortisol)	CR-10 RPE Scale, DSL ACTIVE Cortisol EIA Kit–10-67100–Diagnostic Systems Laboratories

Table 2.1 (continued)

Salazar *et al.* (2020)	27	24.8 ± 3.2	Spanish	Preseason and in-season phases (2-consecutive seasons)	sRPE	CR-10 RPE Scale
Svilar *et al.* (2019)	13	25.7 ± 3.3	Spanish	In-season (~8 weeks)	sRPE	CR-10 RPE Scale
Weiss *et al.* (2017)	13	24.7 ± 4.7	Elite Australia/ New Zealand	Regular season (24-weeks)	sRPE	CR-10 RPE Scale

*RPE = Rating of Perceived Exertion, sRPE = Session-Rating of Perceived Exertion, HR = Heart Rate, TRIMP = Banisters Training Impulse, SHRZ = Summated Heart Rate Zones, IMU = Inertial Measurement Unit, LPS = Local Positioning Systems, TMA = Time Motion Analysis. Note: All participants were male unless stated with: M = Male or F = Female. Studies are listed alphabetically

2.5.1 Heart rate

Objectively assessing HR during basketball training and competition provides information based on the intensity of the exercise experienced by players. Five studies (McInnes *et al.*, 1995b; Vaquera Jiménez, 2008; Torres-Ronda *et al.*, 2016; Aoki *et al.*, 2017; Daniel *et al.*, 2017) in this review used HR monitoring during basketball training (n=2) and competition (n=3). Polar Team (Kempele, Finland), Suunto Pro Team (Vantaa, Finland) and Zephyr (Auckland, New Zealand) were the three reported manufacturers used to provide HR-based data. Many of the devices used by each of these companies have been deemed valid and reliable for assessing HR bpm (Schönfelder *et al.*, 2011; Nepi *et al.*, 2016; Nazari *et al.*, 2019). However, HR has been shown to underestimate the intensity of exercise during high intensity intermittent exercise. As much as a 3-5 second delay is present when HR spikes during high intensity, consequently underestimating the internal load experienced during high intensity intermittent bouts of play in basketball (Fox, Scanlan and Stanton, 2017; Almeida *et al.*, 2019).

HR is generally recorded and reported using a variety of descriptors and units, such as HR_{avg}, HR_{max}, $\%HR_{max}$ based on the number of heart beats per minute (bpm). It should be acknowledged that resting and maximum HR requires accurate measurements from the coaching staff. HR_{max} for example is often recorded using specific performance tests, such as 20-m shuttles, $\dot{V}O_{2max}$ testing and YoYo-IRT (Fox, Scanlan and Stanton, 2017). These descriptors are often used to quantify HR-based internal loads.

HR-based internal loads using ‘training impulse’ (TRIMP) equations, whereby intensity (using resting, average, and maximal heart rate) and duration of the activity are used to quantify the load experienced during basketball. Banister’s TRIMP was the first model proposed in 1991, whereby the average heart rate for the session is weighted according to the relationship between HR and blood lactate during incremental exercise and then multiplied by the session duration (Bannister, 1991; Halson, 2014). One limitation to this model is that it fails to account for fluctuations in heart rate which occur during intermittent exercise, such as basketball. This led to the development of further TRIMP models, such as Edward's TRIMP and Lucia's TRIMP which account for higher intensity exercise. These models categorise HR responses into predefined intensity zones. Bannister's and Edward's TRIMP were used by two research groups in this review (Torres-Ronda *et al.*, 2016; Aoki *et al.*, 2017). Nevertheless, these methods rely on the assumption of a linear relationship between exercise intensity and blood lactate during incremental exercise. The validity and reliability of these methods are commonly assessed by comparing correlations between other psychophysiological load models, particularly the sRPE method. Bannister's TRIMP demonstrates strong significant relationships with sRPE during tactical/games-based conditioning ($r = .60$, $p < .05$) (Scanlan, Wen, Tucker, Borges, *et al.*, 2014), while Lucia's TRIMP correlates strongly with sRPE during simulated basketball activity in the first 0-20 min of play ($r = .66–.69$; $p < .05$) (Scanlan *et al.*, 2017). A more recent, promising individualised training impulse (iTRIMP) model has been proposed to account for the individuality of the heart rate-blood lactate response to incremental exercise (Manzi *et al.*, 2009), therefore reducing the limitations when using arbitrary HR zones and mean heart rate. More research should be conducted using this method in professional basketball.

Noteworthy, are limitations surrounding HR data analysis and collection procedures during daily basketball training. First, only analysing live-time, like TMA techniques, may fail to recognise important and meaningful data during recovery periods (quarter-breaks, half-time etc). Second, appropriately placing HR sensors and strap to the skin around the chest is important, as data loss due to connectivity issues can occur (Matthew and Delextrat, 2009). Lastly, caution should be taken when interpreting and comparing HR results on a day-to-day basis. Fluctuations in HR take place due to several reasons, such as environmental external stressors (Fox, Scanlan and Stanton, 2017), myocardial adaptations over-time (preseason versus in-season) (Oliveira *et al.*, 2013) and even hydration status relating to blood plasma levels can shift the HR response (Watso and Farquhar, 2019). Ultimately, these limitations can obscure the observations in daily HR activity.

Despite some of the limitations associated with the quantification of players' HR-based internal loads, monitoring HR remains to be a convenient, informative, and advantageous method for assessing the individual load imposed on players during basketball, given that practitioners are mindful of the confines. Like the external load method, IMUs, and internal load method, sRPE, HR is a relatively non-intrusive method which requires only a chest/wrist trap to be worn. As HR provides insightful data based specifically on the intensity of exercise or sport, it has been recommended that HR-data be combined with additional player load parameters (Schneider *et al.*, 2018).

2.5.2 Session rating of perceived exertion

Gunnar Borg's rating of perceived exertion (RPE) scale originated over 50 years ago (Borg, 1982). Later, Borg developed the category ratio (CR) 6 (no exertion) to 20 (maximal exertion) scale which demonstrated linear relationships with HR and blood lactate markers during incremental cycle and arm ergometer exercise (Borg, 1987), as well as walking and running (Borg, 1987). The RPE is collected approximately 30 mins following the cessation of exercise by asking "How was your session?" to the athlete. Borg's CR-10 scale was later modified by Foster *et al.* (2001) using different verbal anchors relative to the scale number. Within this same study, Foster *et al.* created an internal load measure which they coined 'session-RPE' (sRPE) and was determined by multiplying the RPE by the duration of the session in minutes. For example, if an athlete performed a 60 min training session which they rated to be a 6 on the CR-10 RPE scale, the practitioner would calculate this as 6 x 60 = 360 arbitrary units.

The sRPE encapsulates the psychophysiological response (load) experienced by the athlete from the training or competition stimulus. Manzi *et al.* (2010) reported significant relationships between individual sRPE and HR-based training loads using Edward's TRIMP and Bannister's TRIMP (r values from 0.69 to 0.85; p 0.001) from 200 training sessions in professional Italian basketball. This review identifies eighteen (n=18) studies which employ the sRPE method for quantifying internal load. The sRPE method is one of the most popular methods employed in professional basketball load monitoring systems, and practitioners are encouraged to use it as a primary measure for load monitoring as it accounts for the individual response to the training dose (Impellizzeri, Marcora and Coutts, 2019).

Two (n=2) studies in this review use Borg's original CR 6-20 scale to obtain the intensity of the training and competition session (Daniel 2017, 2020). However, unlike the CR-10 scale this method has yet to be validated within basketball. Researchers and practitioners ought to take caution when comparing sRPE results reported in the literature. Scaling and verbal anchor modifications in the RPE methodology may obscure results. For example, the sRPE load would appear greater due to the larger multiplication factor using the CR 6-20 scale compared to the CR-10 scale. In fact, it has been suggested that a CR-100 scale may better reflect the differential psychophysiological response and biomechanical stressors experienced in training and competition as this scale is more sensitive and has finer grading compared to the CR-10 scale (McLaren *et al.*, 2018). Coaches should be vigilant when interrogating the professional basketball research and appropriately address the sRPE methodology when reviewing procedures.

Given the few limitations associated with sRPE, consensus statements by Impellizzeri, Marcora and Coutts, (2019), and Coyne *et al.* (2018) deem it valid and reliable for internal load monitoring and highlights it's simplistic and cost-effective characteristics, supporting its popularity within the literature. Researchers are encouraged to illustrate the procedures taken with clarity, especially when collecting the RPE and should consider using validated scales, such as Borg's CR-10 scale over the CR 6-20 scale.

2.6 External load monitoring approaches

A total of 24 studies reported the use of external load monitoring approaches in professional male basketball (Table 2.2). External load quantifies the stimulus imposed on players and can be measured as a function of time (volume) and intensity (McLaren *et al.*, 2018). Inertial measurement units (IMU) appear to be the most widely used external load monitoring method in professional male basketball. Nowadays, most GPS tracking devices include a triaxial inertial measurement unit comprising an accelerometer, gyroscope, and magnetometer. With the ability to use such devices in indoor sports, like basketball, without the support from GPS signals, acceleration-based data is preferable to quantify individual locomotion and identify specific movement patterns. Time motion analysis is a non-invasive video analysis procedure used to quantify movements during training and competition which provides information about an athlete's speed, duration and distances covered in different locomotor movements (López *et al.*, 2014). Positioning systems, such as GPS, Local Positioning Systems (LPS) and Optical Tracking have also appeared in literature as a means of evaluating player external load.

A similar, but important finding compared to the internal load monitoring approaches is the silo of research conducted on external load monitoring in Spain. In fact, 15 out of the 24 studies are reported from professional players in a Spanish basketball team. In addition, it is important to acknowledge that many of the same authors from Spain and Italy report the use of both internal and external loads either within the same study or across separate studies, as exemplified by Svilar and Ferioli *et al*. This raises the possibility that the same cohort of participants is employed across their studies, potentially leading to replicated loading strategies and periodisation techniques in their observational research. The reduced diversity might impede comparisons with other research conducted in different countries.

Moreover, a critical observation from Table 2.2 is the use favourable use of WIMU PRO Realtrack systems to report external loads, which is created in Almeria, Spain. Although these products have been validated (Hernandez-Belmonte *et al.,* 2019), it is important to understand that differences may lie between different devices or techniques used to quantify accelerometery external loads (Nicolella *et al.,* 2018). Therefore, when comparing external loads derived from systems like Catapult innovations and WIMU PRO, the potential disparities inherent in the measurement techniques should be kept in mind.

In the following subsections, we provide a summary of each external load monitoring approach currently used in professional male basketball.

Table 2.2 Study summary: external player load monitoring approaches in professional, male basketball.

Study Reference	Participants (n=)	Age (years)	Country/ League	Duration/ Phase of season	External load method	Technology/Equipment used
Training						
Aoki *et al.* (2017)	9	27.8 ± 6.8	Brazilian	Preseason (6-weeks) and in-season phase (5-weeks)	IMU	Bioharness (Zephyr technology), Piezoelectric technology
Castillo *et al.* (2021)	14	20 ± 2.3	Spanish	Mid-season phase (8 sessions over 8 weeks)	LPS	WIMU PRO Realtrack systems
Schelling and Torres (2016)	12	25.0 ± 4.3	Spanish	In-season phase (4 weeks)	IMU	Tri-axial accelerometer (X8-mini)
Svilar, Castellano and Jukic (2018)	13	25.7 ± 3.3	Spanish	In-season phase (16-weeks)	IMU	S5 devices (Catapult innovations)
Svilar *et al.* (2018)	13	25.7 ± 3.3	Spanish	In-season phase (16-weeks)	IMU	S5 devices (Catapult innovations)
Torres-Ronda *et al.* (2016)	14	25.5 ± 4.7	Spanish	In-season phase (8-weeks)	TMA	Lince sport analysis software
Vazquez-Guerrero *et al.* (2020)	12	29.6 ± 4.5	Spanish	In-season phase (18-weeks)	LPS	WIMU PRO Realtrack systems
Vazquez-Guerrero *et al.* (2021)	12	29.6 ± 4.5	Spanish	In-season phase (18-weeks)	LPS	WIMU PRO Realtrack systems
Competition						
Bishop and Wright (2006)	6	N/A	British	Regular season (5-consecutive home games)	TMA	Noldus Observer Pro Software
Caparros *et al.* (2018)	33	24.9 ± 2.9	N/A	2 regular seasons (246-games)	Optical Tracking	Stats perform
Daniel *et al.* (2017)	10	27.6 ± 5.5	Brazilian	Regular season (6-games)	TMA	JVC HD Everio GZ-HM690 model camcorder

Table 2.2 (continued)

Ferioli *et al.* (2020)	44	26.5 ± 4.4	Italian Division I (n=25) Division II (n=19)	2 regular competitive seasons (10-games)	TMA	GoPro hero 4 camera, SICS VideoMatch Basket software
Ferioli *et al.* (2020)	136	27 ± 5 25 ± 4 26 ± 6 22 ± 5	Italian Division I (n=33) Division II (n=37) Division III (n=36) Division VI (n=30)	Regular season (20-games), each player analysed on one occasion	TMA	GoPro hero 4 camera, SICS VideoMatch Basket software
Garcia *et al.* (2020)	13	19.8 ± 1.7	Spanish	Regular season (17-home games)	LPS	WIMU PRO Realtrack systems
McInnes *et al.* (1995)	8	23.5 ± 3.2	Australian	State competition and practice games	TMA	National M-7 video camera, National Editing Controller NV-A960
Salazar *et al.* (2020)	17	27.5 ± 6	Spanish	Preseason phase (5-games)	IMU	Catapult T6 devices, Openfield v1.14.0 software (Catapult innovations)
Scanlan *et al.* (2011)	10 12	28.3 ± 4.9 26.1 ± 5.3	Elite Australian Sub-Elite Australian	2-games, Mid-season, and end of season (elite players). 3-games, regular season (sub-elite players)	TMA	JVC Everio GZ-HD10 camcorder, Labview software
Scanlan *et al.* (2015)	10 12	28.3 ± 4.9 26.1 ± 5.3	Elite Australian Sub-Elite Australian	2-games, Mid-season, and end of season (elite players). 3-games, regular season (sub-elite players)	TMA	JVC Everio GZ-HD10 camcorder, Labview software
Vazquez-Guerrero *et al.* (2018)	12	25.5 ± 5.2	Spanish	2-day tournament (2-games)	IMU	Triaxial accelerometers (model ADXL326, Analog Devices)
Vazquez-Guerrero and Garcia (2021)	21	27.9 ± 3.9	Elite Euroleague, Elite Spanish League	Preparatory phase (1-game)	LPS	WIMU PRO Realtrack systems

Table 2.2 (continued)

Training + Competition						
Salazar *et al.* (2020)	27	24.8 ± 3.2	Spanish	Preseason and in-season phases (2-consecutive seasons)	IMU	Catapult T6 devices
Svilar *et al.* (2019)	13	25.7 ± 3.3	Spanish	In-season (~8 weeks)	IMU	Catapult S5 devices, Openfield v1.14.0 software
Svilar, Castellano and Jukic (2019)	16	26.2 ± 4	Spanish	Preseason and in-season phases (10-weeks)	IMU	Catapult T6 devices
Vazquez-Guerrero *et al.* (2020)	12	29.6 ± 4.5	Spanish	Competitive season (34 games domestic league, 29 games, Euroleague), 315 training sessions.	IMU, Game Stats	WIMU PRO Realtrack systems

*RPE = Rating of Perceived Exertion, sRPE = Session-Rating of Perceived Exertion, HR = Heart Rate, TRIMP = Banisters Training Impulse, SHRZ = Summated Heart Rate Zones, IMU = Inertial Measurement Unit, LPS = Local Positioning Systems, TMA = Time Motion Analysis. Note: All participants were male unless stated with: M = Male or F = Female. Studies are listed alphabetically.

2.6.1 Inertial measurement units

Ten studies (n=10) included IMU as a means of external load quantification in this review. As mentioned, most GPS tracking devices include a triaxial inertial measurement unit which contains an accelerometer, gyroscope, and magnetometer. Studies which include GPS devices comprising IMUs within them, tend to report triaxial accelerometery data, only, due to limitations with indoor GPS signal acquisition and satellite coverage (Theodoropoulos, Bettle and Kosy, 2020). The devices are usually placed between the scapula of the athlete using a neoprene vest to hold the unit in position, even though unit placement closer to the centre of mass, such as the hip has been suggested to reflect whole body movement with greater accuracy (Westerterp, 1999; Cleland *et al.*, 2013). It is important to differentiate between accelerometer and GPS data as it will determine the variables measured. While triaxial accelerometers only quantify movement via vibration, magnetometers and gyroscopes give extra data based on the direction of travel and orientation of the body, respectively. Magnetometers are used in conjunction with GPS to measure mechanical displacement, thus providing information based on the direction of which a player is moving. Alternatively, gyroscopes quantify the change in orientation or change in rotational velocity, and together with accelerometers are required to provide insightful information to coaches based on velocity, direction, and position of a player. In total, six (n=6) different IMUs were used within the studies reported in this review. Application of IMUs in the determination of external load is primarily based on a metric from triaxial accelerometers, the most reported metric was Catapult PlayerLoad^{TM}. This PlayerLoad^{TM} metric has demonstrated moderate to high test-retest reliability within and between participants, and within participants convergent validity (Barrett, Midgley and Lovell, 2014). Accelerometer load is the sum of the accelerations across all axes of the internal tri-axial accelerometer during movement. Developing IMU companies differ in formula calculations when quantifying accelerometer load, Catapult PlayerLoad^{TM} as the most reported measure in the research is as follows:

- PlayerLoad™ (units: arbitrary units, AU): The square root of the sum of the squared instantaneous rate of change in acceleration in the anterior-posterior (forward), medio-lateral (sideways) and vertical (up) planes (Boyd, Ball and Aughey, 2011; Gómez-Carmona *et al.*, 2019).

$$\sum \sqrt{\frac{(fwd_{t=i+1} - fwd_{t=i})^2 + (side_{t=i+1} - side_{t=i})^2 + (up_{t=i+1} - up_{t=i})^2}{100}}$$

Figure 2.2 Catapult accelerometery PlayerLoad™ calculation. Note: *fwd* = forward acceleration; *side* = sideways acceleration; *up* = upwards acceleration and *t* = time.

Analysing and populating data from IMUs is more time efficient for sport practitioners as default algorithms are built into devices, such as Catapult PlayerLoad™ and STATSport™ Total Load. Table 1 indicates an increasingly large uptake in the use of IMUs in professional basketball within the last six years. The automated technique makes it more appealing for analysing player external loads from training and competition compared to other manual external load monitoring approaches, such as TMA.

2.6.2 Time motion analysis

TMA is the second most used method to monitor external demands in professional basketball. Eight studies in this review include using either manual or semi-automated TMA techniques. Regardless of which analysis method is used, collecting data for TMA follows similar procedures. Usually, cameras are positioned on infrastructure or tripod stands around different angles of the perimeter of the court to capture video footage of the players. Most studies in this review employs manual TMA for analysing player external demands (McInnes *et al.*, 1995; Scanlan, Dascombe and Reaburn, 2011b; Scanlan *et al.*, 2015; Daniel *et al.*, 2017; Ferioli, Rampinini, *et al.*, 2020b; Ferioli, Schelling, *et al.*, 2020). The earliest research identified in this review from McInnes et al. (1995) used manual TMA techniques, which involves frame-by-frame analysis of video playback to assess player movement patterns during basketball. This method requires one or more investigators to classify locomotive movement. While visual analysis is subjective and has the possibility of possessing human errors, reliability and validity of this method have been reported in the basketball literature (McInnes *et al.*, 1995; Hulka, Cuberek and Svoboda, 2014). Advances in technology permits semi-automated TMA, which uses a software to auto-detect player movements and durations within (Bishop and Wright, 2006; Torres-Ronda *et al.*, 2016). Labview (National Instruments, TX, USA) and SICS VideoMatch Basket (VI, Italy) were the two most used TMA software packages in this review.

Movement categories from TMA are reported similarly throughout the literature, for example: stand, walk, jog, run, sprint, low/medium/high shuffle and jumps, are determined for duration and count which are subjectively assessed using the different software and one or more analysts. Nevertheless, obscurity and variations when classifying movement intensities appear throughout the literature. McInnes *et al.* (1995), defines shuffling as either low, medium, or high intensity depending on player foot speed and urgency. Scanlan *et al.* (2011), quantitatively, and more appropriately defines low and high shuffling intensities based on velocities <0.2 $m.s^{-1}$ and >0.2 $m.s^{-1}$, respectively. On the other hand, Ferioli, Rampinini *et al.* (2020), took a similar approach to McInnes *et al* and defined intensities based on urgency according to the investigator’s perspective. However, they define low, medium, and high intensity ‘specific movements’ as stance position, shuffling, rolling, reversing, screening, and cross-over running activities. Yet it is difficult to distinguish stance position and screening intensity thresholds as these isometric movements would fall into the ‘stand/walk’ category. In fact, TMA, and other external methods such as IMUs fail to recognise isometric movements such as screening, stance position and blocking which have varying degrees of muscle recruitment from the upper and lower body, thus comprising a degree of metabolic demand (Montgomery, Pyne and Minahan, 2010).

Another limitation TMA exhibits is analysing data based on live-play time (clock-time) instead of total match-time (including stoppages, breaks and ball out of bounds play time). Differences in low-intensity activities (6.9% increase), as well as distance covered (16% greater) using total match-time compared to live-time have been observed in another court-based sport, futsol (Doğramacı and Watsford, 2006). Additionally, high-intensity activities relative to live-time may overestimate game demands in this category (McInnes *et al.*, 1995; Doğramacı and Watsford, 2006). Many studies in this review include live-time, only (Scanlan, Dascombe and Reaburn, 2011; Scanlan *et al.*, 2015; Ferioli, Rampinini, Martin, Rucco, Torre, *et al.*, 2020; Ferioli, Schelling, *et al.*, 2020).

IMUs have gained much popularity in the last decade, largely due to time efficiency of data analysis, but now, real-time data analysis is possible with IMUs, whereas TMA techniques are applied retrospectively to training or gameplay, making it a more time intensive option for evaluating player external demands (Li *et al.*, 2016). Given the limitations between different TMA techniques and methodologies, caution should be taken when comparing research results.

2.6.3 Positioning Systems

GPS, LPS, and optical tracking, are positioning systems which are used in daily basketball practice and research. This review identified 5 studies which included the use of LPS (n=4) and optical tracking (n=1). While GPS is used in many outdoor sports (Theodoropoulos, Bettle and Kosy, 2020), and indoor GPS systems have been validated (Barbero-Álvarez *et al.*, 2010), this review does not include the use of GPS within professional basketball research for identifying external players loads. A key limitation of GPS technology is its reliance on satellite signals from orbit, which is why the useability and feasibility of this method is limited for indoor sports. An alternative method which has emerged as a more valid and reliable method compared to GPS for monitoring external demands is LPS (Serpiello *et al.*, 2018). WIMU PRO (Realtrack Systems SL, Almería, Spain) is the only LPS reported in this review. WIMU PRO LPS involves placing ultra-wide band antennas (usually six, including one reference antenna) around the basketball court which registers sensors at different frequencies from devices held in neoprene vests between the scapula in the upper thoracic region of the body, like some IMUs. The system operates using triangulations between the devices worn by the athletes and the ultra-wideband antennas, and evaluates the time taken to receive the signal which provides information based on unit positioning using coordinates X and Y (Serpiello *et al.*, 2018).

Although LPS demonstrates superiority in validity and reliability when assessing player velocity and distances covered compared to GPS (Hoppe *et al.*, 2018), there are a few limitations worth noting when using LPS in basketball. One limitation which has been highlighted, is that LPS produces highly reliable results when assessing average velocities and acceptable for positional estimations (Ogris *et al.*, 2012), but the error progressively increases when dealing with higher speeds and high dynamic movements and turning angles (Frencken, Lemmink and Delleman, 2010; Ogris *et al.*, 2012). Another limitation worth considering when comparing LPS results from the literature, is the filter processing techniques and parameter calculations (position, distance and speed) and used between different LPS companies. All the studies in this review includes using a manufacturer's software (WIMU PRO software) to analyse filtered data. Thus, it has been advised that for ease of replicating methodology and facilitating appropriate interpretations of results, that investigators should process raw data independent of these different software (Luteberget, Spencer and Gilgien, 2018).

Furthermore, this review identifies one study which used optical tracking for quantifying external load in professional male basketball players across three consecutive seasons in the NBA (Caparrós *et al.*, 2018). Optical tracking uses cameras to capture video footage from different angles of the court, and creates anchors based on static features in the footage. By tracking the displacement rates and temporal locations of moving 3-dimensional objects (ball and athletes) over-time relative to the anchors, it derives variables such as speed and distance (Oba and Okuda, 2008; Mara *et al.*, 2017). One of the advantages of this external load monitoring system is that like TMA, it is non-intrusive, and the athletes do not wear additional devices or clothing. Nonetheless, practitioners should be mindful about the lack of validation research conducted on optical tracking within basketball, and when cross-analysing results with other external load methods

(Harley *et al.*, 2011). Additionally, proprietary software from different manufacturers is likely to use different vision algorithms to extract positional data.

2.7 Internal training and competition loads

Tables 2.3, 2.4 and 2.5 report internal loads from professional male basketball players during training and competition. Twenty (n=20) studies included in this review report one or more measures of internal load. Six (n=6) studies include HR-based loads, including TRIMP and percentage (%) of HR Lactate Threshold. Sixteen (n=16) studies report sRPE, Weekly Training Load, Total Weekly Load, or a combination of these. Only one (n=1) study includes Blood Lactate Concentration (mmol/l).

As highlighted previously, the sRPE is the most popular internal load method. However, diversity in the reported sRPE quantification technique leads to different load outcomes as seen in Tables 2.3 and 2.4. Doeven *et al.* (2017, 2020) uses the CR-6-20 scale to quantify sRPE, unlike most studies which use the more common CR 0-10 approach. While diversification in professional player cohorts across different countries are encouraged, the differences between the reported internal loads are a result of these different quantification techniques. Consequently, the subsequent subsections outline recommendations for future basketball research, advocating for a more standardised approach to mitigate such discrepancies.

Table 2.3 Internal training loads in professional, male basketball.

Study Reference	**Training sessions (n=)**	**HRavg (bpm)**	**HRmax (bpm)**	**%HRmax**	**TRIMP**	**sRPE (AU)**	**Weekly Training Load (AU)**
Aoki *et al.* (2017)	45	Preseason: 115.8 ± 67.8 In-season: 120.2 ± 7.1			Preseason: 27.1 ± 2.1 In-Season: 21.5 ± 1.6	Preseason: 442.9 ± 89.2 In-Season: 377.1 ± 68.3	
Ferioli *et al.* (2018a)	Preparation period Mid Aug – Mid Oct ~7 weeks						Pro: 5058 ± 1849 Semi-Pro: 2373 ± 488
Ferioli *et al.* (2018b)	Preparation period ~7 weeks.						Pro: 5241 ± 1787 Sem-Pro: 2408 ± 487
Manzi *et al.* (2010)	200						No Game: 3334 ± 256 AU 1-Game: 2928 ± 303 2-Games: 2791 ± 239
(Svilar, Castellano and Jukic, 2018)	13					390.2 ± 135.6	
(Svilar *et al.* (2018)	4-26 per player 300 observations					Guards: 402.9 ± 151.8 Forwards: 385.5 ± 137.3 Centres: 385.1±121.6	
Torres-Ronda *et al.* (2016)	32	5v5:144 ± 17 4v4:142 ± 15 3v3:142 ± 15 2v2:141 ± 15 1v1:142 ± 13	5v5: 172 ± 19 4v4: 176 ± 18 3v3: 177 ± 12 2v2: 174 ± 14 1v1: 170 ± 10	5v5: 83 ± 9 4v4: 85 ± 7 3v3: 86 ± 5 2v2: 84 ± 5 1v1: 82 ± 4			
Doeven *et al.* 2020							1-Game: 8155.11 ± 2870.41 2-Game: 5651.8 ± 2259.72
Ferioli & scanlan *et al.* (2021)						Regular season: T1-123 ± 62 T2- 549 ± 107 Playoff: T1- 84 ± 45 T2- 402 ± 60	Regular season: 1-Game: 2362 ± 437 Playoff: 650 ± 485
Svilar *et al.* (2018)	228					MD-3: 598.2±90.5 MD-2: 441.4±73.4 MD-1: 312.0±92.8	

*sRPE = Session-Rating of Perceived Exertion, HRavg = Average Heart Rate, HRmax = Maximum Heart Rate, %HRmax = Percentage of Heart Rate Maximum, FM = Friendly Matches, TRIMP = Banisters Training Impulse, Weekly Training Load (sRPE x min), AU = arbitrary units. Note: Heart Rate expressed in beats per minute (bpm). Adapted with kind permission from Petway et al. (2020).

Table 2.4 Internal competition loads in professional, male basketball.

Study Reference	Competition sessions (n=)	HRavg (bpm)	HRmax (bpm)	%HRmax	sRPE (AU)	Blood Lactate Concentration (mmol/l)	% of HR Lactate Threshold
Mcinnes *et al.* (1995)		165 ± 9	188 ± 7	87 ± 2		Mean: 6.8 ± 2.8 Mean peak: 8.5 ± 3.1	
Doeven *et al.* (2017)	15				403 ± 135		
Vaquera *et al.* (2008)	5	Point guards: 163 ± 14.3 Forwards: 151 ± 10.3 Centres: 155 ± 9.4	Point guards: 186 ± 11.7 Forwards: 176 ± 8.3 Centres: 177 ± 7.7	Point Guards: 95.6 Forwards: 93.7 Centres: 92.7			
Daniel *et al.* (2017)	6						Defence: 104.2 ± 2.21 Offense: 103.7 ± 1.80 Defence transition: 104.8 ± 2.44 Offense transition:104.3 ± 3.55
Torres Ronda *et al.* (2016)	7	158 ± 10	198 ± 9.3	96.8 ± 2.6			
Ferioli *et al.* (2021)	22				Regular season game: 695 ± 131 Playoff game: 642 ± 77		

*sRPE = Session-Rating of Perceived Exertion, HRavg = Average Heart Rate, HRmax = Maximum Heart Rate, %HRmax = Percentage of Heart Rate Maxmimum, TRIMP, AU = arbitrary units. Note: Heart Rate expressed in beats per minute (bpm) and Blood Lactate expressed in millimoles per litre (mmol/l). Adapted with kind permission from Petway et al. (2020).

Table 2.5 Total Weekly Loads in professional, male basketball.

Study Reference	Training and competition sessions (n=)	Total Weekly Load (AU)
Salazar *et al*. (2020)	1041	Season 1: 2703 ± 887 Season 2: 3096 ± 1227
Doeven *et al.* (2020)		2-game: 7730.5 ± 2499.27 1-game: 9307.8 ± 3028.63
Ferioli & scanlan *et al.* (2021)	83	Regular season: 3087 ± 564 Playoff phase: 2365 ± 408
Leite *et al.* (2013)	98	Preseason: 3776.6 ± 1156.6 Comp phase: 3745.4 ± 1719.8

*Total Weekly Load = weekly training and competition load (sRPE x min), AU = arbitrary units.

2.7.1 Heart rate

Heart rate, including Bannister's TRIMP as reported by Aoki *et al.* (2017) is used during basketball training to investigate the relative cardiovascular response from specific training drills, and help shape position-specific training plans (Berkelmans *et al.*, 2018). Only two studies in this review examine HR during basketball training. Torres-Ronda *et al.* (2016) investigates HR_{avg}, HR_{max} and $\%HR_{max}$ from friendly matches and specific basketball game-based drills (1v1, 2v2, 3v3, 4v5 and 5v5). They report that friendly matches induce the greatest HR_{avg} and HR_{max} response, while 1v1 full court drills are the most physically demanding. Moreover, Aoki *et al.* (2017) reports a very large decrease in Bannister's TRIMP during in-season compared to preseason training (-20.6 ± 3.8; mean difference (%) ± confidence limits (%)). Additionally, HR_{avg} was greater during in-season training (120.2 ± 7.1 bpm) compared to preseason training (115.8 ± 7.8 bpm) with a very likely effect. Manzi *et al.* (2010) reports significant individual relationships for all measures of Edwards TRIMP and Bannister's TRIMP with sRPE, yet unfortunately they do not cite TRIMP statistics. More research should examine HR-based metrics including TRIMP during various training scenarios to draw a more conclusive picture of the physiological demands on players and across different playing positions.

In the literature, double the number of studies investigate HR-based measures during competition (n=4) compared to training (n=2). HR_{avg} during competition ranges from 158 to 165 bpm (McInnes *et al.*, 1995; Torres-Ronda *et al.*, 2016). Vaquera *et al.* (2008) reports position specific HR_{avg} and demonstrates Guards to exhibit the greatest response (163 bpm) compared to Forwards (151 bpm) and Centres (155 bpm) during professional basketball gameplay. Competition HR_{max} varies between 188 bpm and 198 bpm, averaging 193 bpm. Based on the research displayed in Table 2, Guards experience the highest HR (186 bpm), followed by Centres (177 bpm), which is similar to Forwards HR_{max} (177 bpm) (Vaquera Jiménez, 2008). Additionally, Guards reach a higher percentage of their max HR during competition compared to Forwards and Centres. This is perhaps indicative of Guards experiencing greater or different external demands, while inherently having a higher relative fitness level compared to Forwards and Centres.

Lastly, Daniel et al. (2017)is the only study which reports HR Lactate Threshold percentage. HR Lactate Threshold percentage was determined as the ratio between HR threshold speed and peak HR. Lactate threshold speed was considered by the increase of 1 mmol/l in relation to rest levels during a 3-speed (9, 10 and 11 km/h) treadmill running test. After running each speed for 4-min, lactate levels and HR were recorded to provide the HR threshold speed. Interestingly, HR Lactate Threshold percentage was higher during defensive style of play, in particular defence transition, compared to attacking patterns of play (Table 2).

2.7.2 sRPE, Weekly Training Load and Total Weekly Load

sRPE is often measured during individual training sessions, such as the team average sRPE per training session, or the team average weekly accumulated sRPE which is more commonly referred to as Total Weekly Load (training, including games) or Weekly Training Load (training, only) in the literature (Manzi *et al.*, 2010; Aoki *et al.*, 2017; Conte *et al.*, 2018; Salazar *et al.*, 2020; Ferioli *et al.*, 2021). Of the fifteen (n=15) studies which report these internal load metrics, seven (n=7) report team average sRPE for individual training or competition sessions, five (n=5) illustrate the team average accumulated Weekly Training Load, while four (n=4) describe the Total Weekly Load experienced by players from training and competition.

According to the literature, average daily basketball training sRPE ranges from 377.1 to 390.2 AU during in-season periods. Preseason sRPE load tends to be higher than in-season, largely due to the greater training volume demands inflicted on players. Both Svilar *et al.* (2019) and Ferioli *et al.* (2021) report a linear decrease in daily training sRPE the closer the team approaches game-day. This is likely attributed to the natural tapering strategy coaches adopt in the lead up to games to potentially heighten physical performance and reduce residual fatigue. One limitation to the sRPE method is that it can be significantly influenced by contextual factors, such as game outcome (win, loss, or draw) (Fessi and Moalla, 2018) and even the upcoming opposition level (Sansone et al., 2021). While RPE has been shown to decrease following winning games compared to losing games (Fessi and Moalla, 2018), the emotional burden resulting in elevated stress levels can impede performance in tasks that require working memory, retrieval of information and decision making, like in basketball.

Positional differences are also observed when assessing daily training sRPE. Guards appear to experience greater internal loads (sRPE = 402.9 AU) compared to forwards (sRPE = 385.5 AU) and centres (sRPE = 385.1 AU). This may be explained by the greater number of external demands guards experience at varying degrees of intensity during live-play compared to forwards and centres (Ferioli, Rampinini, *et al.*, 2020). Doeven *et al.* (2017) reports competition sRPE loads from fifteen (n=15) professional basketball games. They report the average game sRPE to be 403 AU. However, Ferioli *et al.* (2021) found regular season competition sRPE as 695 AU and play-off competition sRPE as 642 AU. Albeit caution should be taken when comparing these sRPE loads as Doeven *et al.* (2017) uses Borg's 6-20 RPE scale, whereas Ferioli *et al* (2021) assesses RPE using the CR 0-10 RPE scale. Given that Ferioli *et al.* (2021) reports higher sRPE loads yet uses the CR 0-10 scale to collect RPE it could be assumed that training is more demanding for the Italian player cohort based on different coaching practices.

As previously stated, Weekly Training Load is the teams average summated sRPE for each training session over a week, whereas the Total Weekly Load is the teams average summated sRPE for training, including games over a week. Table 2.3 Indicates that Weekly Training Load varies from 2362 to 8155 AU during regular season training. Doeven *et al.* (2020) reports significantly lower Weekly Training Load when 2-games per week are played versus 1-game per week. Manzi *et al.* (2010) states similar results but are not found to be significantly different. Additionally, the preparation period at the start of a basketball season results in greater Weekly Training Load (5058 to 5241 AU) compared to in-season Weekly Training Load (3334 AU) which is likely contributable to the higher volume of training inflicted on players during this phase where conditioning is a focus point during this phase (Manzi *et al.*, 2010; Ferioli *et al.*, 2018).

According to Doeven *et al.* (2020) Total Weekly Load follows similar patterns for 1-game versus 2-games per week as they reported that it could be due to coaches focusing more on maintenance of fitness rather than overloading players to result in less fatigue for weeks involving 2-games. This is also illustrated by Ferioli & Scanlan *et al.* (2021) who identify the play-off phase of a season to inflict lower Total Weekly Load compared to the regular season (Table 3). Regular in-season Total Weekly Load range from 2703 to 3745 AU (Leite, Coutinho and Sampaio, 2013; Salazar *et al.*, 2020). Coaching styles, player age, playing experience and game results are only a handful of factors which might contribute to the differences observed in daily sRPE, Weekly Training Load and Total Weekly Load as seen in Tables 2, 3 and 4. Thus, caution should be taken if it is of the intention of the reader to use these results to inform the training process of current professional basketball teams. Additionally, the use of Borg's 6-20 RPE scale versus the CR 0-10 scale, produce different results, therefore it is recommended that research in this area should take on a more synonymous approach in using the CR 0-10 scale to allow transparency and comparison of results, such as Weekly Training Load and Total Weekly Load. Lastly, more research should focus on inter-positional differences as there appears to be a lack of loads derived from the RPE method (sRPE, Weekly Training Load and Total Weekly Load).

2.8 Summary

Professional basketball is a highly demanding intermittent team sport which involves a variety of movement patterns at different intensities. Therefore, it is crucial to elucidate player loads to help inform the training process for other professional basketball teams and summarise the internal and external load monitoring approaches which are currently employed in the sport. This systematic literature review provides a comprehensive account of the current methods used to monitor training and competition loads and gives an appraisal of the evolving literature in the player load monitoring area. From the results, IMUs are the preferred method of assessing external load, yet the most recent literature appears to adopt LPS as means of collecting positioning data. HR monitoring provides information about the intensity of game play, but it can be a costly load monitoring tool which is likely why the sRPE method is the preferred option for measuring the internal response to training and competition. This review specifically extracted internal player loads from the literature and found that 1) guards incur greater physical demands during training and game-play compared to forwards and centres as exemplified through HR parameters; 2) weeks with 1-game are more demanding than weeks with 2-games; 3) training loads become less the closer to game-day, likely due to a tapering strategy adopted by coaches; 4) Pre-season load is greater than in-season and play-off phases. This review provides limitations with current load monitoring practices and methods used in basketball and addresses future directions for research in these areas. With knowledge of such strengths and weaknesses of current load monitoring tools, as well as the internal loads players experience from training and competition, practitioners can define load monitoring parameters, implement specific recovery strategies at different phases of the season and manipulate certain tactical and technical coaching plans to increase the likelihood of desirable adaptations.

