

THE USE OF
SURFACE ELECTROMYOGRAPHY
WITHIN
EQUINE PERFORMANCE ANALYSIS

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Evidence sources presented in the thesis

Evidence source 1: Williams, J.M. (2013) Performance analysis in equestrian sport *Comparative Exercise Physiology*. 9(2), pp. 67-77.

Evidence source 2: Williams, J.M., Gundry, P., Richards, J. and Protheroe, L. (2013) A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse. *The Veterinary Nurse*. 4(9), pp. 566-572.

Erratum: Williams, J.M., Gundry, P., Richards, J. and Protheroe, L. (2013) A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse. *The Veterinary Nurse*. 5(6), pp. 319.

Evidence source 3: St George, L. and Williams, J.M. (2013) Electromyographic evaluation of approach stride, jump stride and intermediate stride in selected superficial muscles of the jumping horse: A preliminary study. *Comparative Exercise Physiology*. 9(1), pp. 23-32.

Evidence source 4: Williams, J.M., Johnson, C.J., Bales, R., Lloyd, G., Barron, L. and Quest, D. (2014) Analysis of *Temporalis* and *Masseter* adaptation after routine dental-treatment in the horse via surface electromyography *Comparative Exercise Physiology*. (in press)

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Statement of authorship

I can confirm that the research presented in the critical commentary is the product of my own work. The research projects incorporated have been performed, interpreted and prepared for publication by myself in conjunction with colleagues; Table A2 (Appendix 2) explicitly identifies my contribution to the work presented.

Many of the projects were undertaken in collaboration with colleagues from the equine industry and academia, and are outlined in Table A3 (Appendix 3).

Statement of work

I confirm that the work is submitted in partial fulfilment for the degree of Doctor of Philosophy by Publication and that the thesis has not been submitted elsewhere in any other form for the fulfilment of any other degree or qualification. Table A4 (Appendix 4) maps how the evidence presented has achieved the required Doctoral learning criteria.

Statement of training

I can confirm that the training requirement component for the degree of Doctor of Philosophy by Publication has been undertaken via accreditation of 70 credits of prior learning achieved within the Masters of Equine Science, University of the West of England (Appendix 5).

Abstract

Equine athletes participate in a wide range of equestrian disciplines. Performance analysis in sport is the collection and subsequent analysis of data, or key information sets, related to facets of training and / or competition, to accelerate and improve athletic performance. Equine performance analysis research aims to optimise the potential competition success of the horse whilst concurrently promoting health and welfare and increasing career longevity. Despite the benefits associated with performance analysis, its application is limited in equine sport.

Surface electromyography (sEMG) is a non-invasive technique which illustrates recruitment patterns of superficial skeletal muscle and can provide quantitative data on the activity within muscle during dynamic motion. sEMG has the potential to contribute to equine performance analysis particularly via assessment of muscle recruitment, activity and adaptation within training regimens and during competition. The critical commentary demonstrates the potential of surface electromyography (sEMG) as an effective performance analysis tool that could be used to assess the physiological response of muscle during field-based exercise in the horse and provides examples of how sEMG data obtained could guide improvements in the efficacy of training regimens for the equine athlete.

Critical reflection on four peer-reviewed evidence sources was conducted to establish their contribution to equine performance research and to facilitate debate of future research directions for equine sEMG. The research demonstrates the validity of telemetric sEMG as an emerging technology that could be used to analyse muscle performance in the equine athlete for defined events, for example jumping a fence, and to assess performance over time, for example monitoring muscle activity during

interval training. Opportunities also exist to determine the efficacy of muscle-related clinical and therapeutic interventions such as prophylactic dentistry or physiotherapy. The preliminary research presented suggests the use of equine sEMG as a performance analysis tool has most value to assess and compare muscle performance during exercise within individual horses. However further research is required to substantiate this. Future studies integrating larger sample sizes, horses selected from specific equestrian disciplines and breeds, and further exploration of the impact of coat length and sEMG sensor placement on data obtained would be worthwhile to standardise and validate the protocols employed here.

Equine performance is a complex area; future work needs to focus on the individual characteristics that contribute to desired performance goals, but should also evaluate performance as a holistic entity. It is essential for progression in the performance field that research undertaken is shared with the equine industry to enable practical implementation. The use of sEMG in the equine athlete has the potential to increase understanding of how muscle responds to exercise and could help create an evidence-base to inform individual and discipline-specific training regimens. Increased efficacy in training should promote success, enhancing performance and extending career longevity for the equine athlete, whilst indirectly benefiting the horse's health and welfare through improved management practices and injury reduction.

CHAPTER ONE

THE RESEARCH JOURNEY: AN INTRODUCTION

This commentary focuses on the use of surface electromyography (sEMG) in the analysis of the muscle performance of the equine athlete. The evidence sources (Appendices 1.1 to 1.4) demonstrate the potential of sEMG as a quantitative tool for equine performance analysis, which could inform training and management practices within the equine industry.

1.1 What is surface electromyography?

Electromyography (EMG) is the study of the electrical signals that occur when muscles contract (Back and Clayton, 2001; Clayton and Schamhardt, 2001). Kinesiological EMG assesses muscle activity patterns during dynamic motion i.e. exercise (Drost *et al.*, 2006; Winter, 2009). Two main methodologies are commonly utilised by EMG researchers across species to obtain data: indwelling EMG and sEMG (Chapman *et al.*, 2010; Drost *et al.*, 2006). Indwelling EMG requires the insertion of an electrode deep into skeletal muscle, which by its nature limits application primarily to the laboratory (Drost *et al.*, 2006; Hanon, Thepaut-Matieu and Vanderwalle, 2005). In contrast, sEMG is a non-invasive technique that can provide quantitative data on the activity within superficial muscles during dynamic motion in both laboratory and field environments (Drost *et al.*, 2006; Hanon, Thepaut-Matieu and Vanderwalle, 2005; Back and Clayton, 2001). The non-

invasive nature and ability to utilise sEMG in the field presents opportunities for the technology to be used within performance analysis.

1.2 sEMG as a performance analysis tool

Electromyography has been used as a performance analysis tool to assess the efficacy of training and rehabilitation regimens in humans (Richards *et al.*, 2008; Hanon, Thepaut-Matieu and Vanderwalle, 2005). sEMG can identify muscle recruitment through the onset and offset of motor unit action potentials (MUAP) (Winter, 2009) and measure muscle activity-levels via analysis of EMG signal amplitude and frequency (Hanon, Thepaut-Matieu and Vanderwalle, 2005; Hanon *et al.*, 1998). sEMG data provide an objective measure of (muscle) fitness (Duc, Betik and Grappe, 2005) and fatigue (Hanon, Thepaut-Matieu and Vanderwalle, 2005) through EMG frequency analysis. Some equine EMG research has been conducted, but the majority of studies have been restricted to the laboratory environment (Zsoldos *et al.*, 2010a, b; Licka, Frey and Peham, 2009; Peham *et al.*, 2001).

Equine training to date has focussed on cardiovascular and biomechanical assessment neglecting the evaluation of the role of muscles (Ferrari *et al.*, 2009; Rivero, 2007). Skeletal muscles in the horse fundamentally contribute to the biomechanics of locomotion and their ability to sustain performance (through contractions), which will directly influence fatigue during exercise. The development of non-invasive telemetric sEMG systems presents an opportunity to evaluate muscle contribution and adaptation during training and/or competition, providing an objective tool for analysis of equine (muscle) performance in the field, outside of the laboratory and during training and competition.

1.3 Performance analysis in equestrian sport

Performance analysis in sport relies on the objective assessment of data or key information related to training and / or competition, to improve athletic performance (Hughes and Bartlett, 2002). An individual human's or *Equid's* performance capacity is underpinned by the preparation or training regimen implemented for the targeted competition test. The reliability of the existing anecdotal evidence-base for the training practices employed across equestrian sport has been questioned (van Weeren and Back, 2014; Ely *et al.*, 2010; McLean and McGreevy 2010a; McGreevy and McLean, 2007). Training regimens typically aim to prepare the equine athlete for specific competitive tests. Several years of physiological conditioning and technical training (the acquisition of discipline-specific motor skills) are required for the equine athlete to reach their full potential (Leisson, Uaakma and Seene, 2008). However, despite scientific advances and the financial rewards associated with success in most disciplines (Thiruvankadan, Kandasamy and Panneerselvam, 2009), training in equestrianism remains largely based upon tradition which itself is based on anecdotal evidence of prior achievements (McLean and McGreevy 2010a; Powers and Harrison, 1999; Smith *et al.*, 1999).

In human athletes, sport-specific training is commonly used, with training regimens designed to mimic the duration, intensity and frequency of the intended competition to ensure the technical skills and fitness levels required to compete effectively and successfully are established (Bompa and Haff, 2009; Bompa and Carrera, 2005). For example in golf, evidence-based exercise-programmes have resulted in improvements in balance, strength and conditioning, and swing mechanics producing superior motor skill (golfing) performance in recreational golfers (Lephart *et al.*, 2007; Rhodri, De Ste Croix and Oliver, 2013). sEMG data have also identified

which muscles are recruited during golfing-swings and demonstrated differences between the modern and traditional golf-swing are not influenced by expertise (handicap) (Ashish, Shweta and Singh, 2008; Aggarwal, Shenoy and Sandhu, 2008).

In equestrianism, integration of performance analysis has the potential to provide an evidence-base to inform and expand objective discipline-specific training to optimise success and extend career longevity for the equine athlete (McGarry, 2009; Hughes and Bartlett, 2002). sEMG could prove a valuable tool to assess equine (muscle) performance by enabling interpretation of data related to muscle workload during training and competition (Hughes and Bartlett, 2002). Easy to use telemetric systems enable assessment of the physiological responses of muscle (recruitment and activity profiles: contraction strength and frequency) in 'real-time' within 'normal' training environments with minimal disruption to horse or rider. The ability to identify 'real-time' muscle recruitment during exercise could enable coaches to continually assess whether exercises are targeting the muscles they are aimed at, and inform modification, if required, to facilitate subsequent development. sEMG data could also provide comparative values for defined-periods of muscle activity by measuring the total MUAP generated during contractions (Winter, 2009). Understanding how groups of muscles respond within set tasks and across training regimens could help inform the design of training regimens (Ferrari *et al.*, 2009; Rivero and Piercy, 2008). For example, comparison of the workload of right and left locomotory muscle groups could help identify lateral imbalances which could be corrected to create a more balanced horse and prevent overloading injuries (McLean and McGreevy, 2010a). Analysing the frequency spectrum of sEMG data could be used to assess how muscle activity-levels vary over-time in response to exercise intensity, duration and frequency (Hanon, Thepaut-Matieu and Vanderwalle, 2005). Thus increasing

understanding of factors which contribute to muscle fatigue and how to condition muscles to sustain and optimise physical activity to improve performance.

To increase the application of science within the training of *Equidae*, there is a need for high quality pragmatic research, informed by industry requirements and which promotes equine health, welfare and performance using samples that practitioners within the industry can relate to (van Weeren and Back, 2014; Ely, 2010; van Weeren, 2008; Crevier-Denoix 2006). Historically, equine research has concentrated on evaluation of factors related to health and welfare, often conducted using resident university equine herds or clinical data (Williams, 2013). However, there is a lack of applied equine research being undertaken within the actual industry, i.e. utilising horses and riders who are currently training and competing in the equestrian disciplines, especially at elite levels (McGreevy and McLean, 2007). The use of competitive horses is likely to increase the capacity to inform actual practice in the equine industry and limit the common criticisms levelled at academics by equestrian professionals that studies do not use appropriate horses, equipment or fail to mimic industry training practices and competition or (Williams, 2013; Felici, 2006). For example, jumping studies using horses jumping less than 1m when competition horses typically jump >1m and horses ridden in general-purpose rather than jumping-saddles which does not reflect training or competition practices, or the standard of horse ridden by affiliated showjumping riders. sEMG has the potential to bridge the gap between equine professionals and researchers, providing useful data for both parties increasing understanding of muscle physiological response to exercise and training. The development of an applied equine research philosophy which can facilitate dissemination and inform industry practice, underpins the research journey and work developed throughout the thesis (Appendix 8).

A better understanding of muscle physiology during specific exercise combined with examination of how muscle responds to cumulative exercise sessions over time (training regimens) is needed (Ferrari *et al.*, 2009). Using sEMG to assess muscle exercise physiology, using actively competing equine athletes (Felici, 2006), could increase the evidence-base against which current equestrian training regimens can be assessed and, if needed, inform modifications to make regimens more fit for purpose (Hughes and Bartlett, 2002). As a result of the lack of an evidence-base in equine training, it was decided to investigate if sEMG could be used as a valid tool to analyse equine performance through the examination of muscle recruitment and activity in proven equine athletes in the field.

1.4 Hypotheses

The principle hypothesis (H_a) for the collective body of research presented was that sEMG can be used to assess the physiological response of equine superficial muscles during field-based studies and has the potential to be used as an effective performance analysis tool for the equine athlete. Therefore the null hypothesis (H_0) stated sEMG would not be a valid tool to evaluate muscle physiology or to contribute to performance analysis in the equine athlete.

1.5 Research aims:

The overarching aims of the research were to demonstrate:

1. That telemetric sEMG is a relevant technology allowing the evaluation of muscle activity and recruitment during ‘real-life’ assessment of training and competition, and,
2. The potential that muscle activity records obtained via sEMG could be used to guide improvements in training regimens for the equine athlete.

1.6 Research objectives

The work presented aimed to achieve the following research objectives:

1. To analyse the potential of sEMG as a tool to analyse muscle recruitment during defined activities, specifically cantering and when jumping a fence, in the horse,
2. To assess the potential of using sEMG as a comparative tool to enable quantitative measurement of muscle adaptation in the equine athlete:
 - a) to determine progress within training regimens via interval training, and,
 - b) to measure how muscle activity varies over time after routine dental-treatment (rasping), and,
3. To examine the value of using sEMG as a tool to assess performance potential in the individual equine athlete and between cohorts of horses.

1.7 Structure of the thesis

The work presented outlines the development of the research journey and discusses the potential impact of conclusions drawn from it. Development of the central theme, the use of sEMG to analyse equine performance, the principal hypothesis of the thesis and research objectives are stated in this introduction. Chapter Two examines the multifaceted nature of equine performance. Chapter Three reviews the fundamental principles of sEMG as a technology and research tool. In Chapter Four, sEMG research is related to muscle physiology and training principles employed in the equine athlete. Chapter Five discusses the potential of sEMG to analyse performance and future sEMG research prospects. The thesis ends with a summary of the conclusions of the research journey undertaken.

CHAPTER TWO

EQUINE PERFORMANCE

Measuring performance is complex across all sports due to the multiple factors which contribute to the targeted event undertaken. In equestrianism, the presence of a second, inarticulate athlete, the horse, complicates performance analysis further. Chapter Two introduces the equine athlete alongside the concept of equine performance to identify opportunities for increased analysis, via the contribution of field-based technologies such as sEMG.

2.1 The equine athlete

The contemporary domestic horse (*Equus caballus*) is predominately utilised by humans as a companion and / or competition animal. Horse sports are documented to have occurred since the ancient Olympics Games in 680BC (FEI, 2012). In 2011 an estimated 1 million horses were resident in the U.K (BETA, 2011). There is a diversity of different equestrian competition spheres (Figure 1) which have resulted, over time, in the refinement of horse breeds in an attempt to reproduce the characteristics that promote success and longevity in the performance capacity of the equine athlete (Stachurska, Pieta and Nesteruk, 2002).

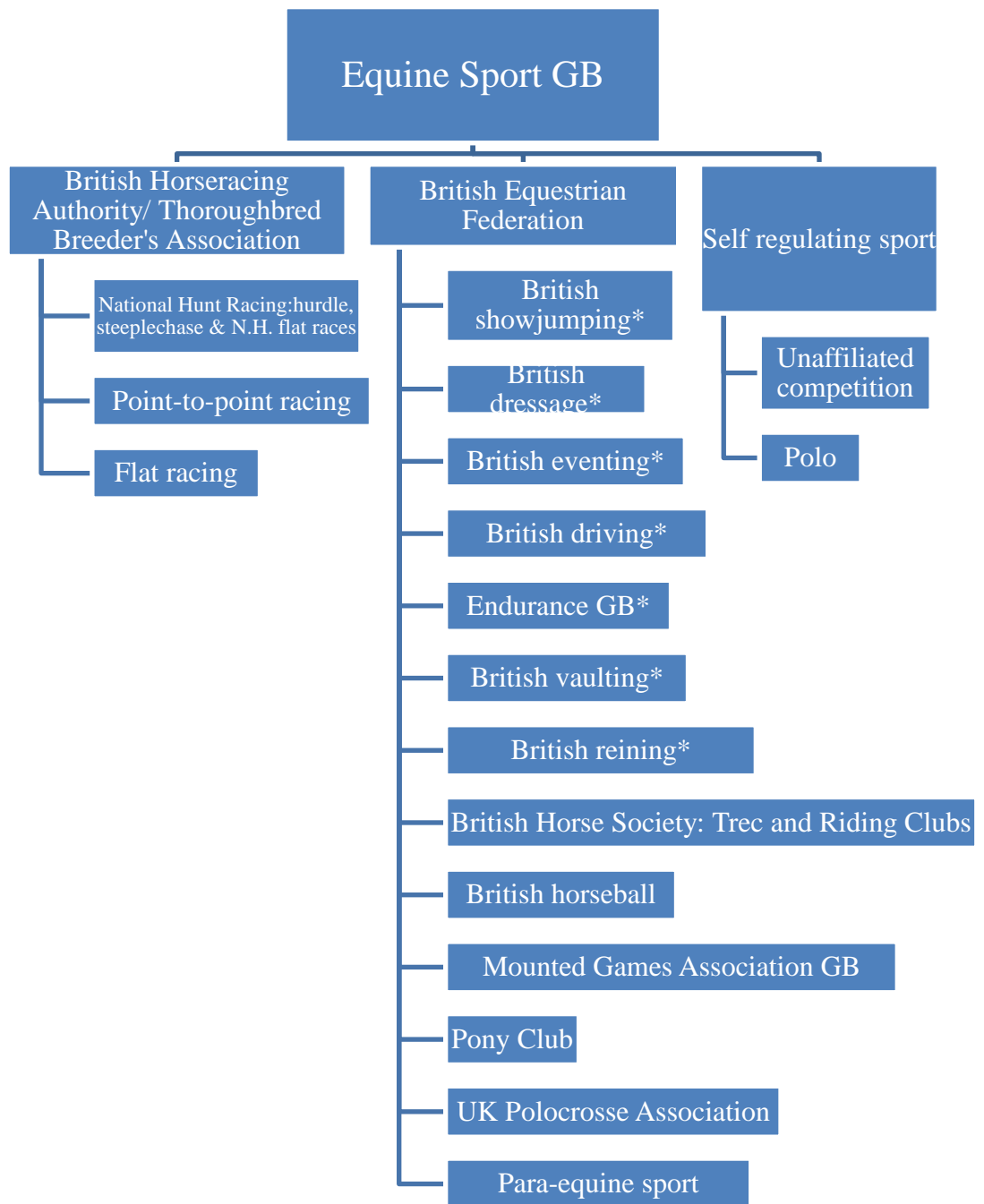


Figure 1: An overview of equine sporting disciplines in Great Britain; *FEI regulated disciplines.

Equestrian sport was reviewed in Great Britain to identify the range of equine sports that occur and the Governing Bodies, where appropriate, which regulate these sports.

Equestrian competitions take place at affiliated and unaffiliated levels (Figure 2). Within competition, individuals are often assigned a status relative to competition experience and success of the rider, horse or horse and rider as a team. The unaffiliated sector mirrors the competitive disciplines; therefore work considering factors related to performance is applicable to both.

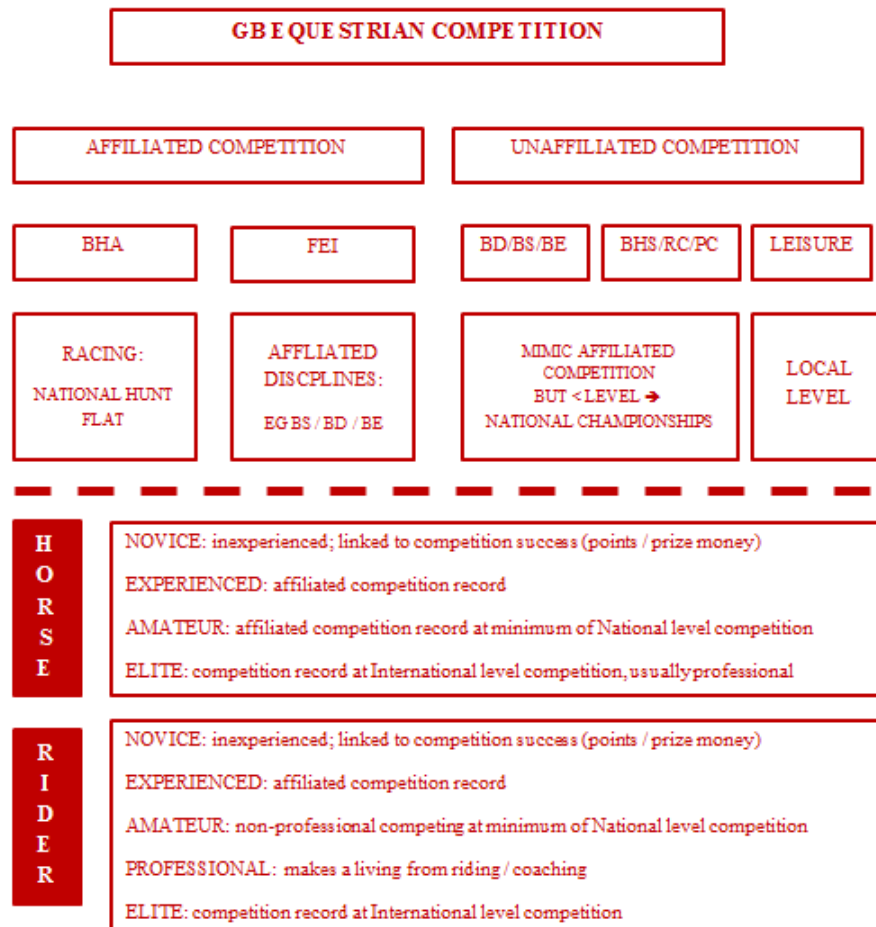


Figure 2: Overview of British equestrian competition. BHA: British Horseracing Authority (FEI, 2014; BHA, 2013); FEI: Federation Equéstré International; BD: British Dressage; BS: British Showjumping; BE: British Eventing; BHS: British Horse Society; RC: Riding Clubs, PC: Pony Clubs.

Unaffiliated and affiliated competitions occur. Participants are 'novice' if they are inexperienced, 'experienced' when they have become practiced at their skill, 'amateur' once competing at National level but do not compete as their career, 'professional' when their career is related to their competitive profile, or 'elite' once international competition participation has been achieved. Many horse owners do not engage in affiliated competition level, preferring to undertake leisure activities with their horse whilst maybe competing occasionally in unaffiliated competition.

2.2 *Equine performance: a multifactorial concept*

Equine performance is a complex phenomenon and many contributing factors interrelate to produce the tangible output observed. Epidemiological methodologies can be employed to review performance related variables such as precursory risk factors to injury or non-completion (Mata, Williams and Marks, 2012; Parkin *et al.*, 2004; Stover, 2003; Williams *et al.*, 2001) or to predict factors related to success (Williams, Heath and Da Mata, 2013; Marlin, Williams and Parkin, 2014). The potential also exists to engage in systematic review of relevant research related to injury, physiological or biomechanical parameters that are intrinsically or extrinsically associated with performance.

Knowledge of the critical components of performance can be utilised to inform training and management protocols for the equine athlete (Williams, 2013). However the challenge that exists in all forms of performance analysis is how to effectively evaluate the degree of interaction between contributing variables in order to analyse their cumulative impact on the final result (Stover, 2003).

Only minimal improvement in performance has been documented throughout equine sport over the last Century, despite targeted breeding programmes and advances in fields which influence performance capabilities, such as equine veterinary science and nutrition (Murphy, 2009; Stachurska, Pieta and Nesteruk, 2002). Improvements in winning times in horse racing are attributed to adaptation in jockey riding styles rather than horse management advances (Pfau *et al.*, 2009). Comparison between modern and historic performance in the other equestrian disciplines can be more complicated as the competitive test undertaken has changed significantly

invalidating direct appraisal between events, as observed in eventing (Williams, Marlin and Marks, 2012).

Defining performance within any sport is difficult as it requires analysis of a multifactorial output often without free access to all the influential factors that contribute to a specific performance (Hughes and Bartlett, 2002). The concept of sports performance analysis is well established in human sport (McGarry, 2009). Performance analysis depends on detailed review of physiological, biomechanical and psychological performance related variables and how these change in different environments, contextualised to the sporting discipline or test, and how they can be managed to optimise performance (McGarry, 2009; Hughes and Bartlett, 2002).

In equestrian sports, performance review requires assessment of the rider and the horse independently, as well as the performance of the horse and rider as a dyad. Analysis of equestrian sport should also consider the influence of the wider coaching and veterinary support teams on performance (Williams, 2013). The presence of the horse as an independent athletic entity that cannot articulate their own reflection of performance complicates analysis, as fundamentally there is no psychological motivation for the horse to succeed (McLean and McGreevy, 2010a). In part, the absence of psychological motivation offers one rationale for the lack of progression observed between comparative generations of equine athletes. However in other aspects of equine science, positive developments have been made. For example, in equine veterinary medicine, knowledge has advanced as practitioners embrace an evidence-based approach to underpin 'normal' protocols and treatment regimens (Vanderweerd *et al.*, 2012). Tendinopathies are the most commonly reported injury in the equine athlete (Singer *et al.*, 2008; Murray *et al.*, 2006; Dyson, 2002; Williams *et al.*, 2001). Advances in equine science have exposed causal risk factors associated

with competitive tests for example: speed (Pinchbeck *et al.*, 2002), drop fences (Singer *et al.*, 2008) and surfaces (Murray *et al.*, 2010), and identified a genetic link with predisposition to tendon injury (Tully *et al.*, 2013). Research has also evaluated emerging treatments which promote an improved prognosis and return to competition such as platelet rich plasma (Bazzano *et al.*, 2013; Bosch *et al.*, 2010) and stem cells (Godwin *et al.*, 2012). Yet despite the advances made, tendon injury remains a leading cause of days lost from training or competition in the horse (Dyson *et al.*, 2008). The reasons for a lack of progression in equine performance remain unknown but could be associated with the limited integration of scientific methods within training regimens or the poor uptake of performance analysis in equine sport in general (van Weeren and Crevier-Denoix, 2006).