Chapter 3 Study 1 – Determination of internal player load during a competitive season in the professional British Basketball League: Pre-season and in-season phases

3.1 Abstract

The necessity for monitoring player load in basketball is crucial for ensuring player readiness. The purpose of this study was to analyse trends in internal load experienced by professional basketball players over the course of a full season playing in the British Basketball League (BBL). The study consisted of ten elite male basketball players from a single team in the BBL (mean ± SD, age: 26.3 ± 3.6 years; height: 195.8 ± 8.1 cm and body mass: 90.3 kg). Weekly Training Load (training only) and Total Weekly Load (training and competition load) were quantified using the subjective session rating of perceived exertion (sRPE) method. Changes in Weekly Training Load and Total Weekly Load for phase of season (preseason and in-season), playing status (starters versus bench players), 1-game versus 2-game weeks and week-to-week fluctuations were assessed. Magnitude-based inferences were used for comparing the probability and meaningfulness of the true differences and the smallest worthwhile changes (SWC). Practical significance of changes in load was assessed using Hedges g effect sizes. The main findings indicated 1) Weekly Training Load and Total Weekly Load varies week-to-week during a season, with the highest variances reaching 232% and 283%, respectively; 2) preseason Weekly Training Load was greater (*most likely*) than the in-season phase; 3) starting players exhibited larger Total Weekly Load than bench players (*very likely)*; 4) Weekly Training Load was higher in 1-game weeks compared to 2-game weeks (*very likely*), while Total Weekly Load was higher in 2-game game weeks compared to 1-game weeks (*possibly*). This study provides insights into the loads experienced by professional basketball players competing in the British Basketball League and may help coaches or sport scientists in making informed decisions about periodisation strategies which are adopted by coaches during specific phases of the basketball season.

3.2 Introduction

Basketball is characterised as a high intensity, intermittent sport, which involves a variety of multidirectional physical movements (Aoki *et al.*, 2017; Ferioli *et al.*, 2018). During an elite basketball season, the excessive physical and psychological demands imposed on players can have the ability to mitigate their state of readiness for gameplay (Ferioli *et al.*, 2018). When an athlete experiences chronically high psychophysiological load, not only can it mitigate their state of readiness, but potentially increase their likelihood of incurring a soft tissue injury (Weiss *et al.*, 2017).

Many basketball leagues experience a congested game schedule, whereby players can participate in two or more 40-minute games each week (Conte *et al.*, 2018; Fox, O'Grady and Scanlan, 2020). Thus, the necessity for monitoring player training loads and game loads during an elite basketball season is imperative. These loads can inform recovery processes, assess acute and chronic psychophysiological responses to training regimes, and enhance periodisation of training for improving player readiness. Load can be categorised into one of two theoretical constructs: internal or external. External load describes the amount of work performed by the athlete, whereas internal load accounts for the psychophysiological response to this work (Impellizzeri, Marcora and Coutts, 2019). It has been recommended that as internal load accounts for individual responses to a training programme, that it be used as primary measure when monitoring athletes (Impellizzeri, Marcora and Coutts, 2019).

A simple, yet effective method for encapsulating an athlete's psychophysiological response following basketball training and competition is the Borg's category-ratio (CR) 0-10 rating of perceived exertion (RPE) scale (Foster *et al.*, 2001; Manzi *et al.*, 2010; Aoki *et al.*, 2017; Fox, Scanlan and Stanton, 2017; Svilar, Castellano and Jukic, 2018). Load is most frequently prescribed on a team basis in basketball; therefore, it is important to monitor the individual response to training and competition to optimise physical performance and reduce fatigue throughout the entire basketball season (Edwards *et al.*, 2018). Many studies which report RPE in basketball are often short observational studies, reporting only on specific periods of training or competition within a basketball season (Alexandre Moreira *et al.*, 2012; Aoki *et al.*, 2017; Doeven *et al.*, 2017; Paulauskas *et al.*, 2019; Svilar, Castellano and Jukic, 2019; Ferioli, la Torre, *et al.*, 2021), while only a few studies investigate internal load using the RPE method across an entire season (Conte *et al.*, 2018; Paulauskas *et al.*, 2019; Doeven *et al.*, 2020). Doeven *et al.* (2020) investigates load in professional male basketball players, while Paulauskas *et al.* (2019) presents load in female basketball players, and Conte *et al.* (2018) in NCAA D1 players.

To date, Manzi *et al.* (2010) and Doeven et al. (2020) are the only two groups of researchers to investigate internal load relative to weekly game schedule in professional male basketball players. Manzi *et al.* (2010) explored 12 weeks of in-season training and competition loads from a professional male basketball team in the Italian Series A league. No significant differences between load in relation to 1-game and 2-game weeks were reported. On the other hand, Doeven *et al.* (2020) investigated the sRPE using the Category Ratio 6-20 RPE scale during a full season in professional Dutch players. Due to the differences in sRPE calculation methods, this makes comparing loads difficult. In addition, much of the research conducted in professional male basketball players stems out of leagues within Europe and the United States, like due to more popularity in these countries than the likes of the United Kingdom. In fact, there appears to be a lack of research conducted in basketball within the UK, even though it is played from amateur to professional level.

Paulauskas *et al.* (2019) conducted one of the most extensive studies in elite basketball, to date. They investigated internal training load in seven elite female basketball teams throughout an entire season during the Lithuanian Women's Basketball League. They found highest weekly changes in training load of up to 120% for training only, and 47% for training and games. Moreover, players with less game time exhibited notably lower game loads than those with high-playing-time. Consequently, coaches should adjust training to incorporate additional metabolic conditioning for players with less game time. One way this could be achieved is through adding post-game conditioning 'top-ups' (Hills *et al.*, 2020). Conte *et al.* (2018) studied the first 10 weeks of a season in a male NCAA-D1 basketball team, they established much greater loads during 1-game weeks, compared to 2-game weeks because of periodisation strategies which are adopted by coaches to help reduce fatigue and possibly induce positive physiological adaptations (Cross *et al.*, 2016). Yet more research should investigate if these trends occur in professional basketball as both training and competition demands are even more intensive than the NCAA D1. Additionally, one study to date has reported internal loads for both pre-season and in-season phases (Aoki *et al.*, 2017). Aoki *et al.* (2017) highlights that the internal load response is mostly altered by the higher volume of training during the preseason. Their results also suggest that the specific basketball training sessions presented higher intensity and lower volume during the in-season phase compared to preseason (Aoki *et al.*, 2017).

Conte *et al.* (2018) exhibited several large spikes in week-to-week training load variation, peaking at 226%. According to the literature, such spikes expose athletes to a greater risk of soft tissue injury (Blanch and Gabbett, 2016; Gabbett, 2016). Gabbett (2016) presented a method which could potentially indicate when an athlete is more susceptible to soft tissue injury. The acute:chronic workload ratio (ACWR), is an athlete's 'fitness' and 'fatigue', which is calculated using either the rolling average model or the exponentially weighted moving average model.
By dividing the acute load (fatigue), which is usually 7-days, by the chronic load (fitness), which is generally 28-days, calculates the ACWR. Gabbett (2016), states a general 10% rule, which claims that if an athlete's load varies by about 10% to the previous week, also known as a 'spike' in load, then the athlete becomes more susceptible to soft tissue injury. Weiss *et al.* (2017) investigated the relationship between training load and injury using the ACWR in professional male basketball players. In retrospect, they indicated that players with an ACWR are at greater risk of injury when <0.99 and >1.5 during a season.

Further study is warranted into the internal load experienced by professional basketball players during an entire season. More specifically, research should be conducted within British basketball given the extent of its nationwide popularity. Adding such research to the body of international basketball research will help inform practitioners about differences in coaching strategies used by coaches when prescribing training, and the differences in load parameters experienced by basketball players from different leagues. Currently, with a lack of research in professional, male British basketball, it makes it difficult for coaching staff to extract information and draw logical, informed decisions when prescribing training load parameters.

Therefore, the purpose of this study was to:

1. Determine weekly fluctuations in internal player load during a full season.

2. Identify differences in training load during pre-season and in-season phases.

3. Examine weekly training and competition load between starting and bench players

And,

4. Investigate if weekly load in 1-game versus 2-game weeks differ.

To the best of the researcher's knowledge, this is the first study investigating internal training and competition load reported by players competing in the elite British Basketball League (BBL).

3.3 Methods

3.3.1 Participants

Ethical approval was obtained from the College of Medical, Veterinary and Life Sciences Research Ethics Committee at University of Glasgow. One week prior to pre-season, informed consent was obtained from an initial sample size of 14 elite senior (>18 years old) male basketball players. However, 10 players (6 guards and 4 centres) were included for final analysis (mean ± SD, age: 26.3 ± 3.6 years; height: 195.8 ± 8.1 cm and body mass: 90.3 kg). Three players were replaced during the analysis period due to being cut from the team (n = 1) and due to injury (n = 2).

Those who failed to participate (n=1) in more than 95% of each training session were excluded from the session analysis.

3.3.2 Experimental Design

The data were collected in this observational study (September – March) during the 2017-2018 season in the British basketball league (BBL). Athletes included in the study played for the Glasgow Rocks professional basketball team (positioning 4th place in the 2017-2018 BBL). The entire study period lasted 29 weeks. This was split into 2 separate phases: pre-season (4-weeks) and in- season (25-weeks). Data were collected from a total of 196 sessions, players participated in 164 training sessions and 32 games (2 pre-season games and 30 in-season games). The in-season phase consisted of either 0, 1 or 2-games per week schedules which informed the second aim of the study. Noteworthy, is 1 week of data was excluded because of managerial handover circumstances. This led to a lack of training attendance in the month of February between the 18th and 27th (week 25) until an interim coach was confirmed. Games were scheduled on Friday, Saturday and/or Sunday each week. Home games were played in Glasgow, Scotland. Away games were played at various venues across England. Players typically participated in 4 to 5 training sessions each week lasting between 60-120 minutes, excluding warm-ups. Each training session duration (start and end of session) was recorded manually by the researcher using the court side timer. While game duration was recorded through the BBL live stats web page (www.bbl.org.uk). Please refer to Chapter 3, *Methods*; *Procedure* for more information on data collection and handling methods. Players performed 1 to 2 strength sessions per week. However, for this study, load data were collected and analysed for basketball training and games only. All players were familiar with the methodology used in the study. External loads were prescribed on a team basis according to the basketball coach's training prescription, with no external input (e.g. sport scientist or strength and conditioning coach).

3.3.3 Procedure

Internal loads for training and competition were recorded from each player 30 minutes following every training session and game. Players were asked ‘How intense was your training session/game?’ while presented with Borg’s CR 0-10 RPE scale. The scale includes numbers corresponding to appropriate descriptors. training load and competition load were quantified according to Foster *et al*, (2001), whereby the RPE value was multiplied by the session duration (min) to produce a workload metric in arbitrary units (AU). Training and competition session duration was recorded from the start to end of each session, including all stoppages and recovery periods.

Total Weekly Load and Weekly Training Load, and sRPE for training and competition sessions were calculated according to Table 3.1. Weekly variance for each metric was assessed and comparisons were made based on different independent variables.

Table 3.1 Calculation methods for quantifying player load variables.

Variable	**Calculation**
Total Weekly Load	Summated weekly sRPE for training and competition
Weekly Training Load	Summated weekly sRPE for training, only

3.3.4 Statistical analysis

All data sets were assessed for normality using the Anderson-Darling test on Minitab (version 18). Weekly changes in load were analysed for each dependent variable. Data are presented as mean ± SD, while weekly variance in loads was investigated using percentages (%). Two-sample t-tests were used to assess differences between weekly loads and Total Weekly Loads according to game schedule (1- vs 2- game weeks), training phases (pre- vs in-season) and playing positions (starters vs bench players). Magnitude-based inferences were used for comparing the probability and meaningfulness of the true differences and the smallest worthwhile changes (SWC) according to Batterham and Hopkins, (2006) using a modified excel spreadsheet (http://sportsci.org/). Practical significance of changes was assessed using Hedges g effect sizes and presented with 90% confidence limits (Lakens, 2013). The effect size magnitudes were classified as follows: trivial = <0.2, small = 0.2-0.6, moderate = 0.6-1.2, large =1.2-2, and very large = >2.0. The smallest worthwhile change was determined by multiplying the between-player standard deviation by 0.2. Quantitative chances of real differences in variables (harmful, trivial, or beneficial) were assessed using predefined qualitative criteria: <1%, most unlikely; 1-5%, very unlikely; 5-25% unlikely; 25-75%, possible; 75-95%, likely; 95-99%, very likely; >99%, most likely. If the probability of having higher or lower values than the SWC by >5%, the true difference was deemed unclear.

3.4 Results

Weekly variances in Total Weekly Load (training and games) and Weekly Training Load (training sessions only) are depicted in Figure 3.1 and Figure 3.2, respectively. The greatest spike in Weekly Training Load occurred at week 15 (232%). Similarly, the highest weekly variance in Total Weekly Load was evident at week 15 (283%).

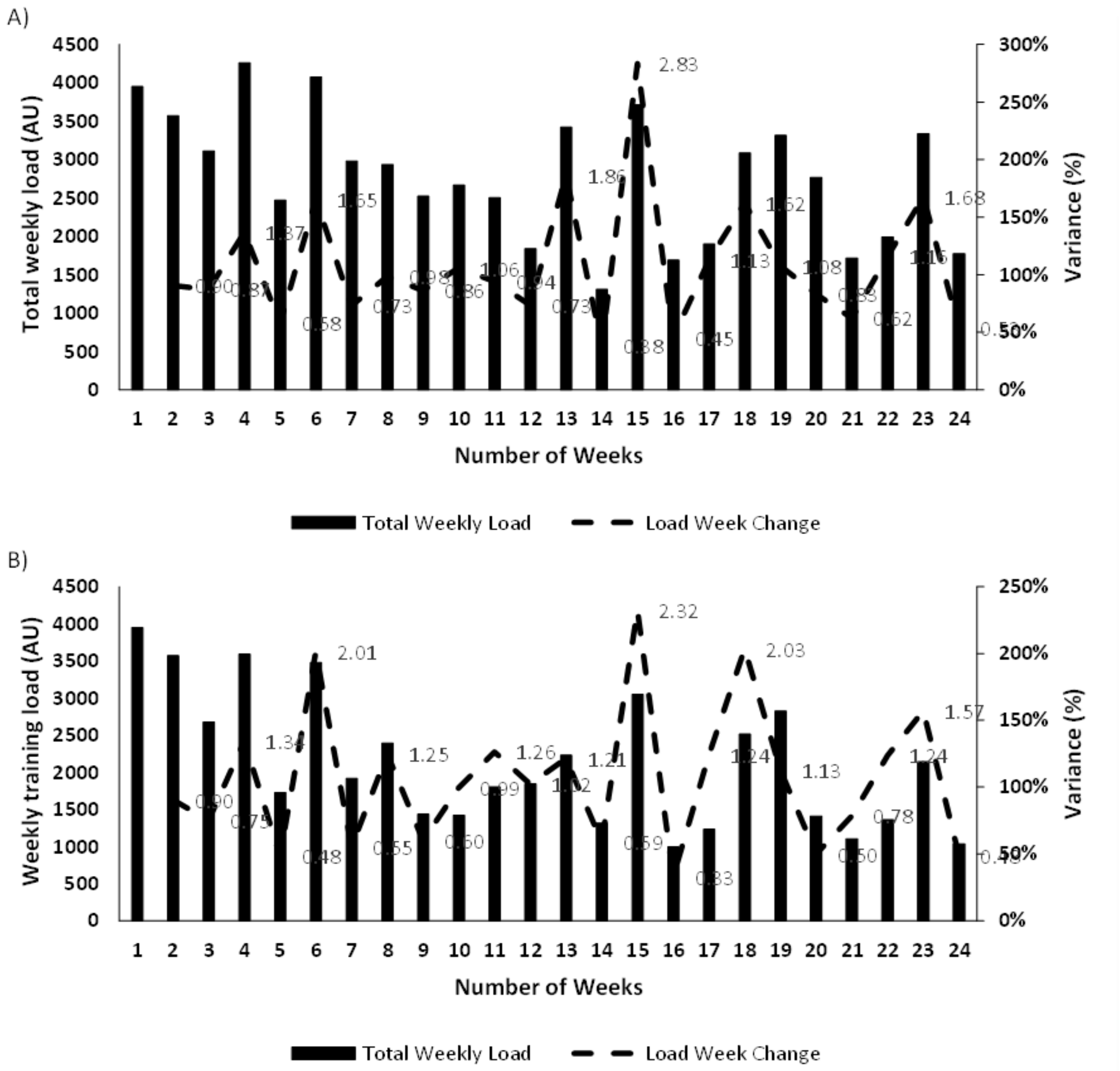


Figure 3.1 A) Total Weekly Load (training and games), and B) Weekly Training Load (training, only) across a full basketball season, including both preseason (1-4 weeks) and in-season (5-24 weeks) phases. Weekly load = session-RPE x duration (min); session-RPE = session rating of perceived exertion; AU = arbitrary units.

Preseason Weekly Training Load was higher (*most likely*) compared to in-season Weekly Training Load (Table 3.2). During the in-season phase, a small (*very likely)* difference was evident between starting and bench players for Total Weekly Load, while unclear differences were apparent for Weekly Training Load. Furthermore, weekly load was lower in 2-game weeks (*very likely small*) compared to 1-game weeks, while a lower Total Weekly Load for 1-game weeks (*possibly small*) was evident compared to 2-game weeks.

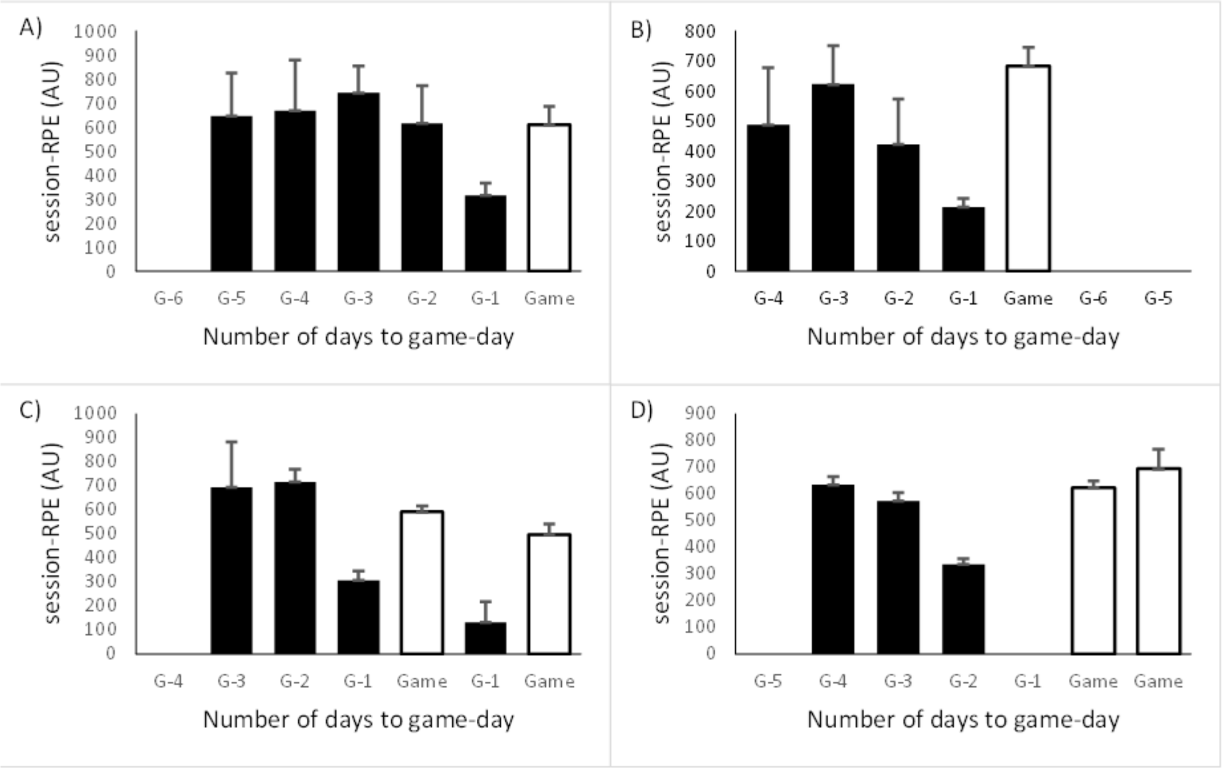


Figure 3.2 Session-RPE for four different weekly periodised training weeks during a season in professional basketball. Session-RPE = session-rating of perceived exertion; G- = gameday minus number of days; AU = arbitrary units.

Four weekly periodised training formats took place during the season which are presented in Figure 3.2. Daily session-RPE followed similar patterns across all four types of training week formats whereby higher session-RPE's were evident in the days positioned furthest away from the game and progressively reduced until gameday, with G-1 exhibiting the lowest session-RPE.

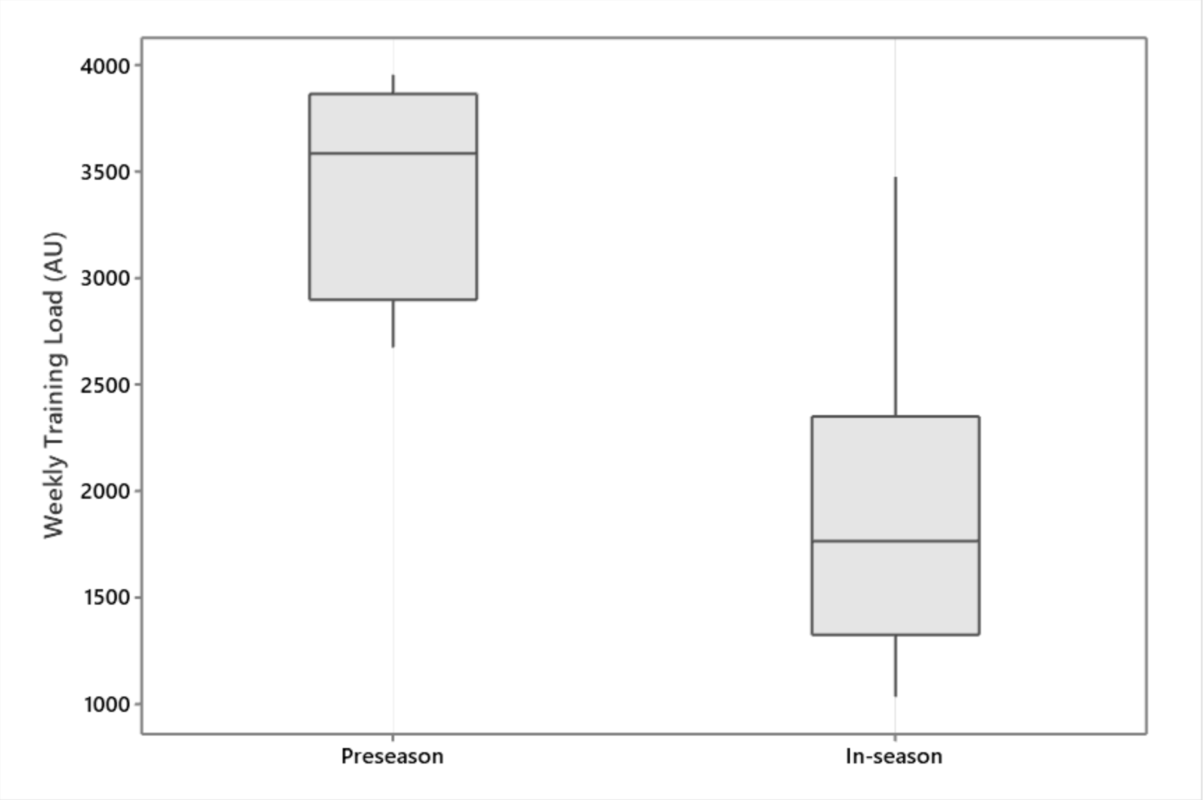


Figure 3.3 Boxplot comparing Weekly Training Load (sRPE x min; AU) between preseason and in-season phases during a basketball season (training, only). Lower and upper box boundaries 25th and 75th percentiles, respectively, black line inside the box marks the median, lower and upper error lines represent the 10th and 90th percentiles, respectively. AU = arbitrary units.

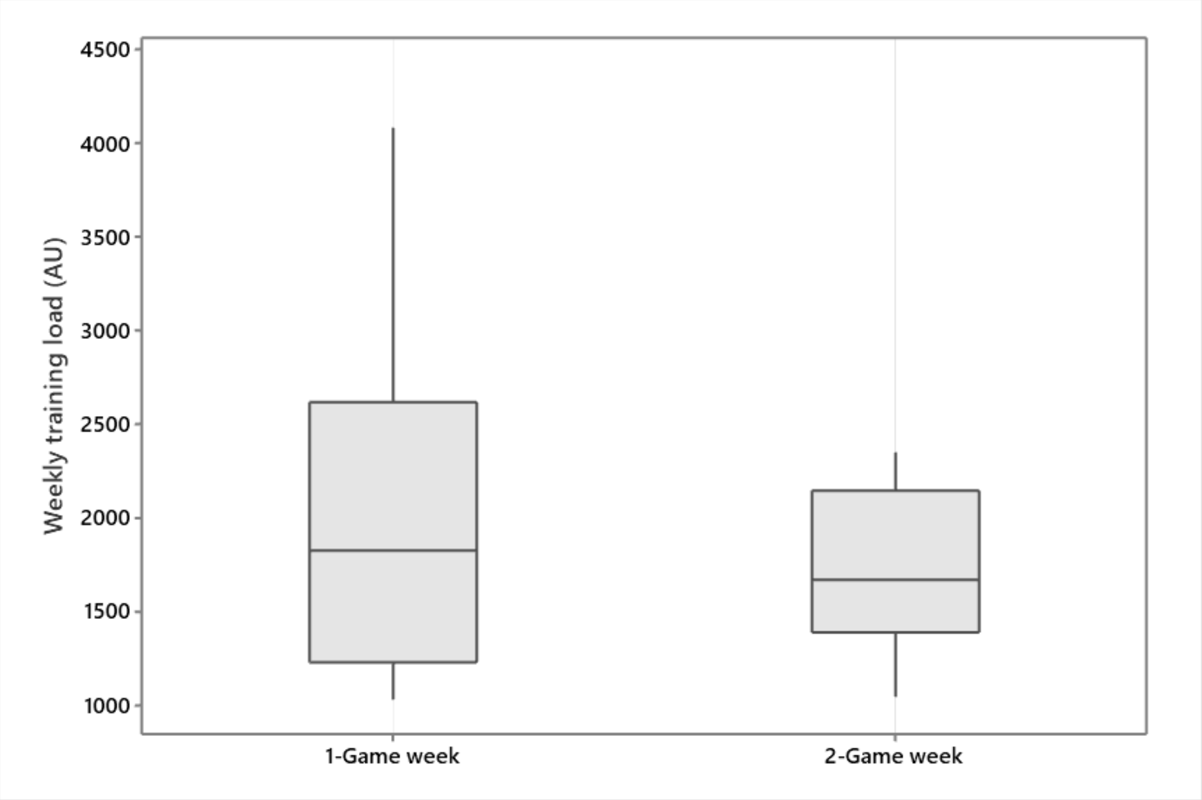


Figure 3.4 Boxplot comparing Weekly Training Load (sRPE x min; AU) between weeks including 1-game versus weeks including 2-games during a basketball season (training, only). Lower and upper box boundaries 25th and 75th percentiles, respectively, black line inside the box marks the median, lower and upper error lines represent the 10th and 90th percentiles, respectively. AU = arbitrary units.

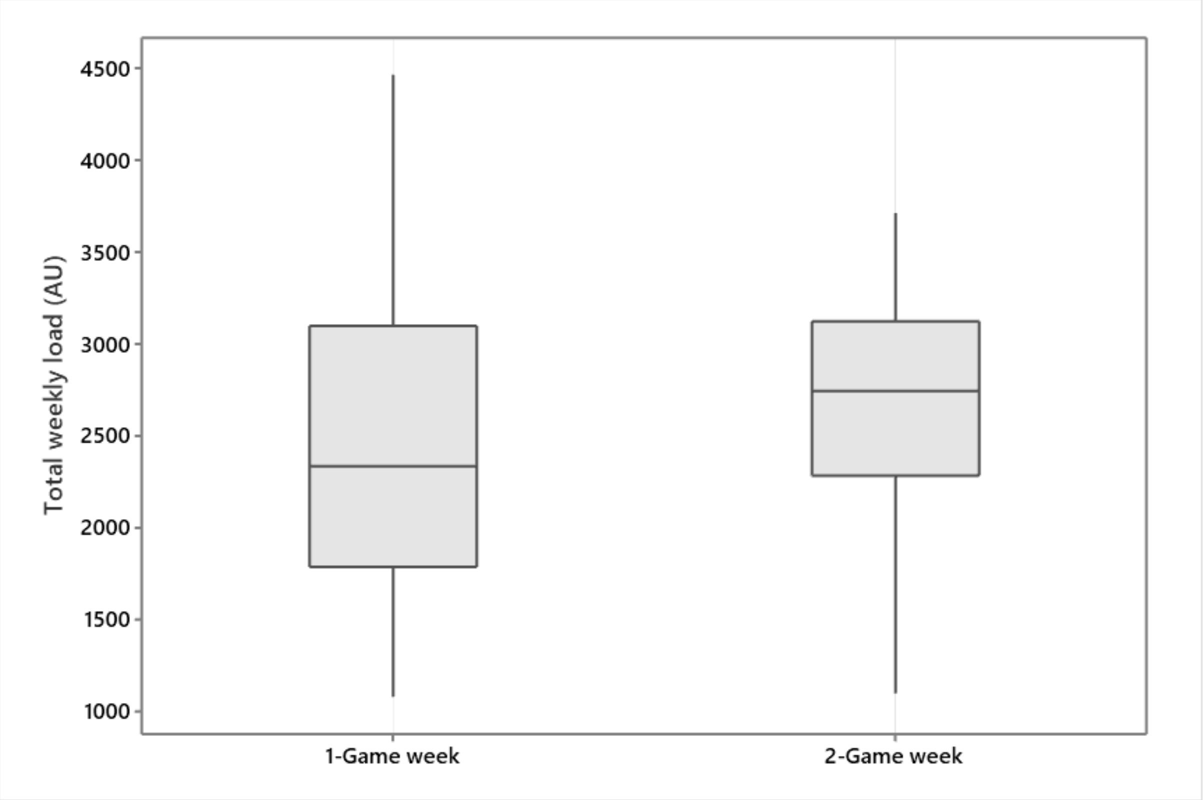


Figure 3.5 Boxplot comparing Total Weekly Load (sRPE x min; AU) between weeks including 1-game versus weeks including 2-games during a basketball season (training and competition). Lower and upper box boundaries 25th and 75th percentiles, respectively, black line inside the box marks the median, lower and upper error lines represent the 10th and 90th percentiles, respectively. AU = arbitrary units.

Weekly Training Load and Total Weekly Load differences for 1-game and 2-game weeks between starting and bench players are depicted in Figure 3.7 and Figure 3.8. Differences in Weekly Training Load were *unclear* between starting players for 1-game week compared to bench players for 1-game week, and *unclear* between bench players for 2-game week and bench players for 1-game week. Starting players for 2-game week yielded a *likely* lower Weekly Training Load compared to bench players for 1-game week. Moreover, Weekly Training Load was *likely* lower in bench players and *very likely* lower in starting players during 2-game week compared to starting players during 1-game weeks, while differences between bench players in 2-game weeks compared to starting players in 1-game weeks were *unclear*. Additionally, *unclear* differences in Weekly Training Load were apparent between starting and bench players during 2-game weeks. A higher Total Weekly Training Load was *likely* and *very likely* different to starting players' Total Weekly Load for 1-game and 2-game week compared to bench players in 1-game week.

However, *unclear* differences were evident in Total Weekly Load for bench players in 2-game week compared to bench players in 1-game week. Finally, starting players generated a higher Total Weekly Load (*very likely)* during 2-game weeks compared to bench players in 2-game weeks.

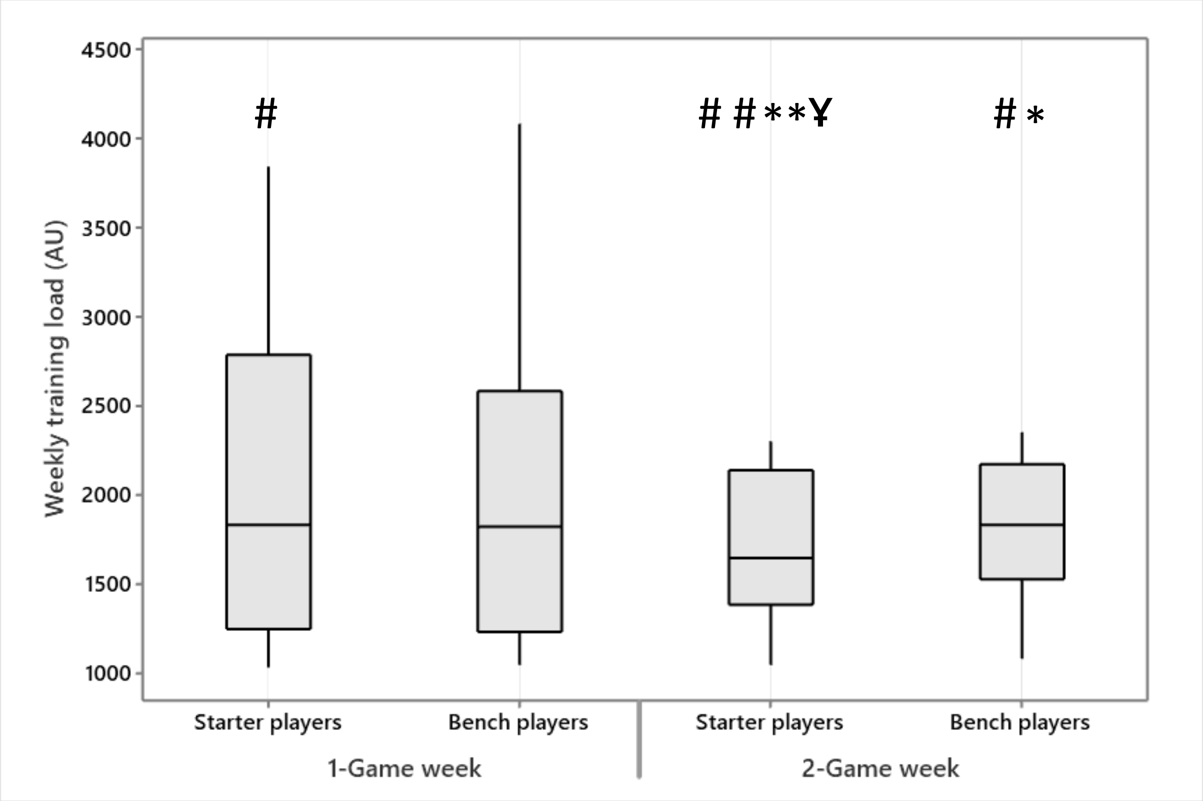


Figure 3.6 Boxplot comparing Weekly Training Load (training, only) between bench and starter players across 1-game and 2-game weeks. Lower and upper box boundaries 25th and 75th percentiles, respectively, black line inside the box marks the median, lower and upper error lines represent the 10th and 90th percentiles, respectively. AU = arbitrary units. Note: # *unclear* and ## *likely* different to 1-game week in bench players; * *likely* and ** *very likely* different to 1-game week in starting players; ¥ *unclear* difference to 2-game week in bench players.

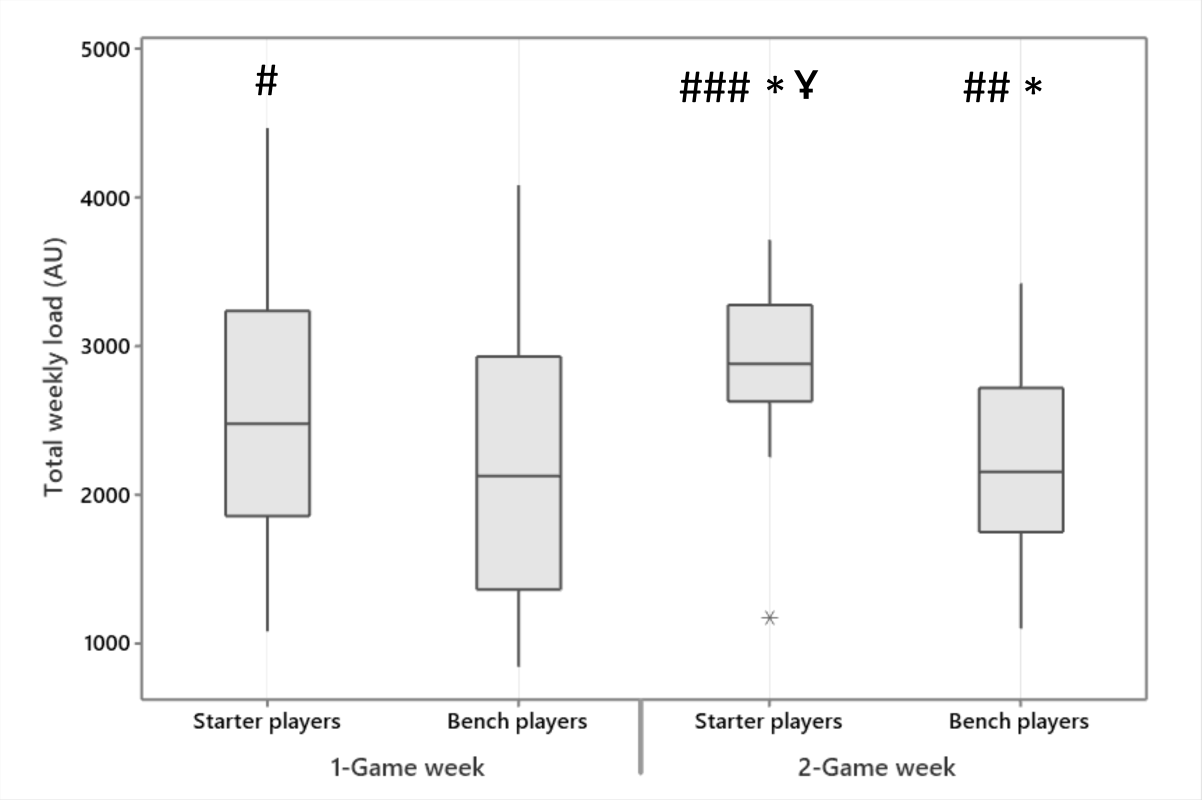


Figure 3.7 Boxplot comparing Total Weekly Load (training and games) between bench and starter players across 1-game and 2-game weeks. Lower and upper box boundaries 25th and 75th percentiles, respectively, black line inside the box marks the median, lower and upper error lines represent the 10th and 90th percentiles, respectively. AU = arbitrary units. Note: # *likely* and ## *unclear and* ### *very likely* different to 1-game week in bench players; * *likely* different to 1-game week in starting players; ¥ *very likely* different to 2-game week in bench players.

Table 3.2 Descriptive analysis for internal load variables between preseason and in-season phases, starting players and bench players, and 1-game and 2-game weeks in professional, male basketball.

Variable	Games per week	Mean ± SD	Mean Difference (90% CI)	ES (90% CI)	Magnitude-based inference
Weekly Training Load	Preseason	3488 ± 545	1577 (944, 2207)	2.26 (1.15, 3.37)	Most likely large
	In-season	1872 ± 691			
Weekly Training Load	Start player	1868 ± 686	11 (-194, 215)	-0.02 (-0.31, 0.28)	Unclear
	Bench player	1879 ± 721			
Total Weekly Load	Start player	2564 ± 792	-424 (-652, -195)	0.56 (-0.25, 0.87)	Very likely moderate
	Bench player	2140 ± 809			
Weekly Training Load	1-game	2024 ± 812	286 (113, 459)	0.38 (-0.50, 1.27)	Very likely small
	2-game	1738 ± 391			
Total Weekly Load	1-game	2458 ± 844	-226 (-435, -18)	-0.27 (-1.15, 0.60)	Possibly small
	2-game	2684 ± 634			

*SD = standard deviation; 90% CI = 90% confidence intervals.

3.5 Discussion

This study investigated Weekly Training Load (training, only) and total Weekly Training Load (training and games) according to phase of season (preseason and in-season), playing status (starter and bench players), and weekly game schedule (1-game and 2-game weeks) in professional male basketball players. The main findings indicate: 1) Weekly Training Load fluctuates week-to-week during a season; 2) preseason Weekly Training Load is higher in preseason compared to the in-season phase; 3) starting players exhibit higher total Weekly Training Load than bench players; 4) Weekly Training Load was higher in 1-game weeks compared to 2-game weeks, while Total Weekly Load was higher in 2-game game weeks compared to 1-game weeks.

Weekly fluctuations

Most professional basketball organisations employ a variety of training load monitoring techniques, with the objective to mitigate fatigue, reduce the likelihood of soft tissue injury, and provide appropriate training stimuli to induce sport-specific physiological responses. Ultimately, enhancing gameplay performance may be a positive consequence to effective training load monitoring (Manzi *et al.*, 2010; Scanlan, Wen, Tucker and Dalbo, 2014; Aoki *et al.*, 2017; Fox, Scanlan and Stanton, 2017). Weekly Training Load and Total Weekly Load in the present study fluctuates week-to-week with the greatest increase at week fifteen by 232% and 283%, respectively. It must be brought to the reader's attention that week fourteen includes the absence of one full training session due to an insubstantial training venue. Coaching staff included an additional training session in week fifteen to make up for the lost practice. This likely contributes to the spike in Weekly Load and Total Weekly Load observed in week fifteen. We would recommend coaches avoid similar periodisation concepts, as this could negatively impact performance and increase fatigue. Conte *et al.* (2017) found similar week-to-week variations in training loads, with the greatest spike at 226%, nevertheless this study was conducted in NCAA D1 basketball players making it difficult to draw comparisons. Anderson et al. (2003) found a positive moderate relationship ($p = 0.01$; $r = 0.68$) between training load increases and injury occurrence in NCAA DIII female basketball players. They state that injuries were more common following breaks from training, such as at the start of the season and after mid-term exam periods and when training load was variation was greatest. To the best of our knowledge no peer reviewed data exists on the relationship between weekly variations in training loads and injury in professional male basketball.

Nevertheless, previous research suggests that Weekly Training Load variation is best maintained between 5-10% to help reduce the likelihood of soft tissue injury (Gabett, 2016). Much of this research is based on previous findings from sports such as Australian football and rugby (Piggott, Newton and Mcguigan, 2009; Cross *et al.*, 2016). Based on research concluded from other sports, a Weekly Training Load variation of 232% could increase the likelihood of injury. It is therefore recommended that basketball coaches monitor and periodise training load according to recommendations (Gabbett, 2016) to reduce such spikes in load.

A study by Weiss, (2017) investigates the use of the Acute:Chronic Workload Ratio (ACWR) in a professional male basketball season. The ACWR is essentially a rolling average of the previous 4-weeks of training load compared to the current week. They indicate that injury incidence is related to very low (<1) and very high (>1.5) ACWR. They establish a “sweet spot” for the ACWR to be between 1-1.5 for reducing the occurrence of soft tissue injury. Unfortunately, this study did not include the ACWR, but is recommended in future to help compare findings based on training load and injury relationships in professional male basketball.

As anticipated, preseason Weekly Training Load was higher than in-season Weekly Training Load which coincides with research conducted by Aoki *et al.* (2017) in professional male basketball players of the Italian Serie A league. This study reported a decrease of 1616 AU, while Aoki *et al.* (2017) reports a difference of 1867 AU between preseason and in-season phases. However, while this study reports the overall Weekly Training Load average of the in-season phase, Aoki only reports 5-weeks in-season, thus caution should be taken when comparing differences. Previous research in team sports indicate that the increased training volume for preseason training accounts for much of the higher training loads experienced by players compared to the in-season phase (Aoki *et al.*, 2017; Ferioli *et al.*, 2018b; Botonis *et al.*, 2019; Coppalle *et al.*, 2019). This approach is naturally adopted by coaches to increase tactical and technical elements of the game, as well as enhancing physiological parameters to prepare the players for the in-season physical demands. Moreover, the large Weekly Training Load standard deviation shown in the in-season phase (Figure 3.3), exemplifies good practice of undulating loads during practice by the coach. Therefore, the strain and monotony of training is likely within normal limits. An important confounding factor that merits consideration is the reduced fitness levels of players during the pre-season phase. It is common for players to take a break during the off-season before commencing their preseason training. As the session-RPE serves as a psycho-physiological indicator of load and has been acknowledged as a measure of fatigue rather than just load, it is plausible that the diminished fitness of players, coupled with an increased state of pain experienced during the accumulation phase, is likely to be reflected in the session-RPE method.

Weekly training periodisation

Comparing the Weekly Training Load between the two different training schedules (1-game versus 2-game weeks) showed that despite the number of games played each week a small difference (*very likely*) was detected between the two weekly profiles, with lower loads experienced during 2-game weeks compared to 1-game weeks. These findings confer with previous research in professional male basketball, whereby Manzi *et al.* (2010) demonstrates a higher Weekly Training Load in 1-game week compared to 2-game week (2436 ± 233 vs. 1722 ± 229, p = 0.001). One less training session per week during several of the 2-game week training schedules likely contributes to the difference found in this study. Conte *et al.* (2018) found similar results in NCAA Division I players, indicating 1-game weeks inflicts approximately 224 AU greater Weekly Training Load (*most likely*) compared to 2-game weeks.

Total Weekly Load (training and games) between 1-game and 2-game weeks exhibited only a small (*possibly*) difference, whereby 1-game week (2458 ± 844 AU) was lower compared to 2-game weeks (2684 ± 634 AU). Comparable findings between Total Weekly Load in 1-game week versus 2-game weeks are reported by Manzi *et al.* (2010) who reports similar differences yet reports no significant differences between the 1-game and 2-game weeks (2928 ± 303 vs. 2791 ± 239, p>0.05 AU). On the other hand, Clemente *et al.* (2019) found regular weeks which include 1-game had moderately greater (yet not significant) session-RPEs than congested weeks, which include at least 2-games (p = 0.201; d = 2.15, moderate effect). They report that the tapering phases before matches may have resulted in a decreased Total Weekly Load, and as such congested weeks which include two tapering phases likely contributes to a lower Total Weekly Load (Clemente *et al.*, 2019). Nevertheless, Clemente *et al.* (2019) only investigates the individual session-RPEs between the two weekly game schedules (1-game versus 2-game), and fails to include the accumulative Total Weekly Load, which makes it difficult to compare. In this study, like Manzi *et al.* (2010), a lower Weekly Training Load (training, only) was found in 2-game weeks, yet unlike Manzi *et al.* (2010) vice versa was found for Total Weekly Load (training and games), whereby 2-game Total Weekly Load was greater 1-game Total Weekly Load. This highlights effective training load periodisation strategies naturally adopted by coaches to prevent spikes in load which might predispose athletes to a greater risk of soft tissue injury (Drew and Finch, 2016). Thus, coaches must account for training schedules which include two or more games per week when prescribing basketball training. Furthermore, a difference of 226 AU between 1-game and 2-game weeks in this study is likely trivial in terms of real-world implications for the players during a basketball season as this would be classified as a relatively small sRPE load.

To add, throughout the season, the coach employed four distinct periodised training formats on a weekly basis, as illustrated in Figure 3.2. It's important to note that statistical analysis was not applied to the weekly formats, but rather, they serve to provide a general visual representation of the coach's common approach to periodising training around the 1-game and 2-game weekly schedules. Subsequent research efforts might find value in investigating the effects of inter-session loads. However, the primary aim of this study was to examine trends in weekly loads over the course of the season.

Playing status

As bench players and starting players participated in the same basketball training sessions in the present study, it is no surprise that Weekly Training Load is similar between bench and starting players, where *unclear* differences were shown. However, as starting players have more game time involvement, this explains the greater Total Weekly Loads compared to bench players (*very likely moderate*). To the researcher’s knowledge, this study is the first to examine playing status and weekly training and competition loads in professional, male basketball. These findings corroborate with Conte *et al.* (2018) who found starting players Total Weekly Load is greater than bench players which is attributed to greater playing duration in games. However, as their cohort is NCAA D1 players, considerations should be taken when drawing comparisons.

A noteworthy finding is the greater loads observed for Weekly Training Load (*likely*) and Total Weekly Load (*very likely*) in starting players during 2-game week compared to bench players in 1-game week. Given the different weekly game schedules recur weekly or bi-weekly depending on fixtures during a basketball season, coaches should consider other metabolic conditioning protocols to supplement the missing game time for bench players, and ensure they are ready for gameplay. Small-sided games (SSG) as a training method has been shown to be effective for enhancing technical and physical qualities, implying gameplay contributes, similarly (Delextrat and Martinez, 2014; Delextrat, Gruet and Bieuzen, 2018). In fact, Gonzalez *et al.* (2013) demonstrates that during a season, starters are more likely to increase vertical jump power and reaction time speed compared to bench players, which is attributed to the increased playing time. Moreover, Gonzalez et al. (2013)highlights how starters are very likely to maintain positive subjective markers of energy and appear possible that they are more alert and less fatigued than bench players. Thus, there are key psychological and physiological considerations for coaches when managing player game time during a season.

3.6 Limitations

While the RPE and session-RPE methods are valid and inexpensive measures for assessing player internal load, one limitation surrounding the RPE method is the inability to discriminate the physiological load from the psychological elements. Therefore, it has been recommended that coaches and researchers combine the RPE with other physiological parameters to help distinguish between afferent and efferent sensory feedback mechanisms (Haddad *et al.*, 2017). Thus, objectively assessing internal load via another means, such as heart rate or muscle feedback could help coaches interrogate specific parts of training or gameplay, especially in rolling sub sports like basketball and hockey where relative intensity would be of interest, whereby the RPE method would be impractical to use during gameplay.

Another key factor to take into account is the limited sample size in this study, which necessitated the use of Hedges g to address potential bias estimates of effect size associated with small sample sizes (Brydges, 2019). It is worth noting that a larger sample of players would likely enhance the statistical power of the study. Given that a typical roster size in professional basketball ranges from 12 to 15 players, it is crucial to consider longer study durations to ensure the attainment of robust and reliable findings. In this particular study, three players were excluded due to injury and being cut from the initial squad. To bolster the sample size, it may be advantageous to consider a study that recruits multiple teams from the same league, thereby encompassing a broader range of players and increasing generalisability. This would offer a more comprehensive perspective and enhance our confidence in the reported results. One such study which incorporated multiple basketball teams in the same league for studying player internal loads was by Paulauskas *et al.* (2019). We recommend future studies to address the issue of sample sizes in basketball and follow similar protocols as Paulauskas *et al.* (2019) if other teams conform to sharing team data.

Lastly, while this is one of the first studies to investigate player internal load across both preseason and in-season phases of a professional basketball team in the BBL, the research period of this study was cut-off prior to the play-off phase of the season. The play-off period is regarded as the most intense phase of the season and is particularly a competition dense period where teams play at least two games every week. In future, studies which compare weekly load and Total Weekly Load between in-season and play-off phases could give coaches an understanding of how players may perceive the load during these different phases and provide insights into the different periodisation strategies adopted by coaches during these periods which is important for managing player fatigue.

3.7 Conclusion

The present results suggest that preseason training load is higher than in-season training load in professional male basketball players, likely because of increased training volume compared to the in-season phase. It appears that Total Weekly Load is greater during 2-game weeks compared to 1-game weeks, and in starting players compared to bench players. Coaches should consider periodisation training load appropriately based on playing status (starting players versus bench players) and weekly game schedules. It is recommended for future studies to include additional external and/or internal load monitoring approaches.

Chapter 4 Introduction to Surface-Electromyography

Recently, Surface-Electromyography, abbreviated as 'sEMG', has been shown as a potential method for monitoring exercise intensity. The development of wearable sEMG permits capturing the collective electrical signal from specific muscles during muscular contraction, which is controlled by the central nervous system. Companies, such as Myontec™ and Athos™ commercialise their wearable sEMG systems for monitoring athlete's internal load responses during their respective sport, yet little research exists surrounding their use in sport and the internal Training Load metrics upon which they report. Chapter four provides a brief account of the origins of sEMG, the development of wearable surface-electromyography and textile electrodes, concepts ins data acquisition and processing and presents Athos's wearable sEMG system as a potential tool for objectively capturing an athlete's internal Training Load.

4.1 Brief history of sEMG

The study of animal electricity captivated the minds of researchers dating back as far as 1666, when Francesco Redi a Tuscan physician, and his associate Stefano Lorenzini, were the first to dissect a Torpedo electric Ray fish and identify the electric organ of the fish as a specialised muscle (de Micheli-Serra, Iturralde-Torres and Izaguirre-Ávila, 2012). Investigations into the relationship between animal electricity and muscular movement continued for years. Between 1772 and 1775, John Walsh crucially demonstrated that Eel fish’s muscle tissue could generate a spark of electricity (Piccolino and Bresadola, 2002). Later, in 1792 Luigi Galvani who is considered one of the most illustrious Bolognese scientists in the field of electrophysiology published an article "De Viribus Electricitatis in Motu Musculari Commentarius" which shows that electricity can incite muscular contractions (Reaz, Hussain and Mohd-Yasin, 2006). Sixty years later, Dubois-Raymond, a German physiologist, learned that electrical activity could be recorded during voluntary muscle contraction, and thus he is coined as the founder of modern electrophysiology. Nevertheless, it was not until 1890 when Étienne-Jules Marey was the first scientist who recorded electrical activity from muscle contraction and termed it “Electromyography”. Marey is regarded the father of EMG (Kazamel and Warren, 2017). In 1917, Pratt F.H highlighted that the magnitude of a muscular contraction was a result of the recruitment of individual muscle fibres as opposed to the size of the neural impulse.

In 1922, Gaser and Erlanger won the Nobel prize for Medicine or Physiology in 1944 for their research for inventing a triode vacuum tube amplifier to be used with a cathode ray oscilloscope for the recording of the electrical signals from muscle. Advances in the electrodes and electronics for recordings over the next couple of decades lead to research by Hardyck and Colleagues in 1966, who were the first researchers to use sEMG for recording muscle activation from the vocal tract during sub-vocalisation which occurs when reading silently. Thereafter, practitioners began to use sEMG for the study of muscle function and sEMG started to be used in clinical settings for the treatment of emotional and functional disorders. Early in the 1980’s, Cram and Steger used sEMG to investigate participants sitting and standing postures, identifying muscle asymmetry and site of muscle activity (Cram and Steger, 1983). During the 1980’s the first modular digital EMG systems were introduced, moving away from analog EMG systems and manual analyses on paper. This development in equipment enabled the uptake of more research conducted on the field of electrophysiology. Since 1993, computer technology software and hardware elements predominate in EMG systems for the recording and analysing of EMG assessments. Developments in sEMG acquisition are forever emerging and in the 21st century textile sEMG electrodes, created and integrated into clothing, are also known as wearable sEMG. Such a wireless system permits use out-with a clinical or lab-based setting and would seem ideal for live sports-based applications. Nowadays, sEMG is widely used for superficial skeletal muscles, whereas intramuscular EMG through use of disposable concentric needle or fine wire electrodes is primarily used for deeper muscle.

4.2 Physiology of EMG signal

EMG measures electrical activity during skeletal muscle contraction which is neurological activated (Reaz, Hussain and Mohd-Yasin, 2006). Thus, it is important to understand the neuromuscular system and the physiological pathways which regulate muscular contraction to use EMG. Starting from a higher order perspective, the main function of the primary motor cortex, situated within the frontal lobe of the brain, is to generate signals to direct muscular movement of the body (Luppino and Rizzolatti, 2000). In brief, axons of pyramidal cells, the main output cells of the motor cortex carry action potentials via upper alpha motor neurones which connect to lower motor neurones in the spinal cord via the corticospinal tract(Porter and Lemon, 1995). The alpha motor neurons located in the spinal cord are responsible for encoding the force contraction of groups of muscle fibres (Porter and Lemon, 1995). This is achieved through orderly recruitment of motor neurons, starting with the recruitment of the smallest motor units. The Henneman's size principle states that as more force is required, motor units are recruited in order corresponding to the magnitude of their force output, from the smallest to largest units based on load of the task, thus exhibiting task-appropriate recruitment (Henneman *et al.*, 1974; Heckman and Enoka, 2012). Movements of the face, neck and face are initiated by cranial nerve nuclei by transfer of pyramidal neurons which carry motor information through the corticobulbar tract located at the base of the brain stem (Felten, O'Banion and Maida, 2016).

The combination of an alpha motor neuron and the muscle fibres in which it innervates by the neuron's axon terminals is known as a motor unit (Heckman and Enoka, 2012). The motor unit is regarded the smallest functional unit of the neuromuscular system. When the propagating action potentials reach the muscle fibre, it activates the contractile proteins resulting in muscular contraction (Heckman and Enoka, 2012). The force of a muscle contraction is controlled by the number of activated motor units recruited to carry out a given task. In a sport context, performing a back squat for 1-reptition, only, with a light load would require low level force output and thus slow-twitch, fatigue resistant muscle fibre recruitment. However, a 1-reptitition back squat with a high load which inflicts high resistance, involves fast twitch fibre, which are less fatigue-resistant, are recruited to achieve the force output required to lift the load. Yet, this muscle fibre recruitment pattern depends on whether task failure is the objective (Schoenfeld *et al.*, 2014; Morton *et al.*, 2019). Larger alpha motor neurons typically innervate larger muscle fibres that generate greater forces.

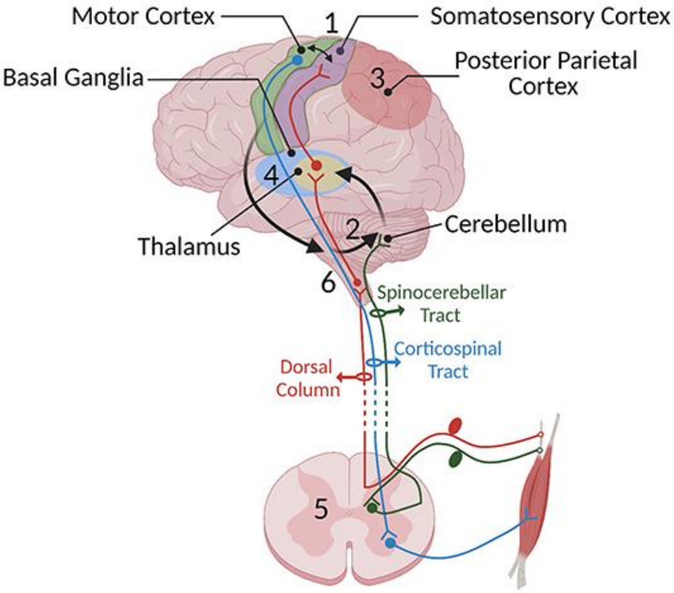


Figure 4.1 Hierarchical pathway for muscle activation dictated by the central nervous system. Reproduced from Asan, McIntosh, and Carmel. (2021).

The neuromuscular junction is the site for the transmission of action potential from nerve to muscle. Here, the neurotransmitter, acetylcholine (ACh), binds to ACh receptors on the surface of a muscle fibre sarcolemma (Kuo and Ehrlich, 2015). The stimulus from the neuron causes a wave of positive charge to reach voltage-gated sodium channels which causes them to open. Positively charged Na ions influx through their associated channels into the cell following the electrochemical gradient (Clausen, 2003). This process is referred to as the depolarization of the sarcolemma. Once a particular threshold voltage is reached, it generates an action potential. Once the inside of the membrane reaches its maximum positive charge the channels close, while simultaneously the voltage-gated potassium (K^+) ions open, causing an efflux of K^+ ions into the extracellular space to restores negative charge inside the muscle cell, maintaining resting membrane potential (Clausen, 2003).

The propagation of the action potential causes a rise in levels of calcium in the cytosol, this stimulates L-type calcium channels (also known as dihydropyridine receptors). In skeletal muscle, these are mechanically coupled to the scaroplasmic reticulum Ryanodine receptors (RyRs) and open them directly (Kuo and Ehrlich, 2015). In cardiac muscle, calcium influx through the L-type channels opens RyRs via calcium-induced calcium release (CICR). Calcium binds to troponin on the myosin filaments which results in cross bridge cycling until contraction is complete (Kuo and Ehrlich, 2015).

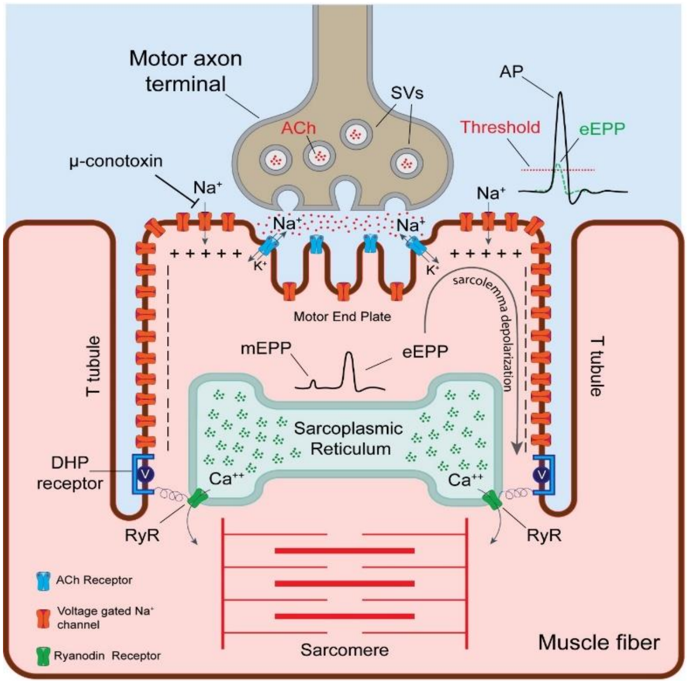


Figure 4.2 Neuromuscular and cellular mechanisms of muscle fibre contraction. Reproduced with permission from Zanetti *et al*. (2018).

The central nervous system (CNS) controls the force produced by a muscle via two distinctive recruitment processes: (i) temporal recruitment and (ii) spatial recruitment (Claudel *et al.*, 2018). Temporal motor unit recruitment is the rate coding process which manages the frequency of activation of muscle fibre contractions (McCarthy *et al.*, 2014). The twitches of a muscle fibre can fuse temporally when successive stimulation of the motor unit occurs from the alpha motor neuron. This results in a greater force through the same amount of motor units than singular muscle contractions by reducing the time between intervals of stimulation (McCarthy *et al.*, 2014). On the other hand, spatial recruitment refers to the activation of more motor units to result in a greater generating force output. Combined, larger motor units' contract in unison with smaller motor units until maximum force production is achieved by activation of all muscle fibres in a single muscle (Purves *et al.*, 2001; Claudel *et al.*, 2018).

The depolarisation of contraction of muscle fibres generates an electric field near each muscle fibre which can be measured in volts (Reaz, Hussain and Mohd-Yasin, 2006). Using EMG, the muscle response to neural stimulation, or electric signal can be measured to assess the muscle activation patterns and strategies during voluntary muscular contraction (Ivanenko, Poppele and Lacquaniti, 2004). Signals measured during a short time interval through EMG represents the train of motor unit action potentials (MUAP). The MUAP is the combination of the depolarisation wave that brings about muscular contraction and the following repolarisation wave (Rodríguez-Carreño *et al.*, 2012). Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) recommends an inter electrode distance of 20mm, which is defined as the centre-to-centre distance between 2 bipolar electrodes on the surface area pick-up of the muscle where the main source of the electrical current is generated (Hermens *et al.*, 2000).

Several spatial and temporal features are typically analysed when interpreting the EMG signal (Rodríguez-Carreño *et al.*, 2012; Baslo, 2017). The EMG signal measures and records the sum myoelectrical activity for the duration of an event. Spatial features include amplitude of the MUAP, and frequency of the MUAP waveform, while temporal features include timing (duration of firing and firing rate) (Rodríguez-Carreño *et al.*, 2012; Baslo, 2017).

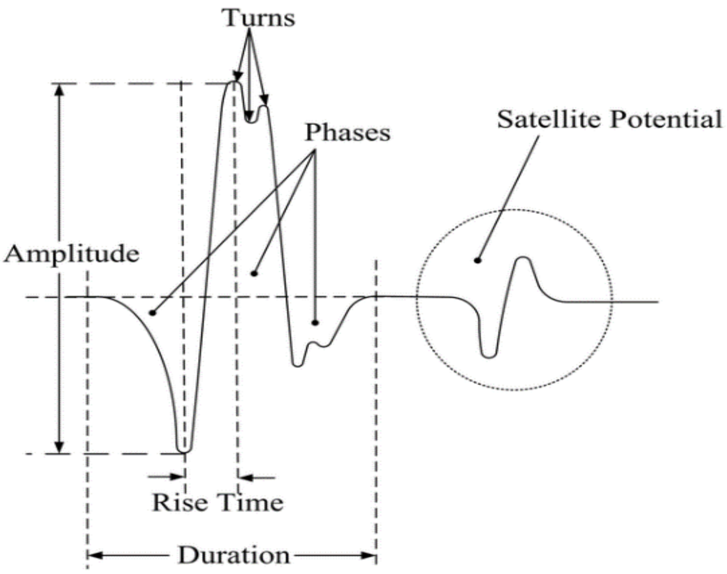


Figure 4.3 EMG characteristics which are assessed in a motor unit action potential (MUAP). Duration = milliseconds; Amplitude = millivolts. Reproduced with permission from Goker. (2014).

4.3 EMG and sEMG comparison

For the monitoring and study of electrical activity in muscles, EMG and sEMG are two frequently used techniques. In order to perform intramuscular EMG, fine wire electrodes (diameter of 50µm or less) are inserted into the muscles themselves (Hermens *et al.*, 2000). This allows for the detailed recording of the electrical impulses produced by muscular contractions. Intramuscular EMG is an invasive (and often painful) method which offers a more accurate and precise evaluation of the activity of specific deep muscle fibres which sEMG cannot detect. Intramuscular EMG is also used to study electrical activity for muscles which have a relatively small cross-sectional area, whereas sEMG is known to provide a global measure of the electrical activity from the superficial muscles under the skins surface (de Luca, 1997). However, due to the relatively large pick-up area (zone) of surface electrodes, unwanted electrical activity can be recorded from neighbouring muscles, known as muscle cross-talk. One of the primary advantages of intramuscular EMG over sEMG is its ability to minimise muscle cross-talk. Nevertheless, while some studies have recently shown sEMG sensors to detect muscular electrical activity of similar levels to fine wire EMG during static and dynamic movements (de Luca, 1997).

The choice between intramuscular EMG and sEMG largely depends on the specific clinical context and the information required. Intramuscular EMG is best used for studies needing high spatial and temporal resolution, and is more appropriate for diagnosing neuromuscular disorders which entails research at the motor unit level, such as myopathies (Merletti and Parker, 2004). However, intramuscular EMG may not be practicable or ethically acceptable for some applications, particularly in research requiring long-term monitoring, due to its intrusive nature. In addition, the insertion of the electrodes requires specialised expertise, and the insertion process is more time-consuming than that of sEMG electrodes. Therefore, the use of sEMG in sport and exercise science is generally the preferred method, especially as understanding agonist and antagonistic muscle activation patterns, fatigue, and performance of muscle, are common objective (Merletti and Parker, 2004). For example, sEMG is used in rehabilitation settings to evaluate superficial hamstrings muscle function and to direct appropriate therapies (Clarys *et al.*, 2010; de Luca, 1997). Researchers can examine the effectiveness of training regimens, evaluate the muscle activation patterns of athletes, and pinpoint potential injury risk factors.

In practical contexts, there is an evident lack of expertise and confidence when it comes to data decomposition and interpreting results for both intramuscular EMG and sEMG. From the perspective of clinicians, there's a clear lack of confidence in using the technologies due to their limited exposure to it and potentially limited mathematical foundation through educational and professional curricula. A group of thirty-five EMG experts from various educational, professional, and geographical backgrounds supported the clinical utility of sEMG for optimising the quantification of muscle and physical function and to define intervention plans (Manca *et al.*, 2020). However, the collective opinion of these experts also confirmed that the use of sEMG was more common in technical/methodological research than in clinical research (Manca *et al.*, 2020). The barriers that hinder the swift implementation of sEMG into practice were reported to be the slow dissemination of research findings and a lack of education on sEMG (Manca *et al.*, 2020), which likely contribute to differing interpretations of findings.

Unfortunately, there is not a single internationally recognised "gold standard" data processing method for both intramuscular EMG and sEMG that is applicable to all situations. While SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) provides guidelines, the appropriate data processing techniques depend on the specific research or clinical goals, which is why the literature reports many different data processing techniques. Nonetheless, established and commonly used methods for processing both types of EMG signals exist. This challenge pertains to both intramuscular EMG and sEMG domains.

The precise research goals and limitations of the investigation will determine which type of EMG or sEMG to use. When precise knowledge of the activity of particular muscle fibres is required, such as when examining the neuromuscular control mechanisms underpinning certain movements or examining the patterns of muscle activation in response to specific stimuli, EMG is preferred (Hermens *et al.*, 2000). On the other hand, sEMG is helpful in situations when non-invasive measures are required, such as extensive investigations with a diverse participant pool or long-term monitoring of muscle activity in naturalistic settings.

In conclusion, EMG and sEMG are two distinct methods of measuring muscle electrical activity. Each method has its own benefits and uses. EMG offers a more precise analysis at the level of individual muscle fibres, however, its invasive nature limits its applicability. sEMG, on the other hand, provides a non-invasive method of measurement, which is more accessible and can be used for a wider variety of purposes. Both methods provide valuable insights in areas such as rehabilitation and sport science.

4.4 sEMG Electrodes

Signals are either detected intramuscularly through fine wire or needle electrodes, or through non-invasive surface electrodes (Reaz, Hussain and Mohd-Yasin, 2006). As previously stated, intramuscular electrodes which penetrate the skin can detect and report a higher quality signal responses of muscle contraction compared to surface electrodes, the latter is usually the preferred method used by practitioners due to the non-intrusive approach (Tuïrker *et al.*, 2013). Surface electrodes are placed and fixed on the skin over the target muscle of interest. There are two types of electrodes: dry and gelled surface electrodes (Merletti *et al.*, 2009). Dry sEMG electrodes are applied directly to the skin. Bar electrodes and array electrodes are common examples of dry electrodes (Merletti *et al.*, 2009). Whereas gelled sEMG electrodes are sponge saturated with an electrolyte gel to enhance conductivity so that current flow into the electrode (Merletti *et al.*, 2009).

The materials which are used to create surface electrodes are gold and solid silver, sintered silver and silver chloride (most common electrode), carbon, mercury and platinum (Jamal, 2012). Surface electrodes are generally used for the study of superficial muscle only and have a larger pick-up area compared to intramuscular electrodes, and thus are non-selective (Benhamou, Revel and Vallee, 1995). However, they pick up mass activity form large proportions of muscle and often from more than one muscle depending on the location of electrodes and area being recorded (Reaz, Hussain and Mohd-Yasin, 2006). Albeit some limitations arise from surface electrodes when measures activation of muscle (please see section 4.4 *physiological influences on the sEMG signal*). sEMG in wearable systems enhance repeatable and unassisted user experience which is always desirable.

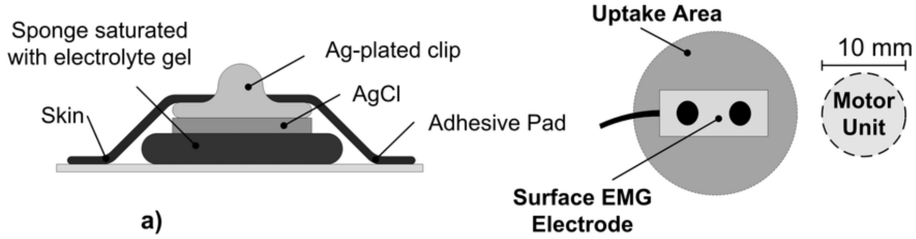


Figure 4.4 Schematic representation of surface EMG electrodes. Reproduced and adapted with permission from Goker (2014).

4.4.1 Textile technologies for sEMG electrodes

Wearable sEMG sensors are often referred to as “textile electrodes” or “textile sEMG electrodes” within the literature and are considered a special application of conductive textiles (Tseghai *et al.*, 2020). The fabricated textile electrode is manufactured through a variety of techniques, exemplified in Figure 4.5. The creation of textile technologies for EMG recording relies on the stable integration of conductive materials into the clothing fabric. Conductive materials, such as conductive polymers, metallic nanoparticles, and carbonaceous materials are explored for textile electrodes. Intertwining conductive yarn with original fabric material by way of embroidery, knitting or weaving is one method of creating textile electrodes for sEMG recordings. However, knitting, weaving and embroidery are costly methods, and are disadvantaged due to the complex fabrication processes involved. On the other hand, the conductive materials can be applied to the original textile using various manufacturing techniques which are more appropriate for mass scaling such as, chemical polymerisation, dip coating, printing methods, physical vapor deposition and electroplating. Advantages and disadvantages of each manufacturing method are presented in table 4.1.

Figure 4.5 Most common methods used in manufacturing electroconductive textiles: Coating and Printing methods, knitting, weaving and embroidery. Reproduced from Angelucci et al. (2021).

Table 4.1 Advantages and disadvantages of textile manufacturing techniques for wearable sEMG systems.

Technique	Advantages	Disadvantages
Knitting	skin comfort; low weight; high elasticity	complex manufacturing process; limitations in the choice of fabrics; damaging of the natural properties of textiles
Weaving	long-lasting fabrics; less likely to shrink when washing; less likely to lose colour	
Embroidery	possibility to lay the base material in all directions rather than in pre-defined ones (enhanced skin-electrode contact)	
Coating	good conductivity; maintenance of the original fibre properties such as density, flexibility, and handiness; resistant to corrosion	high production cost; difficult to scale production
Printing	reduction in production cost; possibility of a large-scale production	durability of printed patterns; optimal performance achieved only with smooth and flat surfaces

Note: Reproduced from Smart Textiles and Sensorized Garments for Physiological Monitoring: A Review of Available Solutions and Techniques. Reproduced from Angelucci et al. (2021).

For companies which integrate textile electrodes into clothing, there are two key considerations based on conductive materials and scalability of the product. Product durability and ability to resist the washing process while still maintaining conductivity widens the usability of the product amongst different populations. This is especially true for athletic use, where the wearer may be exercising at high-intensities and thus perspiring. Frequent washing would be expected if used in the world of sport or exercise. In addition, cheap production costs are important to improve scalability. Currently conductive polymers, such as PEDOT/PSS [Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate)] are active materials which are directly screen printed, inkjet printed, or dip-coated on textile to produce wearable sEMG electrodes. These methods are cheaper than knitting, weaving and embroidery techniques.

In sport, the most advantageous method for textile electrodes is likely screen printing. Smooth surfaces where a conductive polymer can be screen printed on enhances athlete comfortability as well as providing a sweat wicking material, like nylon. The mass scale production, and ability to print onto comfortable textiles to use in sport makes this the preferred method by companies such as Athos™ and Strive™. In sport, conductive materials which are embroidered into the fabric may fray easily or damage the natural material and thus reduce durability of the product.

Textile electrodes for sEMG recordings are becoming more widely used by practitioners in the health and wellbeing field (Tikkanen., *et al* 2013). However, a limited number of companies commercialise their products for use of athlete load monitoring in sport such as Athos™, Myontec™ and Strive™. While the wearable sEMG electrodes imbedded in garments have been validated against standard grade sEMG technologies, little research to date investigates the use of this technique in the field of sport as well as to investigate their load metrics.

4.5 Factors affecting sEMG signal

All electrical activity is recorded by the electrode within their defined pickup zone. Researchers ought to consider several factors which negatively affect sEMG data output. Thus, interpretation of results should be taken with care and appropriate data processing techniques should be applied to the raw signal. Normal sEMG signal amplitude ranges between 0-10 mV (+5 to -5) before amplification. Electrical noise is often detected in the sEMG signal because of several reasons outlined by Raez Hussian and Mohd-Yasin (2006) which are categorised and detailed in Table 4.2.

Table 4.2 Factors which affect the sEMG signal.

Type of electrical noise	**Source**
Inherent electrical noise	Electronic equipment
Ambient electrical noise	Ambient electromagnetic radiation detected on the skin surface
Motion artefacts	Surface electrode interface Surface electrode cable
Inherent instability of signal	sEMG amplitude response is random, firing rate of motor units at rest is unwanted signal (noise)
Direct factors affecting EMG signal	**Source**
Extrinsic	Surface electrode structure and placement, such as location, shape, orientation, and area of detection surface
Intrinsic	Physiological, biochemical, and anatomical factors, such as muscle fibre type diameter and composition, motor unit size and blood flow
Intermediate factors	Physical and physiological factors influenced by causative factors, such as signal cross talk and conduction velocity of MUAP
Deterministic factors	Aspects influenced by intermediate factors such as amplitude, motor firing rate and number of active motor units

Adapted from: Reaz, Hussain and Mohd-Yasin (2006) and Williams (2015).

It is a combination of the mechanisms illustrated in the table above which influence the magnitude of electrical noise ultimately impacting the quality of sEMG signals. While not all electrical noise can be eliminated, most of it can be eliminated or reduced by considering important pre data collection processes which are discussed in sections 4.6 and 4.7.

4.6 Physiological influences on the sEMG signal

A limiting factor when interpreting sEMG recordings is signal crosstalk generated by a neighbouring muscle, an unwanted or interfering signal. Crosstalk occurs because of overlapping action potentials from multiple muscles or motor units detected within an electrode’s pickup zone (Winter, 2009; Farina *et al.*, 2002). In addition, a main causal factor of crosstalk is due to non-propagating signal components due to loss of the intracellular action potentials at the tendons. Crosstalk is known to increase with increasing subcutaneous adipose tissue thickness. Subcutaneous adipose tissue increases the distance between electrode and signal, acting as a spatial low pass filter effect which dampens the amplitude of the surface EMG signal and causing the action potentials to appear more similar at each electrode (Kuiken, Lowery and Stoykov, 2003; Scheeren *et al.*, 2017). These effects can be partly reduced by using high pass spatial filters (Farina and Rainoldi, 1999). If the electrode is positioned between muscles or at the edge of a muscle, crosstalk from other muscles is likely to increase, resulting in a disturbed signal.