2.3 Defining success

Success can be defined as the accomplishment of an aim or purpose or the attainment of fame, wealth, or social status, and in a sporting context often relates to a performance fulfilling an achievement that results in honours (Oxford English Dictionary, 2014). Defining success in sport is complex as it is not a uniform concept. Performance analysis depends on identification of a successful characteristic then examines how to replicate that factor. Therefore within equestrianism, success could be related to performance goals in training, competition or within both of these (Hughes and Bartlett, 2002). In equestrianism success could refer to rider goals, equine performance or the dyad's performance. To complicate matters further, success will equate to different goals on an individual athlete basis. Equally it may vary across sporting disciplines within levels of competition, between

aces or events at the same level due to environmental differences, could be linked to individual or team performance and can also be dependent on the stage of training of the athlete/s (McGarry, 2009).

Multiple measures of success exist in equestrianism. Performance variables are often used in sport to categorise success and facilitate analysis of improvement over time for a discipline or to assess individual progression (Parkin and Rosedale, 2006) (Table 1). However, success on an individual basis may not be linked to winning or placing in an event or to the horse's future breeding potential. Achieving a clear round in showjumping, scoring above a designated percentage in dressage, progressing to the cross country stage at a one day event or completing on horse that is not lame could all be individual goals which translate to success for horse and rider combinations. Equally in training, attainment of small improvements in performance could be considered a measure of success by those involved. The accumulation of such marginal gains has been documented in human sport to improve future competitive performance (Atkinson and Nevill, 2001). Therefore for maximum impact, equine performance analysis should describe, explain and predict performance through examination of the horse's action during defined exercises, training sessions, across a training regimen and at competition related to the outcome (success or not) (McGarry, 2009). The use of heart rate monitors to assess cardiovascular performance, sEMG to measure muscle responses or simply using video to record and review exercise sessions or competitions all have worth to contribute to performance analysis. To maximise the potential of performance analysis, success should be defined i.e. performance goals set and progress compared to previous performance (Williams, 2013; McGarry, 2009; Hughes and Bartlett, 2002). For example, in the sEMG work presented, success was defined as collecting

valid and reliable data in the field which could identify muscle recruitment and activity-levels enabling usable conclusion related to equine performance to be drawn.

Table 1: Examples of equestrian measures of success

A keyword search of equestrian peer reviewed databases identified measures of success in equestrian sport and breeding. Additional discipline and competition success measures outlined by FEI and BHA were analysed to formulate a summary of commonly employed measures of success in the equine athlete.

Competitive performance	<ol style="list-style-type: none"> 1. Genetic analysis of populations and individuals can identify polymorphic genetic markers which can indicate predilection for success related to specific performance variables for example a given race distance. 2. Individual performance in horseracing can be rated by prize money won, winning or cumulative wins and/or places in races, race times, a horse's handicap rating or lifetime earnings. 3. The Olympic disciplines of showjumping, dressage and eventing rank horses (and riders) according to prize money won and competitive success, often via a cumulative points system and accumulated prize money. 4. Olympic, World Equestrian Games or Championship medals.
Breeding performance	<ol style="list-style-type: none"> 1. Winning / placing in specific races of high renown to attain enhanced breeding value (known as attaining black type). 2. Breeding values can be based upon breed society's grading systems where variables are assigned to individual horses' combining an individual's results with that of their offspring e.g. BLUP: best linear unbiased prediction. 3. Offspring competitive success. 4. Reproductive fecundity of stallions and mares. 5. Heritability indices, population measures which quantitatively assess phenotypic expression of performance for set biomechanical or gait-related criteria for selection of superior athletic potential or breeding value in the horse.

Adapted from: Hallman, Breuer and Kuhnreich (2013), Hill *et al.* (2010), Thiruvankadan, Kandasamy and Panneerselvam (2009) and Wallin, Strandberg and Philipsson (2003).

Retirement from elite sport is a common concept across human and equine sport; therefore an alternative approach is to define success in terms of health, welfare and career longevity (Parkin and Rosedale, 2006). Equestrian sport will often consider ‘wastage’ of horses, horses which lose days from training or competition due to injury (Murray *et al.*, 2010; Patterson-Kane and Firth, 2009; Stover, 2003; Dyson, 2002), but will not necessarily consider the number of days horses remain sound, able to train or compete, as a positive performance measure (Parkin and Rosedale, 2006). The pressure to achieve could result in some trainers and riders only considering variables related to competitive success, such as prize money and winning. Success may change the economic value of the horses involved in the sport thereby encouraging trainers and riders to adopt a ‘quick fix’ during training or rehabilitation from injury, to the detriment of the horse’s health and welfare (McLean and McGreevy, 2010a, b). For example, a racehorse may remain in training until it is injured when others are available to replace it (van Erck Westergren *et al.*, 2014). Days lost from training and competing have a significant negative economic impact on the equine industry particularly in horseracing (Dyson *et al.*, 2008; Stover, 2003). Scope exists for further research to explore measures of success linked to productivity measured as time spent in active training and competition, and to increase knowledge of selection factors which promote career longevity (Parkin and Rosedale, 2006). Integration of performance analysis within training regimens and exposure of causative factors associated with injury, poor performance, winning and career longevity have the potential to enhance attainment of competitive success and promote a healthy equine athlete. The fundamental contribution of muscle to locomotion (Bouwman *et al.*, 2010) and the high incidence of musculoskeletal injury in the equine athlete (Tully, 2013) suggest that sEMG could have considerable value

as a performance analysis tool if reliable data can be obtained to measure and assess muscle responses during exercise.

2.4 Why investigate equine performance?

Analysis of performance can be advantageous to sporting achievement. Obvious benefits include promoting competitive success in the combinations evaluated. At elite level, success can include winning medals within international competition leading to increased funding, which has the potential to cascade positively through all levels of the sporting discipline involved (Bosscher *et al.*, 2009). Additional benefits for the wider population observing and participating in sport have also been recorded. For example, success in elite sport has been documented to benefit society through a positive association with national pride, happiness and socio-economic benefits (Hallman, Bruer and Kuhnreich, 2013). Within a discipline, funding may support work to enhance the knowledge of factors which contribute to success or to injury. Therefore increased understanding of competitive demands has the potential to improve health and welfare in all participants via improved preparation for competition (Hughes and Bartlett, 2002).

A substantial number of horses and riders, 998,000 and 3,792,000 respectively, have been identified as partaking in equine sport in Great Britain and represent significant numbers of leisure and amateur level competitors (90%) and professional level competitors (10%) (BETA, 2011). Dissemination of research occurs through the work of parent bodies such as the BHA and FEI, but there is scope for expansion to all levels of competitor including the grassroots, or unaffiliated, horse owner. At an individual level, performance analysis has the potential to be applied into training

programmes to produce competition success, extend career longevity, promote equine welfare or facilitate increased enjoyment within horse and rider partnerships (Walker *et al.*, 2014; McGreevy, 2007; Williams and Kendall, 2007).

2.5 EVIDENCE SOURCE 1

Williams, J.M. (2013) Performance analysis in equestrian sport. Comparative Exercise Physiology, 9(2), pp. 67-77.

Williams (2013) (Appendix 1.1) aimed to establish the contribution of equine science research to improved performance within equestrian sport, specifically showjumping. It showed that clinical and veterinary research provides a solid foundation for equine performance analysis but unfortunately research is often not contextualised or disseminated to industry, preventing practical implementation. Limited applied equine research has been conducted, but projects often utilise equine samples and / or practices which are not accepted as standard by industry, resulting in dismissal of their relevance. Going forward, increased applied equine research based on partnerships between researchers and industry professionals (riders, trainers and horses) is required to facilitate engagement in evidence-based training as part of performance analysis. Extended reflection is provided in Appendix 1.1A.

CHAPTER THREE

AN INTRODUCTION TO

SURFACE ELECTROMYOGRAPHY

Muscles contribute the power to enable dynamic movement during exercise in the horse. Therefore evaluation of their contribution to performance is essential during equine performance analysis. Electromyography is the study of MUAPs, the electrical signals that occur in muscles during contraction, using variable types of electrode (Back and Clayton, 2001; Clayton and Schamhardt, 2001). Chapter Three introduces EMG and compares the different methodologies available for research: indwelling and surface EMG. Key concepts in data acquisition and processing are explored to enable reasoned judgements on the validity of sEMG to investigate muscle recruitment and activity.

3.1 Introduction to electromyography

EMG measures MUAPs during activity. The MUAP recorded is a combination of the depolarisation wave that stimulates contraction and the subsequent polarisation wave-front that follows it (Winter, 2009; Konrad, 2005). The depolarisation wave creates an electromagnetic field which can be measured in volts, representing the sum activity during contraction in the muscle (Reaz, Hussain and Mohd-Yasin, 2006). Electrical activity is recorded by EMG electrodes for a defined pickup zone (Figure 3) which will depend upon the source of the current i.e. where the

depolarisation occurs and the distance from the source of the current to the electrode (Morris and Lawson, 2009).

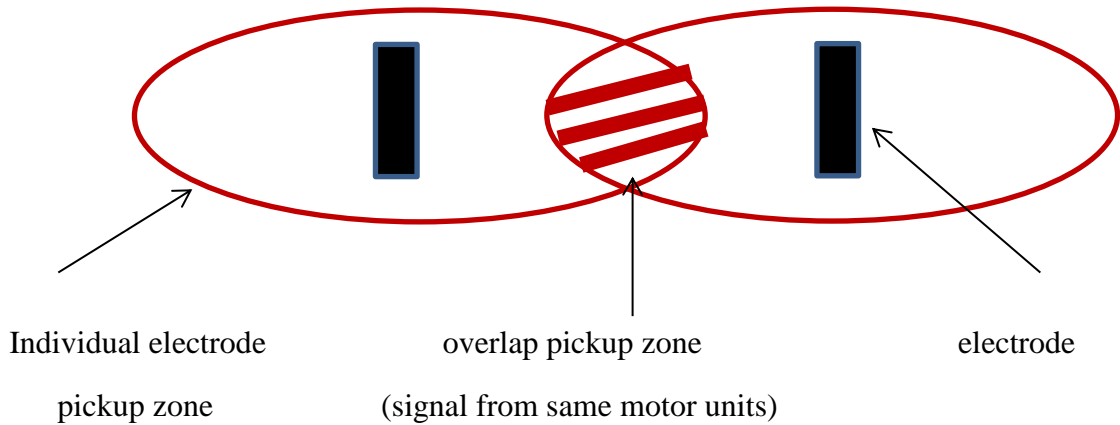


Figure 3: EMG electrode pickup zone.

EMG evaluation of muscle requires the placement of two electrodes at a set distance from each other to record data effectively. Incorrect placement where the two electrodes are too close to each other can result in data anomalies related to the overlapping pickup zone. Each electrode will record motor unit action potentials (MUAP) within its own individual range but there will also be an overlap pickup zone representing where both electrodes are recording the same MUAP.

3.2 Interpretation of the electrical signal

The EMG signal records the sum myoelectrical activity for the duration of a defined event (Reaz, Hussain and Mohd-Yasin, 2006). The features that are commonly analysed within the EMG trace are shown in Figure 4 and Table 2.

Table 2: Electromyography measures of muscle performance

Previous EMG research in humans and horses was reviewed to identify common characteristics associated with muscle contraction which can be measured by EMG. Characteristics were divided into temporal or timing related measures and spatial or workload related measures.

Spatial muscle characteristics	Measures
Amplitude of the MUAP waveform (~1µV to 1MV)	<p>Representative of the neural drive to the muscle and thus the magnitude of the signal roughly proportional to the force produced.</p> <p>Mean, peak or peak to peak amplitude can be measured.</p>
Frequency of the waveform (~1 to 500 Hz)	<p>Representative of the range of frequencies for muscle twitches within the entire or a defined portion of the EMG trace.</p> <p>Spectral frequency or range of the signal can be plotted and post Fast Fourier Transformation (plotting frequency against magnitude) mean or median frequency of the signal, or subcomponent, can be analysed.</p>
Temporal muscle characteristics	Measures
Timing (ms)	<p>Duration of firing (ms): the length of an individual contraction.</p> <p>Firing rate (ms): the frequency of firing during a defined period.</p> <p>Onset and offset of muscle recruitment</p>

Adapted from: Delsys® (2013), Kamen and Gabriel (2010), Richards, Thewlis and Selfe 2008 and Colborne, Birtles and Cacchione (2001).

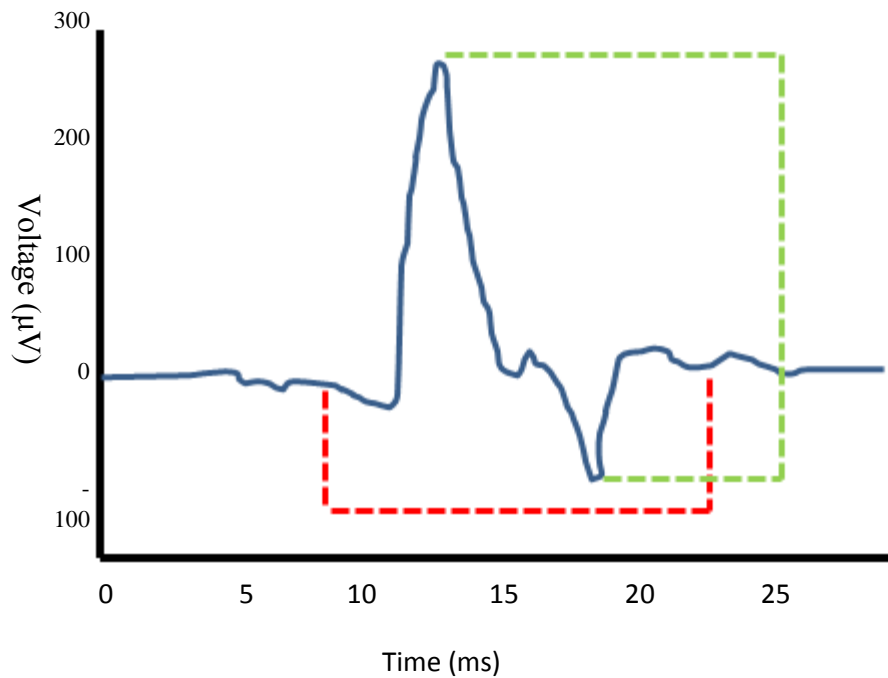


Figure 4: EMG features which can be measured within a motor unit action potential (MUAP): - - - duration of MUAP; - - - peak to peak amplitude of MUAP (adapted from Yousefi and Hamilton-Wright, 2014)

Surface electromyography records motor unit action potentials (MUAP). Analysis of EMG profiles obtained for the MUAP associated to muscle contraction for a defined activity can identify the duration of the MUAP i.e. how long a contraction is. The strength of contraction can also be estimated by measuring the peak to peak amplitude of MUAP within the EMG signal.

3.3 Indwelling versus surface electromyography

There are two methods of kinesiological EMG: indwelling EMG where electrodes are inserted into muscles of interest, and surface EMG where electrodes are applied to the extracellular skin surface above muscles of interest (Winter, 2009; Lamb and Hobart, 1992). Research has concluded that the results from each method are comparative; therefore experimental objectives and conditions should determine the choice of EMG employed (Chapman *et al.*, 2010; Jacobsen, Gabel and Brand, 1995) as their scope varies (Drost *et al.*, 2006) (Figure 5).

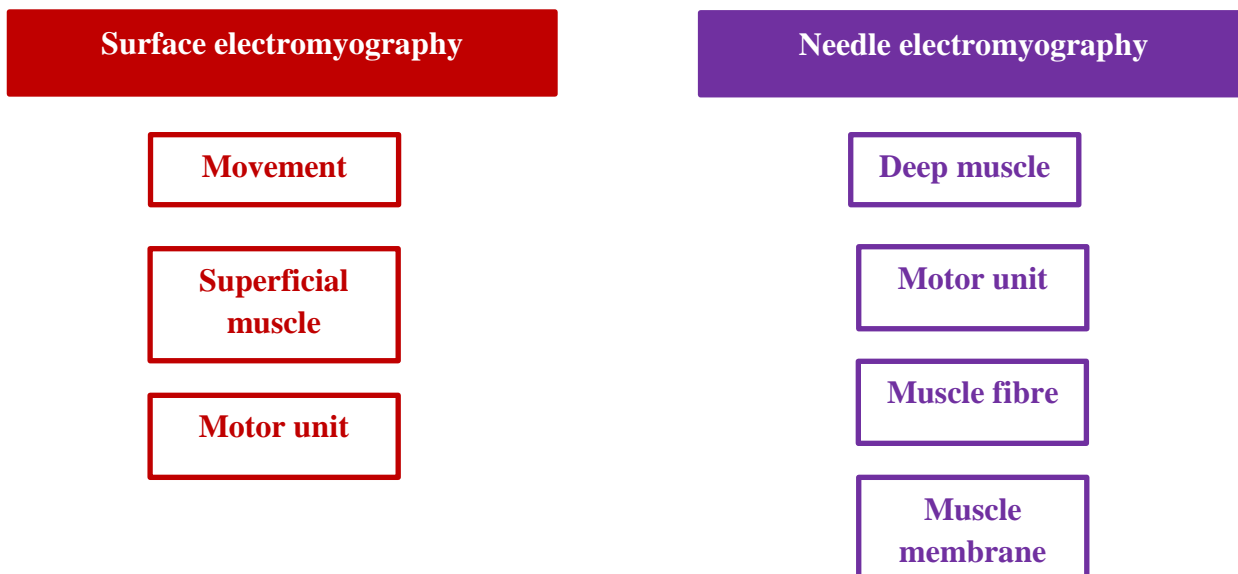


Figure 5: Application of different types of EMG (adapted from Drost *et al.*, 2006)

Two types of electromyography (EMG) exist: surface and indwelling EMG. Surface EMG is non-invasive with sensors attached to the skin whilst indwelling EMG inserts fine-wire or needle electrodes into muscle. Surface EMG and needle EMG were selected to what each technique could be used to measure based upon reviewing EMG research in humans and the horse.

sEMG is a non-invasive technique which illustrates recruitment patterns of superficial skeletal muscle (Drost *et al.*, 2006; Hanon, Thepaut-Matieu and Vanderwalle, 2005; Back and Clayton, 2001). There are two types of surface electrode: active and passive (Kamen and Gabriel, 2010). Active electrodes contain integral amplifiers and do not require the presence of electro- conductive gels and extensive skin preparation of passive electrodes (Drost *et al.*, 2006). Indwelling EMG electrodes are smaller than surface electrodes and two types occur: fine-wire and needle EMG (Winter, 2009; Drost *et al.*, 2006). Both techniques have been used in equine EMG studies (Wijnberg *et al.*, 2003; Roberts *et al.*, 2001; Colborne, Birtles and Cacchione, 2001), however the non-invasive nature of sEMG facilitates access

to competitive equine athletes and is ethically more acceptable for use. Needle and fine-wire EMG are compared in Tables 3 and 4.

Table 3: Comparison of fine-wire and needle EMG

Two forms of indwelling electromyography (EMG) exist: needle and fine-wire EMG. Each method has unique and shared advantages and disadvantages. Previous reviews appraising the use of indwelling EMG were examined to summarise electrode insertion, outline conductivity and the signal each type of electrode records.

	Needle EMG	Fine-wire EMG
Introduction of the electrode	<ol style="list-style-type: none"> 1. Electrodes are inserted via a fine hypodermic needle, 23-28 gauge. 2. Recording wires run through the central cannula and have an uninsulated tip, which is placed into a specific area of interest for the targeted muscle. 3. Electrodes do not remain in the muscle. 	<ol style="list-style-type: none"> 1. Also introduced via a hypodermic needle. 2. Wires are much finer, 50µm in diameter, and once the needle is removed, the electrodes remain in situ within the muscle. 3. Once inserted the proximal end of the wire forms a loop which is taped to the skin surface to anchor the electrode in place.
Conductivity	<ol style="list-style-type: none"> 1. High: constructed from highly conductive metal. 	<ol style="list-style-type: none"> 2. High: constructed from highly conductive metal.
Signal recorded	<ol style="list-style-type: none"> 1. Record any electrical signals which pass within a few millimetres of their location. 2. MUAP recorded will only represent activity in the muscle fibres within the pickup zone for that specific electrode. 	<ol style="list-style-type: none"> 1. Record any electrical signals which pass within a few millimetres of their location. 2. MUAP recorded will only represent activity in the muscle fibres within the pickup zone for that specific electrode.

Adapted from: Kamen and Gabriel (2010), Wijnberg *et al.* (2003) and Rash (1999)

Table 4: Advantages and disadvantages of surface and indwelling EMG

Two types of electromyography (EMG) exist: surface and indwelling EMG. Previous reviews comparing the two methodologies were examined to summarise the advantages and disadvantages of surface EMG and indwelling EMG.

Method	Advantages	Disadvantages
Indwelling: needle and fine-wire E.M.G	<ol style="list-style-type: none"> 1. Indwelling electrodes, particularly fine-wire, exhibit an increased band width, with a specific pickup area of ~50-200µm. 2. Capable of testing deep muscles. 3. Can isolate specific parts of large muscles, use in small muscles or test areas where multiple muscles converge requiring specificity to analyse the area of core interest. 	<ol style="list-style-type: none"> 1. Invasive. 2. Discomfort associated with insertion. 3. Potential spasticity in targeted muscles. 4. Lack of repeatability in placement. 5. Use limited to laboratory. 6. Fine-wire electrodes may break and be retained in muscle.
Surface EMG: passive and active	<ol style="list-style-type: none"> 1. Non-invasive nature facilitates wider applications. 2. Ease of application with minimal pain. 3. Use in dynamic studies, in the lab or the field. 	<ol style="list-style-type: none"> 1. Pickup area for a surface electrode is limited by the distance from the muscle of interest and the detectable MUAPs being produced. 2. The pickup distance is related to the size of MU under evaluation; small MUs, ~ 50 fibres, are limited to ~0.5cm whilst larger units, >2500 fibres, can travel >1.5cm. 3. Data collected are limited to activity in proximal muscles and superficial portions of these. 4. Large pickup areas increase propensity for crosstalk within the signal.

Adapted from: Kamen and Gabriel (2010), Winter (2009), Drost *et al.* (2006) and Rash (1999)

It is normal practice, regardless of EMG type, for two electrodes to be used to reliably assess the muscle under investigation (Richards, Thewlis and Selfe, 2008). The electrodes are placed a set distance apart from each other. Each electrode will detect the MUAP but at a defined point in time, which enables the difference in potential between the electrodes to be recorded (Kamen and Gabriel, 2010). In reality, the signal should be virtually identical at each electrode but slightly shifted in time. It is important to recognise that timing-phasing exists during analysis of the EMG signal to enable accurate interpretation through appropriate selection of filter order (De Luca, 2003).

Consideration of MUAP duration and frequency are also important when contemplating the application of EMG during studies. The duration of the MUAP recorded will be influenced by the choice of EMG method used. MUAP duration represents the functional velocity of the propagating wave-front being detected (Winter, 2009; Konard, 2005). Generally, the faster the velocity of the action potential (AP), the shorter the duration of the MUAP; equally, the larger the surface area of the electrode, the more MUs will be analysed, resulting in an increased MUAP duration (Winter, 2009). The distance from the MU to the electrode will also influence the amplitude and duration of the AP being recorded (Winter, 2009). The duration of the AP increases proportionally the closer the MU is to the electrode, whilst amplitude has a reverse relationship, reducing the further away MUs are situated from the recording electrode (Winter, 2009). Surface electrodes automatically record longer duration MUAPs due to their increased surface area compared to both types of indwelling electrode, but by their nature will not record activity beyond the superficial layers of muscle (Drost *et al.*, 2006; Lowery, Stoykov and Kuiken, 2003).

3.4 sEMG versus indwelling EMG in the horse

Choice of electrode will largely be dependent on the research objectives of individual studies (Rash, 1999). sEMG may exert an advantage in equine research over fine-wire and needle EMG, as sEMG electrodes have the ability to sample larger muscle volumes (more MUs per electrode), which are better suited to the large muscles of the horse and as sEMG is a more ethically acceptable methodology (Winter, 2009). However scope is limited to the surface musculature since examining muscles further away from the skin surface reduces the reliability of the source of the sEMG signal detected (Lowery, Stoykov and Kuiken, 2003). Therefore indwelling electrodes may be the methodology of choice to assess finessed movement, deep musculature or defined MUs (Rash, 1999). The majority of equine EMG work undertaken to date has occurred in laboratory environments attributable to limitations in the technology, for example use of fine-needle systems, fixed electrodes or restricted range in sEMG telemetric systems. Laboratory research can benefit from standardising extrinsic variables such as surface via treadmill use (Crook, Wilson and Hodson-Tole, 2010) but does not mimic the training or competition environment. Evolving technology provides opportunities for increased applied and field-based research using sEMG to analyse equine performance where indwelling systems would prove defunct due to the research environment or because riders and trainers would not sanction using indwelling electrodes in their horses.

3.5 The Delsys® Trigno™ sEMG system

A variety of telemetric sEMG systems for data collection and analysis are available for use in human subjects, but no system has been designed specifically for use in

the horse. The Delsys® Trigno™ Wireless EMG system (Table 5; Plate 1) (Delsys®; Boston, USA) was selected for use in the sEMG work presented after pilot studies performed in conjunction with Delsys® representatives confirmed its suitability for use in dynamic equine research (Delsys®, 2014).



Plate 1: The Delsys® Trigno™ Wireless EMG System (Delsys®, 2014); reproduced with kind permission from Delsys®.

Table 5: Technical specifications of the Delsys® Trigno™ Wireless EMG system

The Delsys® Trigno™ Wireless EMG system was used to collect and analyse sEMG data for Evidence Sources 1.2 to 1.4 in the thesis. The technical specification for key aspects of the unit related to sEMG data collection are summarised from the unit's handbook in the table.

sEMG system	Features
Trigno™ system	Docking station or unit and up to 16 sensors
Docking station / unit	Can record 16 EMG and 48 accelerometer channels simultaneously
Sensors	Each sensor features a pair of EMG electrodes and includes an in-built tri-axial accelerometer (X, Y, Z planes)
EMG electrodes	Each sensor contains four silver electrodes: two fixed active and two fixed reference electrodes which guarantee a 10mm placement distance preventing electrode placement errors during data collection Two differential electrodes are combined with a further two stabilising reference electrodes to reduce interference associated with noise and motion artefacts, providing a fixed EMG observational area of 50mm ²
Range	Up to 40m
Battery life	Up to 8 hours
Resolution	16 bit
Data channels	Dependent on number of active sensors Each sensor = 1 EMG channel and 3 accelerometer channels Capable of recording 16 EMG and 48 accelerometer channels simultaneously, or selected EMG and / or accelerometer channels up to maximum capacity
Sampling rate	2000Hz
Integrated band width filter	f _c 20 and 450 Hz
Common mode rejection ratio	≥80dB
Gain	1000V/V
Signal to noise ratio	<4-5μV from peak to peak
Compatibility with other equipment	The Trigno™ system is compatible with numerous complementary analysis systems including videography and gait analysis software depending on the software available
Data acquisition and analysis software	As standard, once the system is aligned to a compatible laptop, data are streamed live via EMG Works® Acquisition and Analysis software facilitating 'real-time' assessment of the

	signal and subsequent data analysis
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Adapted from Delsys® (2014)

3.6 Data collection

The ideal sEMG study should aim for consistency in the acquired EMG signal (Smoliga *et al.*, 2010). Numerous factors affect the reliability of sEMG data collected or may potentially influence interpretation of results (Reaz, Hussain and Mohd-Yasin, 2006) (Table 6).

Table 6: Factors which influence the EMG signal

The electromyography (EMG) signal will record all electrical activity within its defined pickup zone. The quality of the EMG signal received will also be affected by the location of the sensor and how well it is attached to the subject. Review of previous research identified core factors which can result in interference to the EMG signal. The sources of interference and their impact are provided in the table.

External factors	Sources
Inherent electrical noise	Electronic equipment
Ambient electrical noise	Electromagnetic radiation from the subject
Motion artefacts	Electrode interface Electrode cable
Inherent instability of signal	EMG amplitude is stochastic by nature, the base line motor unit firing rate at rest is not usually wanted within experimental EMG data
Causative factors (direct effect)	Sources
Extrinsic	Electrode structure and placement e.g. location and orientation
Intrinsic	Physiological, biochemical and anatomical factors e.g. number of motor units, fibre type
Intermediate factors	Physical and physiological factors influenced by causative factors e.g. cross talk
Deterministic factors	Aspects influenced by intermediate factors e.g.

	amplitude, firing rates
--	-------------------------

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

The optimal EMG signal represents the total of all MUAPs under investigation and should contain no distortion, noise or artefacts. Prior to data collection, four areas should be considered to optimise the quality of the signal:

1. Amplifier gain and its dynamic range,
2. Input impedance (Z),
3. Frequency response, and,
4. Common mode rejection.

For optimum bio-amplification EMG systems require gains between 100 to 10,000 (Winter, 2009). 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). The input impedance represents the resistance of the EMG unit and should be high enough to prevent attenuation of the EMG signal. Every electrode–skin interface possesses finite impedance influenced by the skin thickness, preparation, and surface area of the electrode and the temperature of the skin, including electrode gel and / or sweat (Kamen and Gabriel, 2010). Indwelling electrodes produce higher impedance than sEMG electrodes, due to their reduced surface area. sEMG units require input impedances $<1000\Omega$ combined with effective skin preparation. If preparation does not occur then values need to increase to $>1\text{m}\Omega$ (De Luca *et al.*, 2010; Kamen and Gabriel, 2010). For indwelling electrodes, the impedance increases $>50,000\Omega$ therefore amplitudes with a least $5\text{M}\Omega$ are required (Kamen and Gabriel, 2010). The

frequency response should be set to enable all the frequencies present within an EMG signal to be collected (Winter, 2009). The EMG spectrum ranges between 5 and 2000Hz, which includes the physiological MUAP amplitudes and non-relevant electrical signals (Kamen and Gabriel, 2010). sEMG data collection units commonly apply frequency ranges between 10 and 1000Hz (De Luca, 2003; Delsys, 2014). Mammals are good conductors of electromagnetic radiation and will absorb signals from nearby power sources potentially introducing anomalies into the EMG signal being recorded (De Luca *et al.*, 2010). The common mode rejection represents the differential amplification required to eliminate these extraneous sources from the functional EMG signal (Winter, 2009).

3.7 Physiological influences on the EMG signal

Intrinsic electrical interference from adjacent muscles may be present in the EMG signal and should be avoided (De Luca *et al.*, 2010; Konrad, 2005). The interference, known as cross-talk, occurs due to overlapping APs from multiple muscles or MUs falling within an electrode's pickup zone (Winter, 2009; Farina *et al.*, 2002). Good experimental design should help to eliminate interference. Researchers need to ensure electrode placement optimises data collection from the muscle of interest and limits cross-talk potential (De Luca *et al.*, 2010). Human EMG researchers benefit from globally affirmed topography for sEMG sensor placement, available via the Surface EMG for Non-Invasive Assessment of Muscles (SENIAM) guidelines (Konrad, 2005). Equivalent guidance unfortunately does not yet exist for the horse; however equine sEMG research should aim to conform to the SENIAM recommendations for data collection and processing.

Other factors may influence muscle fibre conductivity. Temperature has been shown to change the velocity of APs (Kamen and Gabriel, 2010). Cold temperatures depress fibre excitability resulting in a reduced contraction speed, comprising lower spectral frequencies, whilst warmer temperatures increase contraction velocity (Kimura, 2001; Winkel and Jorgensen, 1991). Muscle and muscle fibre length will also influence the frequency characteristics of MUAPs, usually EMG frequency decreases as muscle length increases, whilst shorter fibres produce a higher spectral frequency (Kamen and Gabriel, 2010). The quantity and type of tissue between the electrode and MU will also influence the amplitude and frequency characteristics of the sEMG signal received (Kamen and Gabriel, 2010; Winter, 2009). The dermal layers, in particular subcutaneous adipose tissue, act as a low-pass filter on the EMG signal, effectively dampening it (Konrad, 2005). The dampening effect increases with tissue depth, therefore resultant EMG data are biased (reduced signal transfer) with increased representation of the MUAP from superficial fibres (Kamen and Gabriel, 2010).

3.8 Data processing

There is no set method accepted as a gold standard when processing EMG data (Kamen and Gabriel, 2010; Winter, 2009). Evaluation of the gross EMG signal, in real-time provides visual information re: onset, offset and timing (Delsys, 2013). Raw EMG data are recorded as a sine-wave containing negative and positive values; therefore data processing is required to fully evaluate muscle responses during analysis. Currently, three common applications of the sEMG signal exist (Table 7).

Table 7: The three common applications of sEMG; MUAP: motor unit action potential

Surface electromyography has evaluated muscle recruitment, activity levels, force production, fatigue and muscle relationships to motor skills within clinical studies to assess myoneuralgia and motor disease, during rehabilitation regimens, and for performance analysis during exercise and training. Brief details of how sEMG is used to assess these areas are provided in the table.

Common applications of sEMG in research and for performance analysis	
1	to determine the recruitment and activity of the muscle via onset and offset timing evaluation and calculating the mean MUAP, or comparing MUAP for set events
2	to estimate the force produced by the muscle as it is roughly proportional to amplitude contraction
3	to study how the frequency components vary within the signal and with time to determine whether or not the muscle has fatigued, assessed through plotting mean or median frequency over time

Adapted from Delsys® (2014), Hibbs *et al.* (2011) and De Luca (2003)

Methodologies commonly employed to facilitate further examination for the determination of amplitude, timing and spectral, or frequency, analyses include:

- Categorisation of the frequencies within the signal via the application of filters,
- Half or full wave rectification of the absolute value of the EMG data,
- Application of a linear envelope (after rectification and combined with a low pass filter),
- Integration of the full wave rectified signal (integrated or i.EMG):
 - Over the entire period of muscle contraction,

- For a fixed time period, or,
- Compared to a pre-set (baseline) level

(Delsys®, 2013; Hug, 2011; Kamen and Gabriel, 2010; Winter, 2009).

3.8.1 Filters

During muscle activity, the amplitude of the EMG signal at any given instant is stochastic and will contain multiple frequencies contributing to the force produced (Hug, 2011). Within the signal, the initial MU input is a high frequency signal which ‘fires’ the subsequent muscle twitch, however the muscle fibre acts like a capacitor, therefore contractions produce lower frequency outputs (Winter, 2009). Likewise, external sources of noise could contribute to the frequency domain recorded (De Luca *et al.*, 2010). Therefore filters are applied to ensure only relevant frequencies that contribute to the event being assessed are analysed (Kamen and Gabriel, 2010; Winter, 2009).

Filters are electronic circuits which alter the frequency content of the EMG signal. Filters define which frequencies within the signal are analysed whilst stopping or attenuating unwanted frequencies e.g. noise contamination or frequencies which have been demonstrated through power spectral density analysis to constitute a small percentage of the signal (Kamen and Gabriel, 2010). The application of filters reduces the potential for misinterpretation of data and subsequent spurious results (Winter, 2009). Ideal filters have brick wall responses to cut-off frequencies (f_c) i.e. a 20Hz low-pass filter would remove all frequencies <20 Hz (De Luca, 2003). However, f_c only considers changes in the magnitude of the signal in relation to amplitude frequency. In reality, the magnitude the sinusoid EMG signal represents is related to both amplitude and time, therefore filters need to integrate both frequency

and phase response (timing) within their specification to accurately filter the data obtained (De Luca, 2003; Kamen and Gabriel, 2010). All filters delay the timing of the EMG signal to some extent which would not be a problem if the delay was linear and consistent across all frequencies within the signal, however delays may only exist in certain frequencies distorting the signal (Winter, 2009). Delays in timing between two sinusoids of the same frequency results in each passing through the zero point at different times causing signals to be out of phase creating a phase-lag (Kamen and Gabriel, 2010). Therefore consideration of phase response within the signal is another important aspect that needs to be contemplated when applying filters.

The behaviour of different filter models is shown in Figure 6; practically a filter does not transition from pass-band to stop-band regions (or vice versa) immediately as can be seen by the lack of a 90° angle within each graph. In reality each filter type will have a transition zone where the signal transmission changes from pass-band to stop-band regions or vice versa (DeLuca, 2003).

A filter's 'order' is used to describe the relative steepness of the filter's transition zone and complexity of the filter; the higher the order the narrower the transition zone and the higher the complexity of the filter (Kamen and Gabriel, 2010). It should also be noted that frequencies within the stop-band cannot be eliminated completely. Therefore it is important to establish and apply f_c to demarcate the pass-band and stop-band regions (Winter, 2009). The simplest design is a first order filter, here the transition band reduces the signal by -20dB for every 10 fold change in frequency i.e. attenuates at -20dB/decade, which will reduce the amplitude of the signal by $1/10^{\text{th}}$ for every decade increase in frequency. For each sequential increase in order i.e. 1 to 2 to 3, the level of attenuation will double e.g. a 2nd order filter will

attenuate at -40dB / decade and will reduce the amplitude of the input signal by $1/20^{\text{th}}$ for every decade (Delsys, 2013). Therefore with higher filter orders a lower value for f_c can be used.

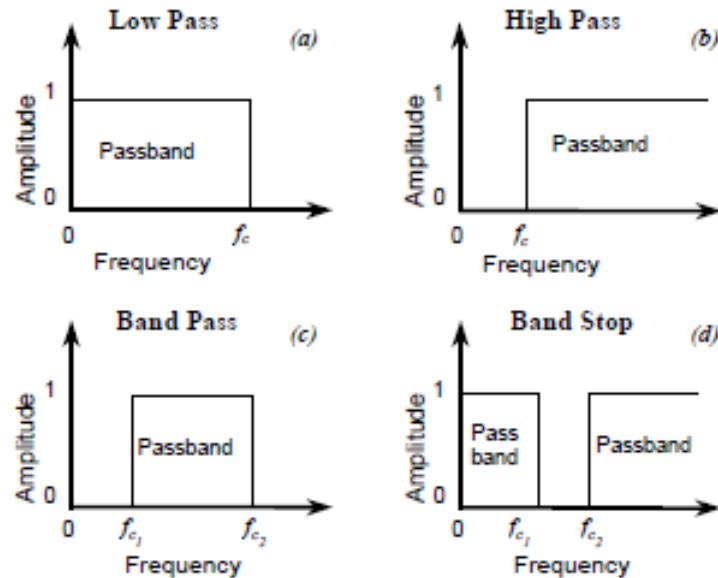


Figure 6: The four basic filter types: where filter response amplitude is 1 are defined as pass-band regions; while frequencies where the filter response amplitude is 0 are defined as stop-band regions. The cut-off frequency is denoted by f_c . (a) Low-pass filter, (b) High-pass filter, (c) Band-pass filter and (d) Band-stop filter (DeLuca, 2003). Reproduced with kind permission from Delsys®.

Filters are applied to electromyography data to remove erroneous data related to movement artefacts, noise or other forms of electrical interference prior to analysis and to remove the impact of time-lag from the EMG signal. Filters utilise the frequency component of the EMG signal to apply one or more cut-off frequencies to isolate the desirable data within the signal. Four basic filter types exist, how each works is outlined in figure 6.

Initially a band-pass filter is commonly applied to raw EMG data; the band-pass incorporates upper and lower f_c to remove noise and limit the data to the ‘active’ frequency domain for muscle activity prior to further analysis (De Luca *et al.*, 2010; De Luca, 2003). A number of filter types are available for further computational analysis: the Butterworth, Chebyshev, Elliptic and Thompson or Bessel filters.

The Butterworth filter is the filter of choice for application of a linear envelope in gait studies (De Luca *et al.*, 2010; Kamen and Gabriel, 2010; Winter, 2009). Butterworth filters are used as their roll rate is maximally flat in the pass-band which minimises the pass-band ripple in the attenuated signal resulting in the production of a smooth wave; they are best suited to applications requiring preservation of amplitude linearity in the pass-band region i.e. linear enveloping in kinesiological EMG (Kamen and Gabriel, 2010). The magnitude and phase responses of Butterworth filters are quantified by the maximum band-pass gain, f_c and the filter order selected for use. Butterworth filters demonstrate a linear phase lag which is only beneficial if the phasing of all frequencies in a signal are consistent (Kamen and Gabriel, 2010).

A delay of 50-100ms occurs between muscle activity and resultant motion (Lamb and Hobart, 1992). Therefore the phase lag of the selected filter is important when considering timing of activity within dynamic muscle studies. An ideal filter will integrate a time delay that is independent to its frequency i.e. each frequency component within the signal will be phased in exactly the same way. Unfortunately exact-phasing is not achievable; therefore the f_c is combined with a filter order, to control for phasing, to create the optimal EMG data for evaluation (De Luca, 2003). A zero phase lag may be achieved by applying a 4th order filter; which in effect passes the signal through a 2nd order filter (analogous to twitch waveforms) twice in a forward and backward direction (Kamen and Gabriel, 2010; Winter, 2009). For the dynamic work presented in the thesis, a 4th order Butterworth filter was applied to manipulate (smooth) the signal and achieve a zero phase lag (Kamen and Gabriel, 2010) to reduce the potential for spurious results to be obtained.

3.8.2 Full wave rectification

Full wave rectification is often the initial building block for analysis of the filtered EMG data (Kamen and Gabriel, 2010; Winter, 2009). The result is a positive signal, which does not cross zero and fluctuates according to the strength of MUAPs facilitating further quantitative analysis. Visual examination of the signal should occur after rectification and will provide functional information on muscle contraction through assessment of signal amplitudes and their duration (Richards, Thewlis and Selfe, 2008).

3.8.3 Linear enveloping

Linear envelopes are the most commonly applied demodulation tests used to analyse muscle coordination and activity within EMG profiles related to rapid movement e.g. gait studies (Kamen and Gabriel, 2010; Hug and Dorel, 2009; Kleissen, 1990; Shaivi *et al.*, 1998). The MU impulse that initiates contraction is a high frequency input; in contrast the resultant muscle twitch is a low frequency output (Winter, 2009). Therefore the application of a low-pass filter, post full wave rectification, to the band-pass filtered EMG signal is analogous to the muscle contraction process. The application of a linear envelope results in a smoothed EMG signal representing the force-time curve of the active muscle (mV) (Kamen and Gabriel, 2010; Winter, 2009), which reflects analytical methods used in biomechanical gait analysis to reduce data anomalies related to the dynamic nature of movement studies (Richards, Thewlis and Selfe, 2008). A wide range of cut-off frequencies (f_c) are reported in the

literature, ranging from 3 to 60Hz, but the majority of human gait studies utilise a f_c <20Hz (Kamen and Gabriel, 2010) (Table 8).

Table 8: Examples of EMG filtering protocols utilised in human dynamic studies.

A range of human surface electromyography (EMG) studies examining dynamic movement were reviewed to identify the filtering protocols applied to the EMG data to facilitate subsequent comparison.

Sport	Filtering protocol applied to EMG data	Study
Downhill running	High-pass filter with f_c of 20Hz Full wave rectification Linear envelope: low-pass filter, zero-lag, f_c of 5Hz	Sheenan and Gotschall, 2013
Rowing	Band-pass filter with lower and higher f_c of 20 and 400Hz, respectively Full wave rectification Linear envelope: low-pass Butterworth filter, 4 th Order, f_c of 8Hz	Turpin <i>et al.</i> , 2011
Pole vaulting	Band-pass filter with lower and higher f_c of 19 and 395Hz, respectively Full wave rectification Linear envelope: low-pass Butterworth filter, 4 th Order, f_c of 5Hz	Frere <i>et al.</i> , 2012
Muscle synergy during cycling	High-pass filter f_c of 20Hz Full wave rectification Linear envelope: low-pass filter, zero lag and f_c of 5Hz	Hug <i>et al.</i> , 2010
Cross-country skiing	Band-pass filter with lower and higher f_c of 20 and 450Hz, respectively Full wave rectification Linear envelope: low-pass Butterworth filter, 4 th Order, f_c of 50Hz	Zoppirolli <i>et al.</i> , 2013
Landing from a drop jump	Band-pass filter with lower and higher f_c of 10 and 500Hz, respectively Full wave rectification Linear envelope: low-pass Butterworth filter, 2 nd Order, f_c of 6Hz	De Britto <i>et al.</i> , 2014

There is no general rule that should be applied to give the most appropriate low pass f_c (Kamen and Gabriel, 2010). The selection of f_c can be derived from muscle twitch times providing a biological basis for the value applied (Winter, 2009), from calculation of -3dB point of the signal (De Luca, 2003) or set at the value which represents 95% of the Total Power of the signal (Kamen and Gabriel, 2010). In humans, twitch times have been extrapolated from isometric EMG analysis for a number of muscle groups (Winter, 2009), however isometric analysis is not achievable in the horse. For dynamic studies, f_c may be defined as the value (Hz) which represents 95% of the Total Power of the movement signal under consideration. F_c selection should be sufficient to reduce EMG variation related to phasing during movement whilst minimising distortion within the signal but will be dependent on the filtering protocol applied (Kamen and Gabriel, 2010; Shiavi *et al.*, 1998). In the absence of a standardised protocol, Vint *et al.* (2001) suggest that a range of f_c combined with low pass filtering are applied to data and subsequent EMG traces overlaid to evaluate variability within EMG profiles to determine the effect of, and to select a suitable value for f_c . The majority of previous equine EMG research has utilised an f_c of 10Hz combined with a Butterworth filter (for example: Zsoldos *et al.*, 2010a, b; Licka, Frey and Peham, 2009).

3.8.4 Integrated EMG

Integrated EMG represents the area under a fully rectified EMG trace. In essence iEMG is the equivalent to the work done by a muscle for a defined activity period, therefore the area increases with contraction and decreases during rest (Richards, Thewlis and Selfe, 2008).

3.9 Interpretation of the processed EMG signal

Interpretation of sEMG data is acknowledged as challenging as a number of factors can influence the resultant signal (Reaz, Hussain and Mohd-Yasin, 2006). Variation in signal amplitude may be attributed to increased numbers of active MUs being recruited or a change in the frequency of activation i.e. the firing rate has increased but the same number of MUs are being recruited (Konrad, 2005; Stegeman *et al.*, 2000).

3.9.1 Muscle fibre profile

Muscle fibre profile will influence the EMG trace produced (Kamen and Gabriel, 2010). An elevated frequency for amplitude of the sEMG signal could be related to an increase in fast-twitch fibre recruitment or a higher firing rate in slow-twitch fibres (both equalling more muscle effort) or could be the result of decreased synchronisation between MUs that are firing (muscle starting to fatigue) (Staudenmann *et al.*, 2010; Winter, 2009; Rahnama, Lees and Reilly, 2006). In contrast, a decreased frequency may be attributed to a reduced firing rate (fatigue) or increased MU synchronisation (coordinated muscle activity; no fatigue present) (Staudenmann *et al.*, 2010; Winter, 2009; Rahnama, Lees and Reilly, 2006).

3.9.2 Contraction type

The category of muscle contraction will also impact the MUAP recorded (Richards, Thewlis and Selfe, 2008). During dynamic evaluation, muscles perform anisometric contractions dependent upon their function. In concentric contractions, tension is reduced as length shortens during muscle contraction. Eccentric muscles display the opposite pattern, with tension increasing as the muscle lengthens during activity. Therefore concentric muscles have to work harder to function effectively than eccentric ones. Although contraction magnitude is individualised, broad characteristics are observed in the resultant EMG trace (Staudenmann *et al.*, 2010). Contractions in concentric muscles will exhibit a larger magnitude than eccentric ones representing their greater workload (Richards, Thewlis and Selfe, 2008).

3.9.3 Comparing events

EMG studies often aim to compare traces across populations or in individuals over repeated events (Hibbs *et al.*, 2011). Comparison of the amplitude of EMG signals between events is challenging due to the variety of confounding variables which at any given point in time may vary and influence muscle activity (Kamen and Gabriel, 2010; Richards, Thewlis and Selfe, 2008). One approach is to normalise the EMG signal to enable comparison. In humans, maximum voluntary contractions (MVC) are commonly utilised (Winter, 2009), however these cannot be achieved in the horse. In dynamic studies, an alternative approach is to compare defined cycles within the EMG trace for example >5 stride cycles in gait analysis (Kamen and Gabriel, 2010). In equine sEMG, normalisation to the EMG signal obtained at rest has been used (Peham *et al.*, 2001) as well as evaluation via comparison of defined events (Zsoldos *et al.*, 2010a, b).

3.9.4 Assessment of fatigue

Metabolically, fatigue occurs when the muscle tissue become ischaemic and the metabolic factors required to facilitate contraction are depleted (Rivero and Piercy, 2008). Mechanically, fatigue can be characterised by a reduction in muscle tension (force); therefore increased numbers of MUs need to be recruited to maintain activity-levels. Simultaneously fatigue changes the characteristics of MUAPs. Larger and faster MUs with short duration activity will drop out of force production first, APs will record a reduced conduction velocity and the remaining active units will synchronise to fire in bursts (Winter, 2009). The consequence is a reduction in the high-frequency components of the EMG frequency spectrum, which when plotted over time consistently results in a net left shift in the mean or median frequency of the signal (Reaz, Hussain and Mohd-Yasin, 2006; Hanon, Thepaut-Matieu and Vanderwalle, 2005; Colborne, Birtles and Cacchione, 2001).

CHAPTER FOUR
SURFACE ELECTROMYOGRAPHY
AND THE EQUINE ATHLETE

Limited research has been conducted to analyse muscle performance during exercise in the horse (Ferrari *et al.*, 2009). Factors which relate to muscle performance are commonly assessed observationally, for example fatigue, or via analysis of allied physiological variables, such as heart rate (for example: Williams and Fiander, 2014). However these techniques cannot quantify recruitment, activity-levels or adaptation in muscle tissue, or account for individual or breed variation; factors which could directly influence performance. Chapter Four reviews the capacity of sEMG as an objective and quantifiable measure of muscle performance related to the core principles of equestrian training and muscle physiology.

4.1 An introduction to muscle physiology

A fundamental knowledge and understanding of the structure and function of equine muscle, and the physiological processes which underpin muscle activity are essential for the EMG researcher (Winter, 2009; Hanon, Thepaut-Matieu and Vanderwalle, 2005). A summary of these are provided in Appendix 10. Muscle is responsible for movement and force generation (Leisson, Uaakma and Seene, 2008). Few studies have investigated muscle architecture and physiology in the horse (Rivero, 2014; Ferrari *et al.*, 2009). The research which is available includes small datasets which lack detail regarding the participants, for example sex, age, fitness level or exercise regimens are often not recorded (Kearns, McKeever and Abe, 2002).

During activity, muscles produce ‘power’: the product of the force generated multiplied by velocity associated changes in the muscle length (Kearns, McKeever and Abe, 2002). Movement is not uniform in its mechanics; different categories of contraction exist and are identifiable in sEMG-traces (Table 9) (Section 4.8.2). Maximal force production is related to the physiological cross-sectional area (CSA) and the muscle fibre profile of an individual muscle (Rivero, 2014; Rietbroek *et al.*, 2007). Force and velocity are dependent on the functional biochemical characteristics of muscle fibres, combined with the configuration of fibres in respect of the muscle in its entirety (Rivero, 2014; Rietbroek *et al.*, 2007; Kearns, McKeever and Abe, 2002). The potential force which can be generated is directly proportional to the number of sarcomeres that are parallel and in series within active muscle fibres (Rivero, 2014; Kearns, McKeever and Abe, 2002). The duration of the force produced, or the contraction, will be reliant upon the ability of the muscle not to fatigue (Rivero, 2014; Rivero and Piercy, 2008). Therefore skeletal muscle also requires an adequate blood supply to support its function, which is achieved via a highly organised integral capillary network (Marlin and Nankervis, 2002).