In addition, the magnitude of noise detected in the signal typically outside signal bandwidth of between 50 and 500 Hz, reduces the biopotential recordings as a result of friction or movement artefact between the electrolyte-skin interface, known as the signal-noise ratio (SNR). In addition, thermal noise can be detected from the electrode impedance. The impedance is a measure of the ability of the skin-electrode interface circuit to resist the flow of charge across the interface. The balance in impedance between electrode sites, and thus position must be kept stable with the skin to reduce this problem and attain a high SNR. By controlling for appropriate surface electrode placement can augment clean data collection from the muscle of interest while limit sEMG crosstalk (Basmajian and de Luca, 1985; de Luca *et al.*, 2010). Guidelines for human experimental designs using sEMG can be found in the SENIAM guidelines (Konrad, 2005).

There other factors can impact the sEMG signal, for instance, cold muscle temperatures can depress the excitability of muscle fibre which results in a slower contraction speed, comprising lower spectral frequencies. On the other hand, warmer muscle fibre temperature can increase the contraction velocity. Another factor is where increasing muscle lengths associate with decreased EMG frequency, while shorter fibres produce higher spectral frequency. Lastly, the depth of the dermal layers can influence the representing sEMG signal, whereby the deeper the layers, like subcutaneous adipose tissue the greater the dampening effect of the signal, thus sEMG is more biased toward superficial muscles. Therefore, intramuscular EMG is better suited for investigating deeper muscles and MUAPs.

4.7 Pre-data collection processes

As mentioned in the sections above, normal sEMG signal amplitude ranges between 0-10 mV (+5 to -5) before amplification. It is important for the sEMG to reduce the magnitude of noise for the best representation of the MUAPs. Prior to data collection keys areas to consider for optimising the signal quality are amplification, input impedance, frequency response and common mode rejection.

Amplification optimises the resolution of the signal in digital form. Peak to peak sEMG signals typically range from 0 to 6mV, thus, to maximise the signal to noise ratio of the sEMG signal, amplifiers require adjustable gains of between 100 to 10 000 (Ahmad, Ansari and Dhanbad, 2012). Amplified gain represents the amount of amplification, representing the ratio of the output voltage to the input voltage, applied to the signal to produce output amplitude of 1 volt (Winter 2009; Rash, 1999). It is vital that pre-amplifiers entail a high input impedance to prevent attenuation of the EMG signal, larger than impedance at the skin. With adequate skin preparation, input impedance of <1kΩ are required (Kamen and Gabriel, 2009). However, investigations which do not require skin preparation the input impedance should increase considerably to >1mΩ to achieve an appropriate signal to noise ratio (Kamen and Gabriel, 2009).

sEMG recordings are usually performed at a set maximum frequency response of 500 Hz and sampled at 1000 Hz to include all possible physiological MUAP amplitudes of the electrical signals detected. Humans conduct electromagnetic radiation which can be detected as unwanted electrical signal, as well as detecting signals from neighbouring muscles in the sEMG output. Through differential amplification, which subtracts the potential at one surface electrode from that at the other surface electrode, and then amplifies the difference. The common mode of rejection ratio represents the differential amplification and provides an index to what extent should these extraneous sources from the functional EMG signal be attenuated from the signal. Therefore, it is advantageous to have the highest common mode rejection possible.

4.8 Signal processing

Raw sEMG essential provides information to the user in a useless format. The raw signal is detected and displayed in a sinewave containing both positive and negative values. To extract useful information, the signal must be quantified which is achieved through several processing techniques.

Studies use different processing techniques to achieve specific information from their sEMG data. As such, there is no gold standard approach when processing the data (Kamen and Gabriel, 2009; Winter, 2009). Indeed, depending on the type of investigation into the electrical activity of the muscle, for example, general muscle activation patterns versus signal decomposition to single MUAPs might influence the researchers' choices when processing data. Williams, (2015) states three common applications of sEMG:

1) to establish the muscle recruitment patterns, plus onset and offset timing evaluation of the muscle, determining the mean MUAP, or comparing MUAP for specific events

2) to estimate the force generated by the muscle which is approximately proportional to amplitude of the sEMG signal

3) to study muscle fatigue through investigation of the frequency components, such as mean or median frequency over time.

To quantify meaningful sEMG data from the original raw signal which only provides information based whether the muscle is on/off, several data processing steps are taken to provide additional information based on signal amplitude and frequency characteristics which include the application of filters, half or full wave rectification, application of a linear envelope and low pass filter or alternatively the root mean square (RMS). In addition, integrated EMG of the rectified signal (area under the curve), which is simplified as the summation of the absolute values of the EMG amplitude is often used as a pre activation index for muscle activity.

The circuitry implemented to the raw signal following preamplification is discussed in the following sub-sections.

4.8.1 Filtering

As previously discussed, the sEMG recording is hampered by noise, thus the analog EMG signal must be filtered following differential amplification. To remove unwanted frequencies e.g., sensor drift, cable noise or cellular phone interference in the contaminated sEMG signal, low and high-band pass filters are used to attenuate these frequencies which reduces the possibility of misinterpretation of results. Filters include the Butterworth, Kalman, Chebyshev and Fourier series. Band-pass filters use upper and lower frequency cut offs (f_c) to eliminate noise while increase active frequency domain in the raw sEMG signal. Filter equations like that of the classical Butterworth filter are often recursive. Signals become out of phase because of delays in timing between two sinusoids of the same frequency which creates a phase-lag. To remove phase-lag, the filters are applied in both forward and reverse directions.

Typically, filters include brick wall responses to cutoff frequencies. Common values for a low frequency cutoff (f_c) are 5 to 20Hz. Frequencies less than f_c are transmitted and if above they are attenuated to zero (Figure 4.6). Whereas in a high pass filter, all frequencies below f_c are attenuated to zero while pass high-frequency signals from the signal, which prevents aliasing from arising in the sampled signal. Typical values for high pass filters are 200 Hz – 1 kHz. There are a variety of recommendations in the literature depending on cutoff frequencies, for example, SENIAM recommends for surface EMG high pass with 10-20 Hz cutoff and lowpass “near 500 Hz” cutoff, whereas ISEK recommends high pass with 5 Hz cut off and low pass with 500 Hz cutoff. Where amplitude signal response is ‘1’ refers to the ‘passband’ region of a filter, where the frequency range is transmitted. On the other hand, the frequency range is attenuated where the filter response amplitude is ‘0’ and is referred as the ‘stop band’ region of the filter. Figure 4.6 illustrates both low pass and high pass filter response.

A high pass filter, which is a first order high pass filter is the simplest in nature. Filters are defined by their order (first, second, third-order, etc) and the frequency they passed through. Filter orders explain the relative steepness (known as the roll-off) of the filters transition zone. Higher order filters are more complex and yield narrower transition zones. A filter’s stop band will not remove all frequencies within its range, thus specifying and applying appropriate fc to establish boundaries for the pass-band and stop-band regions is necessary. For every increase in order (first, to second, to third etc) the degree of attenuation doubles. Every first order filter starts with a 20 dB/decade roll-off, which reduces the signal amplitude a 10th for each decade increase in frequency. Each increase in order, the degree of attenuation doubles, thus a second order filter attenuates high frequencies at -40dB/decade, which is steeper than the first. Therefore, as the filter order increases a lower fc value is used.

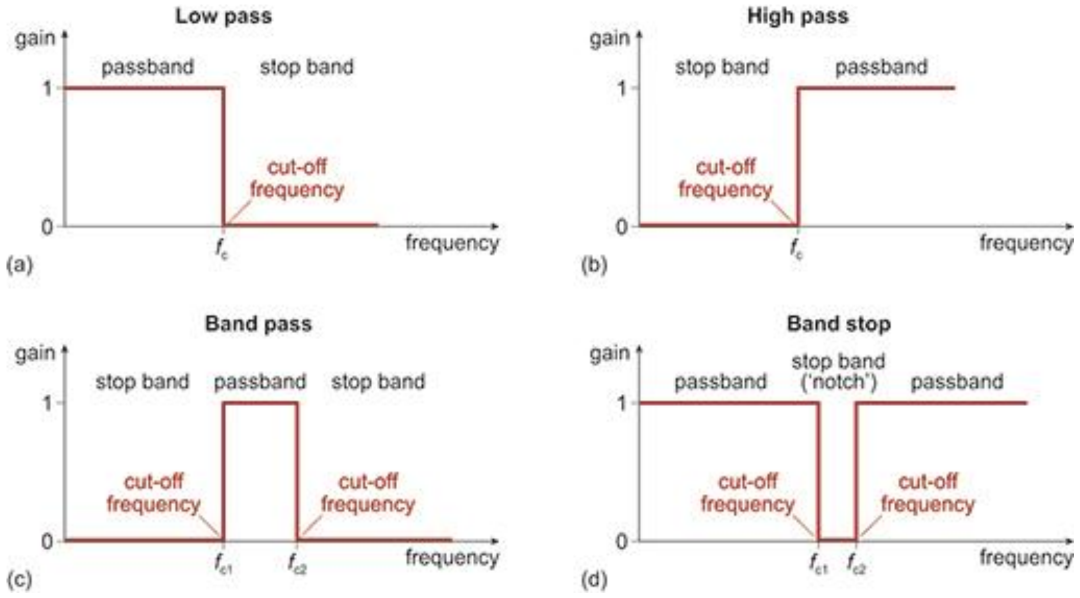


Figure 4.6 Typical filters applied to reduce electrical noise in the raw sEMG signal.

In research which aims to examine locomotion, generally, a Butterworth filter or Root Mean Square (RMS) are most popular for applying a linear envelope. Butterworth loss pass filter is a preferred method as low-pass (zero-lag) filter results in a smooth wave and minimises the ripple in the pass band and rolls off towards zero in the stopband, which explains why they are commonly referred to as a maximally flat magnitude filter.

There is latency response between muscle activity and movement of between 30 – 100ms in duration. This introduces a phase lag in the resultant EMG signal. Thus, choosing filters which do not alter the phase are optimal, especially when assessing the timing of muscle activity and movement. Ideally, a filter integrates a time delay independent to its frequency, where each frequency component is phased in the same manner in the signal output. Thus, the fc is used along with a filter order which controls for this phasing resulting in optimal EMG data for evaluation. The linear envelope process includes passing through the rectified raw EMG signal through a low pass filter such as the Butterworth or Chebyshev, which are known as infinite impulse response filters. By applying theses filter in both forward and reverse directions eliminates the phase lag “zero phase shift”, as a result this process converts the filter to a fourth order filter from second order filters. Following the amplification and filtering of signals, the sEMG signal is rectified using a rectifier module.

4.8.2 Full wave rectification

Rectification is the transformation of the raw sinusoidal wave EMG signal to a positive single polarity signal. There are two types of rectification: full-wave and half-wave rectification. Full-wave rectification is often the preferred method for sEMG analysis as it preserves all electrical activity from muscle contraction. Full-wave rectification adds negative sEMG signal component which is below zero to the positive signal above zero (Figure 4.7). This ensures that the signal does not cross zero and provides an all-positive signal. Alternatively, half-wave rectification removes the sEMG signal below baseline, meaning the average of the data is no longer zero. Rectification of the sEMG signal permits statistical analysis and the study of MUAP signal amplitudes and their duration. Following rectification of the EMG signal, a low pass filter is applied which is important for determining the shape “envelope” of the sEMG signal. Defined as “linear envelope” due to linearity of the mathematical operation related to filtering.

4.8.3 Linear envelope

Finding the linear envelope of the EMG signal is achieved by combining rectification and thereafter applying a low pass filter (fc ~3 to 20Hz) to reduce artefacts. The power density of artefacts is usually below 20 hertz. Linear envelope detection is an applied demodulation method for obtaining valuable information from the waveform of the sEMG signal (Kamen & Gabriel, 2010b). Setting fc to retain 95% of the power density within the movement is recommended to reduce variability in the EMG signal and minimise signal distortion (Shiavi, Frigo and Pedotti, 1998). The linear envelope process, in particular the low-pass filter smooths (rounded edges) the EMG signal, but consequently loses some of the original EMG signal. Linear enveloping is suitable for cyclical motor tasks like running and cycling where obtaining an average of multiple EMG cycles recorded from a particular muscle or group of muscles is desired (Felici, 2006). Thus, the average linear envelope is adopted when examining muscle activation profiles (Frigo and Shiavi, 2005) and identifying the onset and offset of muscular activity.

An alternative approach to obtaining the linear envelope of the EMG signal is by calculating the RMS on a moving window which is measured in volts. Application of a low-pass filter for a given time constant which can range from 24-500 ms. The greater the number of windows (samples) in the signal, the smoother the resultant linear envelope which reduces the amount of original EMG signal. It has been shown that by increasing the time constant of the moving window beyond 25ms bring in detectable delays, thus longer time constants may be used only for study of the mean amplitude (moving weighted average) rather than timing relationships with other events (Merletti *et al.*, 1999). One should not confuse linear enveloping with integrated EMG (iEMG).

4.8.4 Integrated electromyography (iEMG)

iEMG does not entail a low pass filter, but rather the signal is integrated over a given time interval and is referred as the area under the curve, thus it measured in V/s. It can be determined in a variety of ways, such as through mathematical integral of the absolute value of EMG time series, electronically or RMS. iEMG is often used for investigating and quantifying relationships, such as EMG versus force. It is considered the optimal measurement for measuring total muscular efforts during cyclic movements. When the muscle is at rest, the area under the voltage curve decreases and as muscle movement or generated force increases, the area increases (Richards *et al.*, 2008). Computing iEMG can be performed using a simple time integration, integration and reset following a fixed time period, integration and reset following a specific value has been determined from the area under the rectified EMG signal (under the curve).

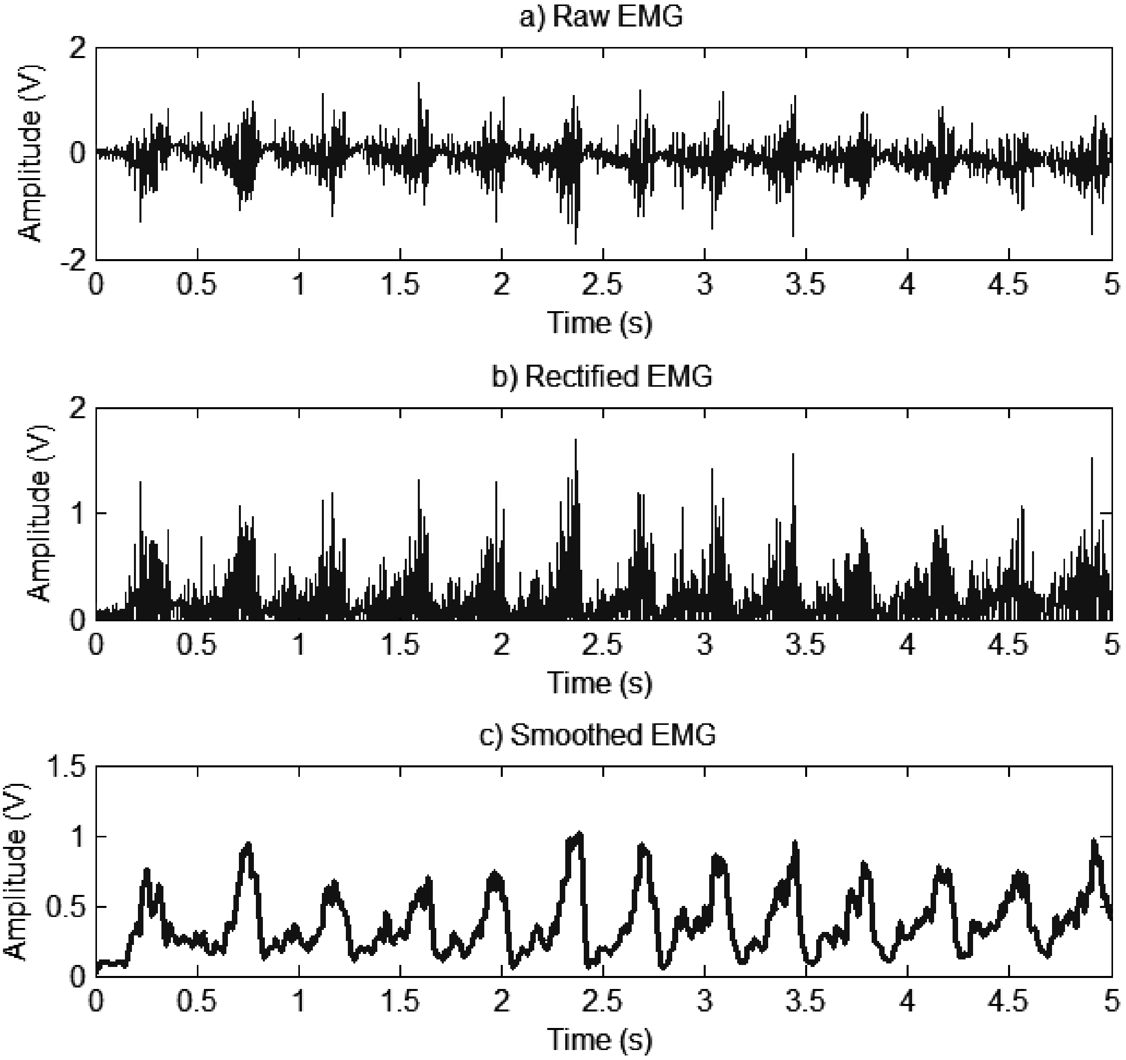


Figure 4.7 Illustration of; a) raw EMG signal to; b) rectified EMG signal. Reproduced from Alvarado et al. (2010).

4.9 Interpreting the processed EMG signal

Interpreting the EMG signal should be preceded with caution as many factors can interrupt or distort the EMG signal which can mislead the researcher during analysis and when stating conclusions. One example is the unsubstantiated claims that researchers make when saying sEMG amplitude is predictive of strength improvements and hypertrophy (Vigotsky *et al.*, 2017). Many sports science methods encompass limitations which are worth considering when using within clinical research. For example, HR electrodes can miss electrical beats by as much as 15%. Nevertheless, most studies warrant HR monitoring in sport as they provide a reasonable method for quantifying athlete's internal and external loads. sEMG has comparable clinical-based drawbacks yet is seen as a valuable tool for gaining insight into the neuromuscular response and for basic scientific work (Vigotsky *et al.*, 2017). While sEMG is used extensively for identifying or studying muscle on/off characteristics, as well as irregular recruitment patterns of muscle excitability in neurogenic and muscle diseases, like neuromyotonia and myopathy, respectively, there is information about muscle patterns and muscle properties which can be extracted from the processed sEMG signal to inform practitioners about the biomechanical response to exercise stimuli.

4.9.1 Interpreting EMG amplitude

EMG amplitude indicators such as RMS, otherwise referred to as the average rectified value (ARV), expressed in microvolts (μV), is calculated over a specified time interval. The RMS amplitude permits interpretation and data analysis of the EMG amplitude. Several scientific relationships and propositions can be derived by practitioners based on EMG amplitude results. In isometric contractions the relationship between force and EMG amplitude is generally linear, or close to linear, which has been exemplified in human knee extensors during isometric leg press exercises (Alkner, Tesch and Berg, 2000). However, linearity between force and EMG amplitude during dynamic movement is less evident, and linearity can also even deviate in isometric contractions depending on muscle type and function and differs according to duration of contraction (Figure 4.9).

In most cases, EMG amplitude indicators increases non-linearly with increases in muscle force output (Guimaraes *et al.*, 1994; Madeleine *et al.*, 2002; Roberts and Gabaldón, 2008; Kuriki *et al.*, 2012). During running, Roberts and Gabaldón (2008) demonstrated a strong positive correlation between force output and mean EMG amplitude (iEMG) recorded from the lateral gastrocnemius during the stance phase. However, they established a very low, and in some cases, absent EMG trace during the swing phase yet a relatively high force output was recorded. They concluded that passive force by the lateral gastrocnemius may result in the relatively high force output and as such, connective tissue components and sarcoplasmic proteins, like titin which acts as a spring-like mechanism obscures the relation between EMG and force production (Roberts and Gabaldón, 2008; Kuriki *et al.*, 2012). In addition, inadequate measurement techniques may also inhibit accurate conclusions of the force-EMG amplitude relationship. Small electrodes cover a tiny proportion of surface area of large muscles, and suboptimal electrode placement on the skin surface might compromise the detection of the greatest source of electrical current from the muscle (de Luca, 1997; Kuriki *et al.*, 2012).

While undoubtedly not absolute, a degree of selective recruitment of muscle fibres appears to occur during specific motor tasks depending on the force required to complete the task (Holt, Wakeling and Biewener, 2014). Oxidative glycolytic (type 2A) and glycolytic (type 2X) fast twitch muscle fibres, which have a larger cross-sectional area than slow oxidative (type 1) fibres, are innervated by larger motor units (i.e. higher threshold), and are recruited when high force output is required. Muscles with a higher proportion of fast twitch fibres usually exhibit greater EMG amplitude (Kupa *et al.*, 1995). Alternatively, type 1 fibres have a greater firing frequency than type 2 fibres, and are innervated by smaller motor units (i.e. lower threshold), which typically exhibit a lower EMG amplitude. However, type 1 fibres can increase their firing rate to equal the force of that by type 2A and 2X fibres to summate in a stronger contraction, which might result in a greater EMG amplitude response during different exercise (DeLuca and Hostage, 2010). Variances in the average EMG amplitude during exercise might be indicative of these selective muscle fibre recruitment patterns (Linssen *et al.*, 1991; de Luca and Hostage, 2010; Holt, Wakeling and Biewener, 2014).

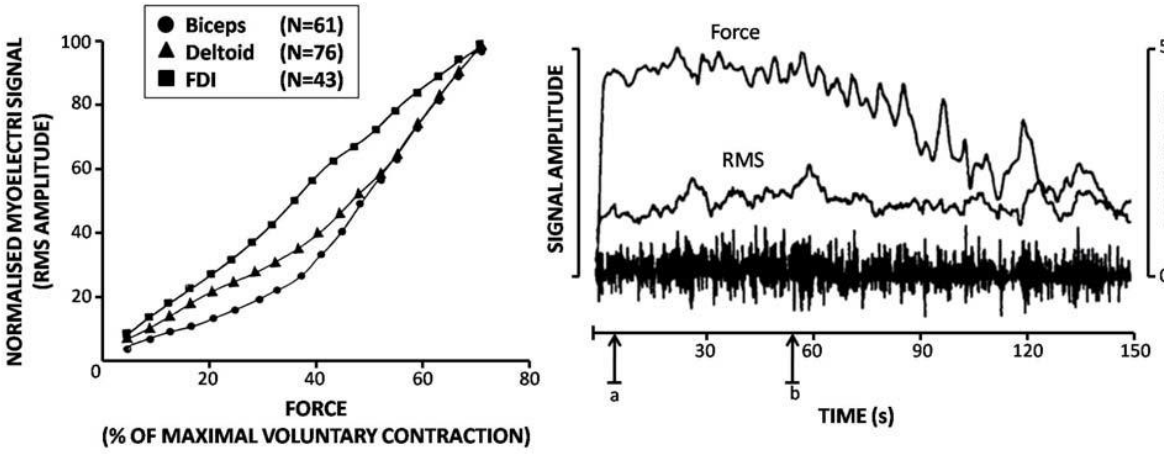


Figure 4.8 Linearity of force/amplitude varies depending on muscle type and function (left); and linearity of the force/EMG relationship can change over time (right). Reproduced from Clarys et al. (2010).

In addition, motor unit synchronisation, which is a measure of the correlated discharge of action potentials by motor units to increase the rate of force during rapid contractions, can increase the observed EMG amplitude. In fact, moderate motor unit synchronisation has shown to increase the EMG amplitude by 60%, whereas a high motor unit synchronisation more than doubled the EMG amplitude (130%) with respect to a no-synchrony conditioning (Yao, Fuglevand and Enoka, 2000).

Moreover, different types of contractions under specific loading conditions can impact the EMG amplitude. It has been shown that isometric muscle contractions, loaded in either concentric or eccentric manners elicit similar EMG amplitude responses as the muscle fibre length remains unchanged (Garner *et al.*, 2008). Although, during dynamic eccentric and concentric muscle contractions the amplitude differs. Isotonic eccentric contractions increase tension experienced in the muscle as it lengthens (Selseth *et al.*, 2000). Alternatively, the tension is reduced as the muscle fibre shortens during isotonic concentric contractions. The greater work which is required by concentric contractions compared to eccentric contractions to meet and overcome the resistance of a load is shown through greater EMG amplitude in the EMG trace(Selseth *et al.*, 2000; Grabiner and Owings, 2002; Garner *et al.*, 2008). Furthermore, muscle contraction speed of voluntary efforts can be reflected in the EMG trace. Typically, the speed of the fastest voluntary effort results in the largest EMG amplitude. Thus, the larger the EMG amplitude detected during specific exercise, the faster the contraction. Alternatively, EMG amplitude is lowest at the slowest speeds (Freund and Büdingen, 1978; Roberts and Gabaldón, 2008).

4.9.2 EMG frequency domain analysis

Through a Fourier transform, the EMG trace can be transformed into sine waves of variable frequencies to assess the contribution which each frequency makes to the raw EMG signal (Reaz, Hussain and Mohd-Yasin, 2006). Often, exercise protocols, such as a constant isometric contraction at a given force threshold, and usually adopted to assess fatigue, is used for obtaining meaningful information through the Fourier transform calculation (Dantas *et al.*, 2010). Squaring the Fourier transforms from each segment of data, and then averaging them, provides the Power Spectral Density (PSD) which characterises the power of each frequency which contributes to the original EMG signal (Stéphane, 2009). These frequency components generally change over time and are studied using spectral analysis. Spectral analysis is an objective method mostly used for the assessment of muscle fatigue (Mills, 1982; Sung, Lammers and Danial, 2009). During the onset of fatigue, there is an apparent shift towards lower mean and median frequencies of the EMG frequency spectrum (Viitasalo and Komi, 1977).

Muscle fatigue is a relatively complex phenomenon which involves both metabolic (peripheral) and central nervous system (central) alterations resulting in less efficient muscle contraction. It has been shown in stroke survivors, that spectral analysis can be used to observe changes in the amplitude and the mean/median frequency of the sEMG signal for providing insight into the relative prevalence of central and peripheral fatigue (McManus *et al.*, 2017). In addition, changes in median frequency of the EMG signal acquired through power spectral analysis, correlates with the relative percentage of muscle fibre type composition in muscle (Sung, Lammers and Danial, 2009; Casabona et al., 2021). Since type 1 muscle fibres are fatigue resistant, shifts in the EMG power spectrum profile toward much lower frequencies have been found during fatiguing exercise, compared to higher frequencies in muscles which are composed of more type 2 muscle fibres (Kupa *et al.*, 1995; Garcia-Retortillo *et al.*, 2020).

Muscle fibre length has also been shown to alter the spectral frequency recorded in the EMG signal, wherein as muscle length increases EMG frequency decreases. On the other hand, shortening of fibres during concentric muscle contractions induce a higher spectral frequency (Kamen and Gabriel, 2010).

4.9.3 EMG Normalisation

Given the many confounding variables which can alter the EMG amplitude and temporal variations in the raw signal, restricts effective interpretation and comparison between different events (Kamen and Gabriel, 2010; Richards, Thewlis and Selfe, 2008). By converting the EMG signal to a relative scale by a reference value from the same muscle, refers to EMG normalisation. This is a key step for interpreting standardised data and to compare individuals, muscles on different days, and EMG activity between muscles (Chalard *et al.*, 2020). While there appears to be no gold standard procedure for EMG normalisation, it is important that the protocol have high repeatability within the same participant in the same session (Halaki *et al.*, 2012). One of the most common approaches is to normalise the EMG envelope during a task to the maximum peak value acquired from the same muscle during an isometric maximum voluntary contraction (MVC) (Yang and Winter, 1984; Burden, 2010). Some studies have used isokinetic MVC normalisation approaches due to values reaching over 100% of their peak isometric contraction. Nevertheless, Halaki and Ginn (2012) have reported that isometric MVC normalisation produces comparable results to isokinetic MVC normalisation, making it the preferred choice for researchers due to the simplistic procedural implications (Burden, 2010). EMG normalisation is important when using sEMG in clinical settings to compare limb and muscle symmetry, and relative activation during different movements.

4.10 Introduction to ®Athos™ sEMG system

Athos™ (MAD, Inc. CA. USA) apparel presents as a potential athlete monitoring system through integration of sEMG into compression garments. sEMG is typically limited to clinical settings, and is an expensive, unportable system. However, recent advancements in sEMG technology, such as wireless hardware increases portability and usability of sEMG in the field of sport. In sport, rehabilitation, and exercise scientific research, sEMG is commonly used to investigate electrical activity of specific muscles during lab-based exercise. Now, with the integration of sEMG into clothing, Athos™, and other companies, like Myontec™ and OMsignal™ purports that their products can capture internal load. To date, there is only one study which reports wearable sEMG internal load during sport (Saucier *et al.*, 2021) and who used Strive™ Sense 3© compression shorts. However, no research has investigated the internal load (referred as "Training Load" in this thesis) metric under controlled exercise conditions. This thesis incorporates Athos's most up to date version of the wearable sEMG technology (compression shorts 2.0). The portable sEMG system for monitoring biometric signals comprises of four parts: compression shorts, Core unit, Athos™ hub and charging dock (Figure 4.10), and Online Training Centre (OTC), which is the online cloud-based platform to present sEMG data to users.

Figure 4.9 Athos™ team charging dock, hub, compression garment (shorts), and Core unit.

4.10.1 sEMG compression shorts

The Athos™ compression shorts 2.0 comprise of a pair of biometric sEMG sensors coupled to the garments fabric which are configured to obtain biometric signals representing the electrical activity of the muscle during locomotion. The shorts are designed with a sweat wicking, breathable material composed of 76% nylon and 24% Lycra spandex which require a cold wash after use and must be air dried to maintain sensor quality. The dry electrodes and electrode leads are composed of an inkjet-printed conductive polymer which comprises of an ether-based conductive thermoplastic polyurethane material. The electrodes are overlaid with a soft conductive silicone which increases the stability of the electrode-skin interface (Figure 4.11). A reference region is located within the electrode region to dissipate noise or static charge from motion artifact, skin-surface interference or any other mechanism resulting in unwanted signal. The reference electrode is equidistant in the pair of electrodes which detects common-mode component of 60Hz noise relative to the user’s skin, which facilitates signal processing. The electrodes are positioned in the shorts across four different regions of the upper leg: quadriceps, glutes, hamstrings, and quadriceps. A mounting module is affixed to the exterior of the shorts right leg, which provides an array of connection regions for communication with the biometric sensors. The mounting module is designed to couple and relay the biometric signals to an Ahos™ Core unit through a set of electrically conductive contacts on the mounting module (Figure 4.11).

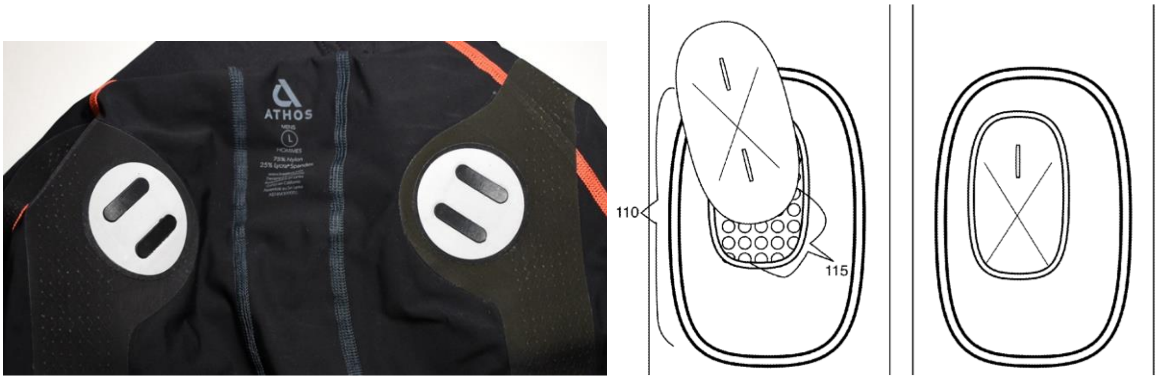


Figure 4.10 a) Athos™ dry electrodes; and b) mounting module for the Core unit and set of contacts.

4.10.2 The Athos™ Core unit

The Athos™ Core unit, a 2.5-inch (6.4-centimeter) long oval plastic unit is composed of a housing, a power source (high power Lithium-Ion battery), signal conditioning module, a set of contacts which are located on the backside and are fabricated with an electrically conductive polymer (Figure 4.12), and an electronics subsystem housed within an internal compartment of the housing of the unit, and which communicates with the set of contacts. The set of contacts are configured to an array of connection regions (Figure 4.12; back view) which enables bioelectrical signal transmission from the sEMG sensors. The electronics subsystem communicates with the set of contacts on the mounting module of the shorts and facilitates electrical signal reception, conditioning, and processing.

The electronics subsystem encompasses a signal conditioning module which conditions and processes the raw electrical signal. The signal conditioning module performs noise reduction processes (low-pass filtering, high-pass filter, band-pass filter, notch filter) and smooths the signal generates linear enveloping, as well as window averaging and computing a rolling RMS value. Furthermore, the signal conditioning module is responsible for amplification and analog to digital conversion of the electrical signal. For more information based on the signal acquisition and processing techniques performed by the conditioning module of the Core unit, please refer to Chapter 5*, Methods; Signal acquisition and processing*. Please note, that although the conditioning module processes the raw sEMG data, the researchers only had access to the processed data, and were not able to manually condition the raw sEMG signal output for study 2 of this thesis. The electronics subsystem stores signal into its memory. In addition, electronics subsystem encompasses a communicator which purpose is to wirelessly transmit processed sEMG data to a processing subsystem (Team hub) through Bluetooth connectivity.

The Core unit also encompasses a tri-axial accelerometer and gyroscope, which is important to determine the Core unit orientation relative to the compression shorts. The Core unit (which has more than one axis of symmetry) is configured to use the set of contacts to establish its orientation. For example, each contact and sEMG electrode is associated with a companion contact and sEMG electrode, which detects a signal differential. Establishing this biopotential signal difference through two paired electrodes is necessary for the electronics subsystem, and signal conditioning module within the Core unit to be able to process raw electrical signals. Ultimately, this permits the determination metrics from muscle activity during exercise.

Noteworthy, the articulated surface of the Core unit comprises of two LED lights which indicate their working status using different colour schemes. For example, a red light indicates the Core unit is low in charge and requires to be charged, while a green light represents the Core unit is fully charged. A blue light is apparent when the Core unit is slotted into the mounting module on the shorts and signifies that electrical data from the user’s muscles is being recorded. A full charge is reported to last approximately ten hours.

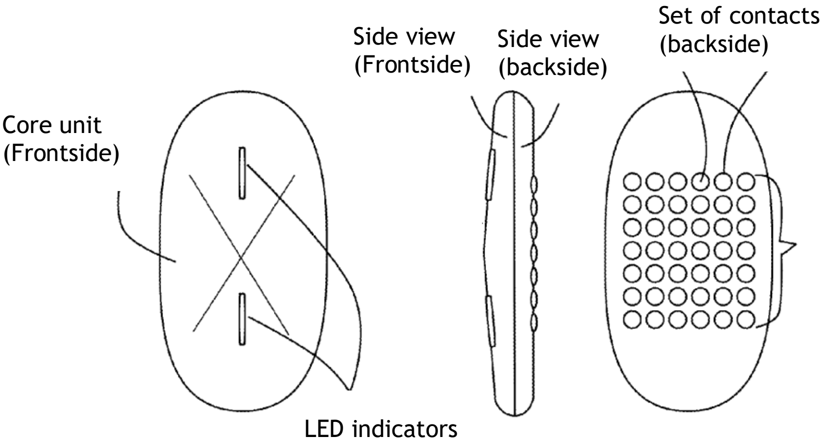


Figure 4.11 Athos™ Core unit and set of contacts on the backside view of the unit.

4.10.3 Data collection process

It is important for the practitioner to adhere to simple procedural guidelines when using the sEMG technology. First, the practitioner must ensure appropriate anthropometric measurements are taken from the athletes to ensure adequate fittings for the shorts. The shorts come in a variety of predetermined sizes (small, medium, large, extra-large etc.), including short and long shorts depending on limb length. Once fittings are established, the athletes are required to wear the shorts, with no underwear, for best electrode-skin contact and to undertake a calibration protocol which involves data normalisation based on peak amplitude of maximum voluntary contraction (MVC). This allows other metrics to be determined, such as Training Load (for more detail, please see *"Athos's Training Load"* subsection below, and Chapter 5; *design and procedures*).

After the calibration protocol, the units are placed into a charging dock (Figure 4.10) which is required to be positioned next (within 20cm) to the Athos™ Hub (approximately 36 cm x 18 cm x 8 cm; weight, approximately 1.4 Kg) for optimum Bluetooth (4.2) frequency range. The Athos™ hub receives the pre-processed data from the electronics subsystem of the Athos™ Core units and is connected to an internet server through Wifi to store and directly upload the data to the OTC to transform the stream of electrical signals into sEMG metrics and biofeedback reports related to exercise behaviour of the athlete or user.

4.11 Validity and reliability of Athos's sEMG sensors

Lynn *et al.* (2018) investigates Athos's sEMG electrodes compared to a research grade sEMG system (Biopac Systems, Inc., Goleta, California) during MVC knee flexion and extension using an isokinetic dynameter at various speeds (60, 180 and 300 degree/sec). Participants performed 7 trials on separate days. Each trial comprised one set of three repetitions at each speed and percent of MVC (%MVC, 50%, 75%, 100%). Measurements were taken from two thigh muscles (vastus medialis and vastus lateralis), and one hamstrings muscle (biceps femoris). Results illustrate strong reliability across trials and speed of contraction for biceps femoris (0.8%), vastus lateralis (7.3%), and vastus medialis (0.2%). In addition, limited variation was established between both systems (Biopac; 10.7%, and Athos; 12%) using the standard deviation of the MVC normalised repetition amplitude. These findings demonstrate strong reliability and validity of the Athos™ sEMG system during the knee flexion and extension exercises.

Snarr *et al.* (2018) investigates the use of sEMG (Athos™ compression shorts) to non-invasively estimate lactate threshold work rate during incremental cycling. Participants wore the Athos™ compression shorts during a maximal cycle test while blood lactate and sEMG (root mean square transformation and averaged at a 10s window) from the vastus lateralis were recorded every minute, as well as HR and $\dot{V}O_2$. EMG threshold and Lactate Threshold were determined through Dmax equations, which defined the point which generated the maximal distance from the lactate and EMG curve. Results show no significant differences between lactate and EMG thresholds relative to work rate, $\%\dot{V}O_{2peak}$ and $\%HR_{max}$. This highlights that EMG and lactate rise similarly, exponentially, as work rate increases. Snarr et al. (2018) provides assumptions to the increase in motor demand as blood lactate concentration rises to maintain force output, exhibiting increased EMG amplitude. They conclude usefulness and viability of the wearable sEMG compression shorts in predicting lactate threshold work rates during cycle ergometry. Importantly, Snarr *et al.* (2018) only investigated the sEMG output from the vastus lateralis, during a semi-static exercise modality. Whereas this thesis (Chapter 5) aimed to interrogate the sEMG Training Load metric which is the sum of activation of all muscles measured by the compression shorts.