4.1.1 Muscle contraction

Muscle contraction is the result of the sequential shortening of individual sarcomeres (Appendix 10, A10.5), the functional unit of contraction, in response to innervation (Rivero, 2014; Yousefi and Hamilton-Wright, 2014; Kearns, McKeever and Abe, 2002). A stimulus generates an electrical signal or AP. The AP progresses through the sensory, central and motor nervous systems until it is received in the basal ganglion of a motor neuron located in muscle to stimulate contraction.

Table 9: Types of contraction in skeletal muscle

Different types of muscle contraction occur in mammals. The key features of each type of contraction were examined and are summarised in the table. Practical examples are provided to enable their identification during movement.

Contraction type:	Key features:
Isometric	Resting length of the muscle body remains of constant length during contractions Muscle force equals load and no movement occurs until fatigued Example: human holding a weight still at arm's length, isometric contraction of the <i>Triceps brachii</i> and <i>Biceps brachii</i>
Isotonic	Muscle tension remains constant, but muscle length varies Muscle force exceeds load on the muscle Examples: eccentric and concentric contractions
Concentric	Resting length of the muscle body shortens during the contraction Tension reduces as muscle shortens: attributed to cross-bridges in the contractile element breaking and reforming in a shortened condition Muscle force exceeds resistance Example: flexion of the human arm, concentric contraction of the <i>Biceps brachii</i>
Eccentric	Resting length of the muscle body lengthens during contraction Tension increases as muscle length increases due to increased loading: greater force required to break cross-bridges and lengthen, than to maintain isometric length External load exceeds muscle force; often assisted by gravity Example: extension of the human arm, eccentric contraction of the <i>Biceps brachii</i>
Isokinetic	Muscle contraction velocity is constant but force varies Analysis method employed on individual muscle within <i>in vitro</i> experiments

Adapted from: Winter (2009) and Rivero and Piercy (2008)

The AP enters the muscle motor unit (MU) at the motor end plate (MEP) and triggers a series of electrochemical events that transfer the impulse along the muscle

fibres (Yousefi and Hamilton-Wright, 2014). The arrival of the AP at the MEP stimulates changes in the ionic properties of the sarcolemma (Konrad, 2005). At rest the intrinsic polarity of the muscle fibre is negative; once an AP arrives acetylcholine is released increasing conductivity within the sarcolemma. The result is an increase in Na⁺ ions entering the fibre which produce a change in polarity (positive) creating a MUAP when the stimulus is of sufficient size. The process is known as polarisation. Polarisation is followed by depolarisation when the K⁺ channels open and the polarity reverts to its resting status (Konrad, 2005). sEMG records the changes in polarity as a MUAP.

Excitation of the MU stimulates contraction in the muscle fibre and is either 100% or 0% (Winter, 2009). APs must be of sufficient size to move sequentially along the fibre producing contraction within successive sarcomeres (Yousefi and Hamilton-Wright, 2014; Kamen and Gabriel, 2010). sEMG records the sum MUAP (amplitude, frequency and timing) for active MUs in superficial muscles within the range of each sensor applied (Drost *et al.*, 2006; Konrad, 2005). Amplitude varies with the MU and muscle fibre type (Table 10) recruited to produce the MUAP measured by sEMG (Yousefi and Hamilton-Wright, 2014; Konrad, 2005). The sum MUAP recorded in sEMG will represent the frequencies (Hz) of the different MU types that are active generating a frequency domain spectrum (Kamen and Gabriel, 2010). Firing rate represents the timing of sarcomere contractions within the sum MUAP recruited (Konrad, 2005; Stegeman *et al.*, 2000). Firing rates vary with MU type and MUs can synchronise firing frequencies when required, for example during fatigue (Kamen and Gabriel, 2010; Winter, 2009).

Table 10: Key features of motor units which can impact force production

Activation of motor units by a propagating action potential stimulated sequential contraction in the sarcomeres of muscle fibres, ultimately resulting in muscle contraction. Knowledge of the types of motor unit and understanding their characteristics aids interpretation of sEMG data. The three types of motor unit and key features are outlined in the table.

Feature	Description
Motor unit type	<p>3 types are recognised in mammalian tissue:</p> <ul style="list-style-type: none"> • slow (S) found in Type I muscle fibres: associated with long duration-low intensity exercise e.g. postural support • fast resistant to fatigue (FR) found in Type IIA muscle fibres: associated with long duration - medium intensity exercise e.g. sustained running • fast fatigable (FF) found in Type IIX muscle fibres: associated with short duration – high intensity exercise e.g. sprinting or jumping
Activation threshold	<p>Related to MU type and size</p> <p>The size of the AP required to recruit MU increases sequentially within S > FR > FF</p>
Firing rates	<p>S: slow</p> <p>FR: intermediate</p> <p>FF: fast</p>
MUAP magnitude	<p>Related to MU type and size, magnitude increases sequentially: S>FR>FF</p>
Sex distribution	<p>Males have increased FF than females</p>
Age related changes	<p>Contraction times decrease in S and FR with aging</p> <p>Force production increases in S units and decreases in mainly FF but also FR units with aging</p>

Adapted from: Celichowski and Krutki (2012)

4.2 Muscle supporting performance

The skeletal musculature of the horse has evolved to facilitate superior athletic performance in comparison to other mammals (Rivero, 2014). Skeletal muscle constitutes approximately 42% of an average horse's bodyweight, which increases to ~55% in the mature, trained equine athlete (Hinchcliff and Geor, 2008). The biological importance of skeletal muscle is demonstrated by its structural and functional plasticity, which facilitates phenotypic adaptation in response to exercise and training (Rivero, 2014; McGivney *et al.*, 2009; Serrano, Quiroz-Rothe and Rivero, 2000).

4.2.1 The influence of muscle fibre profiles

sEMG profiles are dependent on the MUAP production in muscles under investigation (Reaz, Hussain and Mohd-Yasin, 2006). Equine muscles contain a combination of fibre types, producing a muscle fibre profile which will influence the sEMG profile obtained during exercise. Fibre type varies between breeds (Lopez-Rivero *et al.*, 1992), can differ according to function (Choi and Kim, 2009), sex (Ozawa *et al.*, 2000; Choi and Kim, 2009), age (Smarsh and Williams, 2014; Holloszy and Larsson, 1995), and with hormones and fitness status (Bell *et al.*, 2000; Rivero *et al.*, 1995).

Characterisation of fibre type can also be achieved in relation to function through metabolic activity (muscle biopsy and staining) (Rivero, 2014; Lopez-Rivero and Letelier, 2000; Snow and Valberg, 1994), determination of biomechanical force (twitch) measures, through electrophysiological (EMG) indicators (Winter, 2009) or

described by the expression of the myosin heavy chain (MHC) isoform present (Rivero, 2014; Hinchliff, 2007) (Table 11). The MHC isoform most closely expresses the fibre's phenotype and is the main determinant of maximum shortening velocity, force production and fatigability (Schiaffino and Reggiani, 1994; Pellegrino *et al.*, 2003). MHC isoforms are therefore of interest to the sEMG researcher as they could influence selection of participants and subsequent interpretation of muscle activity-levels.

Five MHC isoforms are acknowledged in mature equine skeletal muscle (Leisson, Uaakma and Seene, 2008; Hinchliff, 2007). Fibre type can adapt with training, which is of interest from a performance perspective. Three pure fibre types: Type I, IIA and IIX exist in a single isoform alongside two hybrid types: Type I+IIA and Type IIA + IIX (IIAX), the latter linked to training. Exercise intensity and duration combined with muscle fibre profile (Figure 7) will dictate the recruitment pattern and frequency of contraction and will be reflected in the values of MUAPs recorded during sEMG assessment. For example when assessing progress during repeated interval training bouts, comparison of MUAP amplitude for defined periods of exercise could decline as fibre types adapt to sustained high intensity exercise, representing an effective decrease in muscle workload (Konrad, 2005; Stegeman *et al.*, 2000).



MUSCLE FIBRES RECRUITED: Type I > Type IIA > Type IIAX > Type IIX

LOW INTENSITY

Walk → working trot

Type I⁺⁺⁺ > Type IIA⁺

MEDIUM INTENSITY

Extended / collected trot →
working canter

Type I⁺ > Type IIA⁺⁺⁺ > Type IIAX⁺⁺

HIGH INTENSITY

(OR PROLONGED SUBMAXIMAL EXERCISE)

Galloping and jumping

Type I⁺ > Type IIA⁺ > Type IIAX⁺⁺⁺ > Type IIX⁺⁺⁺

Figure 7: Equine muscle fibre recruitment during exercise. +++ majority recruitment; + minimal recruitment

Research has demonstrated that equine muscle fibres are recruited in a consistently ranked order from I → IIA → IIAX → IIX (Rivero and Piercy, 2008). Low level exercise predominately recruits Type I fibres producing sufficient energy from aerobic fat metabolism. Medium level activity employs Type I fibres combined with Type IIA and IIAX which provide the speed of contraction required for the increased workload; energy production is still generally aerobic. In high level exercise, or prolonged submaximal exercise all fibre types are active using a combination of aerobic and anaerobic energy (Rivero, 2014) but Type IIAX and IIX fibres predominate due to their ATP generation which is required to sustain performance levels.

Table 11: Characteristics of equine muscle fibre types

Prior research was reviewed to identify the key metabolic characteristics that occur in Type I, IIA, IIX and IIAx muscle fibres in the horse. Understanding the physiological profile of each fibre type will aid evaluation of fibre type within exercise.

Classification	Type I	Type IIA	Type IIX	Type IIAx
Function	Sustained isometric or slow, repetitive activity	Short duration, high intensity activity	Short duration, high intensity activity	Adjust with training to complement Type IIA and IIX Medium duration, intermediate activity
Cross-bridge cycles	Slow	Fast	Fast	Intermediate
Speed of contraction	Slow	Fast	Fast	Intermediate
Maximum tension developed	Low	High	High	Intermediate
Oxidative capacity	High	Intermediate to high	Low	Intermediate
Capillary density	High	Intermediate	Low	Intermediate
Lipid content	High	Intermediate	Low	Intermediate
Glycogen content	Intermediate	High	High	Intermediate
Fatiguability	Low	Intermediate	High	Intermediate

Adapted from: Pagan (2013), Rivero and Piercy (2008), Lopez-Rivero and Letelier, (2000) and Snow and Valberg (1994)

4.2.2 Distribution of fibre types

The majority of equine muscles contain a mixture of fibre types (Hyttiäinen *et al.*, 2014). Muscle fibre profiles are determined genetically, individual variation is present due to selective breeding for athletic type and equestrian discipline (Table 12) (Rivero and Barrey, 2001). Profiles also vary between specific muscles according to their individual function, location within the muscle, breed and the functional demands of the discipline horses are being trained to compete in

(Hyytiäinen *et al.*, 2014; Rivero, 2014; Leisson, Uaakma and Seene, 2008; Rivero and Barrey *et al.*, 2001; Lopez- Rivero *et al.*, 1989). Therefore sEMG researchers should consider the potential influence of breed and training status when selecting participants for sEMG research. Knowledge of fibre type related to function is important in EMG studies when selecting sEMG or indwelling EMG and where the performances of muscle groups are compared to prevent misinterpretation of sEMG profiles obtained (Rash, 1999).

Table 12: Factors which can influence equine muscle fibre profiles

Muscle fibre profiles are determined by genetics however muscle function and training regimen can influence them. For example, in racehorses specific bloodlines are anecdotally linked to enhanced performance in flat and jump racing yet horses can have a successful career spanning both spheres. The table identifies the expected muscle fibre types for horses according to genetics, function and discipline.

Factor	Influence on muscle fibre profile		
Genetic predisposition	Endurance athlete Predominately aerobic Increased Type I and IIA fibres	Strength, speed and power athlete Predominately anaerobic Increased Type IIAX and IIX fibres	Intermediate: combination of endurance and strength and conditioning Aerobic and anaerobic Increased Type IIA and IIAX fibres
Muscle function (can be related to training)	Isometric / postural role → increased Type I and IIA fibres	Intense short duration exercise → increased Type IIX fibres	Combination of endurance and strength and power → increased Type I+IIA and IIAX
Discipline: Dressage Showjumping Eventing Racing Polo Endurance	Low-intermediate levels Low level	High levels High levels Flat High goal	High levels Low-intermediate levels Low- intermediate levels National Hunt Low- medium goal Intermediate – high levels

Adapted from: Hill *et al.* (2010), Thiruvankadan, Kandasamy and Panneerselvam (2009), Rivero and Piercy (2008) and Yamano *et al.* (2006)

The range of sEMG sensors is restricted to collation of MUAPs from the superficial portion of muscles under investigation (Kamen and Gabriel, 2010; Winter, 2009; Drost *et al.*, 2006; Rash, 1999). Hyytiäinen *et al.* (2014) reported the fibre profile of equine deep-epaxials relate to their role in postural stability. Lopez-Rivero and Letelier (2000) found differences between fibre composition in superficial and deep *Gluteus medius* samples (Table 13). It appears that superficially skeletal muscles in the horse are organised to facilitate short duration, rapid propulsive force production supported by a predominance of type IIA and IIX fibres, whilst deeper fibres support longer duration, lower intensity activities such as postural support and constitute mainly type I fibres (Lopez-Rivero and Letelier, 2000). Interpretation of sEMG data and their subsequent application to training regimens should relate to superficial muscle topography as sEMG assessment does not reflect the functionality of the entire muscle (Section 3.3).

Table 13: Distribution of fibre type in horses trained for various disciplines

Lopez-Rivero and Letelier (2000) compared biopsy sample results from superficial (2-3cm sampling depth) and deep (6-7cm sampling depth) locations of the Gluteus medius from horses (n=94) competing in a range of equestrian disciplines. Superficial samples contained increased fast twitch muscle fibres than their deeper counterparts.

Activity	Breed	N=	Superficial Muscle Region Percentage ± standard deviation (%)			Deep Muscle Region Percentage ± standard deviation (%)		
			I	IIA	IIX	I	IIA	IIX
Jumpers	TB cross	10	16 ± 4	37 ± 3	47 ± 5	27 ± 8	36 ± 6	37 ± 11
Endurance	Arab / Arab cross	18	22 ± 5	41 ± 6	37 ± 8	51 ± 9	46 ± 8	3 ± 6
Racetrack	Thoroughbred	7	12 ± 2	29 ± 3	59 ± 3	16 ± 1	34 ± 6	50 ± 6
Carriage	Andalusian	7	19 ± 2	33 ± 1	48 ± 2	39 ± 5	32 ± 2	29 ± 4
Dressage	Andalusian	30	20 ± 6	37 ± 6	43 ± 6	33 ± 11	41 ± 6	26 ± 11
Saddle	Haflinger	6	15 ± 3	42 ± 6	43 ± 6	29 ± 6	45 ± 8	26 ± 3
Draught	Chilean crossbred	16	30 ± 9	24 ± 46	46 ± 21	62 ± 10	24 ± 4	15 ± 9

Adapted from Lopez- Rivero and Letelier (2000)

4.3 Principles of training to promote performance

A performance is an external representation of an individual's potential to execute a set task. How well a task is achieved is the culmination of training to optimise the potential of intrinsic variables and the ability to adapt positively to extrinsic variables at that moment in time (Smith, 2003). Training should optimise the genetic, anatomical and physiological characteristics of the horse to produce peak performance, in a specific discipline (Leisson, Uaakma and Seene, 2008). Training to improve performance should include methods to increase fitness, shape the horse's musculoskeletal system for the workload required, promote career longevity and enable the horse to develop the motor skills and psychological attitude to compete (Smith, 2003); (Table 14). Intrinsic and extrinsic factors contribute to performance at any given moment in time. Therefore holistic performance analysis should incorporate review of the dynamic relationships that exist between intrinsic and extrinsic factors during training and competition (Table 15).

4.3.1 Evaluation of training regimens

Training regimens should be designed to achieve competitive goals set for the individual athlete (Smith, 2003). Equine training regimens often do not replicate the demands of competition (Eto *et al.*, 2004). To progress within training, a degree of physiological stress is required to generate adaptation in the horse's musculoskeletal system (Rivero and Piercy, 2008). Each training session will damage the ultrastructure of the tendons, muscles and bone associated with exercise (Leisson, Uaakma and Seene, 2008). Systematic recovery periods should be integrated into

regimens to facilitate repair of subclinical micro-damage, to prevent future injury or training setbacks, and augment enhanced performance (Rivero and Piercy, 2008).

Table 14: Key objectives when training the performance horse

Relevant literature was reviewed to isolate the three core objectives which underpin training for the equine athlete: preparation for competition, improving performance and preventing injury. The potential use of surface electromyography to measure progress towards achieving these objectives is also provided.

Objective 1	Preparing for competition: physiological conditioning to ensure adequate fitness and prevent fatigue
<i>Potential application of sEMG</i>	<ol style="list-style-type: none"> 1. Assessment of muscle recruitment during defined exercises to target development for competition related tasks 2. Plotting the frequency of the EMG signal over time could enable fitness and fatigue to be assessed 3. Comparison of mean MUAP between exercise periods could aid evaluation of training progress
Objective 2	Improving performance: development of a balanced athlete and task-specific conditioning, motor skill acquisition and achievement of ‘expertise through improved neural plasticity
<i>Potential application of sEMG</i>	<ol style="list-style-type: none"> 1. Comparison of the right and left versions of the same muscle could assess balance and contribution to workload 2. Assessment of muscle recruitment during defined exercises to target development and increase plasticity through repetition for specific motor skill tasks
Objective 3	Preventing injury and increasing career longevity: via adequate preparation of the horse and rider
<i>Potential application of sEMG</i>	<ol style="list-style-type: none"> 1. Evaluation of readiness for competition through assessment of muscle physiology to support required workload 2. Promotion of fitness could reduce fatigue related injury 3. Development of a more balanced horse could reduce overloading injuries

Adapted from Ferrari *et al.* (2009), Smith (2003) and Dyson (2002).

Table 15: Intrinsic and extrinsic factors that can influence equestrian training and performance

Understanding the multiple factors that can influence performance is essential to analyse how to improve it. Categories of intrinsic and extrinsic variables which can impact equine performance are provided in the table with examples from research to illustrate their potential impact.

Factors		Examples
Intrinsic	<p>Genetics: Conformation (Wallin, Strandberg and Philipsson, 2003)</p> <p>Physiological responses (Ferrari <i>et al.</i>, 2009)</p>	<p>MSTN gene alleles have been associated with optimum race distance (Hill <i>et al.</i>, 2010) and predisposition to acquire tendinopathies in thoroughbred racehorses (Tully <i>et al.</i>, 2013).</p> <p>However, the phenotypic expression of genes associated with performance will vary depending on the training and management regimens a horse receives.</p>
Extrinsic	<p>Factors which are related to the training or competition environment or management of the horse:</p> <p>Surface / going (Murray <i>et al.</i>, 2010; Williams <i>et al.</i>, 2001)</p> <p>Number of jumping efforts (Pinchbeck <i>et al.</i>, 2004a, b)</p> <p>Jumping downhill obstacles and water jumps (Singer, Saxby and French, 2003)</p> <p>Speed (Pinchbeck <i>et al.</i>, 2004a, b)</p> <p>Farriery (Pinchbeck <i>et al.</i>, 2004a)</p> <p>Race / event distance (Parkin <i>et al.</i>, 2004)</p> <p>Performance demands specifically galloping, jumping and collection (Dyson, 2002)</p>	<p>Firm going increases injury in racing /Poor management of arenas increases injury risk in dressage</p> <p>Increasing jumping efforts increase fall risk</p> <p>Fences cited on inclines and declines, and in water increase fall risk in eventing</p> <p>Horses showing increased speed associated with whip use have an increased fall risk in racing</p> <p>Foot conformation can link to performance</p> <p>Longer races with more runners are associated with increased fracture risk</p> <p>Increase loading strains in the distal limbs</p>

Therefore the balance between training, rest and recovery times within regimens must be sufficient to ensure their suitability to promote improved performance and prevent injury (Seene *et al.*, 2004). Progress during training can also be assessed through the use of biochemical, histochemical and physiological markers and processes in the horse (Fazio *et al.*, 2011; Eto *et al.*, 2004). Common parameters investigated are outlined in Table 16.

Despite exercise testing, the physiological demands associated with different levels of competition and how the individual components within a training regimen contribute to equine performance during competition are not clearly defined (Munk *et al.*, 2014). The amplitude of the response of a horse to training will vary according to the content of the specific programme implemented: exercise type, frequency, intensity, duration and volume, the basal profile of the horse: genetic potential and prior training / fitness status and muscle fibre profile combined with its age, breed and sex (Leisson, Uaakma and Seene, 2008). sEMG could offer a valid tool due to its ease of use and non-invasive nature, which could plot variation and assess muscle performance throughout training regimens (Ferrari *et al.*, 2009)

Table 16: Methodologies used to assess the impact of exercise and training in the horse and their relationship to sEMG

Research has evaluated the methods available to monitor the impact of exercise and training in the horse on the physiological systems (musculoskeletal, respiratory and cardiovascular) and biomechanics of movement which underpin equine performance. Review of relevant research identified the methods used to investigate specific variables to enable how each measures performance to be described. A brief comparison for each method to surface electromyography is provided.

Body system	Evaluation method	Variables investigated	Measures	Relationship to sEMG
Musculoskeletal	Muscle biopsy	Adenosine triphosphate (ATP) content	Representative of energy contribution; increased consumption during contraction	Biopsies are invasive veterinary procedures; sEMG is non-invasive and requires minimal preparation. Biopsy is a retrospective measure of muscle performance, sEMG can provide real-time analysis. Using muscle biopsy to identify muscle fibre profile has potential to complement sEMG when assessing how muscle adapts with exercise over time.
		Myosin heavy chain isoform analysis	Fibre type: enables evaluation of percentage and contribution of muscle fibre types	
		Glycogen	Staining post exercise biopsy can indicate muscle fibre contribution to exercise via assessment of glycogen levels	
		Hypertrophy of fibres	Cross sectional area of fibres can be assessed	
	Blood analysis: enzyme and metabolite assay	Urea / Ammonia(NH ₃)	Increased production with muscle activity	Venepuncture is an invasive veterinary technique, in contract to non-invasive sEMG. Blood analysis is a retrospective measure but can provide increased depth on the
		Aspartate aminotransferase (AST)	Indicative of muscle damage; long half-life ~7-8 hours	
		Creatine kinase (CK)	Indicative of muscle damage; short half-	

			life ~2hours	physiological and metabolic status of muscle compared to sEMG.
		Gamma glutamil transferase	Liver derived enzyme: marker for increased oxidative stress	
		Succinic dehydrogenase	Indicative of mitochondrial activity	
		β -3-hydroxy acyl CoA dehydrogenase (HAD)	Indicative of β -oxidation: lipid utilisation as energy during exercise	
		Phosphofructokinase (PFK)	Indicative of glycolytic activity: carbohydrate utilisation as energy source during exercise and uptake of anaerobic ATP Decreased levels seen with fatigue	
		Pyruvate dehydrogenase	Associated with aerobic ATP production; decreases link to fatigue	
		Nicotinamide adenine dinucleotide (NAD)	Increased levels associated with ATP production; oxidised from pyruvate to lactate by lactate dehydrogenase	
		Lactate (La)	Measure of anaerobic energy contribution to workload; V_{La_4} represents velocity that produces onset of blood lactate accumulation	
		pH	Increased La levels in muscle produce a decreased pH	
		Glucose (Glu)	Plasma concentration: representative of energy source being utilised and therefore workload	
		Insulin	Analyse training-induced alterations in	

		Glucagon Epiphine / norepiphine	glucose kinetics and gluco-regulatory hormonal responses	
	Ultrasonic evaluation	Evaluation of muscle size	Muscle cross sectional area can be assessed to measure hypertrophy and atrophy, changes in size over time	Both sEMG and ultrasound are non-invasive techniques.
	EMG	Surface EMG – superficial muscle assessment Indwelling EMG – deep muscle and individual MU assessment	Muscle recruitment Muscle activity-levels (amplitude, frequency and timing); broad representation of power Individual MUAP and wavelet analysis (indwelling)	Indwelling EMG is invasive requiring fine-wire or needle electrodes to be inserted into the muscle, which limits use outside of the laboratory compared to sEMG.
Cardiovascular (CV)	Heart rate: auscultation, heart rate monitor or Electrocardiogram (ECG)	Maximal Heart rate (HR_{max})	Measures maximum heart rate during maximal exercise test; variable percentages of HR_{max} can be assigned e.g. 60 % HR_{max}	Telemetric HR and ECG monitors are available which are non-invasive and can provide real-time HR rates during exercise in the field.
	Velocity to speed	V_{200}	Velocity speed attained at HR of 200 bpm; can be assessed at variable defined heart rates	sEMG telemetric systems have the capacity to be synchronised to the HR monitors which can incorporate GPS, enabling muscle performance to be considered in relation to speed and HR.
	ECG	Cardiac cycle	Analyse of P, Q, R, S wave and timing within heart rate / pulse	
	Standardised exercise test (SET)	Heart rate / fitness, often incorporates global positioning systems (GPS)	HR exhibits a linear relationship to speed / work intensity Decreased HR should be observed over time with training in repeated SET	CV performance will influence muscle performance as combined with the respiratory system it underpins oxygen transfer to muscle fibres which fuels contraction.