Given the limited research available on the Athos's surface electromyography (sEMG) system and its validation compared to traditional sEMG systems during closed chain, isokinetic movements (Lynn *et al.*, 2018), our perspective is that using wearable textile sEMG electrodes for isolated basketball movements, such as jumping or shooting, is likely to provide more reliable assessment of specific muscle groups. However, it is important to acknowledge that sEMG sensors embedded in a garment may experience some movement during high-intensity movements. Therefore, the confidence in using the Athos sEMG shorts for studying specific superficial muscle groups in the context of basketball is low. Some researchers have suggested that sEMG can be a better global measure of muscle activity on the skin's surface, considering the potential factors that can interfere with the signal, a view we concur with. Athos offers a sEMG-derived Training Load metric, which combines electrical activity from multiple muscle groups (please refer to Chapter 4; *Athos's sEMG Training Load*).

While this metric may provide insightful information regarding neuromuscular demands and muscular load to a relatively valid standard during knee extension exercise (Lynn *et al.*, 2018), it is important to note that as the demands of movement increase, factors like motion artifacts and sensor displacement are likely to become more prevalent during open play in basketball. Thus, we believe that the sEMG Training Load may not accurately capture all muscle activity in such dynamic situations. However, it is worth noting that similar validity issues exist with heart rate sensors and GPS measures. For this reason, the current thesis and research questions in this paper will help address some of the limitations and practical implications of using sEMG-derived Training Load in the sport and exercise field.

4.12 Athos's sEMG Training Load

While the Athos™ sEMG system captures a variety of metrics, the current thesis examines the novel aspect of capturing sEMG-based internal load which is measured in arbitrary units, referred to as "Training Load". The sEMG-derived Training Load is objectively measured and categorised as an internal load parameter associated with muscular stress. Most studies use sEMG to examine electrical activity of a specific muscle in response to an exercise stimulus. However, the sEMG Training Load presents as a novel method for measuring the accumulated electrical activity from a group of muscles.

As previously mentioned, each athlete or user performs a calibration protocol, prior to other sEMG metric population by the Athos™ system. The calibration protocol involves a maximum voluntary contraction to obtain peak amplitude of all eight muscle regions in the shorts. Research demonstrates how EMG amplitude can provide a measure of the magnitude of force generated by the muscle, i.e as force increases, sEMG amplitude increases. Albeit, this relationship should be taken with caution as many factors, such as muscle fatigue, muscle fibre composition, muscle contraction type and electrode placement can interfere or disturb this relationship (*Chapter 4; Interpreting EMG amplitude*). Nevertheless, peak EMG amplitude by way of MVC enables normalisation of data relative to the peak amplitude as a reference level. Once the Core unit's electronics subsystem and signal conditioning module completes filtering processes of the raw electrical signal, the data for each muscle group is then normalised to peak amplitude based on a 0-100 scale. The Training Load (AU) is then calculated as the accumulated muscle activity of all muscle groups combined. A single unit (AU) of Training Load corresponds to 100% activation (based on MVC) of a muscle for one second. Figure X, provides a schematic representation of the processes involved for deriving Training Load, starting from the muscle. sEMG Currently, there is little existing research which investigates sEMG-based Training Load in a controlled setting. Chapter 5 aims to address the sensitivity of sEMG-derived Training Load and examine its correlation with oxygen consumption analysis during a $\dot{V}O_{2max}$ test.

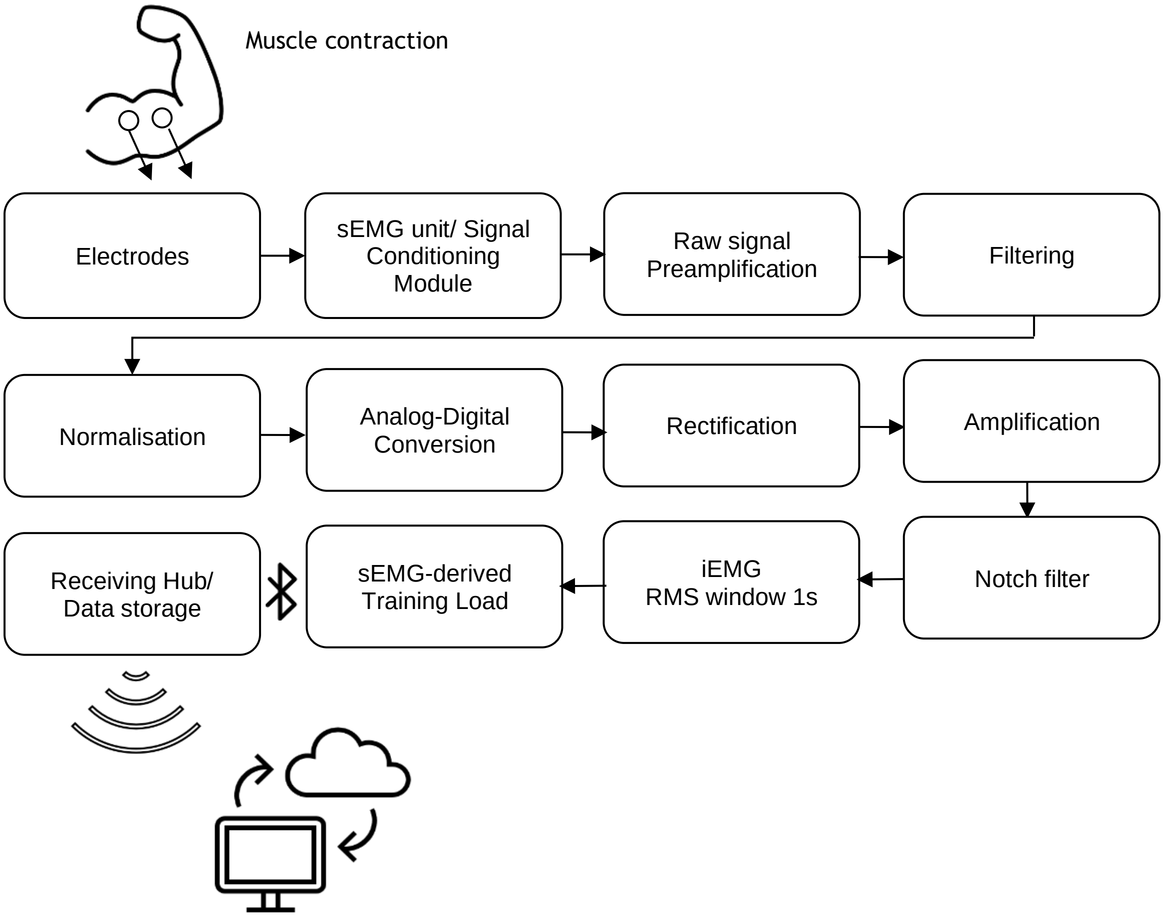


Figure 4.12 Schematic representation of the stages involved in processing the raw sEMG signal to derive Athos's Training Load.

Chapter 5 Study 2 – Differences between a surface electromyography-based compression short internal load and a global positioning systems external load during lab-based exercise protocols – An exploratory study

5.1 Abstract

The Athos™ training system presents as a wearable-technology which integrates surface-electromyography (sEMG) sensors within compression garments, also known as "textile sEMG electrodes", which monitors and provides an internal Training Load metric. Little research exists based on the sEMG-derived Training Load metric during exercise activities using Athos™ sEMG shorts. ***Objectives:*** The purpose of this study was two-fold: 1) to determine the sensitivity of the sEMG Training Load during different running speeds; and 2) to investigate the relationship between sEMG Training Load and accelerometry-based external PlayerLoad™ with oxygen consumption during a standardised treadmill $\dot{V}O_{2max}$ test. ***Methods:*** Ten (n=10) out of an initial twelve (n=12) participants were included in the final analysis (6M, 4F, 24.7±3.4 yrs, height: 174.4±11.3cm, weight: 69.5±10.8kg, body fat: 22.2 ± 8.8 %). Prior to research, participants provided informed consent to participate in the study. Testing was undertaking on two consecutive days. Day one included a 3-Speed Treadmill Test (2-min loads), whereby speeds were categorised into low, moderate, and high. On day two, participants completed a treadmill $\dot{V}O_{2max}$ test which incorporated a 1% gradient increase every minute until participants reached volitional failure. Participants wore sEMG shorts and a Catapult OptimEye X4 unit during all tests. The 3-Speed Test assessed sensitivity of the sEMG Training Load metric by comparing Low-Moderate, Moderate-High and Low-High speed differences via paired T-Tests, while Separate Pearson's product-moment correlations were applied to determine the correlations between sEMG Training Load and accelerometry PlayerLoad™ and $\%\dot{V}O_{2max}$ at the population and individual level. ***Results:*** Analysis of change in sEMG Training Load when grouped as ΔLow-Moderate (meanΔ 49.1 AU, (95% CI = 8.5, 89.8 AU)) and ΔModerate-High (meanΔ

35.6 AU, (95% CI = 18.5, 52.8 AU)) and Δlow-high (mean Δ 84.8 AU, (95% CI = 29.2, 140.3 AU)) speeds during the 3-Speed Test found significant differences ($P < 0.5$), indicating the Athos™ training load metric was sensitive in detecting a work rate difference of at least 2 $km.h^{-1}$. A correlation coefficient ($r = 0.33$) demonstrated a significantly moderate positive relationship between sEMG Training Load and $\%\dot{V}O_{2max}$ ($p < 0.5$) at the population level, and significantly strong relationships for 8 out of 10 participants at the individual level ($r = 0.72 - 0.97$). Whereas the accelerometry PlayerLoad™ was not significantly related to $\%\dot{V}O_{2max}$ at the population level, and only demonstrated significant correlations (one negative) at the individual level in 3 out of 10 participants. ***Conclusions:*** It is shown for the first time that sEMG Training Load is an acceptable tool for measurement of internal Training Load and could be used in conjunction with other player monitoring systems to gain a better understanding of the stresses put on athletes during sport and could potentially be used as a surrogate of oxygen consumption. Higher sEMG Training Load appears to correlate with higher energy expenditure ($\%\dot{V}O_{2max}$). Accelerometry PlayerLoad™ and sEMG Training Load capture different external and internal constructs of load.

5.2 Introduction

Monitoring training load (also known as “load” or “player load”) is often an integral part of the training process in both amateur and professional sport. Data obtained from load monitoring provides insightful information to better understand the physical and psychological stressors imposed on players during training and competition. It is suggested that adequate training load prescription could mitigate the chances of soft tissue injury, reduce illness, and increase game readiness, especially in team sports. For example, in rugby it has been shown that sharp increases in Weekly Training Load by up to 15% of the previous week, increased the likelihood of injury to between 21% and 49% (Drew and Finch, 2016; Gabbett, 2016).

Load is categorised into two theoretical constructs: internal and external load. Internal load provides the athlete's response to a given training stimulus and consists of physiological objective measures such as heart rate (HR) and muscular activity, or psychophysiological subjective measures such as the rating of perceived exertion (RPE) and the session rating of perceived exertion (session-RPE). On the other hand, external load is the physical work completed by the athlete and includes measures such as global positioning systems (GPS), time motion analysis (TMA) and local positioning systems (LPS). Measuring and combining both external and internal loads is known as the dose-response paradigm (McLaren *et al.*, 2018). In essence, training and competition load can help provide scientific explanations for changes in sport performance and thus guide coaches in implementing changes to an athlete's training programme.

While internal and external load monitoring approaches exemplify positive relationships (McLaren *et al.*, 2018), it is recommended that coaches capture a variety of metrics as they are often not interchangeable, for example, the session-RPE method demonstrates strong positive relationships with GPS metrics, such as total distance (r=0.89) and low-intensity distance (r=0.91), but not other GPS metrics such as maximum speed or average speed (Chen, Fan and Moe, 2002). Furthermore, different internal load metrics appear to capture different parameters of player stress. The subjective RPE method has shown weighted mean validity coefficients for assessing exercise intensity of only 0.62 and 0.57 compared to heart rate (HR) and blood lactate, respectively (Chen, Fan and Moe, 2002). Thus, a variety of internal load monitoring approaches are employed in combination with each other to provide deeper insights into the internal load experienced by the athlete (Halson, 2014). Contextual factors such as the upcoming opponent, previous game result (win, loss, and draw) and specific phases of a season (preseason versus in-season) can impact internal loads, especially subjective internal load methods, such as the RPE and session-RPE due to the psychological element it inherits(Barrett, Midgley and Lovell, 2014; Impellizzeri, Marcora and Coutts, 2019; Gonçalves *et al.*, 2020). Thus, other objective internal and external load monitoring approaches are recommended to capture different parameters of the athlete's internal load response.

A novel application of a traditional scientific method which has recently emerged as an internal athlete load monitoring system in sport, is surface-electromyography (sEMG). sEMG is the study of muscle function through the inquiry of the electrical signal the muscles emanate (Basmajian and de Luca, 1985). Conventional methods of applying sEMG are typically restrictive in terms of feasibility and freedom of use during common locomotive activities. The application of individual electrodes to specific areas of the body, and the connection of wires to diagnostic equipment limit its usability because of the restriction to free movement. Now, sEMG sensors are integrated into clothing fabric which poses as a wearable technology, also referred to as “textile sEMG electrodes”, or “textile electrodes" for the detection of sEMG signals during exercise and movement (Colyer and McGuigan, 2018). This offers a convenient solution to using sEMG outside of clinical laboratories and perhaps in the sporting field (Hermann and Senner, 2020). Companies such as Strive™, Athos™ and Myontec™ who offer wearable sEMG solutions purport that their systems capture “training load”, also referred to as “muscle load”. Training load as reported by Athos™ is defined as the sum of muscular activation from all sEMG sensors, divided by a scaling factor. Promising results have been demonstrated using wearable sEMG in a lab-based environment (Finni *et al.*, 2007; Subbu, Weiler and Whyte, 2015; Lynn *et al.*, 2018). However, little research investigates the use and sensitivity of the sEMG-based internal training load metric within dynamic movement activities or sporting environments.

Athos™ compression shorts embed eight sEMG sensors, one on each side of the body for each major muscle group in that area (inner quads, outer quads, hamstrings, and glutes) which eliminates the need for traditional bulky equipment or wires, potentially permitting the use of sEMG in sport. Lynn *et al.* (2018) incorporates an isokinetic dynamometer to assess sEMG output during knee flexion and extension movements at three different speeds and intensities relative to maximum voluntary contraction (MVC) using the Athos™ sEMG system. While the Athos™ sEMG system demonstrates strong validity and reliability compared to a gold standard Biopac system (Lynn *et al.*, 2018), there is a lack of research in dynamic exercise movements. In fact, research using textile sEMG electrodes in the exercise and sporting field tends to lean towards controlled, closed chain and static exercise activities such as weighted leg extension/curl, cycling and even low intensity daily locomotive activity, rather than whole body dynamic exercise movements, like running (Subbu, Weiler and Whyte, 2015). With claims that textile sEMG electrodes can be used in sport to measure internal training load more research needs to be conducted on the ability of the internal training load to assess sport specific movements (Subbu, Weiler and Whyte, 2015). Research surrounding the sensitivity of the Athos™ system to differentiate between different dynamic running speeds, as well as the relationship to other athlete load monitoring systems is important for justifying its use in sport.

One of the most common methods of monitoring external load in sport is via GPS units, otherwise known as microtechnology (Cummins *et al.*, 2013). These devices are typically placed in a pouch located between the scapulae on a neoprene sports vest. One limitation of GPS technology is the transmitting of satellite signals to the GPS technology, limiting its use in indoor sports, like basketball and netball. With recent advancements in GPS technology, units from leading brands like Catapult™ and STATSports™ now incorporate a tri-axial accelerometer which derives a player external load variable (PlayerLoad™), expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (X, Y and Z), which is validated in multiple sports (Montgomery, Pyne and Minahan, 2010; Scott *et al.*, 2013; Halson, 2014; Torres-Ronda and Schelling, 2016). External metrics, such as PlayerLoad™ is often combined with internal loads like session-RPE to help draw associations between prescribed training loads and the athlete's individual response and adaptations to training. Some wearable sEMG products, such as Athos™ incorporates a triaxial accelerometer into their product which produces player Motion Load, calculated similarly to Catapult's PlayerLoad™, although no research has documented information based on the reliability and validity of this measure.

The Athos™ unit is a small oval shaped device which clips into the side of compression shorts (Figures 4.12 and 5.1), which communicates and delivers data wirelessly via Bluetooth to an application available for iOS8+ compatible devices. This allows athletes and coaches to visualise real-time muscle activation biofeedback during exercise and obtain post-exercise information about lower limb muscle groups, such as muscle symmetry between left and right legs, and individual muscle contribution as well as the overall Training Load and Motion Load as previously described. This information could potentially help make informed decisions on how best to prescribe training load, reduce the likelihood of soft tissue injury and direct return-to-play processes. An example of this would be the use of the acute-chronic workload ratio (ACWR), whereby injury risk could increase when an athlete's Weekly Training Load spikes compared to the previous four-week training load average (Gabbett, 2016; Andrade *et al.*, 2020).

The association between integrated EMG (iEMG) of the quadriceps and hamstrings muscles and oxygen consumption suggests that muscle activation may be a representation of individuals' physical exertion (Kyröläinen, Belli and Komi, 2001). Thus, sEMG-based Training Load may pose as a possible surrogate of oxygen consumption during specific treadmill running protocols, such as a $\dot{V}O_{2max}$ test. To date, one study has demonstrated how textile sEMG electrodes used to collected sEMG signals from the vastus lateralis could be used as a viable predictor of lactate threshold work rates during incremental cycling protocol (Snarr *et al.*, 2021). This indicates versatility of sEMG, and with such associations with other internal load parameters, like lactate and oxygen consumption suggests that wearable textile sEMG electrodes may be a viable tool for capturing internal load during dynamic whole-body exercise, such as running.

Therefore, this study aims to investigate the sensitivity of the sEMG shorts derived Training Load during different running speeds, and to examine the associations between sEMG Training Load and external accelerometery based PlayerLoad™ as a possible surrogate of oxygen consumption during incremental exercise. The integration of sEMG technology into convenient, non-invasive compression shorts could make sEMG more appealing to those involved in sport science and for employment of the system into the sporting field. To be considered a valid measurement tool for internal load, research must be undertaken.

5.3 Methods

5.3.1 Participants

Data were gathered from a group of 10 postgraduate university students (4 female, 6 male). Participant details are presented in Table 5.1. Participants were chosen through convenience sampling for practicality, without predetermined characteristics. Institutional ethical approval was obtained from the Research Ethics Committee of the University of Glasgow's College of Medical, Veterinary and Life Sciences before testing. Participants were recruited through word of mouth and via leaflets through the University of Glasgow's College of Medical, Veterinary and Life Sciences department. If interested, they received information sheets detailing study requirements, and later signed consent forms. A Physical Activity Readiness Questionnaire was completed, and participants were free to withdraw at any time. Anonymity by way of assigning participant identification numbers, and thus complying with the European Union’s Data Protection Regulations (GDPR) was procedural conduct. The researchers generated an anonymous email address for each participant containing only their identification number. This email address was used to set up their individual Athos™ accounts, which collected and stored processed sEMG data for later analysis, and thus could not be identified by third parties (i.e Athos™). A first aid trained staff member belonging to the University of Glasgow’s Sport Science laboratory was present during all testing procedures.

Table 5.1 Participant characteristics.

Participant	**Age (yrs)**	**Gender (M/F)**	**Height (cm)**	**Body Mass (kg)**	**Body Fat (%)**	**$\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$)**
1	21	M	186	73	13.5	55.5
2	27	M	179.4	81.27	21.2	36.4
3	25	M	176.8	72.04	17.3	53.5
4	26	M	171	69.6	21	49.0
5	33	M	197.6	92.56	18.4	50.8
6	21	M	170	69.3	16.4	56.2
7	22	F	165	60.2	41.5	38.1
8	22	F	179	64.5	26.1	45.1
9	25	F	158	55.9	26.1	39.8
10	25	F	161.3	56.4	29.9	40.1

Note: yrs = years; M = male; F = female; cm = centimetres; kg = kilograms; $\dot{V}O_{2max}$ = maximum oxygen uptake; $ml.kg^{-1}.min^{-1}$ = millilitres per kilogram per minute.

5.3.2 Design and Procedures

Participants visited the laboratory on two consecutive days. On the first day, participants undertook preliminary anthropometric tests. Body composition and height were assessed using the gold standard BODPOD composition tracking system, an air displacement plethysmograph that utilises whole body densitometry (COSMED, Italy), and a stadiometer (SECA 67310, SECA©, Chino, CA), respectively. Recording body fat percentage was deemed necessary as it may explain any weak EMG signals, conduction velocity and percentage of contraction during different tasks (Kuiken, Lowery and Stoykov, 2003).

Following body composition analysis, participants hip and waist circumference, and thigh length were measured for appropriate sEMG compression short fittings (Athos™, Redwood City, CA, USA). The sEMG shorts were made of 76% Nylon / 24% Spandex Lycra. Once fitted participants attached their Athos™ Core unit to a pouch located on the outer lateral position on the right-side leg (Figure 5.1).

Figure 5.1 Athos™ Core unit (a); and (b) Athos's sEMG-based compression shorts.

Simultaneously, participants were fitted with a Catapult neoprene vest for the insertion of a Catapult OptimEye™ S5 GPS unit into the designated pouch located between the scapula on the back of the vest (Figure 5.2). Additionally, participants were provided a Polar-H10 Heart Rate chest sensor (Polar Electro Oy, Finland) to wear during all research protocols. Athos™ units were connected via Bluetooth to a compatible iOS 8+ device. Figure 5.1 depicts the eight surface sEMG sensors (textile electrodes) embedded in the sEMG compression shorts, covering the Outer and Inner Quadriceps, as well as the Hamstrings and Glutes muscle groups. Athos™ electrodes are designed to provide a bipolar differential EMG measurement with an interelectrode distance of 2.1 cm (Figure 5.3). The electrodes consist of a conductive polymer ink applied to the fabric surface, with stainless steel wires wound twice around the polyester threads. Participants were not asked to shave the skin area relative to the sEMG electrode placing as in a practical setting, skin preparation is not performed when using the Athos™ sEMG shorts.

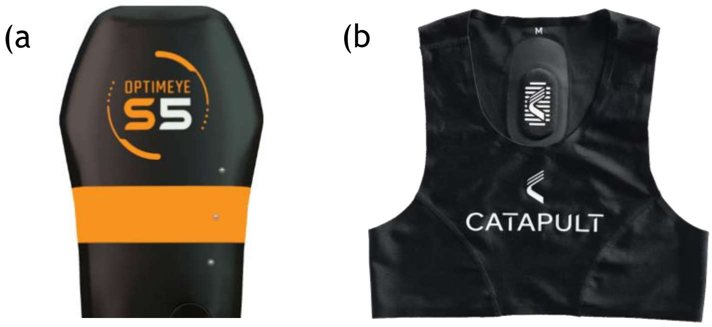


Figure 5.2 (a) Catapult GPS and Accelerometer unit; and (b) Catapult neoprene sports vest.

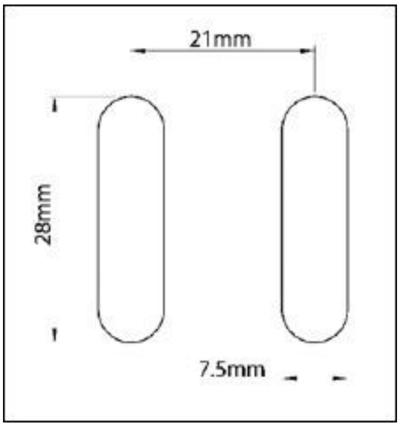


Figure 5.3 Geometry of Athos™ bipolar electrodes.

After fitting all wearable devices appropriately, each participant completed a 10-min standardised warm-up procedure following the 3-stage RAMP (Raise, Activate, Mobilise, and Potentiate) model prior to testing and to allow participants to adjust to all wearable devices (Racinais, Cocking and Périard, 2017). The warm-up aimed to capture a variety of movements in all planes of motion, and with varied intensities (low, medium, and high). This was directly followed by a sEMG calibration protocol published online by Athos^{TM} (2018), which was essential for setting individualised reference points for the calculation of training load. The calibration protocol included three specific movements: seated leg extension, prone leg flexion and prone hip extension. Each movement was performed four times with passively applied low, medium, and high resistance forces, as well as an isometric maximal voluntary contraction (MVC). The level of resistance was achieved by having a researcher apply a consistent force to the ankle of the participants throughout the entire range of motion of the movement. For the isometric contraction sufficient force was applied to the participant whereby they were unable to achieve movement of the limb even when maximally contracting the muscle.

Briefly, the MVCs generated individualised reference points for all muscle groups which the raw integrated sEMG output (area under the curve of the rectified EMG signal) could be normalised against. The integrated sEMG for each muscle group was measured as a percentage of the MVC. With the accumulation of these normalised integrated sEMG values across all muscle groups, calculated the Training Load metric reported in arbitrary units (AU) for a specific period of time. A single ‘AU’ was equivalent to one muscle activating at 100% of the MVC for one second. Once all wearable technology was assessed and working adequately, the participants undertook a 3-speed treadmill test.

5.3.3 3-speed treadmill running test

After anthropometric measures and calibration procedures were completed, participants started the 3-Speed Running Protocol. This test required participants to run on a Woodway PPS Med Treadmill (Woodway, ELG 70 Weiss, Germany) at three different running speeds for two minutes on each speed level. The predetermined speeds for males and females varied. Males performed 8 km.h^{-1}, 10 km.h^{-1} and 12 km.h^{-1} running for two minutes at each level. Similarly, females performed 6 km.h^{-1}, 8 km.h^{-1} and 12 km.h^{-1} running for two minutes at speed, respectively. One female who was 179cm in height, undertook the male running speeds due to longer stride length and to comfortably achieve the higher running speed. Each participant performed a two-minute warm up period of treadmill walking between 4-5.2 km.h^{-1} based on personal brisk walking speed preference. Participants were then instructed on safety procedures and what to do in the case of an emergency. Upon commencement of the test, the first speed level was applied, and participants began this first speed for a period of two minutes. After two minutes, the speed was increased to the second speed level for two minutes, and then the final level for a further two minutes. Once all tests were complete, the treadmill speed was gradually lowered to walking speed until HR was near to resting HR, from there the participants were allowed to dismount the treadmill.

5.3.4 V̇O2max Protocol

The second consecutive day of testing included the $\dot{V}O_{2max}$ test. This was carried out on the 2nd day of testing, as Day 1 acted as a familiarity session for participants who were not accustomed to exercising on a treadmill. The protocol consisted of participants running on a Woodway PPS Med treadmill (Woodway, ELG 70 Weiss, Germany) at 10 km.h^{-1} (males) or 8 km.h^{-1} (females) with a 1% gradient increase every minute until volitional exhaustion was reached (McConnell and Clark, 1988). Upon failure, participants were instructed to place both hands on the safety bars at either side of the treadmill and position both feet at either side of the running belt, to allow researchers to lower the speed to walking pace. A Medgraphics

Ultima cardiorespiratory metabolic cart (MedGraphicsTM, Gloucester, UK) was used for breath-by-breath respiratory gas analysis. Prior to the participant arriving at the lab, a three-litre calibration syringe was used to calibrate the flow sensor on the MedGraphics™ equipment by pushing air through the system, simulating the breathing pattern of a human. Two gas cylinders (21% O_2, 5% CO_2 and 12% O_2) were utilised for the calibration of gas concentration for inspired O_2 and expired CO_2. Following metabolic cart calibration and explaining safety instructions to the participant, subjects were attached with a mouthpiece and nose clip. A headpiece, which affixed to the mouthpiece, was placed over the participants head, and fastened appropriately to prevent unwanted movement of the mouthpiece during the test. A MedGraphics™ sensor which was attached to the mouthpiece and the metabolic cart at the other end measured inspired O_2 and expired CO_2. From here, a two-minute resting gas sample was taken from the participant, which allowed for equipment familiarisation and steady state breathing. A three-minute warm up at 6 km.h^{-1} was initiated after the two-minute gas sample was taken. After the warm-up the $\dot{V}O_{2max}$ test was started at the appropriate starting speed for male or female, as previously indicated. The incline increased by 1% gradient every minute. Participants HR and Borg's CR-10 Rating of Perceived Exertion (RPE) (using a laminated scale to which the participants pointed) were recorded at rest and every one-minute during the procedure which was indicative of the proximity of the participant to exhaustion (Habibi *et al.*, 2014). The RPE rating which the pointed was verbally repeated by the researcher and a thumbs up/down from the participant suggested if it was the number they pointed to or not. Continual encouragement was communicated to the participant by the researcher to help them run for as long as possible. Upon failure, the participant straddled the treadmill, and the speed was reduced gradually to a walking pace, whereby a five-minute cool down was undertaken. At this stage the mouthpiece, headgear and nose clip were removed as the participant continued the cool down. Once HR reached close to baseline levels, the participants was allowed to stop and dismount the treadmill.

5.3.5 Signal acquisition and processing

Athos™ unit electronics subsystem is responsible for signal reception, signal transmission and signal conditioning. Within the electronics subsystem lies a signal conditioning module which filters the data. Please note that the researchers only had access to the processed sEMG data, not the raw data output. Sampled sEMG signals were captured at 1 kHz. The anti-aliasing filter which was applied prior to sampling prevented high frequency noise greater than 500Hz from aliasing into the sEMG spectrum. Filtering included a linear band-pass (23 dB frequencies with centre frequency at 120Hz), notch (removal of 60 Hz noise) filter, rectification and linear envelope were applied. The linear envelope was down sampled by a factor of 25 and smoothed using a 16-sample root-mean-square (RMS) transformation along with a signal conversion from analog-to-digital. Electromyography signals from the compression gear were averaged at a 10-second window. sEMG recordings were considered viable when impedance was below 5 kΩ. Poor contact quality was deemed if loss of contact signal was above 10% of the time. These filtering and signal processes were predetermined by the Athos™ system and thus cleaned sEMG data output, including the sEMG Training Load metric was generated on the Athos™ Online Training Centre platform.

The Athos™ unit also comprised a tri-axial accelerometer sampling at 22Hz which produced the external load metric, Motion Load. Catapult OptimEye™ X4 GPS units also contained a tri-axial accelerometer sampling at 100Hz. The data were accumulated to generate a measure of external load, PlayerLoad™. The equation for PlayerLoad™ can be seen below:

$$\sum \sqrt{\frac{(fwd_{t=i+1} - fwd_{t=i})^2 + (side_{t=i+1} - side_{t=i})^2 + (up_{t=i+1} - up_{t=i})^2}{100}}$$

Figure 5.4 Catapult PlayerLoad™ equation*Fwd* = forward acceleration; *side* = sideways acceleration; *up* = upwards acceleration and *t* = time. Note: PlayerLoad™ is expressed in arbitrary units (AU).

To reduce reliability issues surrounding measurements and inter-unit variability, each participant was required to wear the same pair of sEMG compression shorts, and Athos™ and Catapult™ units across all tests (Johnston *et al.*, 2012, 2014).

5.3.6 Statistical analysis

Accelerometery data from Catapult™, and raw sEMG data from Athos™ were analysed and 'cut' manually according for the 3-speed treadmill and $\dot{V}O_{2max}$ test times. Athos™ sEMG shorts-derived Training Load is the main outcome measure of interest from Athos™. Data were analysed using Minitab (version 18). Scatterplots and boxplots were used to visualise these data. Paired t-tests and 95% Confidence Intervals assessed differences in the sEMG Training Load between each speed level from the 3-Speed treadmill test (low, moderate, and high speed). Raw accelerometry data (accelerometry PlayerLoad™) and the $\dot{V}O_2$ measure over one minute were averaged every one-minute interval during the $\dot{V}O_{2max}$ test. $\dot{V}O_2$ measure was normalized to $\dot{V}O_{2max}$ (%$\dot{V}O_{2max}$). Internal sEMG Training Load was quantified as the sum of the integrated sEMG (area under the curve of the rectified sEMG signal) of the individual muscle groups.

Separate Pearson's product-moment correlations were applied to determine the correlations between sEMG Training Load and accelerometry PlayerLoad™ and %$\dot{V}O_{2max}$ in the composite and individual data sets. Significance level was set at .05.

5.4 Results

Paired sample t-tests revealed the sEMG Training Load was sensitive in detecting changes between three different treadmill speeds (Figures 5.5 and 5.6). sEMG Training Load was significantly higher during moderate speed compared to low speed running by 49.1 AU (95% CI (8.5, 89.8) AU). Similar trends were shown where sEMG Training Load was significantly greater by 35.6 AU in high-speed running compared to moderate-speed running (95% CI (18.5, 52.8) AU). Significantly higher sEMG Training Load was established in high-speed running by around 84.8 AU compared to low-speed running (95% CI (29.2, 140.3) AU). In Figure 5, the moderate-speed level exhibits a narrower interquartile range (IQR) of 57.2 AU, in contrast to the wider range in the high-speed running level (IQR = 104.1 AU). While participant nine's high sEMG Training Load of 450 AU contributes to the upper whisker in the high-speed level's boxplot, the broader dispersion of sEMG Training Load in this level suggests that participant nine's value likely falls within a normal range. However, participant nine appears as an outlier in the moderate-speed level with an sEMG Training Load of 355.1 AU. Please refer to section 5.5 ‘Discussion’ for further explanation.

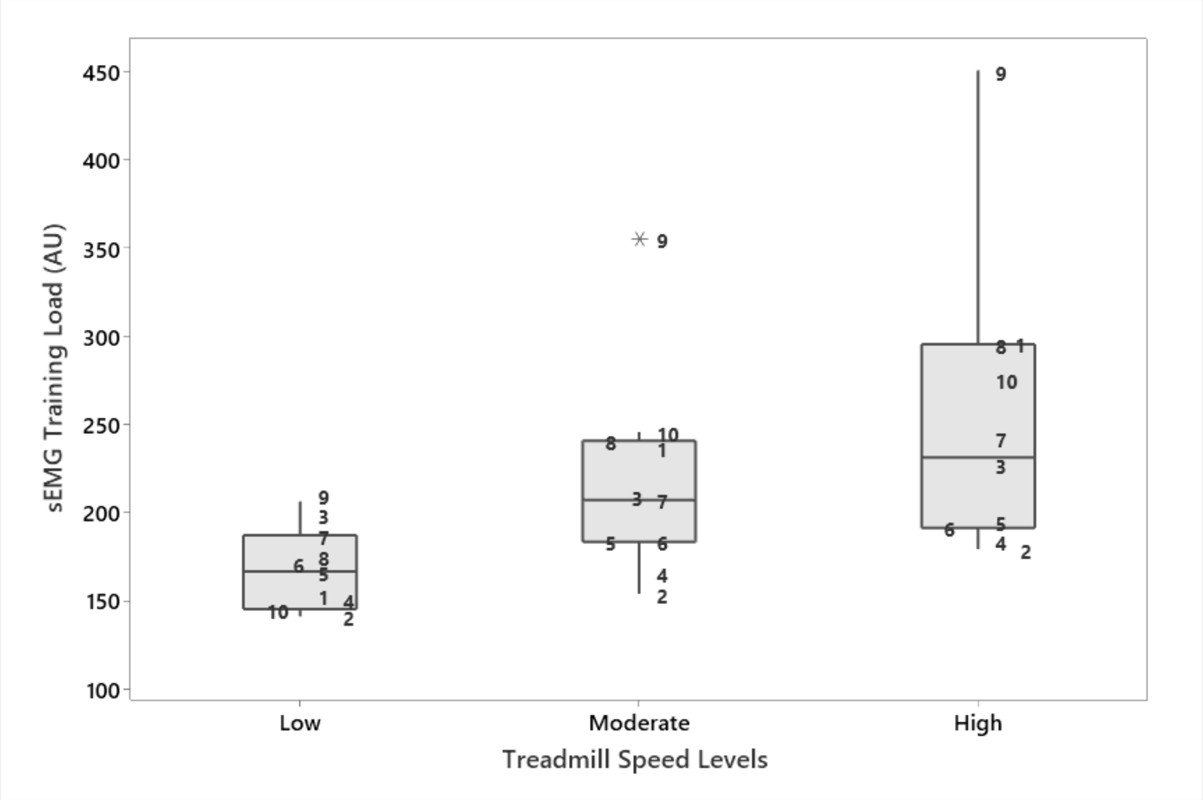


Figure 5.5 Boxplot comparing sEMG Training Load between three different treadmill speeds:8 km.h-1 (low); 10 km.h-1 (moderate); 12 km.h-1 (high) for males, and 6 km.h-1 (low); 8 km.h-1 (moderate); 10 km.h-1 (high) for females.Lower and upper box boundaries 25th and 75th percentiles, respectively, black line inside the box marks the median, lower and upper error lines represent the 5th and 95th percentiles, respectively. Note: numbers presented on the boxplots corresponds to each participant; * represents outliers; AU = arbitrary units..

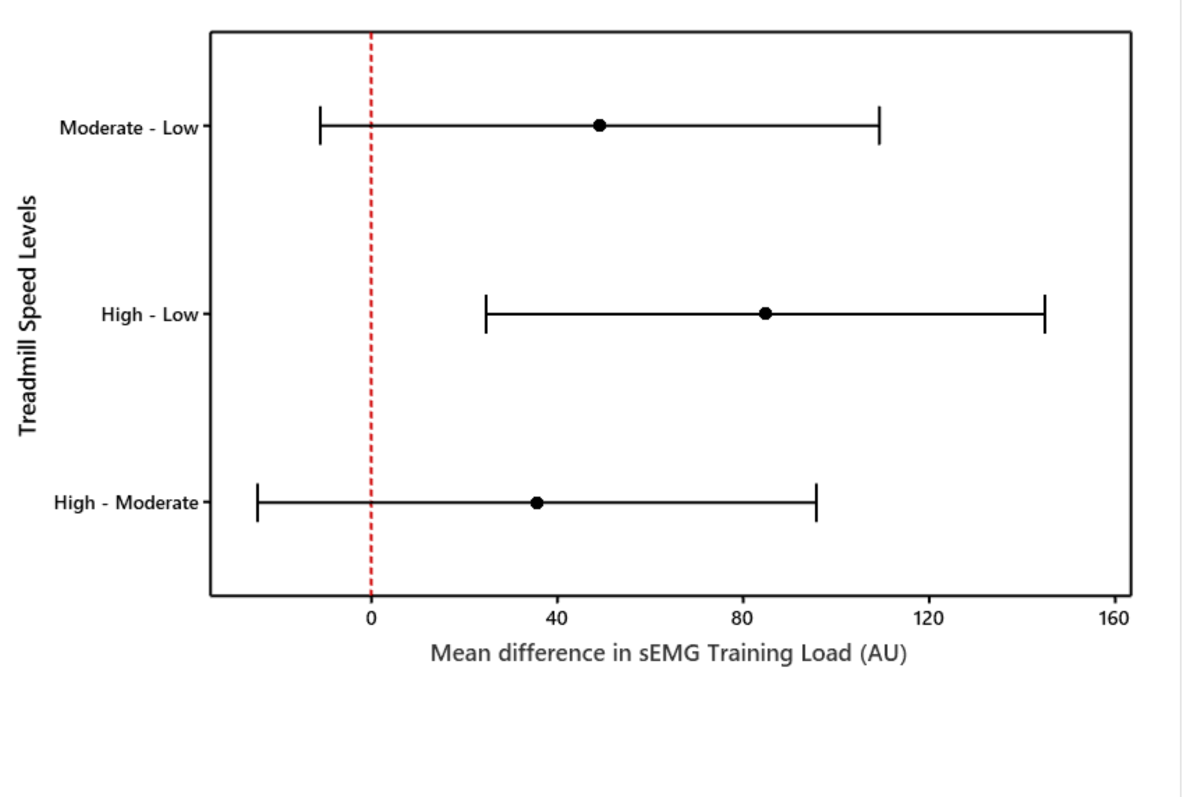


Figure 5.6 Interval plot of mean difference in sEMG Training Load between three treadmill speed levels:8 km.h-1 (low); 10 km.h-1 (moderate); 12 km.h-1 (high) for males, and 6 km.h-1 (low); 8 km.h-1 (moderate); 10 km.h-1 (high) for females.AU = arbitrary units. Note: red line represents line of no effect.

A moderate positive correlation (r = 0.33, *p* = 0.02) between sEMG Training Load and %$\dot{V}O_{2max}$ was found in the composite data set. Higher sEMG Training Load was related to higher $\dot{V}O_{2max}$ during the incremental treadmill running as illustrated in Figure 5.7. However, no correlation was established between Accelerometry PlayerLoad™ and %$\dot{V}O_{2max}$ (r= 0.06, *p* = 0.62).

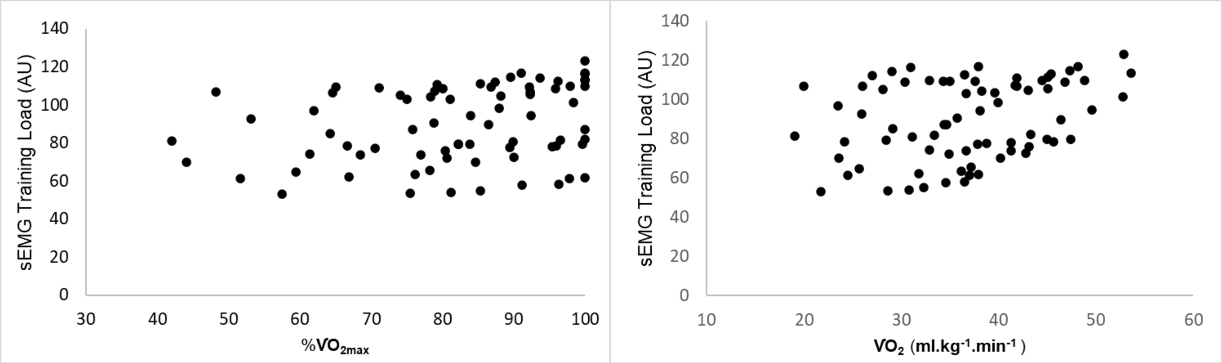


Figure 5.7 Scatterplots representing the relationship of %V̇O2max (a) and V̇O2 (b) with sEMG Training Load during and incremental treadmill V̇O2max test. AU = arbitrary units; $ml.kg^{-1}.min^{-1}$ = millilitres per kilogram per minute; V̇O$_2$ = oxygen uptake; V̇O$_{2max}$ = maximum oxygen uptake. (r = 0.3, *p* = <.05, n = 10).

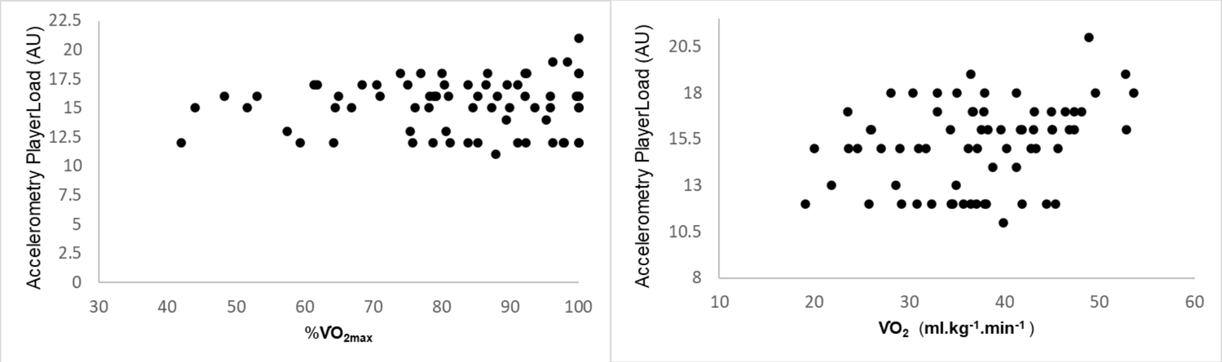


Figure 5.8 Scatterplots representing the relationship of % V̇O2max (a) and V̇O2 (b) with Accelerometry PlayerLoad™ during and incremental treadmill V̇O2max test. AU = arbitrary units; $ml.kg^{-1}.min^{-1}$ = millilitres per kilogram per minute; V̇O$_2$ = oxygen uptake; V̇O$_{2max}$ = maximum oxygen uptake. (r = 0.059, *p* = 0.62, n = 10).

At the individual level, sEMG Training Load exhibited highly significant positive relationships with %V̇O$_{2max}$ in nine out of ten participants, ranging from r = 0.72 to 0.97. Conversely, when examining the relationship between accelerometry PlayerLoad™ and %V̇O$_{2max}$, strong significant relationships were found in only three participants (refer to Figures 5.9 and 5.10). It is important to note that accelerometry PlayerLoad™ demonstrated a much weaker association with V̇O$_2$ compared to sEMG Training Load in the composite data (r = 0.059, *p* = 0.62), and at the individual level, with seven participants demonstrating no relationship. Figure 5.11 highlights the relative change in intensity, showing very strong significant linear relationships between HR and %V̇O$_{2max}$, ranging from r = 0.96 to 0.99 for all participants.

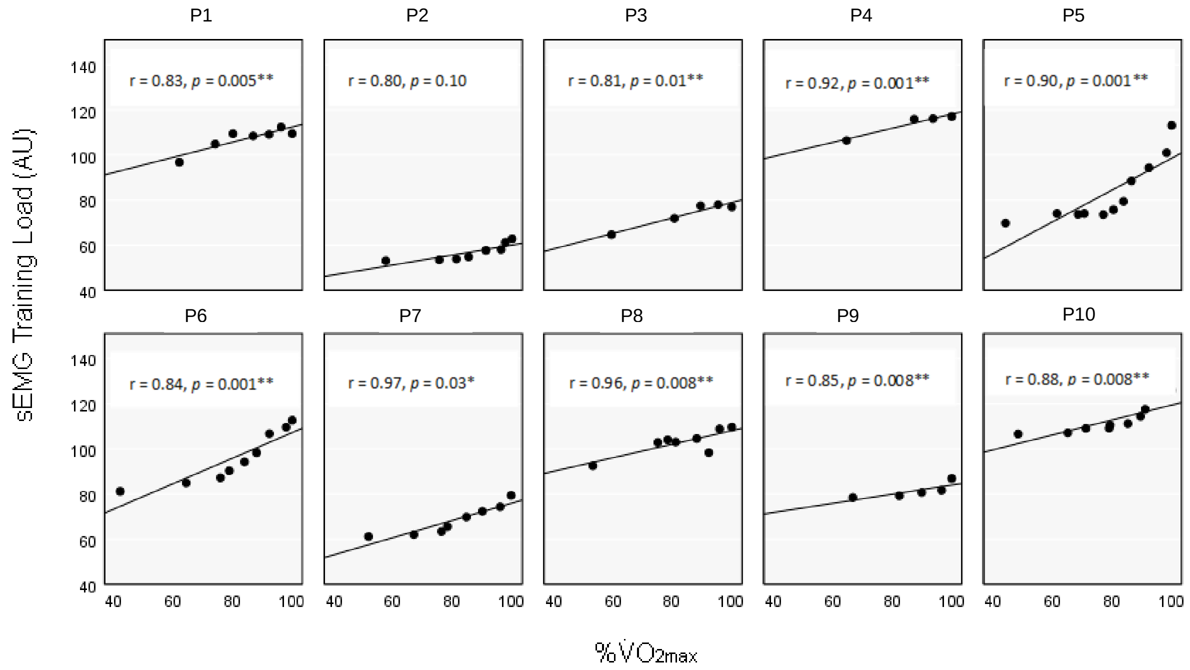


Figure 5.9 Individual scatterplots of each participant's relationship between %V̇O2max and sEMG Training Load (n = 10). AU = arbitrary units; %V̇O$_{2max}$ = percentage of maximum oxygen uptake; P = participant number; **p* < .05; ***p* < .01. Note: black line represents regression fit. The number of data points varies based on the fitness level of the participant; one data represents one minute achieved by the participant during the V̇O$_{2max}$ test.

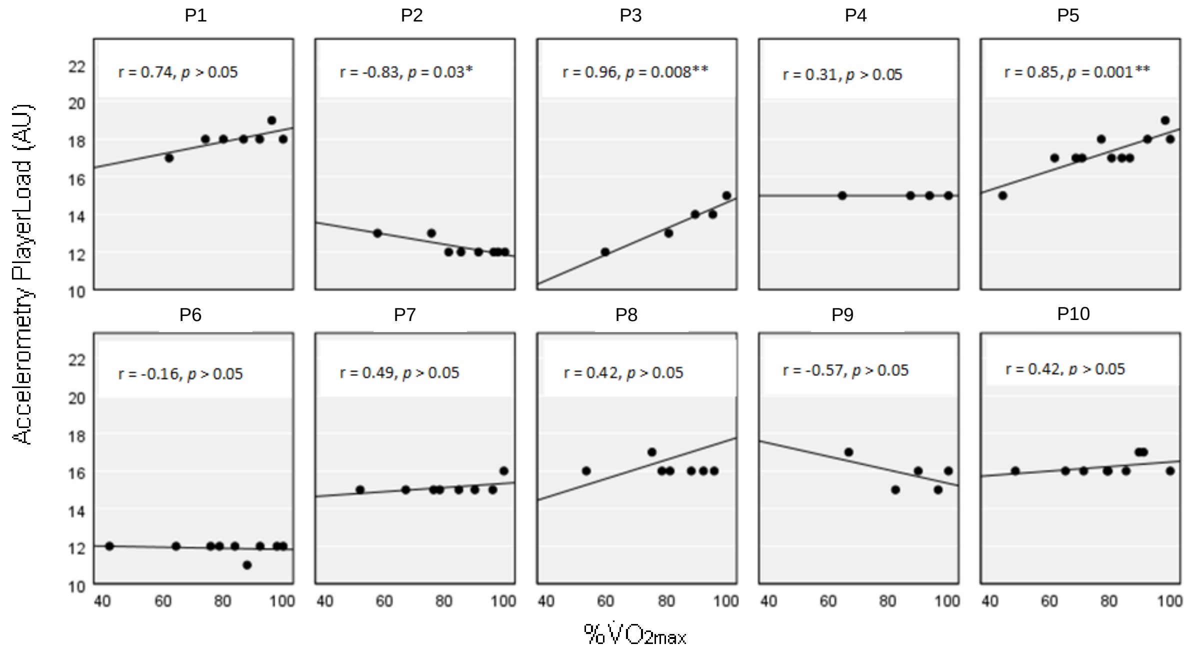


Figure 5.10 Individual scatterplots of each participant's relationship between %V̇O2max and Accelerometry PlayerLoad™ (n = 10). AU = arbitrary units; %V̇O$_{2max}$ = percentage of maximum oxygen uptake; P = participant number; **p* < .05; ***p* < .01. Note: black line represents regression fit. The number of data points varies based on the fitness level of the participant; one data point represents one minute achieved by the participant during the V̇O$_{2max}$ test.

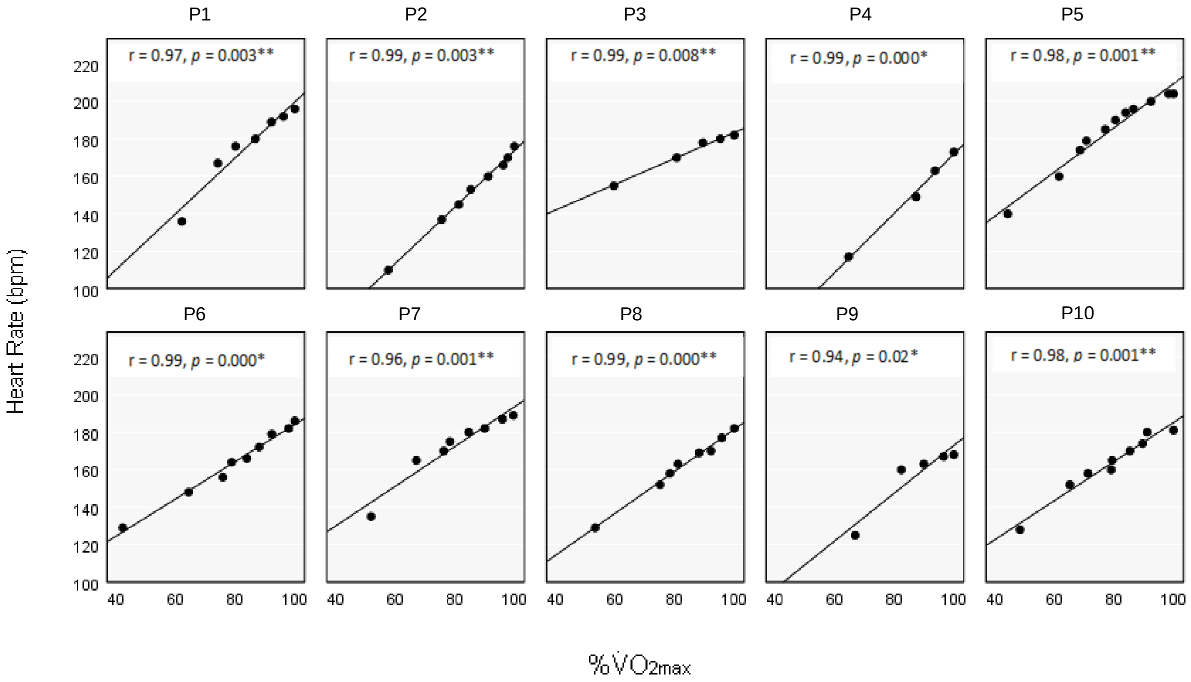


Figure 5.11 Individual scatterplots of each participant's relationship between %V̇O2max and Heart Rate (n = 10).AU = arbitrary units; %$\dot{V}O_{2max}$ = percentage of maximum oxygen uptake; bpm = beats per min; P = participant number; *$p < .05$; **$p < .01$. Note: black line represents regression fit. The number of data points varies based on the fitness level of the participant; one data point represents one minute achieved by the participant during the $\dot{V}O_{2max}$ test.

5.5 Discussion

An important feature of this study is the novelty of wearable sEMG compression shorts in providing an internal sEMG-derived Training Load metric as a potential method for monitoring the athlete's physiological response during dynamic, whole-body exercise. The sEMG Training Load was significantly different between three different running intensities denoted by 2 km.h^{-1} speed changes. These findings indicate that sEMG Training Load is sensitive in detecting small intensity changes during exercise. Additionally, the present study demonstrates that sEMG Training Load moderately positively relates to oxygen consumption, and thus energy expenditure (Kenny, Notley and Gagnon, 2017) during a treadmill $\dot{V}O_{2max}$ test. Accumulated sEMG Training Load increases with subsequent increase in fatigue as indicated by oxygen consumption. Higher sEMG Training Load was related to higher %$\dot{V}O_{2max}$. Moreover, while the sEMG Training Load was significantly correlated to oxygen consumption in 80% of the participants, the accelerometry PlayerLoad™ was related to oxygen consumption in only 30% of the participant pool. This highlights the different parameters which internal and external player monitoring systems may capture from athletes during exercise (McLaren *et al.*, 2018).

While this is one of the first controlled laboratory-based studies to investigate sEMG Training Load during exercise, specifically using Athos™ sEMG shorts, these findings can be compared to earlier research based on using textile sEMG electrodes during different exercise protocols (Lucia *et al.*, 1999; Hug *et al.*, 2004; Tikkanen *et al.*, 2012; Snarr *et al.*, 2018). Findings from the three-speed treadmill test parallel those of Tikkanen *et al.* (2014), who showed that sEMG shorts with embedded textile electrodes can be used in energy expenditure (kJ.min^{-1}) estimations during different treadmill walking and running speeds. They showed significant correlations (r = 0.79 - 0.97; p < 0.001–0.05) between metabolic rate and sEMG at all walking and running speeds, as well as for each treadmill gradient increase for the quadriceps and hamstrings muscle groups. While Tikkanen et al. (2014) results were based on non-standardised exercise protocols for the intention of simulating daily living locomotion, the purpose of this study was to investigate sEMG Training Load during higher intensity exercise using a 3-speed running test.

As the metabolic rate during running is determined by two factors: a) the rate of muscle force development (especially during the stance phase); and b) the volume of active leg muscle (Griffin, Roberts and Kram, 2003; Kipp, Grabowski and Kram, 2018) the sEMG Training Load, as expected, rises in accordance with the change in running velocity and the associated increased gait cycle. An insightful finding emerges from Figure 5.5, where participant nine is identified as an outlier for the moderate-speed level. This distinction can be attributed to the participant's difficulty in sustaining the moderate and high-speed running velocities for the full two-minute duration. Table 5.1 provides insight into participant nine's characteristics, notably their shorter stature and relatively low cardiovascular fitness status (39.8 ml.kg^{-1}.min^{-1}). Collectively, these characteristics likely contributed to inefficient running mechanics, leading to a heightened biomechanical and neuromuscular response. This is evident in the elevated sEMG Training Load as an effort to sustain the increased running cadence during faster running velocities (Dorn, Schache and Pandy, 2012). Previous research has indicated similar results for individual muscles. For example, Chumanov *et al.* (2012) found that as stride rate is increased by 10% during running, activity of the tibialis anterior and rectus femoris increased in pre swing phase, while the medial hamstring activity increased during the mid-late swing phase (Chumanov *et al.*, 2012). Rigorous data analysis performed by the researchers confirmed the integrity of the sEMG data for participant nine. Absence of motion artifacts or signal interference led us to retain this data in our analysis rather than excluding it. This highlights the imperative of incorporating sEMG Training Load as a metric for assessing relative load changes.

A key finding is that sEMG Training Load continues to accumulate with fatigue as reflected by end stages of oxygen consumption and heart rate during the $\dot{V}O_{2max}$ test (Figure 5.11). The mechanisms which contribute to this finding remain largely unexplained but is perhaps the inter-play or combination of physiological and biomechanical components involved during high intensity running. The Henneman's size principle states that as greater force is required, motor units are recruited in an orderly fashion according to the magnitude of their force output (Henneman *et al.*, 1974; Senn *et al.*, 1997), with small motor units (slow-twitch) recruited first, and as more force is required, like in the latter parts of the incremental $\dot{V}O_{2max}$ test, larger motor units (fast-twitch) are recruited, thus exhibiting task-appropriate recruitment. This coheres with the progressive recruitment of fast-twitch fibres during the $\dot{V}O_2$ slow component, whereby oxygen consumption continues to increase when work rate remains constant (Borrani *et al.*, 2001). Nevertheless, this is not as relevant in this study as while velocity was held constant during the $\dot{V}O_{2max}$ test, the gradient of the treadmill increased causing greater force demand. As a result, the larger motor unit action potential amplitudes and their growing firing rates to sustain the necessary force output during fatiguing exercise, might partly explain the stronger association between higher sEMG Training Load and higher $\%\dot{V}O_{2max}$ (Hagberg, 1981). This indicates the possibility of using the sEMG Training Load as a metric for quantifying overall internal load throughout high intensity exercise or sport.

Other muscle recruitment variables such as a biomechanical shift in the interaction of the upper leg muscles during level running compared to uphill running ($\dot{V}O_{2max}$ test) might influence the sEMG relationship with higher oxygen consumption. Approximately 6% greater muscle volume is activated during uphill running compared to level running (Sloniger *et al.*, 1997a). In fact, sEMG patterns of the hamstring's muscles (semitendinosus and biceps femoris) at 40% $\dot{V}O_{2peak}$ undergo a greater range in activation levels compared to the quadriceps during uphill running. Yet, at greater intensities ~115% $\dot{V}$O2peak uphill running requires considerably greater activation of the vastus group (23%), and less activation of the rectus femoris (29%), and semitendinosus (17%), while the greatest activation of the biceps femoris (59.7% ± 15% MVC) at the steepest portion (near $\dot{V}O_{2max}$) of an incremental running test has been shown (Sloniger *et al.*, 1997a, 1997b; Camic *et al.*, 2015). Other between-participant biomechanical and physiological parameters, such as fibre type composition, anthropometric differences, tendon properties and fitness status, as well as running mechanics might influence the sEMG Training Load variable as it accounts for eight different recording sites of the upper leg (Fletchern and MacIntosh, 2017). Moreover, it has been shown that athletes compared to non-athlete's recruit muscle at different rates, especially in higher threshold motor units (Sharafi *et al.*, 2016). Although training status was not recorded in the current participant pool, it should be noted that two participants' $\dot{V}O_{2max}$ exceeded 50 $ml.kg^{-1}.min^{-1}$ which is above the average population score. Tikannen *et al.* (2014) purport the accuracy of quadriceps sEMG for predicting energy expenditure is considerably decreased at walking paces, compared to running speeds. This suggests that the sEMG internal Training Load metric may be a valid surrogate for measuring physical exertion during higher intensity exercise.

On the other hand, accelerometry PlayerLoad™ did not correlate with oxygen consumption during the incremental $\dot{V}O_{2max}$ test in the composite data set. At the individual level, only two participants PlayerLoad™ significantly positively correlated with oxygen consumption, and one participant had a significant negative relationship. From the results, it can be deduced that sEMG Training Load and accelerometry PlayerLoad™ capture different load (internal and external, respectively) constructs. Barrett, Midgley and Lovell. (2014), show betweensubject correlations are trivial-moderate between PlayerLoad™ and oxygen consumption during level ground running at different velocities, whereas within-subject analysis yielded significantly stronger correlations. Nevertheless, this study incorporates a $\dot{V}O_{2max}$ test with a 1% gradient increase in treadmill slope every one minute while the participants ran at a constant velocity. Accelerometry is limited by the technologies inability to quantify the net external work performed in a variety of sports. Accelerometry underestimates energy expenditure by ~73% in cycling compared to walking (Herman Hansen *et al.*, 2014). Accuracy of accelerometry load from gradient walking or running, such as hiking across different terrains or load bearing activities is also apparent (DeVoe and Dalleck, 2001). Lastly, there are many static movements in sport, such as screening in basketball, when an effort is performed without an acceleration (Gómez-Carmona *et al.*, 2020). Relevant to the $\dot{V}O_{2max}$ test in this study, Chang et al. (2019) the error rate of accelerometry output increases as the slope of the treadmill increases and significantly underestimates energy expenditure during walking which conforms with the results of this study.

A major reason why accelerometry PlayerLoad™ fails to reflect the metabolic demand during the incremental $\dot{V}O_{2max}$ test, is primarily inherent to the method of calculation. During uphill running the body must alleviate its own mass, thus the vertical axis (distance travelled) is of great importance, yet this parameter is not recorded in the accelerometric signal during uphill running (Terrier, Schutz and Aminian, 2001). Additionally, accelerometry has previously shown to not account for increased vector magnitude of the vertical and medial lateral planes during treadmill running at different velocities, thus other parameters might not be reflected in uphill treadmill running. However, it has been recommended that if the incline is a known parameter, a predictive algorithm based on individual characteristics could improve the accuracy of the accelerometry load, but only when assessing the gradient of the slope individually. Moreover, the accelerometer mounted to the scapulae does not account for other external body movements, like arm swinging which demands energy (Howe, Staudenmayer and Freedson, 2009). Lastly, accelerometry PlayerLoad™ algorithm during one-minute epochs might not be sensitive enough to detect changes increasing slope treadmill running at a constant velocity, as can be seen with the relatively small arbitrary number output (15-18 AU).

As sEMG can account for a greater degree of cyclical isometric contractions and increased concentric muscular contractions under fatigue to maintain a constant velocity during the stance phase of running (Tikkanen *et al.*, 2014), it is advised that sEMG be used over accelerometry as a surrogate for oxygen consumption during running. It is advised that sport scientists, or researchers analyse sEMG Training Load on the individual level. sEMG Training Load may pose as a viable method for capturing the internal load of athletes during dynamic sport which involve running. In fact, sEMG Training Load could be used not only in conjunction with external load measures to provide a dose-response relationship in sport, but perhaps be used as a primary method of load as it accounts for individual response to a training stimulus (McLaren *et al.*, 2018; Impellizzeri, Marcora and Coutts, 2019). This study highlights the advantageous nature of sEMG compression shorts in providing coaching feedback to athletes based on muscle activation patterns and information surrounding the level of activation in specific movements in sport, like basketball screening. Wearable sEMG could also be used in different training regimes and terrains like military tactical exercises, hiking and uphill cycling or running.

Much like sEMG Training Load, heart rate provides valuable insights into the relative intensity and load of physical activity as demonstrated with the very strong relationships with $\%\dot{V}O_{2max}$ (Figures 5.9 and 5.11). However, it is crucial to acknowledge that heart rate may not always directly align with external measures of load like GPS high speed running (McLaren *et al.*, 2018), especially in activities characterised by variations in muscle groups engaged and diverse physiological demands. To attain a comprehensive understanding of an individual's exercise intensity and physiological response, heart rate should be complemented by other measures such as RPE and sEMG. By employing a multi-modal approach, researchers and practitioners can capture different elements of the overall load picture, thus enhancing the accuracy and depth of knowledge when assessing load. This integrated perspective allows for a more nuanced interpretation of exercise load, considering both cardiovascular responses and muscular activation patterns, and can aid in optimising training protocols, injury prevention strategies, and overall performance enhancement.

5.6 Limitations

As sEMG Training Load accounts for the additional energy demand during uphill treadmill running in the standardised $\dot{V}O_{2max}$ running protocol, incorporating another test which includes a change of direction, like an agility test could provide more insight into the discrepancies between accelerometry output and sEMG output. Although the intention of this study was to examine the sEMG Training Load metric, which is the sum of the eight sEMG recording sites of the upper leg, future research could include a breakdown of each muscle group to provide more insight into the biomechanical components when running on a graded sloped treadmill. Nonetheless, a draw-back in assessing individual muscle groups using sEMG shorts is the necessity of individual fittings. Caution must be exercised when interpreting results from muscle groups as muscle crosstalk signals are likely present. More movement at the skin-surface-electrode can also cause signal artefact during exercise. This limitation is typically evident in people with excessive subcutaneous fat, causing a dampened EMG signal. This study resulted in data loss of 16.7% (two participants) as the amplitude of the high-frequency contact signal exceeded a given threshold for over 10% of the time of testing. Consideration of this in athletic populations would be worthwhile, with the expectation that subcutaneous fat may be less in athletic populations compared to non-athletic participants.

5.7 Conclusion

Results from this study indicate Athos's sEMG Training Load is a sensitive metric that can detect changes in exercise intensity denoted by 2 $km.h^{-1}$ increments. The sEMG Training Load may be a valid surrogate for measuring oxygen consumption during incremental treadmill running. Additionally, the sEMG Training Load is more sensitive to changes in activity intensity than accelerometry PlayerLoad™, which does not associate with oxygen consumption during graded sloped treadmill running. Thus, sEMG shorts could potentially monitor an athlete’s internal training load during sporting activities and movement patterns. While established retailers promote the use of wearable sEMG in sport, to date, little research examines it’s use in the real sporting field. Indeed, to warrant the application of wearable sEMG, extensive research ought to be conducted in the relevant environment. Like many other systematically conducted *feasibility, reliability* and *validity* research protocols, the feasibility of wearable sEMG (textile sEMG electrodes) should first be investigated in the sporting arena, prior to sEMG metric-based analysis.

Chapter 6 Study 3 – Qualitative Feasibility of Wearable sEMG as an Internal Player load Monitoring System in Elite Basketball - A Pilot Study

6.1 Abstract

Introduction: Surface-electromyography (sEMG) electrodes has recently evolved into wearable sEMG smart clothing, posing as a novel approach for monitoring athletes internal load in sport. While research validates textile-based sEMG electrodes in controlled lab-based environments, no research investigates the feasibility or practicality of the wearable technology in the authentic sporting environment. This study explores the feasibility of sEMG shorts on professional basketball players during a competitive season. ***Methods:*** sEMG was recorded in eight (n=8) male professional basketball players during their competitive season. The study was conducted over the 2019-20 British Basketball League season. Players were required to wear the sEMG shorts for more than 80% of training sessions and games. Face-to-face semi-structured interviews were conducted individually with each player at the end of their basketball season to collect qualitative data based on their experience wearing the Athos™ sEMG shorts. ***Results:*** The sEMG technology appeared to be feasible for use in a professional basketball environment. Less than <20% of missing data was recorded throughout the study period because of improper or lack of wear by the participants and WiFi connectivity issues during data downloading procedures. The technology appears to be accepted by participants, demonstrated with a high adherence rate to wearing the sEMG shorts >80% amongst participants throughout the study period. Two participants indicated that comfortability and negative effects on performance were the reasons why they would not wear use the sEMG shorts again. Semi-structured interviews identified six over-arching themes: *comfortability, feedback, technical improvements, perceptions on effects on performance, effects on motivation and would/would not use again*. These themes were deemed

important from the user's perspective following first-hand experiences using the sEMG technology in the basketball training environment.

6.2 Introduction

In recent years, the monitoring of athlete performance as well as training and competition loads inflicted on athletes has become indispensable for the welfare of athletes. As such, the wearable technology industry in sport has exploded in recent years and is ever evolving new techniques for the purpose of monitoring athletes. Technologies, such as Heart Rate (HR) devices, Global Positioning Systems (GPS), accelerometers, Local Positioning Systems (LPS) and Time Motion Analysis (TMA) have improved significantly in terms of feasibility, validity, and reliability in the sporting environment (Roberts, Trewartha and Stokes, 2006; Essner *et al.*, 2013; Hoppe *et al.*, 2018; Nicolella *et al.*, 2018). Surface-electromyography (sEMG) is a traditional lab-based measurement, diagnostic and analysis tool established in the mid-twentieth century for the study of electrical activity of muscle (Basmajian and de Luca, 1985). Simply, sEMG is a sensitive voltmeter that detects depolarizations and hyperpolarisations (increases and decreases in voltage, respectively) that occur on the sarcolemma (plasma membrane of the muscle cell) (Vigotsky *et al.*, 2017). The limited usage of sEMG to laboratory research is dictated by the fact that the global EMG signals (EMG amplitude or conduction velocity) is associated to the activity of many motor units and the properties of the tissue between the electrodes and the muscle fibres. Major barriers to its usability in the field of sport is due to minimal portability as systems are often bulky, unaffordability, and accessibility to technology. Additionally, Vigotsky *et al.* (2017) report that less than 5% of students within higher academic institutions studying in the aeras of Biomechanics, Sport Science, Physiotherapy, Human Movement and Exercise Physiology are taught fundamental principles surrounding neural control of muscles at the motor unit level (Vigotsky *et al.*, 2017). While it is relatively easy to collect global sEMG signals, a lack of knowledge encompassing the application of sEMG and data analysis techniques by professional coaches (sport scientists and strength and conditioning coaches), inherently limits its widespread use in sporting contexts.

As sEMG provides a non-invasive, global measurement of muscle activity, it is suggested that it may be more suitable for movement assessments which require repeated, frequent measurements in a condensed period of time for information based on patterns of activation of multiple muscles, such as in sport and rehabilitation (McManus, de Vito and Lowery, 2020). It is possible to acquire data about an athlete's physical performance and rehabilitation, about preventing muscle fatigue or injuries via analysis of post training sEMG signals collected during the training, which has influenced prehab practices within soccer (Lovell *et al.*, 2018). Moreover, within-participant, within-muscle comparisons of the sEMG signal across various exercises or training sessions could provide insight into muscular force production (Vigotsky *et al.*, 2017). By collecting information based on muscle fatigue, muscular performance, and muscular load from sEMG could create many opportunities for researchers and coaches to influence daily practices within sport through further investigations in the sporting field (Cardinale and Varley, 2017).

A relatively recent and easily applied approach to using sEMG in research is by the integration of sEMG electrodes into clothing fabric, also known as textile sEMG electrodes. Until recently, wearable sEMG in the form of clothing was more commonly employed in health and physical activity related studies (Finni *et al.*, 2011; Tikkanen *et al.*, 2014, 2015; Pesola *et al.*, 2016; Bengs *et al.*, 2017; Gao *et al.*, 2019). However, wireless technology has lately gained traction in the sport industry as a possible athlete monitoring system for obtaining data to examine muscle activation and exercise performance outcomes. As previously described in Chapter 5, Athos™ (Redwood City, CA, California) and Myontec™ (Kuopio, Finland) retail wearable sEMG as athlete monitoring systems. The global smart clothing industry (embedded sensors into clothing) reached an impressive $2.5Bn in 2020 and is projected to reach an approximated $4Bn in 2024 (Hanuska et al., 2016; Luczak et al., 2020).

The novel concept of using wearable sEMG (textile electrodes) in sport could provide coaches, information based on internal load from a biomechanical, muscular perspective. In the literature, research validating textile sEMG electrodes in lab-based exercise protocols predominates. Finni *et al.* (2007) investigated textile sEMG electrodes integrated into compression shorts during bilateral isometric knee extension and demonstrate close agreement with traditional bipolar sEMG signals, validating their use during static, isometric exercise. Lynn *et al.* (2018) compared textile sEMG sensors to a research grade system during knee flexion and extension on an isokinetic dynamometer and report textile sEMG sensors to provide measures which are comparable to a research grade system. Other studies investigated the use of textile sEMG electrodes in functional movements, such as walking, running, and cycling (Tikkanen *et al.*, 2012b, 2014; Colyer and McGuigan, 2018; Snarr *et al.*, 2018). Tikkanen *et al.* (2014) examined accelerometry, HR and wearable sEMG (compression shorts) data and their relationship with energy expenditure as measured by indirect calorimetry during non-standardised exercise tests. They replicate daily walking and running locomotion in uphill and downhill terrain simulated on a treadmill and indicate thigh muscle sEMG to more accurately predict energy expenditure compared to accelerometry, especially in uphill and downhill locomotion. Reports of similar day-to-day and within-session reproducibility of muscle excitation data using textile sEMG electrodes from static and functional movements are reported in the literature (Finni *et al.*, 2007; Colyer and McGuigan, 2018).

Many of these studies are pertinent to the field of wearable electromyography, and for demonstrating the validity and reliability of textile sEMG electrodes during specific lab-based exercise. However, more research should begin to incorporate wearable sEMG in the field of sport (Hermann and Senner, 2020). With companies like Athos™ and Myontec™ who incorporate Training Load and Muscle Load metrics, defined as the sum of the integrated sEMG (area under the curve of the rectified sEMG signal) of the individual muscle groups, should direct researchers into applying wearable sEMG in the authentic sporting environment. Study two (Chapter five) of this thesis advanced from basic locomotion testing as commonly seen in the literature, towards addressing the sensitivity of Athos's sEMG shorts-derived Training Load metric between different running intensities, and its relationship with oxygen consumption during a fatiguing treadmill $\dot{V}O_{2max}$ test. As Athos's sEMG Training Load can differentiate between different running intensities, as well as capture internal load of participants during a fatiguing sloped treadmill running protocol, further research on the usability of wearable sEMG systems in the sporting environment is warranted.

Basketball is a world-wide popular court-based team sport which entails intermittent periods of high intensity activity (e.g., sprinting, shuffling, jumping) intertwined with periods of low and moderate activity (e.g., walking, jogging) in all planes of motion (Stojanović *et al.*, 2018). The sport entails many static yet energy demanding movements and techniques, such as screening, defensive, and shooting which vary in volume according to playing position (Abdelkrim, el Fazaa and el Ati, 2007). With athletes competing as much as two games per week, and training up to five days per week, not including gym-based strength-oriented training sessions, basketball is characterised as an extremely physically demanding sport, especially at the professional level. Thus, it is imperative that valuable load monitoring techniques are considered in basketball for protection against over training syndrome, to adjust and prescribe appropriate training loads as means of achieving optimal player performance.

Several internal and external load monitoring techniques are frequently used in basketball and have endured the rigours of validation research protocols. The rating of perceived exertion (RPE) and session-RPE are two valid subjective methods for capturing the players psychophysiological load from basketball training and competition sessions. The methods require the researcher asking the player “how hard was your session”, and the players respond with a number (usually 0-10) anchored to descriptive to rate the difficulty of the session. Nevertheless, the RPE method is associated with a disadvantage when trying to assess the load inflicted on players during specific parts of the training or competition session as this would require stopping and starting training to collect RPE’s from each player (Moreira *et al.*, 2012; Fox, Scanlan and Stanton, 2017a; Haddad *et al.*, 2017). Additionally, GPS technology is an external load method, and while it has been shown as a valid method in basketball, it has clear drawbacks to satellite signal as basketball is an indoor sport (Cummins *et al.*, 2013; Gómez-Carmona *et al.*, 2020; Waqar *et al.*, 2021). Accelerometry data may not directly capture all the stress inflicted on players, especially during cyclical isometric actions (Gómez-Carmona *et al.*, 2020).

Many wearable technologies for the purpose of load monitoring sport and exercise science undergo systematic research to investigate their feasibility, validity and reliability within controlled research and the sporting environment (Johnston *et al.*, 2014; Beato, Devereux and Stiff, 2018; Best and Standing, 2019; Howe *et al.*, 2020; Hernández-Vicente *et al.*, 2021). Generally, devices which are not deemed feasible in the real-world environment require resolutions to their associated barriers, such as technological advancements and ease of wear. GPS and accelerometers are two examples of external load measures which are regularly updated for ease of application and validity in the field of sport. Impellizzeri, Marcora and Coutts (2019) recommend the internal response to take priority when attempting to account for the load inflicted on players. As such, wearable sEMG systems could provide insights into the acute internal response to training and competition loads, as well as provide insights into muscular patterns under fatigue which could influence injury preventative practices (Cardinale and Varley, 2017). Prior to interrogating the sEMG metrics in basketball, it should first be established by player and coach if the technology is a feasible system use in basketball. No research has investigated the feasibility or applicability of an wearable sEMG system for athlete monitoring in professional sport. It is important for all wearables to follow a similar feasibility, validity and reliability systematic approach before conclusions can be drawn on the effectiveness of the technology in sport. Thus, the current study aimed to address:

1) the feasibility of a wearable sEMG system in professional basketball

and

2) how players perceive using sEMG shorts, and the related feedback they provide.

6.3 Methods

6.3.1 Participants

From an initial twelve (n=12), eight (n=8) professional male basketball players (mean ± SD age: 27.1 ± 5.0 yr; height: 1.97± 0.08 m; body mass: 94.9 ±10.5 kg) were included in the final analysis. Players were recruited from a professional male basketball team playing in the British Basketball League during the 2019-2020 competitive season. Researchers informed all players, coaching staff, and support team of the participation requirements through a presentation. At this stage, the athletes were informed of the beneficiaries of participation in the study, including information about their sEMG outcomes (e.g., sEMG internal loads and muscle (a)symmetry) during training and competition. Participants were given information sheets, offered one week to decide if they wanted to partake in the study, and were informed that failure to wear or complete the study would not result in a disciplinary, and it was fully within their right to cease participation if they decided. All players provided written informed consent before taking part. Ethical approval was obtained from the College of Medical, Veterinary and Life Sciences Research Ethics Committee at University of Glasgow. Four (n=4) players with incomplete participation throughout the season (n=2 relieved by the club, and n=2 through injury) were excluded from analysis.

6.3.2 Design & Methods

The observational feasibility study period lasted 11 weeks from the start of December 2019 to February 2020 and was concluded earlier than planned as a result of the beginning of the COVID-19 pandemic when Scotland and the whole of the UK entered a phase on national lockdown.