	Ultrasound evaluation	Evaluation of cardiac measurements Blood flow within the heart	Assessment of hypertrophy of internal diameter of ventricles, ventricle walls and increases in heart mass associated with training Evaluation of murmurs, heart valve function, stroke volume, cardiac output	Non-invasive technique, often conducted in the laboratory during SET using the high speed treadmill. Potential to use alongside sEMG in this context.
	Blood analysis	Packed cell volume (PCV)	Hydration status	Retrospective measure requiring venepuncture.
		Total red blood cell count	Erythrocyte volume	
		Haemoglobin (Hg) concentration	Measure of Hg available for oxygen transport	Provides useful supplementary information to the sEMG researcher as muscle performance is dependent on oxygen delivery during cellular respiration.
Respiratory	Oxygen capacity	Maximum aerobic capacity (VO_{2max})	Measures maximum oxygen uptake by active tissues during maximal exercise test; variable percentages of maximal oxygen consumption can be assigned e.g. 60 % VO_{2max}	Assessment of respiratory performance is critical as the horse is an obligatory nasal breather, therefore any reduction in respiratory function will reduce oxygen transfer to the muscles influencing their performance. Endoscopy if invasive, but overland telemetric systems are available which can be used in the ridden horse.
	Velocity to speed	V_4	Velocity speed attained at La_4 mol/l (anaerobic threshold); metabolic response to athletic ability; can be assigned to variable lactate concentrations	
	Endoscopy	Dynamic evaluation of upper respiratory tract: overland and treadmill	Assesses upper respiratory tract functionality	

		evaluation occur		
Biomechanics	Kinetic and kinematic analysis	Gait analysis systems, force plate analysis, videography	Evaluation of gait, lameness, jumping and specific movements No direct physiological improvement via training , however development of motor skills associated with movement improve energy efficiency of exercise	Biomechanical telemetric systems suitable for use during ridden exercise are available. Some sEMG units can be synchronised to biomechanical analysis systems enabling muscle recruitment and activity to be coordinated to motion patterns and limb phasing during locomotion.

Adapted from Munsters *et al.* (2013), Lindner *et al.* (2012), Fazio *et al.* (2011), Eto *et al.* (2003, 2004), Geor *et al.* (2002), McGowan *et al.* (2002), Rash, (1999), Harris *et al.* (1997) and Lekeux *et al.* (1991).

The majority of equine training regimens will include a combination of exercise types (Table 17) to mimic all aspects of the competition being prepared for (Leisson, Uaakma and Seene, 2008; Marlin and Nankervis, 2002). Limited knowledge exists to explain how muscle responds to the different categories of training (Ferrari *et al.*, 2009) or how individual performance may differ between horses due to experience, fitness level or conformation. sEMG could identify the impact of different forms of exercise on horses potentially influencing frequency and intensity of training sessions. For example, some horses may find an athletic grid-work session (repeated jumping efforts in canter) the equivalent to a period of galloping. Such information could be used by riders and coaches to design training regimens and monitor progress in individual horses.

4.4 Training equine muscle

Normal training regimens place large physical demands daily on the musculoskeletal system, which are exacerbated by maximal performance during competition. Generally a key aim across all disciplines is to improve the aerobic capacity of the equine athlete (Eto *et al.*, 2004) thus postponing the onset of fatigue and optimising performance. Different exercise types will generate specific adaptations in muscle tissue (Table 18), which can be summarised into three muscle responses, whose expression will be dependent on the individual:

1. Hypertrophy: (HI and SC training)
2. Remodelling without hypertrophy (EN training), and,
3. Remodelling with hypertrophy (combination of HI, SC and EN training)

(Rivero, 2014; Leisson, Uaakma and Seene, 2008; Rivero and Piercy, 2008).

Table 17: Categories of training for the equine athlete

Three main types of training condition the equine athlete for competition. Knowledge of training categories and subsequent adaptations they invoke in equine muscle are required to understand how training underpins performance. Table 17 provides a brief summary of endurance, strength and conditioning and high intensity training and outlines the impact of each category on muscle.

Category	Description	Impact
Endurance or stamina development (EN)	<ul style="list-style-type: none"> • high frequency of repetition • predominately aerobic • long duration - low intensity exercises • for example, long periods of walk and trot 	<ul style="list-style-type: none"> • improved oxidative capacity • increased capillarisation • increased mitochondria • higher ratio of aerobic muscle fibres (I and IIA)
Strength and conditioning (SC)	<ul style="list-style-type: none"> • discipline focused • mimics specific competition demands • aerobic and anaerobic • duration and frequency linked to skill development • for example, grid-work, jumping a course or practising collected dressage movements 	<ul style="list-style-type: none"> • some improvement in oxidative capacity • improved motor skill acquisition • increased muscle fibre synchronicity • muscle fibre hypertrophy • enhanced neuromuscular excitability improving energy when training is linked to specific discipline demands • higher ratio of aerobic muscle fibres (IIA and IIAX)
Speed or high intensity training (HI)	<ul style="list-style-type: none"> • short duration-high intensity activity including anaerobic contribution • low frequency of repetition • for example, canter and gallop interval training 	<ul style="list-style-type: none"> • improved oxidative capacity (IIA) • muscle hypertrophy • increased capillarisation • increased mitochondria • higher ratio of anaerobic muscle fibres (IIX)

Adapted from Leisson, Uaakma and Seene (2008), Hinchcliff, Geor and Kaneps (2008), Yamano *et al.* (2006) and Eto *et al.* (2004).

Successful training regimens need to include a combination of exercise types matched to performance goals. Due consideration of the impact of the frequency, intensity, duration and volume of exercise undertaken relative to sufficient work: rest ratio is also required to prevent injury or setbacks. Again, sEMG could be a

potential tool which could be used to assess how muscles respond within and upon cessation of training regimens.

Table 18: Summary of equine muscular adaptations to training: \pm^1 : primary adaptation, positive or negative respectively; \pm^2 : secondary adaptation, positive or negative respectively, X: does not impact characteristic

Training regimens can generate adaptation in equine muscle. Adaptation can be positive or negative depending on the type of exercise undertaken. This table outlines how muscle responds to endurance, strength and conditioning and high intensity training to support the workload required.

Adaptation	Type of training		
	Endurance (stamina)	Strength and conditioning	Speed (high intensity)
Muscle fibre hypertrophy	- ²	+ ¹	+ ²
Muscle fibre atrophy	+ ²	- ¹	- ²
Increased number of capillaries	+ ¹	X	X
Increased mitochondrial volume	+ ¹	X	X
Increased myonuclear density	X	+ ¹	X
Increased aerobic muscle enzymes	+ ¹	X	X
Increased glucose and fatty acid transport	+ ¹	X	X
Increased muscle glycogen	+ ¹	X	X
Increased Muscle triglycerides	+ ¹	X	X
Decreased post-exercise Muscle lactate	+ ¹	X	X
Increased anaerobic Muscle enzymes	X	X	+ ¹
Decreased anaerobic Muscle enzymes	X	X	- ¹
Increased Muscle high energy phosphate	X	X	+ ¹
Increased Muscle buffering capacity	+ ²	X	+ ¹
Unidirectional IIX → IIA → I fibre type transition	+ ²	X	- ¹
Bidirectional IIX → IIA → I fibre type transition	+ ²	X	- ¹
Increase of IIA: IIX fibre type ratio	+ ²	X	- ¹
Increase of I: IIA fibre type ratio	+ ²	X	- ¹
Increase of IIA: I fibre type ratio	- ²	X	+ ¹

Adapted from Rivero and Piercy (2008).

4.5 Training the 'whole' horse

Exercise and training can stimulate adaptation in muscle physiology and ultrastructure (Rivero, 2014; Leisson, Uaakma and Seene, 2008; Williams *et al.*, 2008). Development in the wider musculoskeletal system will contribute to the biomechanical profile of the horse influencing movement and performance (Walker *et al.*, 2014; Lopez- Rivero and Letelier, 2000). Researchers have analysed the biomechanics that underpin performance in the different equestrian disciplines, for example locomotor profiles in racehorses (Barrey *et al.*, 2001), head and neck position in Dressage horses (Rhodin *et al.*, 2009) and jumping ability in showjumpers (Walker *et al.*, 2014; Lewczuk, Słoniewski and Reklewski, 2006). In contrast, few studies have evaluated gross muscle response to training (Ferrari *et al.*, 2009).

Further knowledge of the short and long term responses in skeletal muscle within locomotion and to training are an essential element to improve overall performance in athletes including the horse (Bouwman *et al.*, 2010). A better understanding of the functional activity levels and recruitment of muscles during exercise, how muscles adapt during training and within competition would provide an evidence-base to objectively develop or modify training regimens to optimise muscle performance (Bouwman *et al.*, 2010; Ferrari *et al.*, 2009). For example a bias for unidirectional exercise has been observed during competition warm-up in showjumpers (Tranquille *et al.*, 2014); this practice may be detrimental leading to injuries due to overloading of the preferred limbs.

sEMG could offer a viable investigative technique to develop the equine performance field (Robert, Valette and Denoix, 2001) in a similar way to its

contribution to human sports. The application of sEMG within human sports analysis is varied. The tool has been used to assess and improve elements of performance in international swimmers such as the stability, accuracy and economy of freestyle swimming strokes (Caty *et al.*, 2007) and the influence of elbow and muscle during phasing in front-crawl swimming strokes (Lauer *et al.*, 2013). Assessment of phases of performance would be beneficial in equestrian sport, for example isolating the relationship between joints and muscles during advanced dressage movements: piaffe and pirouettes, or analysing muscle contribution to the phases of jumping (St George and Williams, 2013).

Fatigue and its subsequent impact on muscle performance have been examined using sEMG, for example repeated play in tennis players (Rotaa *et al.*, 2014) and the influence of bike design on fatigue in cycling (Balasubramnian, Jagannath and Adalarasu, 2014). Equivalent research could be conducted for the equine athlete. Knowledge of muscle related fatigue factors could enhance performance in racing, eventing and numerous equine sports (Ferrari *et al.*, 2009). Whilst little is known regarding the impact of equipment on equine performance (Williams, 2013) and scope exists to explore the role of saddle design, bit type and training tools, such as the Pessoa system (Appendix 6), upon muscle activity and fatigue. Combining gait analysis with sEMG could quantify muscle contribution to locomotion and evaluate muscle adaptation over time (training) or in specific events (skill acquisition or competition).

sEMG has also been used to examine the efficacy of training regimens and potential injury risk in sports. Australian Football players report a high incidence of anterior cruciate ligament (ACL) injury. Donnelly *et al.* (2014) assessed the impact of targeted training, integrating side-steps (a dummy move aimed to confuse the

opponent, that the player is moving in one direction when they then travel in the opposite direction), to reduce ACL risk, in league-level football players. The progress of the targeted training group was compared to a 'normal' trained group using sEMG over 28 weeks. Interestingly, no differences in knee stability or associated muscle strength were found between the groups. However, all trained players increased their muscle strength by an average of 30%. Perhaps due to the acquired increase in strength, knee moments during unplanned side-steps were 80% greater at the end of the study, suggesting that the execution of unplanned side-steps during play carries an increased risk of ACL injury in the latter half of the Australian football season. Donnelly *et al.* (2014) provides a useful template for how sEMG could be used to assess equine training regimens. Numerous components of training have the potential to be studied. However, selecting an aspect of training related to injury data, perhaps distal limb tendinopathies (Butcher *et al.*, 2007), and applying a targeted exercise regime compared to 'normal' practice has the potential to showcase the value of evidence-based training and sEMG as a performance analysis tool.

Parallels can be drawn between the human research examples outlined above and the potential use of sEMG as a performance analysis tool in the equine athlete. Performance analysis by its definition assesses practical aspects of a performance. The non-invasive nature of sEMG combined with small and easy to use sensors can promote practical access to competitive horses and facilitate integration within 'normal' training practices. Furthermore, the data obtained has practical implications which can be easily understood and applied by riders and trainers to modify training if required. From a research perspective, data obtained should increase the baseline knowledge and understanding of how muscle responds and adapts to specific and extended exercise.

4.6 sEMG and the horse

A number of preliminary investigations have been conducted in the horse using sEMG and fine needle EMG (Table 19). The studies are largely preliminary in nature, are laboratory-based and used low numbers of horses, of variable breed, age and health and fitness status, which limit their application to the field-based sEMG and the broader equine population.

4.7 Application of sEMG to training the equine athlete

sEMG has been used to quantify specific training techniques in the horse. Tokuriki and Aoki (1995) measured EMG \pm rider in walk, trot and canter (Table 19). Then proceeded to investigate muscle activity during overland, treadmill and swimming exercise (Tokuriki *et al.*, 1999). However the limited pickup zone of needle EMG (Drost *et al.*, 2006) will not represent the workload for the entirety of large equine muscles. The majority of EMG research uses small numbers of unriden horses, of unknown fitness status, age and mixed breed exercised on treadmills (Table 19) which limit application to ridden exercise in trained athletic horses in the field.

Table 19: Equine electromyography research. TB: Thoroughbred; WB: Warmblood; HST: high speed treadmill; LD: *Longissimus dorsii*; BF: *Biceps femoris*, TFL: *Tensor fascia latae*; VL: *Vastus lateralis*; TB: *Triceps brachii*; GM: *Gluteus medius*; RA: *Rectus abdominus*; DDF: Deep digital flexor; SDF: Superficial digital flexor

It is important to be aware of previous equine electromyography research prior to planning new projects. A keyword search of equestrian and electromyography peer reviewed databases highlighted prior equine EMG research. Details of the studies research objectives, including the muscles investigated, and an appraisal of the EMG methodologies undertaken are given in the table.

Study	Research outline	EMG parameters measured	Appraisal
Tokuriki and Aoki, (1995) Needle EMG	Investigated EMG activity in TFL and middle BF during walk, trot and canter with and without a rider Sample: 4 adult TB, 451±20kg	Inset and offset of muscle activity related to phases of stride at each gait for 5 consecutive strides EMG data were high low-frequency filtered at 34Hz Mean duration of EMG activity was expressed as a % of stance or swing	Cadaver examination informed sensor placement EMG and kinematic analysis Analysis ± a rider reported similar EMG parameters Consistent patterns for muscle recruitment across horses Invasive technique Gross muscle activity based on limited MUAP (needle EMG)
Cheung <i>et al.</i> (1998) sEMG	Assessment of muscle activity of the long digital extensor muscle (right hind limb) at walk and trot in unfatigued and fatigued horse Test undertaken in untrained horses and then again after 8 weeks of training Sample: 8 TBs, 5 geldings; 3 mares, 480-560kg, sound, no exercise >3months	Data high pass filtered f_c 40Hz 5-7 EMG bursts measured in 8s collected period Mean root mean square each burst calculated – high variance reported across group therefore converted to logarithms prior to statistical analysis	HST provides standardised environment Shaved skin should reduce noise artefacts Untrained data provided reference state to assess ratio of fatigue to unfatigued HST limits full application to field and ridden conditions Manual placement of electrodes could introduce noise High pass filter could remove viable data between 20-40Hz
Giovagnoli <i>et al.</i> (1998) sEMG	EMG analysis of <i>splenius</i> muscles to quantify balance requirements during transportation Sample: 8 healthy Warmbloods,	EMG and ECG data were recorded prior to transport for reference values Right and left splenius EMG activity recorded during transport	Example of use of EMG within behavioural research

	4.9±1.7 years	Root mean square MUAP amplitude calculated, then compared to reference state to facilitate their expression as a percentage in individuals	
Tokuriki <i>et al.</i> (1999) Needle EMG	Investigate EMG activity of <i>splenius, brachiocephalicus, TB, brachialis, extensor digitorum communis, flexor digitorum communis, VL</i> and <i>quadriceps femoris</i> during overground walking, swimming in a circular pool and for walk and trot on a treadmill Sample: 6 TBs, 453±34.3kg, 6.5±3.9years, acclimatised to exercise prior to study	Raw data assessed No filtering protocols reported	EMG and kinematic analysis EMG activity was related to stride characteristics overground and on the HST but was more continuous when horses were swimming Invasive technique Gross muscle activity based on limited MUAP (needle EMG) Needles inserted 10cm into middle of muscle therefore EMG data collected could represent deep muscle (postural) activity
Robert, Valette and Denoix, (2000) sEMG	EMG activity in GM and TFL during trot on HST at varying speeds and inclines Sample: 4 healthy mature horses, 3 Selle francais, 1 Trotter, 525±25kg 8±2.5 years, used 6 days/week in riding school, acclimatised to HST	Mean onset, offset and duration of muscle activity for 10 consecutive strides were isolated for each slope / speed condition EMG data were rectified and iEMG calculated Timing and iEMG differences were compared between muscles and for speed / slope within muscles	EMG and kinematic analysis Shaved skin should reduce noise artefacts Muscle recruitment occurs early during locomotion as speed increases and in an inclined condition (6%) The use of exercise integrating increased speed and slopes has the potential to build muscles during training Manual placement of electrodes could introduce noise EMG data filtering protocol not reported; if iEMG calculated from the entire frequency spectrum, data include noise
Colborne, Birtles and Cacchione, (2001) sEMG	Pilot study: EMG and kinematic indicators of fatigue in deltoid muscle Sample: 3 TBs, 8, 9 and 14 years Trained to gallop on HST	EMG data collected during incremental HST exercise test EMG data were recorded for 3s every 15s during exercise test Median frequency of EMG data were calculated for 4-5 bursts of EMG	EMG and kinematic analysis Shaved skin should reduce noise artefacts Fatigue appeared to correspond to reduction in median EMG frequency but are dependent on lead leg changes Unknown history of horses: training status could influence onset of fatigue and presentation

		activity within 3s samples to analyse fatigue	Manual placement of sensors could introduce noise
Peham <i>et al.</i> (2001) sEMG	Investigated activity of the <i>Musculus longissimus</i> at T5, T12, T16, L3 and on 2 sacral bones during induced extension and lateral flexion at stance. Clinical application of EMG as a tool to diagnose back pain. Sample: 15 horses, 5-20 years, 450-700kg, various breeds No clinical signs of back pain	3 x 10s measurements for ventral, left and right lateral flexion and extension Measured maximum amplitude MUAP of individuals across 3 trials and mean correlation coefficients between spinal movement and EMG across the group EMG data normalised to T12 maximum amplitude EMG data filtered: Butterworth low-pass, 7 th order, f_c 10Hz.	Shaved skin should reduce noise artefacts EMG and kinematic analysis Identified T12 as optimum location for EMG of the back Manual placement of EMG electrodes could introduce noise Larger standard deviations at some markers suggest skin displacement occurring
Robert, Valette and Denoix, (2001) sEMG	Evaluate the effects of speed and slope on the activity (EMG) of splenius, LD and RA during trot Sample: 4 healthy horses, 3 Selle Francais, 1 Trotter	Measured onset and offset of muscle activity, duration of activity and iEMG (every 1ms) during trot strides and stance (10 strides at each slope / speed) Means calculated across the group EMG data band pass filtered 5-400Hz	EMG and kinematic data analysis HST provides standardised environment Preliminary evidence for use of slopes/speed in training Manual placement of electrodes can introduce noise LD sensors at L3 give limited EMG data Peham <i>et al.</i> (2001) Results not fully applicable to ridden exercise
Robert <i>et al.</i> (2001) sEMG	Investigate the effect of speed on back kinematics and muscle activity at trot: LD and RA Sample: 4 healthy horses, 3 Selle Francais, 1 Trotter, 506±21kg, used daily in riding school and HST acclimatised	EMG data collected for 10 consecutive strides at each speed Onset and offset of muscle activity and iEMG calculated at each speed	EMG and kinematic data analysis Muscle offset and onset consistent but occurred earlier in stride cycle with increasing speed Increasing speed affected duration of muscle activity (reduces) Manual placement of electrodes could introduce noise LD sensors at L3 give limited EMG data Peham <i>et al.</i> (2001) Results not fully applicable to ridden exercise
Robert <i>et al.</i> (2002) sEMG	Evaluation of how spinal muscle activity (<i>splenius</i> , TB, GM, TFL, LD and RA) and kinematics change with increasing speed at trot	EMG measured onset and offset of muscle activity and iEMG for each horse over 10 strides at each trot speed on HST	EMG and kinematic analysis HST standardises environment Only left side data reported Some muscles (e.g. TFL) move extensively during

	Sample: 4 adult horses, 3 Selle Francais, 1 Trotter, used daily in riding school and HST acclimatised	Recruitment patterns were consistent during trotting across horses, but occurred earlier in stride cycle as speed increased	locomotion potentially introducing noise Results cannot be fully applied to ridden exercise
Wijnberg <i>et al.</i> (2002) Needle EMG	MUAP analysis of the subclavian, <i>triceps</i> and <i>lateral vastus</i> muscles to establish their normative EMG values Sample: 7 healthy, mature Warmbloods, 3 geldings, 4 mares Used for riding lessons	EMG data were recorded over 20ms periods and bandpass filtered at 5-10Hz Amplitude and duration of MUAPs were recorded	Invasive technique Gross muscle activity based on limited MUAP (needle EMG) Filtering at 5-10Hz reports noise not functional data Choice of muscles and high amplitudes reported suggest noise contamination Care should be taken using these data as reference values
Licka and Peham, (2004) sEMG	EMG assessment of LD activity (T12, T16, L3) on HST in trot at variable speeds Sample: 15 adult horses, 15-20 years 450-700kg, clinically free from back pain	Minima and maxima, and peak amplitudes of EMG related to stance and swing EMG data were rectified and filtered using Butterworth lowpass filter f_c 10Hz, 5 th order	LD stabilises vertebral column during dynamic motion Maximum EMG amplitudes found at T12 and reduce caudally Data are recommended as reference state to compare to horses with back pain – small numbers and individual nature of EMG suggests caution
Wijnberg, (2004) Needle EMG	Clinical application of EMG in diagnosis of neuromuscular locomotor problems Sample: 108 horses, various breeds 38 mares, 59 geldings, 11 stallions 7.7 ±3.8 years, 548±86kg	Method as per Wijnberg <i>et al.</i> (2002)	EMG influenced clinical diagnosis in 12% of myopathy and 30% of neuropathy cases, demonstrating potential of EMG to discriminate between normal and abnormal muscle function Invasive technique Variation in breeds influential in muscle activity profiles but acceptable for defining onset / offset of muscle recruitment
Tessier <i>et al.</i> , (2005) Fine wire EMG	Measure the EMG activity of the <i>stylopharyngeus</i> muscle in exercising horses to correlate it with breathing patterns Sample: 5 Standardbreds, 3 geldings, 2	EMG data recorded for 10 breaths during last 15s at each speed during HST exercise test Onset and offset of muscle identified from raw EMG	Use of HST standardises environment EMG activity then measured as area under wave / duration of contraction in non-rectified data Results not fully applicable to ridden exercise (HST)

	mares, 5-12 years, examined normal respiration (physical and endoscope exam at rest, during exercise on HST)	Moving time average of EMG activity (100ms) and peak activity recorded Data filtered 6 th order Butterworth filter, band pas 50-5000Hz,	
Hodson-Tole, (2006) sEMG	Investigation of effect of speed and incline on EMG activity in <i>brachiocephalicus</i> and TB at walk and trot on HST Sample: 6 horses, 525.8±17.4kg HST acclimatised Judged free from lameness	EMG and kinematic analysis Raw EMG data filtered Butterworth 3 rd order, high-pass filter f_c 20Hz EMG intensity (integrated or iEMG) calculated over time to determine timing of peak activity and duration of activity in each stride Mean onset, end and duration of EMG activity were calculated as percentage of stride duration	Data collection from each head of the <i>biceps brachii</i> HST provides standardised environment EMG data consistently related to stride characteristics across cohort Unknown athletic and fitness status of horses Results not fully applicable to the ridden horse iEMG as a measure of 'power' is considered unreliable
Holcombe, Derksen and Robinson, (2007) Fine wire EMG	EMG activity of <i>palatinus</i> and <i>palatopharyngeus</i> during respiration in exercising horses (HST exercise test) Sample: 6 horses ,4 geldings, 2 mares, 4-10 years with no respiratory abnormalities (physical and endoscope exams at rest and HST)	Band pass filter 50-5000Hz, then EMG data rectified and moving time averaged Raw EMG used to identify onset and offset of activity Average EMG activity recorded for 10 breathes during last 15s at each speed of EMG data reported as percentage of activity at 6m/s	HST provides standardised environment Invasive technique Manual placement can introduce noise EMG activity not defined (what is MUAP amplitude?) HST exercise test not fully applicable to ridden exercise
Walkeling <i>et al.</i> , (2007) sEMG	EMG evaluation of left and right LD (T14, T16, T18, L2) lengthening and shortening during walk (incline / level) and trot (level) on the HST Sample: 5 geldings, 1 mare, 9±2years	EMG data high pass filtered f_c 24Hz, then extrapolated to 100 points / stride and lateral data compared Timing of onset and offset of muscle activity related to stride characteristics EMG intensity (iEMG) was calculated	EMG and kinematic analysis Cadaver examination informed sensor placement Shaved skin should reduce noise artefacts Walk to trot exercise on an inclined surface increased iEMG ECG interference resulted in noise in the data collected

		each condition Mean EMG parameters were reported across the group	50% phase shift between lateralised EMG data: using filter order could eliminate phase lag and improve accuracy Participant selection could have influenced EMG traces iEMG across the cohort not as reliable as individual comparison
Zaneb <i>et al.</i> , (2007) sEMG	Determination of position of sEMG electrodes for equine muscles: LD, GM, BF and long digital extensor Sample: 5 hindlimbs	Cadaver dissection and ultrasound evaluation to identify midpoint location of muscle belly for optimal sEMG sensor placement	Validity of advised sensor placement tested (sEMG) in live horses Unknown breed, age, status of horses' hindlimbs Details of 'live' sEMG test not provided
Licka, Frey and Peham, (2009) sEMG	Evaluation of LD (T12, T16, L3: right and left) during walking on HST Sample: 15 horses, 4 mares, 2 stallions, 9 geldings, 9 warmbloods, 4 standardbreds, 2 halflings, 5-20 years, 450-700kg, not used for riding, no clinical signs of back pain, acclimatised to HST	EMG data recorded for 2x10s periods at walk to give 15 motion cycles EMG data were 5 th order, Butterworth low-pass filtered f_c 10Hz Minima and maxima amplitudes of EMG data converted to %RA activity	EMG and kinematic analysis Assessment of EMG in individual horses Shaved skin should reduce noise artefacts Lateral differences recorded in EMG data reported Horses had 3 training sessions prior to data collection, but these are not comparable to athletic horses
Zaneb <i>et al.</i> , (2009) sEMG	EMG assessment of back and pelvic muscles (<i>longissimus thoracis</i> , <i>semitendinosus</i> , BF, GM and extensor <i>digitorum longus</i>) during walk and trot in chronically lame and non-lame horses Sample: 12 non-lame and 12 lame horses	Mean, maxima and minima EMG muscle activity (amplitude), and maximum to mean and minimum to mean ratios calculated for walk and trot on HST Compared between lame and non-lame horses	EMG and kinematic analysis Variation in muscle use was detectable in lame horses using sEMG
Crook, Wilson and Hodson-Tole, (2010)	Evaluate how musculoskeletal system adapts to cope with positive and negative slopes (0%, +10% and -10%) Assessed activity in GM, BF, <i>vastus</i>	EMG data collected for minimum of 50 strides, for each condition EMG intensity recorded (iEMG) EMG data filtered using Butterworth,	EMG and kinematic analysis Shaved skin should reduce noise artefacts Treadmill assessment provided standardised environment Atypical strides removed prior to analysis

sEMG	<i>lateralis gastrocnemius lateralis</i> , <i>extensor digitorum longus</i> at walk and trot Sample: 6 adult Welsh Mountain mares, 378±89kg	3 rd order, high pass filter, f_c 20Hz Mean and SD iEMG calculated across the group Trot data normalised to mean iEMG at walk	Highly mobile muscles selected are which could introduce noise Manual placement of electrodes could introduce noise Normalising to walk data could introduce error as EMG parameters shown to vary with gait
Groesel <i>et al.</i> , (2010) sEMG	Validation of a preliminary biomechanical model of the equine back, comparing shortening of LD (right and left at T12, T16 and L3) via integrated EMG with biomechanical model (spine of 13 year old TB mare post mortem) at stance Sample: 10 horses, 5-20 years, 450-700kg, various breeds, no signs of back pain	iEMG data for mean of 3 trials measuring maximum amplitudes of individuals Filtering protocol as per Peham <i>et al.</i> , 2001 mean correlation coefficients between spinal movement (relaxed, induced flexion, after flexion) and EMG across the group	Telemetric EMG + kinematic analysis Proposed LD plays key role in lateral flexion Use of 1 spine to develop model could limit accuracy Manual placement of electrodes could introduce noise EMG measurement at T12 includes MUAP from related to nearby muscle activity
Wijnberg <i>et al.</i> , (2010) sEMG	Investigating the effect of head and neck position on single fibre EMG in <i>serratus ventralis</i> muscle after exercise Sample: 7 healthy base-level trained Dutch sports horses, 5 mares, 2 geldings, 10.3±3.6 years, 531±47.3kg	Method as per Wijnberg <i>et al.</i> (2002) 20-30 MUAP (amplitude and duration) per head and neck position selected per horse Post-exercise head and neck data used as reference EMG assessed across cohort	Head and neck positions influenced the magnitude and timing of muscle activity Hyperflexion reported most EMG activity Information gained could be used to inform training regimes Invasive Unridden exercise therefore cannot be applied to riding
Zsoldos <i>et al.</i> , (2010a) sEMG	EMG assessment of <i>splenius</i> activity and head and neck kinematics during walk and trot on HST Sample: 6 horses: 2 TB, 2 trotters and 2 WBs, 2 geldings, 2 stallions and 2 mares, 8-20 years old, 450-700kg Examined – healthy and sound	EMG data collection at walk and trot for 10s Maxima and minima (peak to peak) amplitudes recorded for 30 mean motion cycle per horse EMG data filtered: Butterworth 5 th order, low-pass filter f_c 10Hz	Stabilising function of splenius to head and neck not established – supports that sEMG records superficial rather than deep (postural support) muscle activity Postulates right and left splenius activity is synchronous Variability in intra-individual EMG parameters reported
Zsoldos <i>et</i>	sEMG	Maxima and minima (peak to peak)	EMG and kinematic analysis

al., (2010b) sEMG	Measured activity of <i>rectus abdominus</i> and oblique external abdominal muscles during walk and trot on HST Sample: as per Zsoldos <i>et al.</i> (2010a)	recorded for mean of 10 EMG EMG data filtered: Butterworth 5 th order, low-pass filter f_c 10Hz Ratio of OEA: RA activity calculated, compared between walk and trot	Lateral variance reported in EMG data Walk correlated to motion more than trot Variable speed (horse selected) could influence EMG data, increased values linked to increasing speed Participant variety could influence EMG data
Crook, (2014) sEMG	Investigated if draft loading (>10 and 20% body mass) increase EMG intensity and duration of action in vastus lateralis and gastrocnemius lateralis Sample: 5 Irish cob geldings, 490±65kg, Trained to draft load (lorry tyre)	EMG and kinematic analysis EMG data collected for 10 consecutive strides and normalised to each horse EMG intensity (iEMG) measured	Draft loading can be used for strength training after injury or to improve athletic performance Loading increased EMG intensity and duration of contraction in both muscles No EMG data analysis protocols provided
Takahashi <i>et al.</i> , (2014) Fine wire EMG	Evaluating fatigue in SDF and DDF muscle during maximal exercise linked to their roles in the development of tendinopathies Sample: 6 TB horses, 461-557kg	EMG data band pass filtered 10Hz and 200Hz iEMG, median frequency and stride frequency were measured for warm up (trot), 100-105% maximal exercise and warm down (trot)	Fitness status of horses not established and could influence EMG results (muscle fibre profile varies with training) Bandpass width should ideally be extended for frequency analysis of EMG data Data reported across the cohort, not reliable in EMG evaluation Significant results reported but $P>0.05$ (0.055 and 0.063) HST exercise test not directly applicable to ridden exercise

Information gained in EMG studies related to muscle recruitment or activity levels during exercise can contribute to the training knowledge base. For example, the response of selected forelimb, hindlimb, back and abdominal muscles to trot exercise at increasing speeds and incorporating variable inclines have been assessed (Crook, Wilson and Hodson-Tole, 2010; Hodson-Tole, 2006; Robert, Valette and Denoix, 2001, 2000; Robert *et al.*, 2002; 2001). The research identified multiphasic activity in individual muscles that corresponded to gait and the phases of locomotion (Crook, Wilson and Hodson-Tole, 2010; Robert, Valette and Denoix, 2001). Generally, increasing velocity and use of an incline (>6%) stimulated muscle recruitment earlier in stride cycles than at slower speeds accompanied by contractions of greater magnitude but reduced duration (Robert, Valette and Denoix, 2001, 2000; Robert *et al.*, 2002; 2001). The results suggest that integrating high-speed exercise is appropriate for equine disciplines such as flat racing, a combination of speed and an incline could be beneficial for National Hunt racehorses and the use of an incline alone more beneficial for conditioning sports horses. Although it must be noted that riding-school standard horses were assessed and different results could arise in trained athletic samples (Felici, 2006).

Understanding the recruitment patterns of muscle could inform exercise selection within training regimens. Zsoldos *et al.* (2010a; b) studied head, neck and abdominal muscles of the horse at walk and trot. Their work highlighted increased *Rectus abdominus* activity in walk compared to trot and that hyperflexion recorded increased activity for head and neck muscles. The abdominal muscles underpin functionality in the equine back and aid transfer of force from the hindlimbs during locomotion; the results suggest that exercises at walk which activate the abdominal muscles would be valuable as a component of training for the equine athlete.

Hyperflexion is a contentious training technique whose value and ethics are questioned (McLean and McGreevy, 2010b). EMG suggests hyperflexion generates muscle development which could contribute to the debate. The examples reviewed demonstrate the potential of sEMG to reinforce the relevance of training regimens. However the small samples used necessitate further work incorporating larger numbers drawn from groups homogenous for breed and / or discipline in order to substantiate the conclusions formed.

4.7.1 Muscle recruitment

Knowledge of muscle recruitment patterns via EMG could contribute to evidence-based training for the equine athlete. Fine-wire EMG has been used to link respiratory muscle dysfunction with dorsal displacement of the soft palate, a career-limiting disorder in racehorses (Holcombe, Derksen and Robinson, 2007; Tessier *et al.*, 2005). Numerous sEMG studies have investigated muscle contribution to locomotion (Section 4.6, Table 19). For example, Crook, Wilson and Hodson-Tole (2010) assessed hindlimb muscles during locomotion on inclined and declined gradients. The incline condition recorded increased EMG parameters in all muscles, a pattern which was repeated during the decline condition except for the digital extensor muscle. An increased workload is required to retain a consistent speed during locomotion in the transition from level ground to an incline (Robert, Valette and Denoix, 2001; Cheung *et al.*, 1998). The decline condition is more interesting, as a lay observer may believe the effort required to facilitate locomotion downhill could be reduced from the other conditions, however increased stabilisation is required for controlled locomotion which necessitates an amplified muscle response. Although

the transferability of the value ranges for the EMG parameters studied may be limited by the choice of breed, the general principle supports training over undulations to condition the musculoskeletal system for locomotion over variable terrain.

4.7.2 A balanced athlete

Increased skeletal symmetry has been linked to enhanced performance in Thoroughbreds (McManus, 2002; Manning and Ockenden, 1994). Therefore asymmetric individuals could present with an increased risk of injury or poor performance (Williams, 2011; Walker *et al.*, 2014). Trainers often comment on a horse's natural 'side' or 'rein', representing the directional bias where the horse presents in better balance and has enhanced suppleness. The majority of equestrian disciplines require a balanced, symmetrical athlete (McLean and McGreevy, 2010a). Therefore the concept of developing a balanced equine athlete is core to achieving optimal performance and preventing injury. Training and rehabilitation regimes in sports horses aim to equalise asymmetrical musculoskeletal development and / or lateral differentials which may be present but are often not key components in racehorse regimens. The manifestation of motor predilection in animals has been measured via lead leg / paw / hand preference during gait (Tomkins, Thomsen and McGreevy, 2010; Poyser, Caldwell and Conn, 2006; McGreevy and Rogers, 2005; Klar, 1999), dominant eye use (De Boyer des Roches, Richard-Yris and Henry, 2008; Larose *et al.*, 2006), nostril choice during olfaction (De Boyer des Roches, Richard-Yris and Henry, 2008) and orientation of tail wagging (Sinsicalchi *et al.*, 2010).

sEMG has identified lateral biases in the horse (Peham *et al.*, 2001; Zsoldos *et al.*, 2010a). Differences in activation of muscles on either side of the body may be related to training, acquired pathologies or simply be normal for the muscle under investigation. The results found by Zsoldos *et al.* (2010a) suggest that the *Rectus abdominus* demonstrates bilateral activity, whereas the external oblique muscles appear to operate unilaterally corresponding to the active side of the horse. Although even within the small sample studied (6 horses), 67% variance in *Rectus abdominus* activity was observed. sEMG could provide further evidence to assess the impact of functional (recruitment), inherent and acquired laterality on performance in the equine athlete. Functional information could be used on a practical level to design training regimes and influence management decisions to maximise the welfare and career length of the sports-horse. For example, assessment of lateral recruitment of the *Longissimus dorsi* during competition specific exercises could identify a horse's 'weaker' side and be repeated to monitor the progress of targeted training to equalise lateral performance.

4.7.3 Fitness and fatigue

An important objective of a training regimen is to ensure the equine athlete has sufficient fitness to complete the performance task they are preparing for and to prevent fatigue (Ferrari *et al.*, 2009). Plotting the MU contraction required to sustain workload over time can identify changes in a muscle's capacity for continued exercise i.e. provide a measure of fitness or fatigue (Hanon, Thepaut-Matieu and Vanderwalle, 2005). However, sEMG researchers should not assume that all muscles perform in the same way (Smoliga *et al.*, 2010). The remit of a muscle is dependent

on its specific function at a given moment in time; muscle function may stabilise movement or initiate it (Hanon, Thepaut-Matieu and Vanderwalle, 2005; Saunders *et al.*, 2004). Muscle may be weight bearing or not, which will also affect recruitment profiles and power generation during work (Smoliga *et al.*, 2010) (Section 3.9.1). Equally performance variables will contribute to workload, for example speed of locomotion or the added weight of a rider, and may exert an influence on muscle workload. To date the majority of equine sEMG research has considered muscles associated with locomotion (Section 4.6, Table 19). Therefore exercise intensity and duration will dictate the recruitment pattern and frequency of contraction within the muscle fibres (Rivero, 2014) (Table 20).

Table 20: Muscle fibre recruitment during exercise in the horse

Equine training regimens are designed to prepare the horse for the physiological test competition represents. Different types of exercise recruit specific muscle fibres and can help trainers design appropriate training regimens. This table links exercise type to equine gait and identifies which muscle fibres will be recruited during its execution.

Exercise type	Fibre recruitment
Low intensity exercise: walk – working trot	Predominately recruits Type I fibres producing sufficient energy from aerobic fat metabolism
Medium intensity activity: extended /collected trot – working canter	Employs Type I fibres that combine with Type IIA, providing the speed of contraction required for the increased workload Energy production is still generally aerobic
High intensity exercise: extended / collected canter – gallop	Recruits all fibre types providing a combination of aerobic and anaerobic energy pathways. Type IIB fibres predominate due to their high propensity for ATP generation, required to sustain performance at higher levels.

Adapted from Rivero and Piercy (2008) and Marlin and Nankervis (2002).

Fitness level, duration of exercise and nutritional status of the horse will influence the extent to which exercise can be sustained and contribute to the onset of fatigue (Rivero, 2014), and should ideally be standardised or interpreted during sEMG research. It is important that fatigue is recognised as a process and not a defined failure point, as in reality it is a progressive event. In the equine athlete, determination of the onset of musculoskeletal fatigue is challenging beyond visual recognition of its occurrence (Colborne, Birtles and Cacchione, 2001). Analysis of heart rate and blood parameters, such as lactate, can provide quantifiable indicators of fitness and fatigue status but do not encompass muscle performance (Cheung *et al.*, 1998). The onset of fatigue in the horse is characterised by decreased stride frequency accompanied by increased stride length and suspension (Ferrari *et al.*, 2009) representing physiological changes in the associated muscles of locomotion. At fibre level, fatigue generates a shift in recruitment from aerobic to anaerobic muscle fibres accompanied by increased synchronisation in firing rate (Kamen and Gabriel, 2010; Colborne, Birtles and Cacchione, 2001). During fatigue larger MUs 'drop out' before smaller units (De Luca *et al.*, 1982) retaining fine movements longer than gross movement. sEMG data can be extrapolated to provide objective measures of fitness (mean frequency/ time) and fatigue (median frequency / time), which are commonly deployed in the human athlete (Duc, Betik and Grappe, 2005; Hanon, Thepaut-Matieu and Vanderwalle, 2005).

EMG assessment of muscle fatigue has been successfully undertaken for the horse in the laboratory (Colborne, Birtles and Cacchione, 2001; Cheung *et al.*, 1998) but not in the field (training and competition environments). Colborne, Birtles and Cacchione (2001) assessed fatigue in the deltoid muscle of thoroughbreds during a maximal exercise test on a treadmill. A reduction in the median frequency of the

EMG signal over time illustrated that fatigue occurred in all horses. Clues to the presence of fatigue also appeared to be present within the raw EMG data collected, as the exercise test progressed, the duration of deltoid contractions associated with stance increased. Care should be taken regarding the interpretation of raw EMG data, as variance associated with increased movement could be the result of noise generation or the introduction of movement artefacts (De Luca *et al.*, 2010; De Luca, 1997). Interestingly, EMG amplitude was shown to increase at trot measured after the onset of fatigue compared to a non-fatigued state in thoroughbreds studied by Cheung *et al.* (1998). Unfortunately fatigue was confirmed via observation post exercise rather than evaluating the median frequency of the EMG signal over time which could confirm its presence more accurately (Hanon, 2005). Selecting appropriate methods to assess fatigue are critical. Takahashi *et al.* (2014) reported trends for SDF and DDF muscle fatigue using fine-wire EMG. However the deep location and reduced pickup zone of electrodes limit application to the whole muscle and the critical superficial component more responsible for dynamic locomotion. The preliminary studies suggest that the EMG signal reflects physiological changes occurring in muscle associated with fatigue or its onset, although confirmation through increased numbers of horses is needed. Recent developments in telemetric sEMG systems (Delsys, 2014) provide the potential to test fatigue onset within training programmes and could be used to promote evidence-based approaches enhancing performance (fitness) and reducing fatigue-associated injuries.

4.7.4 Training versus competition

Time spent by the horse in training preparing for competition greatly exceeds that in actual competition (Verheyen, Price and Wood, 2009). Emerging evidence (Verheyen, Price and Wood, 2009; Singer *et al.*, 2008) suggests that the majority of injuries in the equine athlete occur during training. However access to horses in training is challenging. It is logical, as performance preparation is a key goal for training regimes, to assume that trainers formulate programmes which at least mimic or may exceed the perceived demands of competition potentially increasing injury risk. Therefore to be able to design scientifically informed training regimens and preventative management strategies, knowledge and understanding of the physiological fitness required to successfully complete the competition task is crucial (Ferrari *et al.*, 2009). Evaluation of performance variables should be complemented by evaluation of risk factors associated with injury in training or competition, or which contribute to poor performance within competition (Stover, 2003; Williams *et al.*, 2001). Telemetric sEMG offers researchers a tool which could be used in training and / or competition to analyse exercise related demands in muscle tissue, to prevent injury acquisition, enhance event preparation and optimise performance.

4.7.5 Injury

Training and competition, regardless of discipline, exposes the equine athlete to the occurrence of injury. Locomotion patterns adapt with training (Thorpe, Clegg and Birch, 2010; McGuigan and Wilson, 2003). Musculoskeletal injury is the main protagonist for days lost from training or competition in the sports and race horse (Murray *et al.*, 2010; Patterson-Kane and Firth, 2009; Singer *et al.*, 2008; Dyson,

2002). For example, a high incidence of superficial digital flexor tendon (SDFT) pathology occurs across equine sport (Tully *et al.*, 2013; Thorpe, Clegg and Birch, 2010). Butcher *et al.* (2007) postulated that Deep Digital Flexor (DDF) muscle fatigue caused SDFT overloading due to its impact on the synergistic function of the tendon, ligament and muscle unit in the distal limb. Targeted conditioning of the DDF muscle could exert a positive increase in load-bearing capacity of the SDFT and DDFT during exercise, which has the potential to reduce injury (Takahasi *et al.*, 2014). The relationship between DDF muscle and tendinopathies remains supposition due to the detrimental lack of research on muscle performance. sEMG could provide a method to objectively assess muscle recruitment and adaptation during training for defined exercises or repeated events assessed over time. Or could expose conditioning exercises which could reduce the incidence of injuries where muscle is indicated in the aetiopathogenesis of acquired pathologies (Verwilghen *et al.*, 2009) such as the postulated relationship between the S/DDF muscle status and S/DDFT pathology (Butcher *et al.*, 2007).

4.8 Challenges in equine sEMG research

The relatively novel use of sEMG in equine research and lack of standardized methodology has led to variability among studies (Zaneb *et al.*, 2007) especially in the interpretation of EMG data. The majority of work has investigated the un-ridden horse under experimental conditions (Section 4.6, Table 19), therefore, these results cannot be directly extrapolated to horses ridden under ‘normal’ circumstances (Robert *et al.*, 2002; Buchner *et al.*, 1994). A number of factors may affect the reliability of sEMG data collected and / or influence the interpretation of results

gained during experimentation (Table 21). Further research is required to understand the impact of extrinsic factors in changeable field-based conditions on sEMG data and to identify what represents suitable inclusion criteria for study participants.

Table 21: Variables which can influence the reliability or interpretation of sEMG data during equine research

Care should be taken during experiment design to limit the impact of intrinsic and extrinsic parameters which have the potential to affect the reliability of sEMG data collected or their subsequent interpretation. Various examples of factors which could influence sEMG data are presented to illustrate their potential impact on research design.

Variable	Potential impact
Local metabolic status of muscle (Smoliga <i>et al.</i> , 2010)	Selecting horses of unknown fitness for dynamic evaluation could result in anomalies in data collection related to their fatigue
Participant selection (Felici, 2006)	Selecting non-athletic horses would not enable comparison of the results to competitive horses
Muscle temperature (Wijnberg <i>et al.</i> , 2001)	Temperature has been shown to affect muscle activity in humans; a 1 ^o C increase in temperature produces a 5-10% decrease in MUAP and inconsistent amplitude profiles
External temperature (Reaz, Hussain and Mohd-Yasin, 2006)	Temperature, particularly in field based training or competition studies which may include repeated bouts of exercise, can influence muscle temperature and thus performance
Acquired pathology in muscle groups under investigation (Groesel <i>et al.</i> , 2010; Peham <i>et al.</i> , 2001)	Pathologies could produce abnormal loading profiles or redistribution of recruitment as a compensatory adaptation resulting in misinterpretation of data

4.8.1 Preparation

Skin tone, skin preparation and adhesion protocols may affect the quality of the sEMG signal received (De Luca, 1997). Dirt or grease, interference from other

equipment, skin or sensor displacement, from muscle movement, and activity of muscles in close proximity to the one being examined, can generate myoelectric crosstalk and generalised electrical ‘noise’ (Bergh *et al.*, 2014; De Luca *et al.*, 2010; De Luca and Merletti, 1988) (Table 22). Validated protocols for sEMG use on the horse and the future development of an equine sEMG sensor placement map would be worthwhile.

Table 22: Sources of noise in the sEMG signal

When incorporated into the EMG parameters being collected, noise can make it difficult to differentiate which frequency components of the sEMG signal are directly relatable to the muscle under investigation (Groesel et al., 2010). Therefore, knowledge and understanding of how to limit noise interference is important for sEMG researcher. Common sources of noise are highlighted in the table.

Source	Potential impact
Electrode placement (Morris and Lawson, 2009)	<ul style="list-style-type: none"> • Some sEMG systems require placement of two electrodes at a defined parallel distance from each other to facilitate signal collection • Having to repeatedly and manually attach electrodes can result in placement error influencing the accuracy of data collected introducing noise errors (De Luca, 1997)
Inappropriate placement of sensors (De Luca, 1997)	<ul style="list-style-type: none"> • Sensors should be aligned to muscle fibre direction • Location is important: sensors should sit over the maximum circumference of the belly of the muscle under investigation avoiding tendon insertions which can generate noise (Konrad, 2005) • In human sEMG research SENIAM guidance dictates ideal sensor locations (SENIAM, 2013) • For the horse, a detailed knowledge of muscle anatomy and architecture is required to ensure a suitable location is selected • Marking the location of sensors is recommended to reduce human error during repeated periods of data collection

4.8.2 Dynamic evaluation

Evaluation of EMG parameters during dynamic movement presents additional challenges to the researcher. Movement is associated with changes in the length of the muscles instigating it. During locomotion in the horse, protraction and retraction of the limbs will result in cyclical patterns in the signal received which mimic the movement patterns of the muscles regardless of adhesion protocols employed. Reliable EMG data collection and analysis has been found in dynamic evaluation of leg, torso and arm muscles during human running (for example: Smoliga *et al.*, 2010) and horses working on a treadmill (for example: Colborne, Birtles and Cacchione, 2001). However, individual assessment of specific muscles should be undertaken as it cannot be assumed that muscles located within a region, or which work synergistically, or antagonistically, demonstrate similar EMG properties (Smoliga *et al.*, 2010). There is a lack of normative EMG values established for equine muscles (Wijnberg *et al.*, 2001). Therefore more studies are required to estimate reliably if basal sEMG parameters for muscle activity during different gaits and exercise conditions exist for the superficial muscles across all horses, defined samples such as discipline specific equine athletes, or whether sEMG values are specific to individual horses as reported in human athletes (Huber *et al.*, 2011; Hug *et al.*, 2010).

4.8.3 Speed

Speed exerts a noteworthy influence on the level and duration of muscle excitation in equine muscles during locomotion (Crook, Wilson and Hodson-Tole, 2010; Robert *et al.*, 2002, 2001; Robert, Valette and Denoix, 2001, 2000). Significant increases in

sEMG intensity related to escalating velocity during trotting have been observed in the *Gluteus medius* (GM) (Crook, Wilson and Hodson-Tole, 2010; Robert *et al.*, 2002; Robert, Valette and Denoix, 2000), *Biceps femoris* (Crook, Wilson and Hodson-Tole, 2010) and *Triceps brachii* (Hodson-Tole, 2006; Robert *et al.*, 2002). The raised activity has been linked to kinematic changes, specifically the reduction in stance duration which accompanies speed increases (Crook, Wilson and Hodson-Tole, 2010; Hodson-Tole, 2006; Robert *et al.*, 2002; Robert, Valette and Denoix, 2000; McLaughlin *et al.*, 1996; Back, Schamhardt and Barneveld, 1996). Decreased stance duration has also been correlated with increased sEMG intensity and decreased duration of muscle activity in the *Gluteus medius* (Robert *et al.*, 2002; Robert, Valette and Denoix, 2000) and *Triceps brachii* (Hodson-Tole, 2006; Robert *et al.*, 2002) during high speed exercise. Therefore in the ideal dynamic sEMG study, speed should be standardised to prevent misinterpretation of data between or within subject across different exercise tests, unless it is in itself a research objective.

Within applied (ridden) equine research, speed is predominately determined by the rider. Governing bodies within UK equestrianism dictate average speeds for each level of competition in an annual rule book (British Dressage, 2014; British Eventing, 2014; British Showjumping, 2014) experienced riders, therefore may be better placed to replicate a 'level' rather than a specific speed. The use of complementary global positioning software (GPS) can provide accurate speed and distance data during equine locomotion (Witte, Hirst and Wilson, 2006). An alternative approach is to normalise for speed within data collection or within data analysis by establishing an acceptable range related to a performance test and reject runs which do not achieve these criteria, or through the use of a placing fence or pole to standardise between jumps. Both approaches have been used in human sEMG

research successfully (Hibbs *et al.*, 2011). Ultimately the research objectives set will determine the approach taken.

4.8.4 Individuality

By its nature the musculoskeletal system enables a wide range of movements. Individuality within EMG profiles is a theme observed throughout equine research (Crook, Wilson and Hodson-Tole, 2010; Smoliga *et al.*, 2010; Cheung *et al.*, 1998) and is comparable to the high inter-subject variability reported in muscle activation for human subjects (Huber *et al.* 2013; Nair *et al.*, 2010; Araujo, Dyarte and Amadio., 2000). In humans, although EMG signals are considered highly individual, research has shown that muscle activation and timing patterns during movement are consistent between subjects (Huber *et al.*, 2011; Hug et al 2010, De Luca 1997). In horses, data variability is considered to reflect inter-subject variance in muscle fibre profiles (Sections 3.9.1 and 4.2.1) (Nordander *et al.*, 2003; Wijnberg *et al.*, 2001) or actual differences in motor patterns (Smoliga *et al.*, 2010). Skin thickness, depth of subcutaneous fat and distribution of sweat glands and sweat production may also result in variability in magnitude of MUAP recorded (Nordander *et al.*, 2003). Differentiation between physical or motor issues can be difficult to facilitate in the horse due to the inability to normalise data to a static MVC (Hanon *et al.*, 1998). However in dynamic evaluation, cyclical patterns within the signal correspond to stride patterns and could therefore facilitate normalisation via synchronisation. An alternative approach within comparative evaluation is to utilise a reference state. For example Cheung *et al.* (1998) effectively analysed fatigue data collected in their work with baseline fatigued EMG data to assess adaptation within horses studied.