A familiarisation and sEMG calibration process (previously described in Chapter 5) was carried out on the first day of the study period. On this day, each player’s anthropometric measures including, height (m) (SECA 213, stadiometer) and body mass (kg) (Beurer GS-410 scales), hip and waist circumference and thigh length (cm) (SECA Circumference Measuring Tape) were recorded to designate each player with appropriately fitted Athos™ (Redwood City, CA, California) sEMG compression shorts which were integrated with textile electrodes. Researchers distributed a pair of sEMG shorts and a pre-allocated sEMG Core unit which collects and stores the sEMG data to each player. Procedures for the handling of the sEMG shorts and Core unit were demonstrated to the players via visual and verbal instructions by the researchers.

Thereafter, the players were asked to change into the sEMG shorts and slot the Core unit into a pouch located on the outer exterior of the shorts on the right-side leg until they heard a click, which signified the Core unit was fixed into place. Following this, a 5-min calibration protocol was performed on each player which involved completing seated leg extension, prone hip extension and prone knee flexion movements under four resistances dictated by application of force from the researcher: low, medium, high, and isometric maximal voluntary contraction (MVC). The forces were determined and manually applied to the participant by the researcher holding, or 'pushing' the anterior aspect of the ankle for the seated leg extension movement, and posterior aspect of the ankle for the prone hip extension and prone knee flexion movements. The calibration protocol was necessary for setting sEMG thresholds. Every muscular contraction performed in training and competition is relative to their MVC sEMG amplitude (%MVC). Training Load (AU) was calculated as the sum of muscular activation from all sEMG sensors, divided by a scaling factor.

After each training or competition session, players exchanged their worn pair of sEMG shorts for a clean pair to wear in the next training or competition session. Athos™ Core units were collected from each player upon the sEMG shorts exchange. Researchers washed the used pair, and this daily cycle continued each day to ensure players were continuously supplied with a fresh pair of shorts for the following session.

An instructional information sheet detailing the handling procedures of all the supplied materials was given to each participant. The instructions were also printed and displayed on the regular changing room wall which are summarised in Table 6.1.

Table 6.1 Fit and wear instructions for sEMG compression shorts.

Athos™ sEMG shorts Fit and Wear instructions

Before use

- Ensure your shorts are fitted tightly to the skin, not baggy anywhere. They may feel tighter than usual compression shorts.
- Wear your shorts without underwear to ensure each sensor can work effectively.
- You can wear your Basketball shorts to be worn on top of sEMG shorts.
- Ensure the Athos™ Core Unit is fixated into the allocated pouch and the blue light on the Core unit is flashing blue.
- Avoid lotions, creams and tape under the shorts.
- Ensure to insert the Core into the allocated pouch on the shorts until you hear a click.
- Data is being collected if the blue light is flashing on the Core unit.

After use

- Unclick the Core unit from the shorts by pushing the outer rubber positioned above the Core unit.
- Carefully remove the sEMG shorts and place into the individual fine-wash laundry bags and place on your dressing room bench.

6.3.3 Data collection

After each training session, the researcher collected all Core units, slotted them into the Athos™ Team Solution Docking System (Chapter 4; Figure 4.10) which automatically downloaded the sEMG data to the Online Training Centre (OTC) user interface which presented all sEMG metrics (Table 6.2) provided, including the Training Load metric. The sEMG metrics were summarised into a player report which was printed and displayed on the changing room wall every morning for the arrival of all players. The main purpose of the feasibility element of this study was to: 1) determine player adherence to wearing the sEMG shorts; 2) determine the rate of clean Training Load data, as well as lost data; 3) provide rate of lost data due to technological issues; 4) consider the procedural implications. Percentages were determined for categories 1-3. It's important to note, that this study only investigated the sEMG metrics and not the Motion Load, triaxial accelerometer data. Nevertheless, all metrics were presented to players in a daily report.

Table 6.2 Glossary of Athos™ metric calculations.

sEMG Metric	Calculation
Training Load	The sum of muscular activation from all sEMG sensors, divided by a scaling factor.
Intensity	Training Load/Sec of a session.
Acute: Chronic Training Load Ratio	The average training load of your acute load (7 days) is compared to the average training load of your chronic (28 load).
Anterior: Posterior Ratio	The sum of inner and outer quad training load divided by the sum of hamstring and glute training load. A value greater than (>) 1.0 is more anterior
Quad: Hamstring Ratio	The outer quad training load divided by the hamstring training load. A value greater than (>) 1.0 is more outer quad dominant while less than (<) 1.0 is more hamstring dominant. (Training load outer quads) / (training load hamstrings)
Glute: Hamstring Ratio	The glute training load divide by the hamstring training load. A value greater than (>) 1.0 is more glute dominant while less than (<) 1.0 is more hamstring dominant. (Training load glutes) / (training load hamstrings)
Left: Right Ratio	Percent difference between left and right muscle group, where left is the reference side. A positive imbalance has more training load on the left, a negative imbalance has more training load on the right.
Motion Load	Magnitude of the changes of the tri-axial accelerometer.

A qualitative approach was used to determine the acceptability of Athos™ sEMG shorts. Remote semi-structured scoping interviews were conducted with each player during April 2020. Interviews were conducted through Zoom™ (Zoom Video Communications) on a one-to-one interviewee-to-player basis (Irani, 2018). The interviews lasted 16-20 minutes in length and were arranged between 10:00 am and 13:00 pm. An individual Zoom meeting link was sent via email comprising a designated time slot for the interview. The researcher obtained verbal consent from each player to audio record (Zoom) the interview to permit speech-to-text transcribing, retrospectively. The players were informed that the interview recordings would be destroyed upon completion of transcription. The semi-structured interviews encompassed the following areas for questioning: 1) participant demographics; 2) experience of using sEMG shorts during basketball; 3) thoughts surrounding comfort/discomfort; 4) experience of the shorts when playing basketball; 5) thoughts on the sEMG feedback; 6) experience of handling procedures with the sEMG shorts; 7) suggestions and feedback for the Athos™ company; 8) thoughts on the management process of the sEMG shorts; 9) additional thoughts not covered about the sEMG shorts. Data were obtained through flexible open-ended questions, within the predetermined thematic framework and prompts were provided by the interviewer for clarification purposes, if necessary, and to allow the participant to explore different facets of the research question based on their thoughts, feelings, and beliefs towards the sEMG shorts. The interviewer followed previous guidelines in expressing non-judgemental responses to the interviewee for encouraging honest answers (DeJonckheere & Vaughn, 2019). A systematic approach to data analysis was adhered to when coding and analysing the data. Data analysis was conducted by the main researcher (KA) and cross-referenced by a second researcher (VP) to reach agreement. This included recognising and describing patterns, themes, and typologies across participants.

It is noteworthy that the coaches’ perceptions were considered for qualitative analysis. However, we found that this feedback might not completely align with the primary objective of evaluating the system's usability among professional athletes. Considering the coaches' perspectives could be seen as a potential next step or a separate case study in the broader exploration of implementing sEMG short in the sporting environment. For this study, our focus remained on assessing the system's direct usability and effectiveness from the athletes' standpoint, ensuring their experiences and insights were at the forefront of our analysis.

6.3.4 Qualitative Rigour

Guidelines for effective qualitative research were followed throughout the study period to improve the rigour and quality of data collected (Cypress, 2017; Thomas & Magilvy, 2011). Confirmability was obtained by keeping an audit trail in a journal, which was reviewed daily by both researchers to identify newly emerged themes relating to the sEMG equipment. This permitted reflexivity, and for improving the credibility and trustworthiness of interviewee responses when exploring different themes which might have emerged during the research process. To reduce biased responses from the participants they were asked for complete transparency and honesty as their responses should reflect their true thoughts, feelings and beliefs in answering each question. This was reinforced by advising participants not to appease the researcher (interviewer) because the sEMG technology was not theirs, but rather they were researching it and required true reflections. Participants were also reminded that their involvement in the study and their responses to questions would not be fed back to coaches and/or used for purposes of team selection.

6.4 Results

6.4.1 Feasibility

Results are stated in accordance to aim 1) determine player adherence to wearing the sEMG shorts; and aim 2) determine the rate of clean Training Load data. A total of n = 349 data points were included in the analysis, of which n = 296 were clean, usable sEMG data points, resulting in 82.1% of total data. A total of n = 37 training sessions was included in the analysis. The mean adherence rate for wearing the sEMG shorts was 97.6% throughout the study period. Noteworthy, one player did not adhere to wearing the shorts in n = 5 (13.5%) training sessions. In addition, two further players in one session each did not wear the sEMG shorts due to forgetting to apply them. Reasons are detailed in the interviews and discussed later.

The following results address aim 3) the rate of lost data due to technological issues. Poor skin-electrode contact quality resulting in unusable data, accounted for 8.1% of total missing data. Faults by players when applying the sEMG shorts (wearing boxer shorts beneath the garments), and faulty technological components (sensor depreciation, unit hardware damage or unit dropout) of the sEMG shorts resulted in 2.0% of missing sEMG data. Additionally, errors surrounding the syncing process (Wi'Fi signal loss or failed internet connection) of the sEMG data from the Athos™ Core units resulted in the omission of 5.4% of sEMG data.

The researchers journaled areas to consider when employing the wearable sEMG technology in sport, which addresses aim 4) consider the procedural implications. The results are as follows and discussed in more detail in the discussion sub-section titled, *Procedural Implications*.

Researchers using the wearable sEMG technology in sport should:

1) Ensure appropriate fittings for higher quality electrode-skin contact.
2) Frequently address the procedural implications to the players for appropriate application of the textile sEMG shorts.
3) Consider the time it takes for the unit collection process, downloading and reporting data when devising standard operating procedures.
4) Consider the differences in presenting sEMG data to the coach and players. The data are context specific, e.g. an injured player compared to a non-injured player.
5) Be aware of the sEMG preparation and handling care procedures. Each player having two pairs of sEMG shorts makes this process more time efficient.
6) Check quality of sEMG sensors frequently
7) Position the team Hub to acquire strong WiFi and internet connectivity. Internet connectivity is essential for backend data processing.

8) Consider the internet speed for downloading data.
9) Be aware of the time sEMG calibration protocols take, and how often they should be performed.

6.4.2 Qualitative

A thematic analysis was performed post-transcription of the interviews to denote the perception of players using the Athos™ apparel. Six central themes arose from the semi-structured interviews: *comfortability, feedback, technical improvements, perceptions on effects on performance, effects on motivation and would/would not use again*. Sub-themes under each central theme are organised as general responses (endorsed by 87.5-100% players), typical responses (endorsed by 50-75% players) and variant responses (endorsed by 25-37.5% players). Table 6.3 outlines a summary of the player responses within each of central theme and sub-themes which arose from the analysis.

Table 6.3 Summary of central themes, sub-themes and responses based on findings from semi-structured interviews in professional basketball players on the use of sEMG-based compression shorts.

Central Theme	Sub-theme	Response	Paraphrase
Comfortability	The sEMG shorts are comfortable	General	*“Felt comfortable”* *“Felt like normal compression shorts”* *“They feel great, and they were breathable”* *“Didn’t notice a difference compared to under shorts”* *“They felt good”* *“I liked how they felt, man, like they were just normal for me”* *“Overall, they felt comfortable enough”*
	The sEMG shorts are tight	Variant	*“Tight around the bottom of my thighs”* *“They felt a bit tight at the start but were fine”*
sEMG Feedback	sEMG feedback validates effort	Typical	*“Confirmed that I was working hard”* *“The coach could see how hard I worked with my Training Load”* *“They showed, umm, shorter training sessions were sometimes harder than longer sessions, which I felt too”* *“I saw how intensity and volume differences can change my Training Load”*
	sEMG data highlights muscle (a)symmetry	Variant	*“It found muscles which needed improvement to prevent injuries”* *“I used the feedback to help my hamstring activation which was low compared to my quads”* *“I like how it provided muscle ratios to see my imbalances”*
	sEMG data is difficult to interpret	Variant	*“I didn’t really understand it”* *“Hmm, it was tricky to get my head around the ratios”*
Technical Improvements	Core unit improvements	Variant	*“Could maybe make the unit slot more stable?”* *“Could make the unit smaller”* *“forgot to check the blue light, so they could maybe make a sound instead?”*

	No improvements	Typical	*"They don't need improved"* *"I thought they were 100%"* *"Can't think what I would make different"* *"Nothing really needs improved"*
Perceptions of effects on performance	sEMG shorts improves performance	Typical	*"It helped my basketball man, I always wanted higher numbers."* *"The fact I knew my weaker muscles, meant that I could work on those areas, so yeah, like, I think it helped my performance"* *"They increased my effort and probably improved my performance, like maybe that was psychological, I don't know"* *"Helped my basketball"*
Effects on Motivation (psychological)	sEMG Training Load increases motivation	Variant	*"It actually motivated me to have better scores than the others, and so that the coach could see it as well"* *"I always wanted to make my ratios better, so that motivated me a fair bit"* *"They increased my effort"*
Would (not) wear again	Would wear again	Typical	*"I'd wear them again in training"* *"I'd wear them again if the club continued to use them"* *"I would love to keep wearing them"* *"I liked them, so yea I'd use them again"* *"I'd like to wear them for longer"* *"Yea bro, I could wear them again"*
	Would wear in strength (gym) training	Variant	*"I would wear them in the gym"* *"It would be interesting to wear them in the gym and see my stats"*
	Would not wear again	Variant	*"Nah, I probably wouldn't wear them again, man"* *"I'd say it's 60/40 that I wouldn't wear them again"*

Note. General indicates responses from 7–8 participants (87.5–100%), Typical indicates responses from 4–6 participants (50–75%), and Variant indicates responses from at least 2 but not more than 3 players.

6.4.2.1 Comfortability

All players commented on the comfortability of the sEMG shorts. Interestingly, most players responded to the first open ended question in the interview by reporting on the comfortability of the sEMG shorts. Two sub-themes arose from the results, comfortability (general) and tightness (variant).

sEMG shorts are comfortable - (*General response)* - Player responses in this general sub-theme included: the shorts were easy to wear, felt comfortable and were like normal compression (base-layer) shorts. Eighty-three percent of the players presented positive experiences towards the comfort of the shorts. One participant explained the following:

> *"Yeah, they just felt normal, I didn't notice a difference compared to the under shorts I usually wear".*

When asked what he meant by normal, he replied,

> *"Like, I always wear Under Armour or Nike tight shorts under my basketball training shorts, and they felt… like no different to them, maybe slightly thicker, but I never noticed them on me or anything… I actually liked them because they were breathable around the insides of the legs."*

sEMG shorts are tight - *(Variant response)*. Only one participant expressed their experience based on the tightness of the shorts around the lower part of their thigh. Yet, they understood the value of this, and it would not deter them from wearing them again.

> *"So, yea, I wore them regularly throughout the week. Umm, I thought the shorts were comfortable once you got them on, sometimes they were tricky to put on because they were tight around the bottom of my thighs, but obviously they needed to be for them to work. Umm, other than that I thought they were comfortable once you got used to them, it's just like another pair of new trainers really."*

Only one player endorsed “stickiness” as a response, thus it did not meet the criteria for a variant response. However, this was an interesting response which was brought to light and deemed appropriate for mentioning. The player said,

> *“Also, like whenever I put them on the sensor things on the inside kept pulling the hair on my legs, because they were rubbery and a bit sticky or something.”*

6.4.2.2 sEMG Feedback

Most players experienced the sEMG data feedback to be helpful. Some found that the sEMG Training Load validated their effort in training (typical), while others found it useful to find out more about their muscle symmetry (variant). While one participant did not find the sEMG feedback helpful as they did not understand it (variant).

sEMG Training Load validates effort - *(Typical response).* Players expressed that sEMG Training Load validated their effort on court, the sEMG Training Load data can differentiate between more intense and less intense sessions and the coach might see how hard they actually work. For example, a player described,

> *“I thought as well, the training load data was helpful and kind of showed us how hard each session was and it kind of confirmed that I was working hard because sometimes I felt like the coach didn’t think I was.”*

sEMG data highlights muscle (a)symmetry - *(Variant response).* Two responses were reported within this sub-theme. Players identified areas which may be more predisposed to injury, and sEMG data provided information about potential muscle imbalances. One player commented,

> *“Yea, like it helped me identify areas which I needed to work on. I used the feedback to help my hamstring activation was low compared to my quads. My previous injuries must have led to that muscle imbalance, which I found interesting. And the coach helped me work on exercises to improve that and prevent another injury in my hamstring which I did a while ago.”*

sEMG data is hard to interpret - *(Variant response).* Two players indicated a lack of understanding around the sEMG feedback. One player did not understand most of the metrics except for Training Load while another player highlights how it was tricky to fully understand:

> *"I know it found muscles which needed improvement to prevent injuries, but… umm I found like, the muscle ratios tricky to fully understand, y'know, but I always try to look into things too much.*

6.4.2.3 Technical Improvements.

Two sub-themes were established based on future suggestions for the sEMG shorts. These sub-themes incorporated the current players total acceptance of the current technology, while the other was based on a few technical improvements to the Core unit.

Core unit improvements - *(Variant response).* Responses in this sub-theme resulted in players highlighting aeras of improvement for the Core unit, as well as the allocated slot in which the Core is fixed into place on the outer right-side leg of the shorts. A player commented,

> *"The wee unit got knocked out sometimes during contact which disturbed practice, because Coach stopped whatever drill we were doing at the time, for a few seconds until I put it back in. So, they could maybe make the unit slot on the shorts more stable?"*

Another stated,

> *"It's easy to put the unit in and out like. Umm, I'm not sure if it would be possible, but they (Athos) could make the unit a bit smaller cause I fell on it once and it dug into my leg."*

No improvements - *(Typical response).* This sub-theme entailed four responses about the current technical proficiency of the shorts, as no technical improvements were recommended, for example, one player said,

> *"They did a good job. I don't really have other suggestions to give to be honest, man. They don't need improved in my opinion.*

6.4.2.4 Perceptions of the effects on performance.

Half of the interviewed players perceived the sEMG shorts to positively benefit their performance, either directly or indirectly. This led to this central theme, and one sub-theme (typical response), sEMG shorts improve basketball performance.

sEMG shorts improve basketball performance - *(Typical response).* Players provided perceptions based on the benefits of wearing the sEMG shorts when playing basketball. While players could not directly provide evidence for the improvement in basketball, they perceived the sEMG shorts to either directly or indirectly improve their performance. One player indicated a direct effect of wearing the shorts on their performance, responding to the first interview question,

> *"I liked them. You know, they were good on me, like I didn't notice them on when playing ball. Umm, I thought it helped my basketball, man, cause like I always wanted to have better numbers, so it made me work harder."*

When asked, "*what numbers do you mean?*" he said,

> *"Like umm, the Load it gave us."*

Another player commented on an indirect positive effect of wearing the shorts on their basketball performance,

> *"I thought they were very beneficial. Cause they could find out the weak points in my body, and you could tell, you could see over a long period of time how I made progress, which helped my basketball, for sure."*

Another response was not included in Table 1, as it was only endorsed by one player, though interestingly they believed the shorts restricted their movement and thus negatively impacted their basketball performance, stating,

> *"Honestly bro, I didn't really like them. I felt like they, uhhh… like restricted me from playing my best."*

6.4.2.5 Effects on motivation

This central theme was presented in the data, some players commented on the impact the sEMG data had on their motivation to intrinsically work harder by improving their own sEMG feedback. In addition, the sEMG data feedback motivated the players to work harder because they knew the coach would see their data, posing as an extrinsic motivational factor. On the other hand, while it was not endorsed by more than one participant, one player found it demotivating for them when the coach reviewed their sEMG stats.

The shorts motivated me to work harder - *(Variant response)*. Two players indicated how wearing the shorts motivated them to play harder during the training sessions

> *""It actually motivated me to have better scores than the others (players), and so the Coach could see them as well, so I think it pushed me in this way"*

Another player stated how it negatively affected his motivation, saying,

> *"I didn't like how Coach would always see my stats, because mine was always lower than the other players, but that was because I was coming back from*

> *injury, I mean that sort of… like it sort of demotivated me… or more, frustrated me at times.”*

6.4.2.6 Would/ would not wear again

Two players reported that they would *not* use sEMG shorts again, while the majority said they would use sEMG shorts again, and in a gym (strength training (environment). The players responses were categorised into the following three sub-themes.

Would wear again - *(Typical response)*. Most players said they would either continue to use them in basketball training or would use them again in a basketball context. One player explained how he would continue to use them in basketball, but they would wear a longer pair of shorts to the ankle for more data on the lower limb, for instance,

> *“I’d love to keep wearing them. Another thing is that I would really like to see the data from a longer pair of shorts, in my eyes as a player the more data we have on our bodies the better… If I had the chance to wear them again, then yea I would like that. And umm… if I could, I would wear them in the gym too to see different activation patterns during those sorts of exercises.”*

Would wear in strength (gym) training - *(Variant response)*. Two players commented on how they would like to see their stats in a strength training (gym) context. One player said,

> *“I’d like to them for longer next time. It would be interesting aswell to wear them in the gym and see my stats from those sorts of exercises”*

Would not wear again – *(Variant response)*. Two players reported that they would not wear them again, one player was more strongly positioned towards not wearing them again than the other player, for example, one player said,

> *“You know I appreciated them, man… but, Nah I probably wouldn’t wear them again, man. It’s just the fact that I felt restricted”*

6.5 Discussion

This is the first observational and qualitative study to investigate the feasibility and acceptability of wearable sEMG technology as a potential player load monitoring system in professional sport. Key findings demonstrate a very high adherence rate to wearing sEMG-based compression shorts in professional, male basketball players. A mix of technological and hardware issues in the sEMG shorts and errors made by players in applying the sEMG shorts resulted in the omission of 17% of collected data. Qualitative analysis performed on recorded semi-structured interviews with the basketball players revealed six central themes based on their interaction and experience of using the wearable sEMG technology in training. This study elucidates implications of using sEMG compression shorts within a professional basketball environment and will discuss the integration of the key findings with current literature.

Feasibility

Players exemplified a very high adherence rate (97.6%) to wearing the sEMG shorts over the course of the observational period. A review, incorporating insights from over one-hundred strength and conditioning coaches (S&CC) working within collegiate and professional levels, states mixed compliance rates to wearing devices in sport (Luczak *et al.*, 2020). However, Luczak *et al.* (2020) fails to report quantitative data to support the coaches claims, making comparisons to this study difficult. Perhaps, the mixture of coaching levels (colligate and professional) results in mixed opinions and beliefs about why some players do and others do not wear the shorts. For example, collegiate players do not get paid for their sport, which might reduce the external motive to adhering to wearing the shorts, unlike the players in this study who were professional level. S&CC explain how comfortability, material quality, effects on performance, personal motivation, as well as cultural reinforcement into the importance of wearable technology are all factors which contribute to compliance rates in wearing devices amongst athletes in sport (Luczak *et al.*, 2020). Few studies report professional athlete adherence to wearing devices, largely attributable to more investigative studies and fewer observational approaches undertaken by researchers in this area (Cardinale and Varley, 2017; Aroganam, Manivannan and Harrison, 2019). What's more, as most professional sporting organisations already incorporate wearable technology for athlete monitoring, establishing a sense of normalcy to wearing it in training and competition. Thus, professional athletes might consider wearing devices as a staple part of their job, which ultimately increases accessibility to investigative research using wearable devices. With such a lack of research in the field of professional sport, comparisons with wearable fitness devices in the general population could provide some comparable findings based on the qualitative findings which are discussed in the qualitative sub-section of this discussion.

Two factors, which might contribute to higher adherence of wearing smart devices during physical activity, can be drawn from existing research. Mansfield et al. (2016) indicates higher compliance rates to wearing accelerometers (>80%) compared to heart rates monitors (34%) each day, over a six-week period in stroke patients' rehabilitation phase. Mansfield *et al.* (2016) stated that compliance to fitting the heart rate monitor strap appropriately would likely have been improved if daily reminders and instructions were provided to the participants to prevent improper wear. The current study provided participants with daily reminders, instructions and prompts to wearing the sEMG shorts, which could have contributed to the high adherence rate (2% missing data). Lewis et al. (2020) found in an online survey with adults who possess their own wearable fitness device(s), that general health information reported by the wearable devices during physical activity and sport, as well as motivational cues, because of the information, are two of the most important factors which contribute to better compliance in wearing devices. As the current study incorporated the sEMG technology for athlete load monitoring, the coaches and participants were given daily feedback based on each training session they performed while wearing the sEMG shorts. This might have increased the participant's internal motivation and will be discussed in more depth within the *Qualitative Understanding* sub-section.

Overall, 82.1% of sEMG data were determined usable following Athos™ backend data processing. In total, 17.9% of missing data were because of mistakes made by players when applying the sEMG shorts, faulty technological components, poor skin-electrode contact quality, and errors arising from data syncing procedures between the Core unit and Athos™ hub or Online Training Centre (OTC). The OTC is an online cloud-based platform which stores the sEMG data and presents the data to the practitioner. Textile sEMG conductive electrodes are disadvantaged compared to wet electrodes due to missing gel. This can result in inadequate skin-electrode contact quality, lead to a weaker or disturbed electrical signal which does not reflect the true electrical response from the working muscle. The poor electrode-skin contact quality can often be mitigated by local perspiration to act as an electrolyte or by manually adding pressure to the electrode to increase electrode-to-skin contact quality (Guo et al., 2020). The missing rates of sEMG data in the current study is somewhat similar to previous research which investigates data loss from wearable devices in sport. For example, heart rate sensors inherit similar errors to sEMG sensors when assessing the cardiovascular electrical signal, resulting in data errors of up to 30% during exercise (Bent *et al.*, 2020), approximately 12% more data lost than in the present study. Likewise, external measures such as GPS, also exhibits similar rates of missing data of between 9% and 20% due to typical faults made by players when wearing the devices and technological errors in using GPS during team sport (Colby *et al.*, 2014; Hoppe *et al.*, 2018). Although not specified in the current literature, GPS devices are required to be turned on through a button and can sometimes be accidently turned off through sport by unintended contact to the button, or by the practitioner not turning on the device appropriately before supplying the player. The Athos™ Core units in the current study do not require being turned on, and thus may be advantageous in this respect.

Qualitative Understanding

It is common for coaches to enforce wearing load monitoring devices as a non-negotiable in professional sport. Thus, player perceptions about the technology is important for coaches to know as it could help explain resistance to wearing the technologies in sport (Havlucu et al., 2017). Additionally, providing players more autonomy can positively shift behaviours to where players feel their choices are more authentic, this increases long-term buy-in and could improve adherence to wearable devices in sport. A shift in the research to this more co-design approach, or by giving players a choice is warranted. From the qualitative analysis via semi-structured player interviews, six overarching central themes were established: comfortability, feedback, technical improvements, perceptions of effects on performance, effects on motivation and would/would not use again. Each theme will be discussed according to the current literature.

All players identified comfortability of the sEMG shorts as a key topic when reviewing their experience and interactions with the technology. As previously mentioned, comfort for wearable devices is one of the most critical factors for increasing player adherence to wearing devices in sport (Luczak *et al.*, 2020). Most players indicated that the sEMG shorts were comfortable and not unlike many other base layer clothing products used in sport, such as Nike^{TM} and Under Armour^{TM} products. Optimal clothing pressure for obtaining comparable sEMG signal to a standard grade Ag/AgCl electrode is above 10 mmHg (Kim, Lee and Jeong, 2020). Commercially available compression garments for the lower limb range between 10-20 mmHg (Hill *et al.*, 2014). Meanwhile, An et al. (2018) reports an optimal clothing pressure of 30 mmHg as participants began to feel uncomfortable at 30 mmHg. On this note, two players in the current study endorsed the sEMG shorts as feeling tight. While it is necessary for sEMG-based compression shorts to be tight to reduce noise and motion artefact, the present study did not account for the pressure of the sEMG shorts, this should be a future consideration for future research on sEMG within sport. This subjective feedback can vary between players.

Regarding sEMG feedback from the technology, players indicated the sEMG Training Load feedback is useful in validating their effort and work output in training, consistent with previous research based on the association between the rating of perceived effort (RPE) scale and sEMG (Fontes *et al.*, 2010; Cruz-Montecinos *et al.*, 2019), as well as energy expenditure, HR and sEMG (Tikkanen *et al.*, 2014). Players reported how their data could be observed positively by their coach, thus players may have modified their behaviour in response to their awareness of the coach seeing their sEMG feedback, something referred to as the Hawthorn effect. This might have reinforced their compliance to wearing the sEMG shorts. On the flip side, two players did not fully understand the sEMG metrics, consequently they may de-value the technology compared to teammates, as it has previously been established that informative feedback is the single most important variable to improve engagement with the wearable technology. In addition, some players valued how they could learn about their bodies, by identifying muscle asymmetries using the specific sEMG ratios (Table 6.2). Players who are invested in improving longevity in their sport, would see this as advantageous as muscle asymmetries could increase the likelihood of injuries such as ACL ruptures and hamstring strains (Hewett *et al.*, 2005; Liu *et al.*, 2012; Zech and Wellmann, 2017). Future research could investigate the sEMG ratios, and their validity in injury surveillance. This type of feedback could potentially reduce soft tissue injury rates, save professional clubs money, and improve the rehabilitation process (Shenoy, 2010).

Most players perceived the sEMG shorts to be technically sound, requiring no alterations or modifications. That said, three players did comment on how the sEMG technology could be improved. Most importantly, one player discussed an element of the sEMG shorts which concerned their safety. They noted how falling on the Core unit hurt their quadricep, so advised on making the unit smaller. Coaches ought to consider the nature of the sport, the shorts in this instance are likely not suitable for contact-based sports, such as rugby or martial arts, where the quadricep is typically a targeted area (Brooks *et al.*, 2005; Ji, 2016). Another player mentioned how the coach had to pause training because their unit fell out of the shorts pouch. While it only occurred once during the study period, coaches should consider this technological fault when monitoring important parts of training. Coaches may require assurance that units will remain attached during training drills and matches so there is minimal disruption (if units were to fall out and require reattachment).

Direct and indirect positive effects of the sEMG technology on the players basketball performance were observed. Some believed it directly improved their performance, yet the technology is not a performance aid, as such. Albeit, a placebo effect has been shown to increase athletic performance, in that if the players *believe* they are administered a performance aid, it relates to enhanced and sport performance (Beedie, 2007; Roelands and Hurst, 2020). Others used the sEMG feedback to identify and thus be to work and improve their body's weaknesses, which indirectly helped them perform better. In summary, we could hypothesis that sEMG technology positively impacts players perceptions, ultimately improving their performance.

Intrinsic motivation and perceived trust of wearable device feedback are predictive factors for continued use of the technology (Rupp *et al.*, 2016). One player who found the sEMG feedback disheartening because of their lower sEMG Training Load compared to their peers found the technology de-motivating, especially because the coach could see their metrics. This player was injured, which likely attributed to a lower Training Load. For this reason coaches should be aware that the sEMG feedback is context specific and unique to the individual, thus should not in compare to other players, similar to HR and sRPE internal load measurements (Bartlett *et al.*, 2017). Meanwhile, more players found the sEMG technology intrinsically motivating. Identified Regulation (Dei and Ryan, 1991) is a type of motivation that reflects reasons for behaviours to be associated with a person's values and important to their personal goals and this seems to be what best represents what is shown in the present study. This type of intrinsic motivation appears to improve performance even when the players still have the same level of competence (Arribas-Galarraga *et al.*, 2017). True intrinsic motivation is the most self-determined form which can lead to adopting positive behavioural changes, such as engagement and wellbeing (Lonsdale, Hodge and Rose, 2008). One player commented on how the short restricted their body movement resulting in negative impact on basketball performance. This was the same player who did not wear the shorts for five sessions in total and commented on the tightness of the shorts. Coaches should be aware of the subjective responses to wearing the shorts.

Overall, 75% of players said they would use the technology again during their basketball training. This demonstrates a high level of acceptance amongst professional athletes. Ease of use and comfortability, the beneficial perceptions of the effects on performance, as well as the increased motivational aspects to training as a result of wearing the sEMG shorts likely attribute to these findings. Importantly, the two players who would not wear the shorts again, are those who found the sEMG metrics de-motivating as the coach can see how their metrics might be lower than teammates, while the other player found the shorts restrictive.

6.4.3 Procedural Implications

Noted in the results section of this study, the researchers journaled procedural implications for using the wearable sEMG technology. For practitioners wishing to adopt a wearable sEMG system for the intention of load monitoring in professional sport, the following will provide potentially insightful information to consider before implementation.

It is recommended that all players anthropometrics, such as height, body mass, lower limb length and waist circumference are measured correctly and the sEMG shorts are fitted accordingly. Motion artefacts resulting from electrode-skin displacement can negatively impact the feasibility of the shorts during sport, thus the sEMG shorts should be tight to the skin to encourage best electrode-skin contact. In addition, frequently addressing the procedural implications to the athletes increases player adherence to wearing the sEMG shorts appropriately and reduces the likelihood of faults due to inappropriate application ultimately leading to data errors.

If accessible, a changing room is convenient for practitioners to collect used shorts and Core units from all players in exchange for a clean pair of sEMG shorts the following day. The sEMG shorts require a cold machine wash and air dry overnight, thus having two pairs of shorts in rotation for each player is an important consideration, especially as professional athletes can train up to two times per day. Moreover, professional teams which do not have a kit manager or a venue without washing machines should re-consider their use. Noteworthy, is the 90-day warranty of the shorts, their life expectancy is somewhat lower than other load monitoring approaches due to regular washes. Thus, frequent sEMG sensors checks for signs of deterioration is necessary.

Although not documented in the current study, data downloading from the units to the OTC requires a fast internet speed to increase the speed of this process. The researchers downloaded the data and reported to the players and coach the following morning. Twice, the internet dropped out resulting in lost data. Additionally, it took several hours for all data to appear on the OTC, unlike the Sonra 4.0 StatSport GPS units take <2 min to download a full team 2 hr training session and provide within-session live feedback. Thus, the wearable sEMG system used in this thesis it would not be suitable for coaches who desire immediate feedback on the training session. That said, sEMG data should be reported to player and coaches on the individual level, and not compared to team members due to the internal nature.

Prior to monitoring any activity, a 5-min sEMG calibration protocol for each player is required to establish sEMG amplitude thresholds relative to different muscular contraction intensities. Coaches must consider the additional time and manpower this requires, especially in team sport, before using the technology. Another consideration is how often this calibration should be completed. In the present study, the sEMG calibration protocol was only performed once, which might be suboptimal as sEMG amplitude and frequency characteristic have been shown to change because of muscle adaptions and changes in muscle recruitment patterns due to training (Oliveira and Gonçalves, 2009). Future research might want to allow time for weekly calibration with their athletes, although a daily procedure would be optimal as residual fatigue (central and peripheral) could affect the muscles efficiency and consequently alter the electrical activity of the muscle and thus EMG trace (Doud and Walsh, 1995). Daily sEMG calibration could help off-set some of the effects of residual fatigue by individualising the sEMG MVC thresholds each day, which would likely provide more accurate data. In addition, coaches should be aware of calibration protocol limitations. Research has shown that dynamic ballistic complex sports movements can exceed the 100% MVC by as much as 160% and 226% of MVC (Clarys *et al.*, 1983; Jobe *et al.*, 1984). In this manner, setting sEMG thresholds based on %MVC might be best performed using sport specific movements.

6.6 Limitations

While this two-part feasibility and qualitative study provides practitioner and athlete perspectives on the practicality and usability of a wearable sEMG system in professional sport for load monitoring purposes, it is possible that semi-structured interviewing failed to uncover additional information from the athletes on their experiences of using the sEMG compression shorts (DeJonckheere and Vaughn, 2019). Often interviewers may not probe for answers effectively, listen to interviewee responses or correctly formulate an appropriate follow-up question(DeJonckheere and Vaughn, 2019). On this note, a question to obtain information on the novelty of wearable devices from the players could help explain the high adherence rates observed in this study. Those of have previously not worn devices in sport, might appreciate the technology more than those who have in the past. For example, according to (Berlyne, 1970), novel stimuli promote enjoyment and interest, while novelty has been stated as one of the Basic Psychological Needs (Bagheri and Milyavskaya, 2020). In this sense, novelty of wearing the sEMG shorts could promote participation in wearing the sEMG shorts (Shin *et al.*, 2018).

In retrospect, the study could have investigated the average time of data syncing. In professional sport, immediate or time-efficient reporting of player load data is sought after by practitioners and coaches. In intensive competitive periods, like the play-offs in basketball, the need to make player changes, implement specific recover techniques and to rest certain players can be decided using certain training load parameters (Halson, 2014; Akubat *et al.*, 2018; Wiig *et al.*, 2019). Yet, making informed decisions based on training load measures to influence training and recovery practices is best done as quickly as possible to optimise the time required to elicit the desired outcome (Wiig *et al.*, 2019). This should be a focus point for future research using sEMG shorts in professional sport.

During the semi-structured interviews, we encountered certain challenges related to terminology when posing questions about the sEMG technology to the participants. Our participant group consisted of players from America and Eastern Europe, with varying levels of English proficiency. As a result, some responses were brief and lacked the depth of opinion and information we were seeking. To mitigate this issue, we took proactive steps by providing additional prompts and offering suggestions based on our interpretation of their intended responses, subsequently seeking their confirmation. Moving forward, it is important for researchers to consider such cultural and language-related factors when conducting focus groups with mixed cultural basketball teams. While our cohort managed without the need for a translator, having one present in future studies could potentially facilitate stronger and more comprehensive feedback from participants, ensuring a richer understanding of their experiences and perspectives on the sEMG technology in sports which have a diverse participant pool.

Lastly, while it was not the purpose of this study, an investigative study is warranted on the sEMG Training Loads within the context of training drills, and to compare differences, similarities, or relationships with other internal load measurements, such as HR and sRPE during the competitive season. By improving study deign characteristics, might help practitioners determine the practical value of implementing the sEMG system into their training environment. Based on previous research using GPS and HR load parameters, the sEMG system could potentially provide coaches with a better understanding of how to analyse and apply the sEMG data for load monitoring purposes, or even to monitor the effectiveness of training for improving cardiovascular fitness (Berkelmans et al., 2018; Schneider et al., 2018; Owen et al., 2020; Ravé et al., 2020).

6.7 Conclusion

For the first time, a wearable sEMG system, employing sEMG-based compression shorts, demonstrates encouraging outcomes in terms of practicality and usability within the realm of professional sports. These results hold significant promise for effective load monitoring applications. Most players perceived the technology useful and exemplified high adherence rates to wearing the sEMG shorts during a basketball season. The sEMG shorts are relatively easy to use, which enhances their accessibility to potential users. Ease of use, benefits on basketball performance, and novelty of the sEMG shorts, are all factors which might increase intrinsic motivation, and thus enhance adherence to using the sEMG shorts amongst basketballers. Caution should be taken when presenting and feeding back recorded sEMG data to players and coaches, as this could negatively influence the players behaviours towards using the sEMG technology. Additionally, while the wearable sEMG technology provides similar clean data to other load monitoring approaches, the time taken to collect, download and report data may be somewhat slower than other load monitoring systems used in sport. In total, seventy-five percent of professional basketball players reported they would use the sEMG shorts again in training, which demonstrates a high level of acceptance amongst professional basketball players in the field of load monitoring in sport.

Chapter 7 Thesis summary

The objective of this section is to examine the current findings and assess them within the context of the initial aims and goals of the thesis. Moreover, this segment will offer practical implications, with a specific emphasis on how the research outcomes hold relevance for professionals engaging with professional basketball players and load monitoring. Furthermore, a discussion into the strength and limitations of the cumulative research will be undertaken, followed by proposals for prospective research surrounding the wearable sEMG athlete monitoring system.

7.1 Summary of Aims and Objectives

In the realm of sports performance monitoring, the global smart clothing sector (embedded sensors into clothing) is forecast to reach an immense value of $4Bn in 2024 (Hanuska *et al.*, 2016; Luczak *et al.*, 2019). This market inversely relates to the ever-increasing money loss professional sport organisations incur due to athlete injury, especially in highly valued professional leagues like the English Premier Soccer League and National Basketball Association (Lewis, 2018; Eliakim *et al.*, 2020). Professional basketball is a physically and mentally demanding high-intensity intermittent sport, whereby players can frequently experience competing as many as three times per week. However, the load imposed on players during training is as a modifiable risk factor, and according to the scientific literature, appropriate prescription and monitoring of the load inflicted on players during basketball training could potentially reduce the likelihood of soft tissue injury, improve player wellbeing, and even increase player performance (Impellizzeri, Marcora and Coutts, 2019). Currently, a plethora of load monitoring approaches is employed in basketball to measure different athlete internal and external load metrics, including heart rate monitors, accelerometers, GPS devices and time motion capture systems. Each method involves capturing different parameters of load placed on the athlete, for instance HR monitors objectively captures the physiological response specifically from the cardiovascular system, while the RPE method records a psychophysiological response (Impellizzeri, Marcora and Coutts, 2019).

Leading researchers in the field of athlete load monitoring recommend internal load to be used as a primary measure as it accounts for the individual response to the imposed demands (Impellizzeri, Marcora and Coutts, 2019). Internal loads in basketball can be assessed through methods such as HR monitoring, as well as the sRPE method (Vaquera Jiménez, 2008; A Moreira et al., 2012; Haddad et al., 2017; Berkelmans et al., 2018). However, the sRPE method poses problems in accounting for load during specific time frames of a training session due to the lack of feasibility in the data collection process. In addition, aggregating load over multiple training durations likely disguises the true nature of the internal load placed on the athletes (Weaving *et al.,* 2020). For example, training for 5 minutes at an RPE level of 10 produces the same sRPE as training for 50 minutes at an RPE of 1.

With the existing expansion of the wearable technology industry in sport, and the combined curiosity from athletes, coaches and researchers in trying to build a holistic view of the athlete's response to training has led to the emergence of wearable sEMG. Surface-Electromyography was first introduced in the 1960s when Hardyck and his researchers were the first (1966) practitioners to use sEMG to record laryngeal muscles activity to detect subvocalization while reading (de Luca, 1997; Reaz, Hussain and Mohd-Yasin, 2006). However, recently sEMG electrodes has been integrated into clothing, known as textile sEMG electrodes. sEMG-based compression shorts, used in this thesis, can monitor muscular electrical activity during exercise. To date, there has been little research into the internal load metric (sEMG Training Load) which the sEMG shorts captures. In addition, no research up to this point on the feasibility and acceptability of sEMG shorts in professional sport has been published. Until lately, wearable sEMG was more commonly employed in health and physical activity related studies (Finni *et al.*, 2011; Tikkanen *et al.*, 2015; Pesola *et al.*, 2016; Bengs *et al.*, 2017b; Gao *et al.*, 2019). However, wearable sEMG has recently gained traction in the sport industry posing as a possible athlete monitoring system for obtaining data to examine muscle electrical activity, functional status of skeletal muscle as well as internal load. Two forefront companies, Athos™ (Redwood City, CA, California) and Myontec™ (Kuopio, Finland) retail wearable sEMG compression shorts as athlete monitoring systems. This potentially new objective internal player load monitoring system accounts for the muscular, or biomechanical load, imposed on players and can fill gaps in accounting for parameters of load which current methods do not capture. This is exemplified in the current thesis findings, in particular Chapter 5, which shows the distinct internal parameters due to the variance in associations between HR, sRPE and sEMG loads compared to oxygen consumption during running.

Thus, the overarching aim of this thesis was to investigate the feasibility and acceptability of a novel wearable sEMG system in a professional basketball environment for monitoring athletes' internal load. This was achieved through examining the sensitivity of the sEMG-derived Training Load in lab-based exercise protocols, and then applying the system into the real-world basketball environment. More specifically this was systematically performed through four separate investigates (Chapters 2, 3, 5 and 6) which are summarised below:

Study 1 (Chapter 2) explored the current landscape of commonly employed internal and external load monitoring approaches in professional male basketball, as well as presented internal loads which are reported by professional players and teams. Results revealed the sRPE method is the most popular internal load method used for capturing internal loads, while inertial measurement units are favoured for monitoring external load in professional male basketball. A large variability in the internal and external loads reported in the literature was largely dictated by the different training volumes and training load prescriptions adopted by coaches across different leagues. A variety of internal and external load approaches are employed in professional basketball. While this is an essential step to understanding the landscape of load monitoring approaches currently used in basketball and the resultant load outcome measures, there is little similarities between the internal and external loads reported. This makes it difficult for practitioners to compare loads and strategies used to best periodise load. In addition, different loads are apparent because of the coaches weekly training strategies being different from one another. It should be noted that there is a large amount of research conducted in professional Spanish basketball players, thus bias may be present in the findings.

Study 2 (Chapter 3) examined the internal loads experienced by professional male basketball players throughout an entire season within the British Basketball League (BBL). Results revealed the preseason is the most demanding phase of the season, where players experience greater Weekly Loads compared to the in-season phase attributed to greater training volume experienced by players. Total Weekly Loads (competition and training, combined) is significantly greater during 1-game versus 2-game weeks, whereas Weekly Load (training, only) is higher in 1-game weeks compared to 2-game weeks. In addition, starters experience greater Total Weekly Loads compared to bench players. Lastly, the sRPE is a valid and reliable, global measurement to assess the internal load for a full training or competition session but is likely not suitable for capturing internal loads during specific parts of training or gameplay. The author of the present study stresses that these findings are the first to be conducted outside of mainland Europe, and while comparisons can be made between studies, it is important to remember that all coaches adopt different strategies to periodise training. As an observational study, this is common place in professional sport. Lastly, it is encouraging to find similar results relating to the lower training loads reported by bench players compared to starting players. These results, along with similar findings from studies () can help to inform coaches about the need for extra metabolic conditioning (load) for these players, to could help them to stay aligned with the fitness of the starting players.

Study 3 (Chapter 5) examined the novelty of wearable sEMG-derived Training Load during controlled, dynamic exercise in a lab-based environment. Results revealed a significant weak positive correlation between $\%\dot{V}O_{2max}$ and sEMG Training Load during a standard grade incremental $\dot{V}O_{2max}$ test in the composite data. However, significantly strong relationships for eight out of ten participants at the individual level was found between sEMG Training Load and $\%\dot{V}O_{2max}$. Moreover, the sEMG Training Load is a sensitive metric in detecting small 2 $km.h^{-1}$ changes in running velocity (exercise intensity). The sEMG Training Load can capture isometric contractions during graded sloped running, unlike external measures such as accelerometry PlayerLoad™. The sEMG Training Load displays promising results for monitoring athletes internal load in the sporting field which requires demanding movement patterns, including isometric contractions during change of direction movements and sport specific techniques, like screening in basketball. To gain a fully comprehensive understanding of athletes' load by capturing biomechanical (muscular) measures through sEMG, subjective psychophysiological measures, like sRPE and objective physiological measures, such as HR, is imperative to draw a picture of the different loads experienced by participants during exercise. Like all internal load measures, the sEMG Training Load in this thesis reflects the athlete's relative load (Chapter 5), which necessitates individual analysis.

Study 4 (Chapter 6) investigated the feasibility and practicality of sEMG shorts in a professional basketball environment. Results revealed a high adherence rate to wearing the sEMG shorts during the study period. The sEMG shorts were highly accepted by professional basketball players, as 75% of the cohort stated that they would wear the sEMG shorts again in training. The technology delivered clean data, rates at which parallel other objective internal and external load monitoring approaches, like HR and GPS. The semi-structured interviews identified six overarching central themes which were considered important aspects for using the sEMG shorts by the players. Most players perceived the sEMG shorts shorts as comfortable. Two players endorsed the sEMG technology as de-motivating, however, the majority found it intrinsically motivating and perceived it to benefit their basketball performance. Nevertheless, the wearable sEMG technology used in this study lacks behind other objective load monitoring technologies in the field regarding time-efficiency in data downloading and processing techniques. Therefore, it would not be suitable for many professional organisations where decision makers (e.g., coaches and sport scientists) require immediate feedback to make an informed decision in a timely manner (Buchheit and Simpson, 2017).

This thesis offers insights into the load monitoring approaches employed in professional basketball, as well as illustrating internal loads which professional British Basketball players' encounter. This study highlights the initial stages of research on utilising sEMG shorts to monitor internal load, and it is important not to misinterpret the practical implications of the findings, which will be discussed in detail in the next subsections. However, before discussing the practical implications from the current thesis, it is crucial for the reader to fully comprehend the current constraints of traditional sEMG methods for monitoring electrical activity of the muscle (refer to Chapter 4 for more information). For example, despite the promising results in Chapter 6, sEMG, especially over intramuscular EMG, has encountered debates due to uncertainties linked to capturing intended muscle electrical activity. These uncertainties persist even when employing gold standard techniques (de Luca, 1997, 2010; Manca et al., 2020). Hence, prudence should be exercised in interpreting sEMG-derived Training Load, even in cases where the system utilised in this study aligns with gold standard sEMG methodologies (Lynn et al., 2018). It is important to bear in mind that studies which explore textile sEMG electrode validity (Finni *et al.,* 2007; Lynn *et al.,* 2018) are only as good as the method they are comparing them against. Therefore, assessing validity in comparison to the method's initial reference remains a fundamental consideration for researchers when interpreting sEMG signals from validated textile sEMG electrodes.

7.2 Practical implications

The current thesis emerged several practical implications which should be considered for practitioners working in basketball as well as other professional sports.

The systematic literature review (Chapter 2) indicated a variety of different internal and external load monitoring approaches currently employed in professional male basketball. The sRPE method appears to be the most widely used, identified as a cost-efficient internal load method, even though previous limitations have been identified in its aggregated calculation using duration (Weaving *et al.,* 2020) (refer to 7.1 Summar Aims and Objectives in this Chapter). For external load monitoring, accelerometers are the most used devices in professional, male basketball. Coaches can utilise this research to consider employing appropriate load monitoring approaches with their professional basketball team, especially if they wish to compare player loads published in the existing literature. In addition, based on a team’s playing status during specific phases of a season (preseason, in-season, playoffs), the internal and external loads reported in the systematic literature review can be used to inform coaches and sport science practitioners about different load periodisation strategies of competitor teams. This holds especially true for teams which are competing in Spain, as the systematic review identifies a series of research conducted by researchers in this country (Svilar, Castellano and Jukic, 2018; Torres-Ronda *et al.*, 2016; Vaquera *et al.*, 2008). Nevertheless, caution ought to be exercised when comparing loads as different practices and training philosophies adopted by coaches result in varied load outputs. The limitations surrounding observational research is highlighted in Chapters 2 and 3.

The current thesis, for the first time presents player internal loads from the professional British basketball league (BBL). Weekly Loads (training only) were greater in weekly game fixtures involving 1-game compared to 2-game weeks. However, Total Weekly Load (training and competition) was greater in 2-game weeks compared to 1-game weeks. Thus, coaches should account for the extra load in 2-game weeks and prevent prescribing excessive training loads to prevent unnecessary spikes, which might lead to greater risk of soft tissue injury (Gabbett, 2016). The study also demonstrated training strategies naturally adopted by the coach which systematically reduced training loads each day closer to game-day likely to reduce residual fatigue. This is recommended in the sport science literature and should be considered to optimise player readiness for game-day (Aquino *et al.,* 2016). In support of much of the existing research, it was established that basketball players experienced greater training loads during the pre-season compared to the in-season phase (Aoki *et al.,* 2017; Freitas *et al.,* 2013; Salazar *et al.,* 2020). This is likely to induce favourable acute physiological responses for subsequent adaptation to cope with the demands of the in-season phase and increase fitness parameters such as repeated high intensity efforts (Ferioli *et al.*, 2018). However, coaches should account for the associated injury risk and illness with increased training loads (Jones, Griffiths and Mellalieu, 2017). Coaches might consider using these findings to employ a similar loading strategy to induce a supercompensation training effect during the preseason period. The study increases construct validity of the sRPE method as an effective global internal load monitoring tool.

To add, Chapter 5 showed that unlike sEMG Training Load, accelerometery PlayerLoad™ did not correlate to oxygen consumption (%$\dot{V}O_{2max}$), likely because of the 1% increase in gradient slope during the treadmill test (Terrier, Schutz and Aminian, 2001; Chang *et al.*, 2019). Because they capture two different parameters of load (internal and external), the sEMG Training Load effectively captures the heightened muscular demand required for concentric contractions to sustain the designated uphill running workload. Thus, the wearable sEMG shorts could be a more suitable method than accelerometry PlayerLoad™ during varied running terrains (uphill and downhill) when trying to objectively capture load (Terrier, Schutz and Aminian, 2001; Chang *et al.*, 2019). However, it's essential to acknowledge that the fundamental idea underpinning each load monitoring approach is to establish a dose-response relationship between the external work (load) executed and the corresponding internal response. Therefore, in scenarios where financial circumstances permits, adopting a combination of internal and external load monitoring techniques, like accelerometery, HR and wearable sEMG would significantly contribute to refining this relationship.

Moreover, the outcomes of Chapter 5 emphasise that sEMG-derived Training Load exhibits a more pronounced individual-level correlation to oxygen consumption unlike the weaker correlation found in the aggregated dataset. Consequently, practitioners are advised to interpret the objective sEMG Training Load data on a per-athlete basis. Previous research has stressed that due to individual characteristics, such as age, training experience, fitness and movement technique, will result in a relative response to training, and thus should always been analysed on an individual level (Halson, 2014). This tailored analytical approach can offer more accurate insights into the internal demands experienced by the athlete.

Companies like Athos™ offer their solutions to assess specific muscle electrical activity (i.e. biceps femoris or vastus lateralis). However, to confirm or refute the companies claims in using the sEMG shorts to monitor specific muscle groups during exercise, dedicated studies need to be conducted, delving deeper into the technology's capabilities. It must be acknowledged that the sEMG shorts used in this thesis come in a variety of different sizes but are not truly tailored to the athlete's anthropometrics. Therefore, variation in the individual's limb size, muscle composition, shape and size would limit textile sEMG electrode placement, especially during higher intensity movements, which can lead to data loss or signal interference (Colyer and McGuigan, 2018). Therefore, it is more fitting to state that the sEMG shorts provides a general electrical response from the lower limb muscle groups (glutes, hamstrings and quadriceps), and not specific muscles. Companies should consider either improve tailoring the short sizes, or mitigate claims of measuring sEMG from specific muscles, while practitioners should ensure that athletes wear sEMG shorts that fit as closely to actual size as possible. This increases the amount of clean, useable data to interrogate.

Lastly, the findings in Chapter 6 showed a very high rate of acceptance of sEMG shorts amongst professional basketball athletes, with 75% of players stating they would use the technology again. In addition, 97% adhered correctly to wearing the sEMG shorts during the study period, showing that it is relatively easy for athletes to follow the correct procedures when using the sEMG shorts during training. Coaches who are debating on the adoption of wearable sEMG in their organisation should refer to Chapter 6, subheading, "procedural implications". In summary, the qualitative results should encourage research practitioners and coaches to empathise with players who do not adhere to wearing the technology for load monitoring. For instance, one player thought the sEMG shorts made them play poorly, this should be considered if coaches want their athletes to play at their best. In general, there is only a small number of studies based on perceptions of professional athletes surrounding wearable technology (Fleming et al., 2010; van Rooijen et al., 2010; Havlucu et al., 2017; Rapp and Tirabeni, 2018, 2020). This is likely due to the non-autonomous culture often adopted when athletes are paid for playing sport. Nevertheless, Chapter 6 can inform coaches who seeks player perspectives and practical implications on the sEMG technology. While a strength to the current thesis is establishing promising results using wearable sEMG to monitor training load during running, coaches should be aware that field-based studies are limited, and more 'investigative' studies are needed before implementing the technology to confidently monitor training load in a sporting environment.

7.3 Strengths

The novel approach the research took on the use of sEMG shorts for capturing internal load (sEMG Training Load) during whole-body dynamic exercise, as well as the feasibility and acceptability of wearable sEMG in a professional sport context is a strength. Existing research using sEMG shorts for assessing internal load during dynamic, whole-body exercise is limited. In fact, the majority body of literature reports sEMG signals from single muscle groups using wearable sEMG (Finni *et al.*, 2007; Tikkanen *et al.*, 2012, 2014; Colyer and McGuigan, 2018). In addition, perspectives on wearable sEMG have not been qualitatively examined with athletes in the professional sport environment, until now. Albeit sEMG shorts are currently used and commercially sold for athlete monitoring in sport (Hermann and Senner, 2020). The current PhD addresses the lack of knowledge on this topic. In particular, the research collected data based on the perceptions which professional basketball athletes had in relation to wearing sEMG shorts during training, as well as highlighting the feasibility, and providing procedural implications from the practitioner's viewpoint.

The mix methods approach of collecting quantitative and qualitative data in this thesis provides a more holistic understanding of the wearable sEMG shorts for monitoring load in professional sport (Kay *et al.*, 2018). Most research is sport science focuses on quantitative analysis to draw statistical significance. However, as shown in much of the basketball research, statistical power is low due to small inherently sample sizes. Thus, the added qualitative analysis encapsulates details and context about complexities contained by the statistical significance in a richer sense. Qualitative methods (e.g. semi-structured interviews, thematic analysis, journalling) used in chapter 6, alongside the quantitative analysis, uncovers areas of concern when employing wearable sEMG technology from the athlete and research practitioner's viewpoint. These methods allow both the user (athlete) and researcher to provide insights and contemporary reflections or opinions on using the technology. This player-feedback centred approach to uncovering issues which might not otherwise be recognised by statistical methods provides strength to the research methodology by answering the ‘how’ and ‘why’ of certain behaviours toward the wearable sEMG (Pathak, Jena and Kalra, 2013; Sutton and Austin, 2015). Surprisingly, the body of research surrounding professional athletes’ perceptions (qualitative) on wearable devices in sport is modest (Fleming et al., 2010; van Rooijen et al., 2010; Havlucu et al., 2017; Rapp and Tirabeni, 2018, 2020). These methods would be helpful for coaches who may work in individual sports, like tennis or boxing.

Another strength to the current thesis is that for the first time, internal loads were reported from professional players in the British basketball league (BBL). The longitudinal nature of the season-long study design in Chapter 3, provides coaches with insights into the trends in loads which players experience during specific phases of the season. The findings support previous literature, which establish heightened internal loads during the preseason versus lower loads in season (Aoki *et al.*, 2017; Ferioli *et al.*, 2018b). However, the findings shed light into some of the different periodisation strategies adopted by coaches on a weekly basis, while the reported loads are both above and below loads reported in teams within mainland Europe (Chapter 2; Table 2.3). Only a handful of studies report internal loads from an entire basketball season in professional male basketball (Doeven *et al.*, 2020; Ferreira *et al.,* 2021; Salazar *et al.,* 2020; Svilar *et al.*, 2020). Many organisations do not wish to disclose this type of information as it could be viewed as advantageous to opposing teams.

Lastly, the main researcher of this thesis was embedded in the basketball team throughout the entire duration of this thesis. This allowed for the researcher to build rapport and trust with the basketball players. Building rapport and trust with participants is key for sport consultancy efficacy and to enable authentic interviewee responses (Sharp and Hodge, 2014; DeJonckheere and Vaughn, 2019). While the researcher’s knowledge in qualitative analysis was limited up to this point, it is worth mentioning that the researcher tried to maintain a subjective self-awareness of their potential biases (Adams-Quackenbush *et al.*, 2019) towards the wearable sEMG technology as means to sustain the integrity of the research and data collection process. Moreover, the researcher's knowledge of the cultural differences within the team, as well as being familiarised with the training facilities, facilitated the delivery of the study designs in Chapters 3 and 6, and helped to prevent logistical constraints during data collection.

7.4 Limitations

The relatively small sample size used throughout the thesis could be deemed a limitation. However, a full basketball team roaster typically consists of 12-14 players. Due to contextual limitations, such as players being cut from the team and injury, reduced the initial sample sizes for Chapters 3 and 6. Some studies with similar sample sizes in basketball incorporate Cohens d as an estimate of the standardised mean difference between groups, whereas Hedges g was used in Chapter 3 which provides more accurate estimate of effects in small sample sizes typically below 20 participants (Brydges, 2019). Considering the current literature based on internal and external player loads within basketball, the sample sizes of the present research match those previously reported (Manzi *et al.*, 2010; A Moreira *et al.*, 2012; Aoki *et al.*, 2017). Nevertheless, more participants in each chapter, especially Chapter 5, could have strengthened the research and statistical power of the relationship between $\%\dot{V}O_{2max}$ and sEMG-derived Training Load in the composite data. To add, the data collected in Chapters 3 and 6 are representative of professional male basketball players, thus generalising results to less skilled players, different sport athletes and different genders should be taken with caution.

A challenging limitation to overcome, is the variance of the sEMG signal due to the adaptation of certain muscle characteristics over time, such as cross-sectional area, muscle fibre composition and peak force ability (Carvalho et al., 2014; Shekhar et al., 2017). As a result, peak amplitude of the sEMG signal during a MVC would likely vary on a day-to-day basis, which previous research has indicated (Howatson and Someren, 2005). Due to the sEMG onboarding session only being completed on the first day of testing (Chapter 5; methodology), and not on both days would have either underestimated or overestimated the true sEMG Training Load for a given workload. This is because the average envelope of the sEMG signal was calculated according to sEMG thresholds set during the first calibration protocol. Therefore, practitioners are encouraged to regularly perform sEMG calibration protocols with athletes who train frequently.

While the novelty of implementing wearable sEMG shorts in professional sport for load monitoring is perceived as a strength in the lens of the researcher. On the flip side, novelty research often leads to a shortage of result comparisons from within the literature (Cohen, 2017; Wang, Veugelers and Stephen, 2017). Therefore, definitive conclusions based on the thesis findings are difficult to establish and sometimes unreasonable to declare. For example, while promising results were shown based on the feasibility and acceptance of wearable sEMG in professional basketball, we cannot assume similar results would be shown in other sport environments.

Specifically in Chapter 6, the results indicated that the Athos™ Core unit fell out of the shorts during training. The basketball coach of the team was apprehensive of the possibility of a fine being imposed on the club if a Core unit fell out of the shorts during a game, as this could be viewed by league officials as a performance enhancer. This restricted research being conducted on the application of the sEMG shorts in competition. Unable to obtain valuable insights into the players experiences using the sEMG shorts during competition, is a limitation. In numerous instances, competitive games heighten psychological pressures (Giovanini *et al.*, 2020) and present different logistical constraints compared to training. Thus, applying the feasibility and player perception results on the wearable sEMG technology cannot be extrapolated to competition.

Following the commencement of this PhD, to date, one study incorporates the use of wearable sEMG in sport, specifically basketball (Saucier *et al.*, 2021). This could be viewed as a limitation surrounding the novelty of using the sEMG shorts in the sporting environment within Chapter 6. However, Saucier *et al.* (2021) employs Strive™ Sense 3© sEMG-based compression shorts, whereas this thesis utilises Athos™ sEMG shorts. Moreover, Saucier *et al* cohort includes NCAA D1 male basketball players unlike this thesis which includes professional male basketball players. They investigate differences in loading sEMG variables and accelerometery outputs based on playing position between basketball training and competition. Yet, to the researcher's knowledge only one study validates the Strive™ Sense3© textile sEMG electrodes to a standard grade sEMG system during the back squat exercise. Whereas this PhD introduced using the sEMG shorts to monitor load during running and investigate the sensitivity of sEMG Training Load during different running intensities. Moreover, an essential step which is neglected in the literature is the feasibility and acceptability of the technology amongst athletes in the field. This pivotal step is warranted before interrogating sEMG metrics in the sport context.

Moreover, it must be expressed that the financial burden of using the wearable sEMG technology comes as a major constraint for amateur clubs, especially if you compare it to cost-free methods, such as the sRPE method (Chapter 3). Thus, the research in Chapter 6, is inherently biased to professional sports and cannot be generalised to amateur basketball teams. For example, the sEMG shorts require a cold wash after every use and need air-drying conditions. This the shorts might only be feasible for clubs with a full-time kit manager, which amateur clubs may not have. Considering the trade-off between benefits and costs should be undertaken cautiously. If the main goal is to objectively monitor internal load, then opting for Polar HR monitors could be a cost-effective choice, as they are approximately half the price of the sEMG team solution employed in this study.

7.5 Future research directions

The present thesis opens a gateway for future research to be conducted on wearable sEMG compression garments in the professional basketball environment, as well as many other sports. The wearable sEMG technology had high acceptance rates amongst professional basketball players within the current thesis. The main step forward for research based on the the current thesis results, should prioritise investigating differences between sEMG Training Load and other internal and external loads such as HR, RPE, accelerometry and GPS variables within specific basketball drills during training. Previous research adopts this approach to gain insights into the different physiological, psychological, and biomechanical load parameters in which internal and external load measurements account for during training (Casamichana *et al.*, 2013; Scanlan, Wen, Tucker and Dalbo, 2014; Sobolewski, 2020). Specifically, researchers should use the technology to investigate the muscle response from various basketball drills, such as common training game-based drill formats, like 3v3 and 5v5, as well as half court and full-court. Previous research by Torres-Ronda *et al.* (2016) used HR to quantify load and identified 1v1 to be more demanding than 2v2 and 3v3. It would be interesting to know if the sEMG-derived Training Load would show similar results. In addition, establishing relationships between GPS or accelerometer load metrics with sEMG-derived Training Load during specific basketball drills could help coaches understand the does-response relationship between the work performed and internal response of players. Understanding the strength of dose-response relationships between players external load and the resultant sEMG Training Load (internal response) during common basketball drill configurations could help coaches adequately prescribe and periodise training, as well as increase the confidence of using sEMG in the basketball environment (Halson, 2014).

Similarly, future research could consider establishing dose-response relationships between sEMG Training Load and key fitness performance indicators, which has been shown in previous research, like soccer (Fitzpatrick, Hicks and Hayes, 2018; Rago *et al.*, 2019). External loads can be tactically prescribed to induce key fitness parameters due to the nature of the dose-response relationship established between loads and fitness status of players (Clemente, Clark, *et al.*, 2019). This results in different drill configurations, such as SSG’s to be used for metabolic conditioning protocols (Zanetti *et al.*, 2022). If a specific sEMG Training Load over a time period is shown to relate to a specific fitness outcome, like strength levels for instance which is important for many sports, might inform coaches of how much sEMG Training Load is required to induce the strength benefits. Interventions for establishing if sEMG Training Load correlates with specific fitness outcomes could strengthen many training practices and help with tactically periodising training.

Another area for future research, is improving the design of the wearable sEMG technology itself. For instance, at present the technology is limited to non-contact sports and is not ideal for contact sports. The sEMG technology hardware as shown in Chapters 4 and 5, illustrates the Athos™ Core unit which attaches into the rubber mounting module on the right side of the shorts. This presents a problem for any contact made to upper leg during sport, as direct impact is likely to result in the Athos™ Core unit falling out of the shorts (which resulted in minor data loss in Chapter 6), and/or cause pain to the athlete. Therefore, it is recommended that future research addresses the sEMG technology design, perhaps by miniaturisation of the Athos™ Core unit, or by incorporating it into the shorts where it is safe for full-contact sports. This would make it more appealing for research in sports such as Rugby or Judo, where athletes experience frequent contact of the upper leg.

In future research, a promising avenue lies in exploring a full-body sEMG suit, which may offer a more comprehensive representation of whole-body muscle load, subsequently surpassing the use of sEMG compression shorts for assessing the upper leg alone. Practitioners are encouraged to understand this limitation and analyse the data in the context of the shorts providing information relative to the upper leg of the body. Full-body sEMG compression suits are currently available, but no research has investigated their use in a sport and exercise setting but has recently been investigated in E-textile design optimisation research (Ohiri *et al.*, 2022).

Moreover, sEMG's efficacy in measuring isometric muscular contractions (Alkner, Tesch and Berg, 2000), a type of contraction frequently encountered in basketball, cannot be overlooked. Future research could investigate isometric contractions, like screening in basketball to understand the internal load during these movements. This could be performed in conjunction with video analysis techniques during training. It is known that external methods of load, such as accelerometers and GPS devices cannot account for the load inflicted on players during these intense static movements (Gómez-Carmona et al., 2020).

In future, research might consider the integration of multi-modal wearable devices. Using a variety of internal load methods in conjunction with each other builds a more holistic view of athlete load. For example, investigations have been published on using pressure insoles in combination with a MVN motion capture suit comprising 17 inertial measurement units (Xsens, Enschede, Netherlands) to analyse joint kinetics in skiing (Lee *et al.,* 2017) and short-track speed skating (Purevsuren *et al.,* 2018). The MVN suit has recently allowed for the integration of Delsys portable sEMG system into their platform, allowing live feedback from both systems simultaneously. With improved integration functionality due to programming languages and artificial intelligence, this is an exciting era for the wearable tech field in sport. This might offer nuanced insights into the interplay between different internal responses, such as the cardiovascular (HR) and muscular (sEMG) systems, but also between internal and external loads. These technologies could discern meaningful patterns amidst the deluge of data and perhaps strengthen models to identify individual injury risk, as well as tracking rehab efficacy (Ruddy *et al.,* 2019; Schuermans *et al.,* 2017).

The wearable sEMG technology provides a variety of data metrics (Chapter 6; Table 6.2) other than internal training load, such as anterior: posterior (A:P), glute: hamstring (G:H) and quad: hamstring (Q:R) ratios. More controlled studies could interrogate their construct validity and reliability against traditionally used methods to assess such ratios (Torres *et al.,* 2021). An example of this is the preliminary research associated with this thesis, which demonstrates that the left leg of basketball players is associated with greater stability indicated by the Q:H ratio. This is likely due to the left leg being the dominant leg in basketball, thus repeated muscle recruitment patterns may have stimulated the anterior dynamic stabilisers of the knee (List of Abstract Posters: An investigation of Athos's integrated surface-electromyography biofeedback system in relation to current lower limb instability status in elite basketball players).

Lastly, as mentioned a limitation in this thesis pertains to its lack of applicability to amateur level basketball players and other sports (Chapters 2, 3 and 6). This warrants further research using the sEMG technology across a variety of sports and participant genders. Examining whether the findings from this study hold consistent in different sport contexts, such as soccer or hockey, would yield valuable insights. Additionally, coaches would benefit from understanding more of the distinct procedural implications that arise in various sporting scenarios. Expanding research efforts on using wearable sEMG within the different sport domains is crucial to confidently deploy the technology for monitoring athletes, as this can contribute to more definitive conclusions about the practicality, accuracy, and reliability of wearable sEMG technology.

7.6 Conclusion

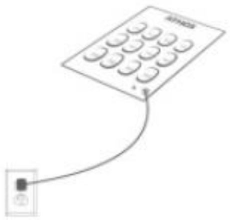
This thesis presents valuable insights into the psychophysiological responses encountered by professional basketball players throughout a full BBL season. Additionally, it delves into the innovative realm of employing wearable sEMG compression shorts for internal load monitoring during exercise. For the first time, this study showcases the feasibility and high acceptance rates of wearable sEMG amongst professional basketball players in the real-world training environment.

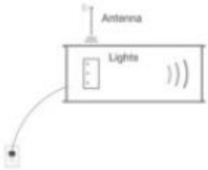
Collectively, the outcomes of this research offer sport scientists, strength and conditioning coaches, and research practitioners a deeper understanding of the practical considerations linked to integrating wearable sEMG technology in sports. However, it's important to note that the current results from this thesis are preliminary. Further investigation is needed to establish the reliability of wearable sEMG in the real-world training environment before coaches and research practitioners can confidently adopt it for load monitoring purposes. Furthermore, it's important to acknowledge that the sEMG shorts used in this study solely assess a fraction of whole-body muscle load (upper leg). Therefore, future research should address the challenge of capturing sEMG Training Load from the entire body during sport using sEMG.

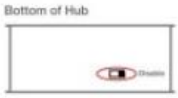
Lastly, this research sets the stage for more in-depth explorations into the various sEMG variables captured by wearable technology. This foundation opens the door for further investigations that can provide deeper insights into the diverse aspects of sEMG measurement.

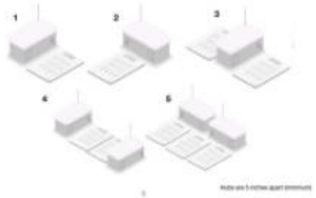
Appendices

A1









A2

Participant 1 – Interview Transcription

R: I will take you through a series of questions, based on the Athos shorts. It is an informal discussion. There is no right or wrong answer.
Firstly, do you give verbal consent to participate in this study? And do you mind if I record you while we converse?

S5: Yes, I consent to participate in this discussion and I am fine with being recorded.

R: I have two basic demographic questions to begin with: what age are you and do you identify as male or female?
S5: I am 23 and male

R: So you obviously used the Athos kit during training sessions in previous months, can you tell me about the experience of wearing the Athos kit?
S5: Good, it showed me how hard I was working from day-to-day as time went on. It was also interesting to see the data because I had a knee injury. So I found it interesting to see the difference in load between each leg.

R: How did you feel when wearing the shorts?
S5: Yeah, they just felt normal, I didn't notice a difference compared to the under base layer shorts I usually wear.
R: Could you provide more detail?
S5: like I always were under armour or nike base layer shorts, and they felt no different to them, maybe slightly thicker, but I never noticed it when on the court. I actually like them cause they were breathable around the insides of the legs.

R: What did you think of the specific feedback that the shorts gave you?
S5: I thought it was interesting. I thought it was what it was going to be because I didn't have much strength considering my knee injury. It confirmed that I needed more strength training to make my legs more equal. It was good to see the specifics and to see how far each leg were away from each other, I didn't really like seeing my load sometimes though.
R: Why did you not?
I didn't like how Coach would always look at my load, cause mine was always lower than the others because I was coming back from injury, so it kind of demotivated me sometimes.

R: Could you provide more detail about the specifics?
S5: I saw how my leg which was sore was much weaker. I would like to see more data in future to see if my leg gets stronger, or like, activates more.
R: What did you think about the management process of the shorts?
S5: It was great as well, and having two pairs of shorts was good. I was one of those people sometimes who forgot to wear them to training. I thought it was better when I was given a pair in the morning to put on. I probably would never be able to use them in time at home, so, I thought that was a good idea.

R: Could you provide more detail around putting them on and taking them off?
S5: Well, KA (researcher) was always there to give use our units in the changing room. So I couldn't forget to wear them really.

R: Could you tell me more about the core units?
S5: I thought they were quite basic. A few times I forgot to check if the blue light was on, so maybe it didn't pick up my data. Umm, I'm not sure if it would be possible, but they could make the unit a bit smaller cause I fell on it once and it dug into my leg. I found it easy thought to put in and out of the shorts. Ohh, and also, I thought the shorts were tricky at times to take off.
R: what do you mean by that?
S5: Hmm, like, I mean when you are sweaty they feel like they are quite sticky to your leg, so you get worried about damaging them when you take them off. But to be fair, them seemed to be fine and the pads in the inside never seemed to deteriorate compared to some of the others I saw, which was good.

R: Do you have any suggestions or feedback after wearing the shorts?
S5: Not really, we covered most training sessions, and didn't wear them for the light shooting sessions, which I thought was fine. We wore them for training sessions which was more like game situations which was better.

R: Could you tell more here, do you have any positive or negative feedback?
S5: Not really, just that with us wearing them as often as possible provided more accurate data.
R: What sort of data?
Like I felt to get better feedback I had to wear them more, its just like anything else really. The more you do it the better it gets, just like basketball even.

R: Is there anything else that we haven't covered that you'd like to comment on?
S5: Not really, maybe the only thing would have been good to wear them during preseason testing to see what I could use during the season to improve on, like my knee injury.

R: would you use them again or not?
S5: Umm, I'd say it's 60/40 I wouldn't use them again, I'm not 100% sure if I would or not to be honest.

R: Thank you for your time, and participation. I will cut the recording now.

Glossary

Terms	**Definition**
Action potential	The change in electrical potential along the membrane of a muscle cell/ nerve cell.
Athos Training Load	Surface-electromyography based training load, determined as the sum of electrical activity over time detected from muscle contraction.
Band-pass filter	A bandpass filter s a device that passes frequencies within a specified range and rejects (attenuates) frequencies outside that range.
Crosstalk	Unwanted, recorded electrical activity caused by other (neighbouring) contracting muscles, movement, or equipment interference.
Cut-off frequency	The frequency at which energy flowing through is reduced rather than passing through.
External load	The physical work being performed by the athlete in the form of movement.
Fast twitch (muscle fibre)	A type of muscle fibre which are recruited for ballistic and powerful actions, but only for short durations and fatigue quickly.
Filter	System(s) for refining the frequency range when collecting electromyography data; different types exist.
Frequency domain	The analysis of sEMG in terms of their frequency components, rather than time.
Frequency spectrum	Also known as ‘spectral frequency’, is the range of frequencies within the EMG signal relating to activation of motor units.
Internal load	The relative biological (or psychophysiological) stressors experienced by the athlete during training and competition”.
Impedance	Impedance is opposition to alternating current flow within an electrical circuit. Skin hydration is one example which effects impedance in EMG measurements.
Mean MUAP	A general representation of the muscle load based on average EMG amplitude.
Mean Frequency	An alternative measure of muscle load, more often used in detecting muscle fatigue, but less reliable than the mean MUAP amplitude.
Motor unit action potential (MUAP)	The sum of the extracellular potentials of muscle fibre action potentials of a motor unit.

	Defined as the time from the start of motor unit activation on muscle fibre until the end of their repolarization phase.
Notch filter	These filters attenuate signals within a specific frequency, also known as a band-stop filter.
Noise	Unwanted electrical signal due to motion artefact, impedance and muscle crosstalk.
Pass-band	Removes low and high frequencies from the EMG signal, but allows transmission of signals without attenuation by a filter.
Rating of perceived exertion	A rating based on the personal experience of how hard a training or competition session was. Typically rated using Borg's category ratio 0-10 scale.
Slow-twitch (muscle fibre)	A type of muscle fibre which are recruited for low-force tasks or long distance endurance activities and are typically smaller in cross-sectional area than fast twitch fibres.
Surface-electromyography	A non-invasive technique for assessing the myoelectric output of a muscle.
Peak amplitude	Maximum (peak) EMG amplitude recorded within a defined period of muscle activity. Generally, peak amplitude categorises the intensity of muscle activation.
Psychophysiological response	The individually, perceived stress experienced by players encompassing both psychological and physiological stress.
Player load	External and/or internal load recorded from athletes.
Periodisation (training)	Method of prescribing and managing athletic or physical training
Root mean square	A value which is used to quantify the electric signal as it reflects the electrical activity during contraction, and is calculated using a moving window.
Training load	The internal or external load imposed on players during training or competition. Often, "training load", "player load" and "load" are used interchangeably within the literature.
Total Weekly Load	The weekly training and competition load, computed as the 7-day sum of the daily session rating of perceived exertion.
Weekly Load	The Weekly Training Load, only, computed as the 7-day sum of the daily session rating of perceived exertion.

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