Therefore researchers in equine sEMG should select the method which is best placed to achieve their research objective.

The sEMG research in the Evidence Sources presented showcases preliminary work evaluating muscle performance and examines how the challenges introduced were overcome, appraises their impact upon the research outcomes formulated and highlights the potential of the technology to be integrated into sports performance analysis for the equine athlete.

4.9 EVIDENCE SOURCE 2

Williams, J.M., Gundry, P., Richards, J. and Protheroe, L. (2013) A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse The Veterinary Nurse, 4(9), pp. 566-572.

Erratum: Williams, J.M., Gundry, P., Richards, J. and Protheroe, L. (2013) A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse. *The Veterinary Nurse*. 5(6), pp. 319.

Williams *et al.* (2013) (Appendix 1.2) assessed if sEMG could be used to measure *Superficialis gluteal* (SG) muscle activity-levels (mean MUAP amplitude and frequency) and fatigue (frequency/time) during canter interval training in nine National Hunt (NH) racehorses in the field (on the gallops). No differences between MUAP amplitude and frequency levels existed across the cohort ($P>0.05$), but for individuals' amplitude did differ (58%; $P<0.001$) and frequency (1st to 2nd run increased: 33%; 1st to 3rd runs, increased: 22%). Lateral differences in frequency were recorded across the cohort ($P<0.05$) and in 67% of horses ($P<0.01$). Reliable sEMG data were obtained for the SG muscle in the field demonstrating the potential remit of sEMG as a performance analysis tool in the equine athlete. The results suggest that muscle performance is an individualised characteristic in horses and therefore training regimens should be designed on an individual basis to promote success.

4.9.1 Rationale

Epidemiological studies (for example: Mata, Williams and Marks, 2012; Singer *et al.*, 2008; Parkin *et al.*, 2004; Pinchbeck *et al.*, 2002) had highlighted that factors related to musculoskeletal health were associated with injury and performance in equine sport. In human sport, sEMG has been used to analyse muscle recruitment and activity during training and rehabilitation (for example: Guidetti, Rivellini and Fugure, 1996), but little work had been undertaken in the horse and that which had occurred was within laboratory environments not the field. Interval training is a common approach undertaken when training racehorses. Therefore the preliminary study examined gluteal muscle responses during canter interval training to gain knowledge of recruitment patterns and to identify if the system had value to assess performance.

Working hypothesis: sEMG could be used to measure and compare muscle activity, through MUAP, and fatigue, via mean frequency over time, for defined exercise periods in the National Hunt racehorse.

4.9.2 Research methodologies and limitations

The trainer had previously worked with the research team, which facilitated free access to horses in training and providing an ideal industry-based research partner. A pilot study ensured that the experimental protocol did not overtly interfere with normal yard routine, established topography for sEMG sensor placement and that the sensors remained in-situ during exercise with no adverse aesthetic or welfare implications. No equine equivalent to the SENIAM (human) EMG guidelines exists

(SENIAM, 2013). Therefore sensor placement was informed by previous equine research (Zaneb *et al.*, 2007), with care taken to place sensors on the muscle belly in the direction of the underlying muscle fibres, avoiding origin and insertion points to reduce cross-talk (Konad, 2005). The use of thoroughbreds in established training ensured horses conformed to a similar 'type' and presented with well-developed musculature. Therefore muscles of interest were easily identified allowing researchers to use anatomical landmarks to facilitated accurate repeated sensor placement in multiple subjects reducing potential placement error (De Luca, 1997) The outline of the location of each sensor was marked in chalk, in case sensors became detached or moved during dynamic motion and photographs were taken to compare sensor locations between exercise days.

All horses participating were entered for races, which required appropriate competition etiquette; therefore the ideal skin preparation, removing all hair from the sensor site, was not realistic. The team was concerned that presence of hair between the skin-sensor interfaces could generate cross-talk and needed to establish that the degree of noise generated as a result of skin displacement and dirt did not negate data validity (De Luca *et al.*, 2010). Data recorded in two thoroughbreds with a coat length of 2mm for 10 strides of working trot on a level surface were compared to equivalent data obtained in two college horses with a coat length of 0mm i.e. ideal skin preparation. Differences were found but these were not significant. However, maintaining a good contact between the sensor and the horses' skin during cantering was problematic. The adhesive-interface of the sensor was not sufficient to affix it to the horse and additional adhesive tape was required to hold the sensors in place. Unfortunately as the horses exercised, they sweated which reduced the effectiveness of the adhesive tape resulting in sensors becoming displaced or falling off generating

noise interference. Noise was removed when selecting data for analysis. Using the equipment in the field also presented challenges. The range of the system was smaller than envisaged; consultation with Delsys® and Professor Richards confirmed that an open environment could reduce the telemetric range. Sensors also incorporated a time-out function which was initiated when the range of the base unit was exceeded. The pre-canter exercise warm up (hacking) exceeded the range therefore the experimental protocol had to be adapted allowing only a snap-shot of muscle activity to be assessed and necessitating horses to be held at the base of the gallops to activate the sensors.

Due to the problems experienced, it was important to ensure that the data collected were reliable and did not include contamination. Initial review of the pilot data found a clear pattern that mapped to failure of the interface connection of the sensor which informed removal of spurious data prior to analysis. Dynamic studies can result in unavoidable endemic noise components which may lead to erroneous interpretation (DeLuca *et al.*, 2010), to prevent errors, appropriate real-time data evaluation and filtering protocols were undertaken upon data selected for defined periods of canter, representing a consistent number of strides, (Hibbs *et al.*, 2011; Zsoldos *et al.*, 2010a, b). Further improvements in the study design could have been achieved by synchronising sEMG and kinematic data using gait analysis (Hug, 2011) or heart rate data to assess accuracy in workload evaluation (Cheung *et al.*, 1998). Unfortunately additional analysis was not feasible due to the trainer not wishing to overload horses with further analysis equipment.

De Luca *et al.* (2010) advocate filtering to expose the relevant components in the raw signal. The filter protocol applied affiliated to previous equine research (Zsoldos *et al.*, 2010a, b; Licka, Frey and Peham, 2009) and was supported via discussion

with Professor Richards. Data processing was performed using Delsys® analysis software (Delsys® EMG Works™ Version 4.13) and incorporated a hardware band-pass filter, f_c of 20 and 480 Hz respectively, (Delsys®, 2014) (Section 3.5) to eliminate noise components (data $<20\text{Hz}$) within the signal and prevent misinterpretation of the data during subsequent analysis (DeLuca *et al*, 2010). Prior to evaluation of the mean MUAP and PAF, band-pass filtered data were full-wave rectified and a 4th order Butterworth low-pass filter with a f_c of 10 Hertz (Zsoldos *et al*, 2010a, b; Licka *et al*, 2009) applied to create a linear envelope to reduce the impact of phase-lag within the signal (Kamen and Gabriel, 2010; Winter, 2009). Consideration of the f_c threshold was undertaken to ensure the most appropriate value and method was selected for the study. The composition of the SG muscle varies between individual horses; thoroughbreds have been shown to recruit all muscle fibre types during high intensity exercise (Yamano *et al*, 2006). As the horses investigated were of variable fitness, it was assumed that the level of exercise in relation to fitness level may recruit variable fibre numbers, and thus muscle twitch times could vary. Histological examination of the equine *Gluteal medius* had previously reported a predominance of fast twitch fibres in the superficial fascicles moving to slow-twitch fibres deeper within the muscle (Lopez-Rivero *et al*, 1992). By its nature, sEMG will record superficial muscle activity; therefore it is likely that sEMG profiles recorded for the horses' SG muscles corresponded to superficial fast-twitch activity. The lack of validated muscle twitch times for the equine SG preventing this method defining f_c (Winter, 2009). Similarly, total power within the signal varied between horses and runs, thus was not considered appropriate for selection of f_c (Kamen and Gabriel, 2010). Evaluation of EMG profiles using a 4th Order Butterworth filter but with differing f_c between 10-25 Hz was conducted, and

the resultant EMG profiles overlaid for comparison, with little variance exposed (Vint *et al.*, 2001). Therefore it was decided to set f_c at 10Hz analogous to previous work in the horse (Zsoldos *et al.*, 2010a, b; Licka *et al.*, 2009).

Erratum: initial analysis of fatigue was conducted in error on data post-20Hz low-pass filtering. To accurately analyse fatigue, calculation of the mean frequency over time for the full frequency range of functional data (26-120Hz) was required (Hanon, Thepaut-Matieu and Vanderwalle, 2005). Therefore the analysis was re-run and the revised results confirmed fatigue was not present for any participants, suggesting that horses were cantering at differing intensities throughout the exercise period rather than displaying a sequential increase in workload.

4.9.3 Contribution to the field of equine performance

The study successfully demonstrated the potential use of telemetric sEMG as a performance analysis tool in the horse. Interpretation of the results is limited due to restrictions in the experimental design which only allowed a ‘snap-shot’ of muscle activity to be evaluated and future studies which evaluate the entirety of a single training session and comparative sessions within a training regimen are warranted. However the range of significant results found within individual horses rather than across the cohort suggest that whilst recruitment patterns were consistent across the sample, muscle performance (contribution to workload) was unique to each horse and therefore sEMG may have most value when analysing individual performance.

Interpretation of the sEMG signal is acknowledged as difficult (Hanon, Thepaut-Matieu and Vanderwalle, 2005) as determination of the quantity, and sequential recruitment of, muscle fibre types is impossible without applying fine-wire EMG techniques, the use of which are ethically constrained in the horse. EMG profiles analysed MUAP amplitude and frequency, both of which have been used to examine force production in muscles (Kamen and Gabriel, 2010). Although frequency is considered a less reliable measure of workload compared to amplitude, both parameters will influence MUAP driving locomotion (Kamen and Gabriel, 2010). The lack of significant differences in MUAP amplitude suggest force was generally consistent between runs across the group whilst the individual variation found was associated with lateralisation, proposing a functional relationship with the leading hind-leg in canter. MUAP frequency analysis also identified lateralised muscle performance and differences between the first run up the gallops (potential warm up) and subsequent runs. MUAP frequency represents the range of muscle twitches that contribute to contraction (Kamen and Gabriel, 2010). Interpretation of how different factors influence MUAP frequency is not possible through sEMG data, however muscle length, fibre profile, MU recruitment and firing rate can be influential (Staudenmann *et al.*, 2010) and could propose explanations for the differences observed. During cantering the SG extends the hip, retracts and supports outward rotation of the hind limb therefore MUAP frequencies will increase during concentric contractions of the SG, the predominate function, and reduce during eccentric activity. Thoroughbreds generally have higher ratios of Type IIA and IIX fibres in the superficial SG due to their breeding and training (Lopez-Rivero and Letelier, 2000). Equally, during canter exercise, large numbers of fast-twitch fibre types IIX and IIX would be recruited (Yamano *et al.*, 2006). The increased MUAP

frequencies found between the initial and subsequent runs in the majority of individuals suggest an increased workload perhaps representing recruitment of more Type IIX fibres (Yamano *et al.* 2006; Lopez-Rivero and Letelier, 2000). Similarly lateral differences in SG MUAP frequency indicate unequal contribution between right and left SG muscles during locomotion, although this was not always associated with the leading hind leg.

Dynamic evaluation can introduce variability in sEMG data obtained as a result of skin and muscle movement across repeated muscle contractions (Groesel *et al.*, 2010). Whilst protocols were employed to limit these effects as much as practicable, movement phenomenon had to be addressed within analysis. Defined epochs within the trace can be used as an additional filter within the signal (De Luca, 1997), for example identification of muscle activity synchronised to the phases of locomotion can be used (Colborne, Birtles and Cacchione, 2001; Peham *et al.*, 2001). Zsoldos *et al.* (2010a, b) had successfully demonstrated that direct comparison of related EMG events was valid when evaluation of overall muscle activity was the defined objective. Repeated sEMG profiles for defined bouts of activity within subjects was one of the core objectives of the study therefore the latter approach was deemed appropriate.

Practically, refinement is required to facilitate use by the trainer although it was reassuring that the trainer could envisage the potential applications of the system. After completion, the team discussed the limitations encountered with Delsys®. The company has subsequently marketed a remote unit which can be attached to a person, or in equine research to the rider, to facilitate longitudinal data collection for up to 48 hours which will be beneficial to future projects.

4.9.4 Implications and questions generated

Whilst it was rewarding to be investigating a novel field, the lack of established equine sEMG protocols was challenging. The study was a first step to understanding muscle responses within exercise bouts and how these adapt between interval training sessions in the equine athlete. Core temporal parameters in the EMG signal: onset-offset of muscle recruitment and timing patterns, are generally consistent in humans (Huber *et al.*, 2011; Hug *et al.* 2010, De Luca, 1997). A pattern also observed here. Therefore in essence the gross functionality of muscles related to specific tasks was the same between individuals i.e. the SG muscle retracts the limb during canter in all horses in a fundamentally similar and consistent manner. Our data reported individualised patterns for muscle activity as postulated in previous equine work (Zsoldos *et al.*, 2010a; Roberts *et al.*, 2001) and in humans (Huber *et al.* 2013; Nair *et al.*, 2010; Felici, 2006). By its nature the musculoskeletal system enables a wide range of movements. Muscle workload to facilitate movement will be influenced by a horse's conformation, muscle distribution, physiological status, established biomechanical patterns, farriery and numerous other factors. Therefore it is unsurprising that the EMG profiles recorded were highly individual. sEMG evidence currently suggests that individual horses and humans possess a unique physiological footprint representing how muscle responds at fibre and MU level to produce gross function (Hug *et al.*, 2010). Due to the small number of horses examined, further research in more subjects is required to fully substantiate this. Practically, sEMG could offer riders and trainers a tool to compare how individual horses respond to training, allowing them to implement training regimens designed to optimise individual potential.

The revised results (Appendix 1.2A) suggest that the interval training protocol investigated did not generate sufficient workload to observe muscle fatigue in the horses studied. The conclusions drawn in the original article remain valid: sEMG is a tool that could potentially be used to assess how equine muscles respond to training, to ascertain muscle recruitment and to assess fitness levels in horses. Further consideration of the laterality bias uncovered in the racing thoroughbred sample would be worthwhile. Motor laterality may be acquired through training or injury (McManus, 2002; Manning and Ockenden, 1994). Increased distal limb injuries are associated with leading limb preference in N.H. racehorses (Parkin *et al.*, 2004) and jumping technique in showjumpers (Walker *et al.*, 2014) therefore addressing lateral bias in horses could potentially reduce injury acquisition. However since the majority of UK racetracks are right handed (Racing Post, 2014), training to promote a right canter lead (forelimb) bias may promote superior performance and be desirable by racehorse trainers. Therefore assessment of lateral muscle contribution to exercise may be one application of sEMG within equine performance analysis.

4.10 EVIDENCE SOURCE 3

St George, L. and Williams, J.M. (2013) Electromyographic evaluation of approach stride, jump stride and intermediate stride in selected superficial muscles of the jumping horse: A preliminary study. Comparative Exercise Physiology. 9(1), pp. 23-32.

St George and Williams (2013) conducted an exploratory case study to identify recruitment patterns in the superficial gluteal, *Triceps brachii* and *Longissimus dorsi* muscles during the different phases of the equine jump. sEMG data were recorded for repeated jumping efforts (>1.20m) for one experienced jumping horse. Mean MUAP amplitude (mMUAP), for the duration of muscle activity during each phase of the jump, and mean peak amplitude frequency (PAF), for the maximum contraction during each phase of the jump, were compared. No significant differences in mMUAP were found between muscles across all strides ($P>0.05$). PAF values did differ ($P<0.025$) between the approach and jump strides, and jump and intermediate strides in the superficial gluteal and *Triceps brachii* muscles respectively. Anecdotally, equestrian coaches have suggested that jumping strides are an extension of the horse's canter stride. The lack of differences found in overall muscle workload represented by mMUAP amplitude supports industry opinion. The variability observed in PAF reflects the differing functional roles of the muscles investigated during the different phases of equine jumping.

4.10.1 Rationale

Few studies have assessed showjumping performance during training, existing research has predominantly evaluated biomechanics (for example: Clayton and Barlow, 1991; Powers and Harrison, 1999) rather than training (Tranquille *et al.*, 2014; Walker *et al.*, 2014). A project was devised to assess muscle recruitment during jumping in an elite showjumper to test speculation by equestrian coaches that jumping strides were extensions of the horse's canter stride. Developing a better understanding of the contribution of individual muscles during routine exercise has the potential to inform future training regimens in the equine athlete.

Working hypothesis: sEMG could be used to identify onset and offset of muscle recruitment and muscle activity-levels during jumping in the horse.

4.10.2 Research methodologies and limitations

It was important for the project that participating horse/s were experienced and capable of jumping at affiliated competition level over a height which facilitated a true bascule. Discussions with equestrian coaches reinforced the anecdotal opinion that showjumping horses often preserve energy and effectively canter over jumps that are <1m high (Winfield, J. and Bracken, C., personal communication, 2012). Therefore to obtain validation for the project from professional riders and coaches, access to horses experienced in affiliated showjumping competitions > 1m was required to enable comparison to competitive showjumpers. The final heights utilised and horse selection was informed via consultation with a National level coach. Originally, a sample size of 4-6 horses was planned in accordance with

previous sEMG studies (for example: Zsoldos *et al.*, 2010a, b). Inclusion criteria were applied to equine participants and their riders (Table 23). Suitable horses proved difficult to source, which combined with accessibility to the arena and the coach, reduced the sample size to a single subject.

Table 23: Inclusion criteria St George and Williams (2013) (Winfield, J. and Bracken, C., personal communication, 2012)

Selection of suitable inclusion criteria for participants in equine sEMG research is essential to prevent noise contamination or incorrect interpretation of the results gained. A premise of the study undertaken was to assess EMG profiles in athletic horses to facilitate transfer of conclusions formed to competition samples. The inclusion criteria selected for horses, riders and acceptable jumps are given in the table.

Subject	Inclusion criteria
Horses	<ol style="list-style-type: none"> 1. Free from lameness, fit and healthy to engage in jump training (assessed by the rider and coach) 2. Have affiliated competition experience (>1 year) jumping over 1.40m courses 3. Ridden by the same experienced rider for a minimum of 1 year
Riders	<ol style="list-style-type: none"> 1. Fit and healthy to engage in jump training (assessed by the rider and coach) 2. 2+ years' experience competing at >1.20m affiliated showjumping
'Good' jump	<ol style="list-style-type: none"> 1. A consistent and straight approach to the fence with no deviation 2. Approach had an established canter rhythm at a competition relevant speed (350mpm) 3. The horse cleared the fence and did not knock any poles 4. The horse's take-off was not too close (<1.20m) to the fence 5. The horse did not stand off the fence (take off >2.0m)

Causal relationships evidenced by a single subject are specific to that individual, and therefore inhibit extrapolation of the results to the wider population (Teut and Linde, 2013; Gerring, 2004). However, due to the current gap in knowledge, it was concluded that this project was warranted as an initial proof of concept study, which could lead to future conclusive studies incorporating an increased sample of jumping horses (Powers and Harrison, 1999). It is important to reinforce that the results obtained and conclusions drawn are specific only to the horse used in the study. To ensure sufficient data from the single subject, the methodology incorporated multiple repeats of the jumping procedure. Consultation with the equestrian coach informed inclusion criteria for a good jump to mimic professional and competition expectations of 1.20+ showjumping horses and to decrease the likelihood of including jumping efforts which did not represent a characteristic jump for the horse used (Table 23) (British Showjumping, 2014; Winfield, J. and Bracken, C., personal communication, 2012) However, using one subject was a weakness in the study and future research is required to validate conclusions using multiple subjects.

The research environment allowed accessibility to the EMG sensors, therefore live data could be reviewed and sensors reapplied if problems with electrode connectivity were suspected. An increased number of muscles were included in the research design from the previous study; sensor placement corresponded to the locations suggested in Zaneb *et al.* (2007). Visual examination of the data suggested all sensors were actively recording data. However, once filtered the quality of the right sided data were questioned as the amplitudes within the sEMG profile contained multiple irregular spikes, rather than a sinusoid profile, suggesting noise contamination (De Luca, 1997; De Luca *et al.*, 2010). Therefore the right data were removed from the study preventing investigation of lateralisation.

The lack of digital synchronization between the Delsys® Trigno™ system and video footage introduced potential temporal errors when affiliating sEMG data to the biomechanics of the phases of the jump. The Delsys® system is capable of harmonization with video or gait analysis equipment; however the additional software to facilitate synchronization was not available. Therefore synchronization was achieved manually during data collection and was re-evaluated during subsequent analysis using Dartfish™ (Dartfish Team Pro 5.5™, Switzerland) software and EMG Works™ (Delsys®, Boston, USA) analysis to establish if the timing error was acceptable. The accuracy of panning video-cameras has been questioned in kinematic jumping work, as parallax error can reduce accuracy (Clayton and Barlow, 1989). However, more recent evaluation in horses has suggested the use of hand-panning cameras provide the large field of view required to record several strides without reducing the quality of accuracy observed during static videographic assessment (Cassiat *et al.*, 2004). The effects of parallax error on scale accuracy in videographic data analysis should not have a significant influence on the data analysis of our study, as the video recordings were simply used to determine the phases of the jump based on temporal data in order to synchronize phase onset and duration with sEMG data, and did not directly contribute data for analysis. Ideally the inclusion of gait analysis technology to systematically quantify the biomechanical contribution of each segment of the horse and the phases of the jump and canter would have occurred simultaneously to EMG evaluation. A timing error of 0.04s was present between frames for the sEMG data and the stride kinematics recorded. Osis *et al.* (2014) found that 89-94% of predicted foot strikes during kinematic analysis of human runners occurred within a 0.02s timing error, suggesting the error reported here could reduce the efficacy of the analysis. Digitally

synchronization reduces timing error further, for example an error of 0.006s was reported in galloping thoroughbreds (Seder and Vickery, 2003). Therefore for future sEMG studies comparing muscle function to kinematic variables, digitally synchronized gait analysis is recommended. However the practicalities of applying multiple technologies to elite level horses could reduce access to participants due to time constraints, rider misconception of their impact on performance and / or breaching competition regulations.

4.10.3 Contribution to the field of equine performance

The participating rider and coach felt that the sEMG system could be incorporated into a training session without any detrimental influence to the performance of the horse. The 'real-time' data held worth to the coach within the session as it highlighted muscle recruitment during exercise, underpinning the coach's observations. The application of sEMG to confirm or identify recruitment and contribution of muscles during exercise could be used to tailor exercises to muscle development. Alternatively, establishing baseline data for a horse in a set task could be compared over time to monitor progress within a training regimen or to identify changes which could reflect the development of a subclinical injury. The study provided initial objective support for the hypothesis that jumping is an extended canter stride and supports training practices which emphasise the quality of the canter, although further investigation in more subjects is required to apply the findings wider than one horse. A unidirectional bias has been identified during showjumping training (Tranquille *et al.*, 2014) and opportunities exist to optimise jumping technique potentially reducing distal limb strain and associated injuries

(Walker *et al.*, 2014). Further practical studies are required to validate training protocols, such as developing a ‘jumping canter’, currently implemented throughout equestrian sport and sEMG could prove a valuable tool in this process.

4.10.4 Implications and questions generated

Longitudinal sEMG projects which map repetitive training bouts using larger samples of competitive horses are required to confirm the results of preliminary investigations. Building a larger evidence-base will increase knowledge and understanding of muscle response to exercise and using actively competing horses should promote dissemination to the equestrian industry. sEMG is a tool which could facilitate collaboration with riders and coaches as the practical applications of the technology and the ‘real-time’ visual output can be easily translated into the performance sphere; for example quantifying muscle recruitment, assessing fatigue during competition or evaluating the efficacy of warm-up protocols.

4.11 EVIDENCE SOURCE 4

Williams, J.M., Johnson, C., Bales, R., Lloy¹, G., Barron, L. and Quest, D. (2014) Analysis of Temporalis and Masseter adaptation after routine dental-treatment in the horse via surface electromyography. Comparative Exercise Physiology (in press)

Williams *et al.* (2014) used sEMG to identify if *Masseter* and *Temporalis* muscle activity changed after routine dental-treatment (rasping) in ten horses of variable breed and age, with consistent dental pathology. MUAP amplitude for the duration of 5 chewing cycles and the peak amplitude contraction from each cycle were compared between weeks across the cohort and individuals. Limited changes in muscle activity occurred across the cohort. For individual horses, MUAP increased and decreased in both muscles ($P < 0.05$) but PAC was consistent ($P > 0.05$). The results suggest that routine rasping triggers specific adaptation in the activity patterns of the *Masseter* and *Temporalis* reflecting the increased lateral excursion and power stroke observed post-dental treatment in individual horses.

4.11.1 Rationale

Routine rasping is an essential component of the annual health care programme for all horses. Equine dentition is hypsodont; feral *Equidae* graze >18 hours a day to sustain adequate nutrition, producing sufficient attrition of the occlusal surfaces to prevent dental pathologies developing (Dacre, 2006). In contrast, the modern equine athlete is often subjected to restricted grazing, with forage-based diets replaced by cereal-rich diets which reduce mastication time-budgets causing abnormal wear patterns (Buschang, 2006; McBride and Long, 2001). Rasping is required to remove

sharp buccal and lingual points on the teeth which can cause ulceration of the gums producing pain when ridden (Pascoe, 2010; Scoggins, 2001; Dixon, 2000). The bit is a key communication interface between horse and rider; pain may negatively impact performance via control issues during riding (Scoggins, 2001). Dental pathology may cause affected horses to drop food when eating or chew food insufficiently to optimise digestion (Pascoe, 2010; Linkous, 2005; Scoggins, 2001). If pathology is left untreated, resultant adaptation can produce abnormal chewing cycles reducing nutritional intake (Dacre, 2006; Dixon, 2000). All of which can have a negative impact on equine performance (Pascoe, 2010; Dacre, 2006; Dixon, 2000).

Our prior research had explored best practice in the use of motorised dental tools (Williams, Parrott and De Mata, 2011; Williams, McGarian and Johnson, 2011) and evaluated the impact of prophylactic rasping on chewing patterns in the horse (Johnson, Williams and Nankervis, 2013). Kinematic analysis identified the distance travelled by the mandible during lateral excursion, sideways movement of the mandible during chewing, and that the power stroke increased after rasping. The *Temporalis* and *Masseter* are the key muscles associated with chewing and as such the variation in lateral excursion and the power stroke observed were hypothesised to be the result of muscular adaptation within these muscles. Therefore sEMG was employed to explore muscle adaptation.

Working hypothesis: Masseter and Temporalis activity, measured by MUAP amplitude and peak amplitude contraction, would increase and decrease respectively, during the 6 week period after routine dental-treatment.

4.11.2 Research methods and limitations

Johnson, Williams and Nankervis (2012) established a suitable protocol to assess pathology and to analyse the impact of dental-treatment. Kinematic changes post-rasping were evidenced by increased lateral excursion and an amplified power stroke. However no plateau had been attained within the data suggesting ongoing adaptation. The *Temporalis* and *Masseter* are the two largest muscles associated with mastication and occupy superficial topography on the equine head, facilitating sEMG analysis. *Masseter* assessment was challenging due to superficial compartments which have multiple muscle fibre directions. Sensor placement was aligned to proximal fibre direction established via dissection of cadaver samples at Hartpury College. Selecting participants from HorseWorld enabled optimal skin preparation protocols (0mm clip / shaved skin) thus reducing potential external interference to the EMG signal (De Luca *et al.*, 2010). The horses were not elite athletes and presented with variable pathologies, which was not ideal but typical of opportunistic sampling in equine research. However, participants were easy to access, had prior experience of dentistry and EDT assessment concluded that all horses met set inclusion criteria for low grade pathologies of comparable severity. Therefore the subjects represented a viable cohort for research and as their teeth also needed rasping, there was limited ethical impact from the potentially invasive dental treatment. The majority of domesticated horses require rasping on a routine basis regardless of their function. Therefore as an initial concept project to establish if rasping initiated muscular adaptation, the fundamental nature of the results gained are applicable across the general equine population.

A six week research period was selected primarily as it was feasible for the research team and HorseWorld, but also due to the nature of chewing. Rivero (2009) recorded

muscular adaptation related to interval training (high intensity, short duration) in thoroughbreds after 8 weeks. However, mastication is a low intensity, long duration activity recording daily time-budgets of 12-16 hours in the free-grazing horse (Ellis, 2010), therefore it was believed that a 6 week period post-dentistry should encompass muscle adaptation, if it occurred.

HorseWorld is a charity and the horses used were retired, which allowed free access to them at all times and placed no restrictions on preparation, which would have occurred in competing horses. The lack of time constraints enabled the research team to assess 'real-time' EMG and accelerometer data, and repeat collection as needed, to ensure 5 chewing cycles of sufficient quality were recorded on each occasion. As the team had no prior experience of sEMG in the *Masseter* or *Temporalis* of the horse, a power spectral density plot was performed to analyse frequency contribution to the entire EMG signal and inform subsequent data processing. Band-pass filtered data were full wave rectified prior to visual identification of the components of the mastication cycle; to aid in synchronisation the accelerometer function of all the EMG sensors had been activated during data collection to enable simultaneous evaluation of movement direction. The choice was made to exclude the kinematic data within the manuscript as the focus was muscle adaptation. Prior to statistical analysis, a linear envelope smoothed data to facilitate comparative analysis between EMG and kinematic data (De Luca *et al.*, 2010). Five chewing cycles of consistent data quality were selected. Data were filtered with a 4th order Butterworth filter using a f_c of 10Hz, analogous to kinematic data, and 100Hz, maximum frequency of collected data, to select the most appropriate f_c (Zsoldos *et al.*, 2010a; Vint *et al.*, 2001). The filtered traces were overlaid and little variation in the extent of smoothing of the EMG sinusoids was found. Therefore 10Hz was selected in accordance with

previous equine and human kinesiological EMG research ($f_c < 25\text{Hz}$) (Kamen and Gabriel, 2010).

MUAP amplitudes recorded during chewing changed in the *Masseter* and *Temporalis* muscles for individual horses after rasping. MUAP amplitude broadly represents muscle workload (Reaz, Hussain and Mohd-Yasin, 2006). In normal mastication, the *Masseter* drives lateral excursion and provides the strength of the power stroke controlling attrition rates and the *Temporalis* closes the jaw during chewing (Johnson, Williams and Nankervis, 2013). The changes observed in muscle workload appear to reflect kinematic changes associated with rasping and a changing drive from the *Temporalis* back to the *Masseter* during chewing, thus restoring 'normal' mastication.

4.11.3 Contribution to the field of equine performance

To our knowledge, this was the first study to evaluate muscle adaptation associated with kinematic changes after dental treatment. Rasping promoted 'normal' mastication generating *Masseter* and *Temporalis* muscle adaption to support the increased lateral excursion and power stroke observed (Dixon, 2000). *Masseter* and *Temporalis* workload varied (increased / decreased) on a discrete basis for individuals although peak contractions remained consistent. Therefore the frequency of dental treatment should be evaluated on an individual basis not generalised (occur annually) in horses.

The duration of muscle adaptation post-rasping could not be confirmed. Pain and nutritional status are acknowledged to influence ridden performance in the equine

athlete and are associated with dental pathology (Cook, 2003; Hintz, 1994). Rasping removes buccal and lingual points preventing further ulceration and allowing current ulcers to heal reducing mouth pain, which should improve ridden performance (Linkous, 2005; Scoggins, 2001; Dixon, 2000). Restoring balance in the dental arcades increases lateral excursion resulting in better attrition of food and more effective chewing which could increase nutrient uptake (Dixon, 2000). Faecal fibre length does not appear to change post-rasping (≥ 4 weeks), suggesting no associated improvement in digestibility (Zwirglmaier *et al.*, 2013; Carmalt and Allen, 2008). The fluctuations in MUAP observed here suggest that muscles are adapting for ≥ 6 weeks post-rasping, therefore benefits associated with digestibility may not be instantly observed. Further work increasing knowledge of the impact of dental-treatment on digestibility and performance is required. Developing an understanding of when to schedule rasping within training and competition schedules could optimise performance in the horse.

4.11.4 Implications and questions generated

The conclusions were not unexpected; however, validating anecdotal observations is a key remit of research to underpin the necessity and efficacy of routine procedures. It was hoped that the research could be disseminated in the Equine Veterinary Journal; however the manuscript was not considered to be within the scope of the Journal. The rejection epitomises the lack of journals with a specific focus to applied equine research or equitation science projects. The results provide fundamental knowledge of muscle adaptation after rasping, and as such provide an evidence-base for future research to build upon.

It would be of interest to conduct a longitudinal study measuring and evaluating the long term mastication profiles of horses, to show how mastication is affected over time by the development of dental pathology and different diets. Results could inform the frequency of routine rasping and include evaluation of pathology on ridden performance.

CHAPTER FIVE

DISCUSSION

Chapter Five critically reviews the results of the evidence sources found in Appendices 1.2 to 1.4, to assess the potential of sEMG as a valid performance analysis tool for use in the equine athlete. Reflection on personal development that occurred during the research journey is provided in Appendix 8.

5.1 Field assessment of sEMG in the equine athlete

Williams *et al.* (2014), St George and Williams (2013) and Williams *et al.* (2013) demonstrate that sEMG can be used to assess the physiological response of superficial muscles during field-based exercise in the equine athlete (Appendices 1.2 to 1.4). Interpretation of sEMG data can be challenging (Staudenmann *et al.*, 2010) (Sections 3.2 and 4.8) but when analysed in the broader context of a horse's health status, fitness level and muscle profile, the information obtained could make a valuable contribution to performance analysis. sEMG appears more effective when assessing or comparing individual performance (Sections 4.9.4 and 4.11.3). Therefore, although the results are consistent with the principal hypothesis presented, further research is required to fully accept it. Using sEMG to analyse muscle contribution to performance in the equine athlete is recommended.

sEMG assessment of interval training in racehorses (Williams *et al.*, 2013) found that SG recruitment patterns were related to swing and stance in canter and were consistent across horses. However, individual variation in the contribution (power

provided) of muscles was individualised as reported in humans (Felici, 2006; Guidetti, Rivellini and Fugure, 1996). The use of sEMG in the field was successful with sensors remained attached to the horses during dynamic exercise. Appropriate monitoring of real-time data and subsequent selection and filtering protocols effectively removed noise contamination (De Luca *et al.*, 2010). Motor lateral biases were found in most horses. Interval training did not fatigue racehorses working at submaximal exercise levels. The results suggest that implementing bespoke training programmes for individual horses designed to promote muscle performance to match competition (race) requirements could enhance performance. Using sEMG to monitor and reduce lateralised recruitment of muscles could reduce acquired injury associated with uneven loading in the horse.

An exploratory case study assessed muscle recruitment in the jumping horse (St George and Williams, 2013). As a proof of concept investigation, the results provide a preliminary evidence-base to suggest that jumping strides are extensions of canter strides which could inform training practices. However further analysis in multiple horses is required to validate the conclusions formed. The ability of sEMG to identify recruitment patterns during movement could be applied across different exercises to assess their value in equine training regimens.

The use of sEMG to assess muscle response to routine treatments in the horse, could inform when prophylactic health care should occur in relation to training to optimise performance (Williams *et al.*, 2014). Changes in *Masseter* and *Temporalis* performance were expected after routine rasping. The lack of a plateau within the sEMG data suggests that muscle adaptation occurred throughout the 6 weeks after dental-treatment. Understanding timeframes for muscle adaptation, associated with exercise or as a result of therapeutic interventions, would be valuable to help inform

the duration of training regimens in preparation for competition. Specific knowledge of mastication changes could influence equine performance through the horse's response to the bit whilst adaptation is active.

The application of sEMG to demonstrate how muscle adapts to therapeutic interventions could be used to assess the efficacy of complementary therapies. For example, a survey of 2554 dressage competitors found that 80% of riders initially engaged complementary therapists when their horses were lame rather than seeking veterinary intervention (Murray *et al.*, 2010). The use of sEMG could establish the efficacy of complementary therapies which 'treat' muscle pathology (Buchner and Schildboeck, 2006), for instance therapeutic ultrasound, or which manipulate muscles to promote flexibility, such as massage.

5.2 Muscle recruitment

The functional contribution of muscles to motor tasks and the coordination patterns which occur between muscles during activity are critical to fully understand the neurophysiology and biomechanics which underpin performance (Hug, 2011). The work presented (Williams *et al.*, 2014; St George and Williams, 2013; Williams *et al.*, 2013) has successfully and consistently identified onset and offset of muscle recruitment enabling sEMG profiles related to gait, mastication and jumping to be established.

Accurate assessment of muscle function through recruitment patterns has the potential to inform performance analysis in the equine athlete (Hug *et al.*, 2010) (Sections 4.9.4 and 4.10.3). The lack of a scientific evidence-base for equine training

and performance analysis is evident (Williams, 2013; Ely *et al.*, 2010; Ferrari *et al.*, 2009). Telemetric sEMG systems may contribute to the development of an evidence-base on muscle recruitment during anecdotal practices. For example verifying the use of training practices and aids to develop muscle strength or promote hypertrophy such as hyperflexion (Zsoldos *et al.*, 2010a) or the Pessoa system (Appendix 6). Preliminary sEMG examination has demonstrated that using the Pessoa increases epaxial muscle workload during walk and trot compared to without it (Williams, unpublished data). Another application could be assessing the role of grid-work to improve jumping technique building on the work of St George and Williams (2013).

The real-time visual display presents raw EMG data as a sinusoid, but with training it is relatively easy to identify muscle onset and offset within the signal. Using real-time data could demonstrate to coaches if the muscles they believe are being recruited are active, indicate duration of activity and provide an approximation of activity-levels and synergy when viewed simultaneously (Hug, 2011; Hug *et al.*, 2010) (Section 4.10.3). Information obtained could be used to check exercises are meeting training objectives or if adaptation within a technique could be utilised to target set muscles (Felici, 2006), aiding muscle development post-injury or in preparation for competition.

ISES 2012 provided an opportunity to present a practical overview of sEMG to peers and industry to demonstrate the potential of the system as a performance analysis tool using a pair of international driving horses (Appendix 9). Despite limitations imposed by the situation, real-time data (gluteal muscles) identified lateralisation of muscle activity linked to direction of travel and workload within the driving pair. Data analysis reaffirmed the conclusions drawn from the raw data providing an effective demonstration of the system's value in real-time analysis of performance.

5.3 Muscle activity

sEMG data can quantify muscle activity identifying synergistic relationships within defined events to facilitate comparison of muscle performance or which could monitor muscle adaptation over time (Hug *et al.*, 2010). The research presented (Williams *et al.*, 2014; St George and Williams, 2013; Williams *et al.*, 2013) demonstrates how sEMG may be used to measure and compare muscle activity-levels: MUAP amplitude and frequency, in the horse, during practical field-based events. However, it should be remembered that the sEMG data represent cumulative muscle activity for the period under investigation (Konrad, 2005). Equine muscle activity-levels appear individualised in contrast to the consistent temporal patterns observed for recruitment and duration of specific muscle actions (Sections 4.9.4, 4.10.1 and 4.11.3). Workload intensity and duration will alter the number and type of fibres being actively recruited, the duration of MUAPs, amplitude magnitudes, firing rates and synchronisation (Hanon, Thepaut-Matieu and Vanderwalle, 2005) (Section 4.2.1). Intrinsic and extrinsic factors, such as temperature and sweat production, may also influence data obtained (Reaz, Hussain and Mohd-Yasin, 2006) (Sections 3.7 and 4.8). Therefore it is critical when interpreting sEMG results that a holistic view of performance is evaluated, with due consideration of factors which could potentially explain variation reported between runs, individuals or over time (Konrad, 2005; Stegeman *et al.*, 2000). sEMG data appear most valuable to plot progress and identify differences in workload between events for individual horses (Sections 4.9.4 and 4.11.3). Data presented do not represent a finite understanding of the minutia of muscle activity. However from a performance perspective collating baseline data which future data can be compared to could facilitate measurement of progress during training For example, judging the contribution of key muscles to a

set motor task (Section 4.10.3), analysing muscle lateralisation (Section 4.9.4) to assess a horse's balance or being able to quantify muscle fatigue could all add to the practitioner's toolkit (Hug, 2011; van Weeren and Crevier-Denoix, 2006).

Reliable and valid data are required to recommend the use of sEMG as a field-based performance analysis tool for the horse. Kinesiological sEMG presents challenges to the equine researcher (Felici, 2006) (Section 4.8). All measures practicable were applied to promote reliability during data collection, processing and analysis in the projects undertaken (Sections 4.9.2, 4.10.2 and 4.11.2). Skin preparation, analysis of real-time data, selection of appropriate and high quality segments of data for analysis and removal of spurious data by filtering should prevent errors (Sections 3.6 and 3.7) (De Luca *et al.*, 2010). However it should be noted that limited comparative equine data exist to validate the results obtained.

5.3.1 Measures of muscle activity

Human EMG researchers will often analyse simple measures of muscle activity such as sum MUAP amplitude, peak amplitude contractions or duration of contractions to assess muscle workload (Hibbs *et al.*, 2011; Kamen and Gabriel, 2010; Winter, 2009). Mean and median MUAP frequency analysis can also be used to assess muscle workload but are not considered as reliable as amplitude-related measures (Kamen and Gabriel, 2010). Plotting mean or median frequency over time can quantify the presence or not of fatigue during a defined event (Hanon, 2005). Previous equine EMG studies (Sections 4.8.1, 4.8.2, 4.8.3 and 4.8.4) have used a variety of measures to assess muscles (Section 4.6, Table 19).

A key consideration across the studies presented was which sEMG analyses to use. EMG activity (amplitude) has been shown to increase, with an earlier onset of contraction, as velocity of movement increases during kinematic research in horses (Robert *et al.*, 2001) and humans (Rahnama, Lees and Reilly, 2006). In dynamic situations, MUAP amplitude represents a more reliable measure of sum muscle activity than MUAP frequency analysis, as it remains relatively consistent regardless of changes in velocity (Hibbs *et al.*, 2011). However muscle contraction amplitude and workload can also vary with exercise type, duration and intensity, the stage of a sequential event assessed e.g. stance and swing, or between individuals or repetitions within the same subject (Rivero, 2014; Felici, 2006). Consecutive assessment of peak amplitudes provides a complementary measure to assess muscle performance (Hibbs *et al.*, 2011). Due to the dynamic nature of the work undertaken, mean MUAP amplitude and peak amplitude assessment were selected to enable comparative analysis of muscle workload interval training (Williams *et al.*, 2013) and chewing cycles post dental-treatment (Williams *et al.*, 2014) (Section 3.9.3). The research represented preliminary investigations into Kinesiological EMG; therefore analysis of mean MUAP frequency to assess workload was undertaken to compare each measure in the horse (Williams *et al.*, 2013). Median MUAP frequencies were selected and plotted over time to provide fatigue profiles for individual horses (Williams *et al.*, 2013).

Evaluation of muscle workload is advantageous when evaluating performance. MUAP data can be extrapolated to estimate muscle force via iEMG (Staudenmann *et al.*, 2010), a measure which has been used in equine research to facilitate muscle workload comparison (Section 4.6, Table 19). Force estimation requires normalisation to MVC values, (Kamen and Gabriel, 2010; Staudenmann *et al.*, 2010)

which are not an option for the horse (Section 3.9.3) negating the use of iEMG in the Evidence Sources presented. Peham *et al.* (2001) used a maximal contraction obtained during data collection to enable normalisation of subsequent related muscle activity. However, the reliability is questionable as basal values for MUAPs are not established across equine muscles. An alternative method is to compare data from related events within a defined movement cycle (Zoldos *et al.*, 2010a, b) (Section 3.9.3). The initial run on the gallops (Williams *et al.*, 2013), the approach stride (St George and Williams, 2013) and the chewing cycles pre-dentistry (Williams *et al.*, 2014) represented valid reference states to enable subsequent assessment of muscle performance over time.

5.4 Comparison to previous equine EMG studies

Williams *et al.* (2014), St George and Williams (2013) and Williams *et al.* (2013) analysed muscles which previous equine EMG research had investigated in the laboratory (Wijnberg *et al.*, 2003; Roberts *et al.*, 2001) using non-invasive telemetric sEMG to facilitate data collection in training and management environments. Wijnberg *et al.* (2003) evaluated *Triceps brachii* activity using needle-EMG but data are not comparable to the values recorded in St George and Williams (2013) since needle-EMG record fewer MUs, representing activity deep in the muscle, than sEMG sensors (Section 3.3 and 3.4). Mean MUAP values for the SG during interval training may be considered partially comparable to sEMG data reported by Roberts *et al.* (2001) for the GM. Roberts and colleagues recorded MUAP ranges of 10.6-76.3mV across four Selle Francais' GM at variable speeds between 3.5-6m/s, at walk and trot on a level to 6% inclined gradients. An increased average MUAP of 160mV

was found in the SG of nine thoroughbreds during cantering at ~5.4m/s in interval training on an inclined gallop (Williams *et al.*, 2013). Increased speed (walk>trot>canter>gallop) and inclined gradients require higher workloads, increasing muscle activity-levels (Hibbs *et al.*, 2011; Peham *et al.*, 2001). The higher amplitudes (Williams *et al.*, 2013) may represent the increased workload associated with variable terrain and the incline of the gallops found in the field compared to laboratory assessment on a treadmill (Hibbs *et al.*, 2011). Alternatively the increased muscle-mass of trained thoroughbreds compared to research horses, could enable a greater volume of SG fibres to be recruited during exercise (Rivero, 2014; Choi and Kim, 2009; Rivero *et al.*, 1995). Or the variability could reflect functional differences between the SG and GM (Hyytiäinen *et al.*, 2014; Rivero and Barrey, 2001; Lopez- Rivero *et al.*, 1989). Future work to compare SG and GM activity at walk, trot and canter is warranted to fully explore their synergistic relationship.

Evaluation of the *Masseter* and *Temporalis* muscles response to dental-treatment reported lower MUAPs than recorded in the locomotory muscles investigated. Chewing represents longer duration, low intensity exercise (Ellis, 2010) compared to cantering and jumping (Rivero, 2009). The mastication muscles would be expected to constitute a higher percentage of type IA and IIB fibres (Section 4.2.1) compared to that of the SG, for example, where increased type IIX to facilitate shorter, high intensity exercise would be found (Yamano *et al.*, 2006). The nature of mastication could recruit deeper compartments of the muscles investigated which sEMG would not report (Drost *et al.*, 2006; Lowery, Stoykov and Kuiken, 2003) (Section 3.9.1). Differences observed are postulated to relate to the differing functions and subsequent fibre profiles of the muscle groups studied.

5.5 Laboratory versus field assessment

A key aim was to test the value of sEMG as a performance analysis tool in the field i.e. equestrian training and competition environments. Laboratory investigations of performance analysis are easily implemented in some sporting disciplines such as cycling (Felici, 2006). For horses, incremental high-speed treadmill exercise tests can be used to assess fatigue and evaluate cardiovascular or respiratory performance (Barrey *et al.*, 1993) offering scope for analysis of muscle performance (Colborne, Birtles and Cacchione, 2001). The laboratory environment generally does not mimic actual training and competition, or facilitate ridden work. Therefore conclusions drawn could be considered only partially valid due to the controlled environment. Furthermore, integration of non-athletic participants in human EMG analysis lack clarity in contrast to studies which utilise elite athletes, where more explicit outcomes related to specific performance are observed (Felici, 2006). For instance, trained athletes demonstrate an increased propensity for MU synchronisation with muscles containing increased fast-twitch fibres than their healthy non-athletic peers (Felici, 2006; Sadaoyama *et al.*, 1988; Semmler and Nordstrom, 1998). Differences between sprint and endurance athletes are reported such as for conduction velocity (Sadoyama *et al.*, 1988). Therefore the selection of elite and discipline-specific athletes in a field environment (St George and Williams, 2013; Williams *et al.*, 2013) was integral to support the investigation of sEMG and to establish if the technique was a valid performance analysis tool for the equine athlete.

Using horses actively engaged in competition presented challenges related to access and the research protocols applied. Access limited the sample sizes particularly in the showjumping study (Section 4.10.2). Competition etiquette prevented 0mm skin clips which may have introduced interference (noise due to dirt or skin: sensor

interface movement) into the EMG signal (De Luca *et al.*, 2010; De Luca and Merlotti, 1988) (Section 4.9.2). Data were successfully collected within horses' normal exercising routines and judicious observation of the real-time EMG signal and application of appropriate filtering protocols (De Luca *et al.*, 2010) removed anomalies prior to data analysis (Sections 4.9.2, 4.10.2 and 4.11.2). Frequency domain analysis of the EMG signal during cantering in the field, post band-pass filtering and rectification, identified a range between 20 and 120Hz (Williams *et al.*, 2013) which is similar to Colborne, Birtles and Cacchione's (2001) range (~15 to 100Hz) on the treadmill. Treadmills produce changes in stride characteristics and the belt contributes towards the energetic cost of locomotion (Weishaupt *et al.*, 2010; Barrey *et al.*, 1993), which could account for variation in the frequency spectrums.

5.6 Individuals versus defined samples

The high degree of inter-subject variability in sEMG profiles suggests that for examination of muscle activity, sEMG would have most value as a comparative analytical tool within individual horses (Sections 4.9.4 and 4.11.3).

The body of research (Williams *et al.*, 2014; St George and Williams, 2013; Williams *et al.*, 2013) suggests that gross muscle function is consistent across horses. All horses recruit their SG to flex their hip and within this movement the temporal characteristics: onset and offset of recruitment and the duration of the associated contraction will be broadly consistent (Huber *et al.*, 2011; Hug *et al.*, 2010, De Luca, 1997) (Section 4.9.4). Therefore performance analysis using EMG to compare muscle recruitment during movement, even when skilled, can be successfully conducted across subjects (Williams *et al.*, 2014; Huber *et al.*, 2011). However the

spatial characteristics: type of MU recruited, synchronisation, MUAP amplitude and frequency are associated with muscle ‘power’ or workload during contractions. Assessing the spatial parameters associated with muscle performance will produce unique physiological footprints for individual horses. An individual’s sEMG profile will also reflect the unique biomechanics associated with movement during their execution of the exercise. Variation in heel strike during running in humans influences muscle performance as could the angle of the hoof-pastern-axis during cantering in horses (Guidetti, Rivellini and Fugure, 1996). Therefore analysis of individuals’ EMG profiles may prove most useful when analysing equine performance (Huber *et al.*, 2011; Hug *et al.*, 2010) (Sections 4.9.4 and 4.11.3).

Variation in muscle sEMG profiles occur between individuals and breeds of horse (Hibbs *et al.*, 2011) (Sections 4.2.2, 4.6, Table 19 and 4.8.4). Inter-breed research has been conducted (Zsoldas *et al.*, 2010a, b; Licka, Frey and Peham, 2004) however breed variation could influence the data obtained. For example, Zsoldos *et al.* (2010a,b) assessed EMG parameters in thoroughbreds, warmbloods and trotters and found different muscle fibre profiles in their superficial muscles affecting the EMG data obtained (Lopez- Rivero and Letelier, 2000). Sample selection is particularly interesting when formulating conclusions from research and relating these to practical implementation in breed-specific training and management strategies; for example in thoroughbred racing. Therefore increased homogenous breed studies may be warranted, such as Williams *et al.* (2013) to increase breed specific knowledge. However, grouping horses related to inclusion criteria (Williams *et al.*, 2014) may be the most appropriate approach for the use of sEMG in clinical or therapeutic studies.

A high level of individual variation occurs throughout equine EMG research (Williams *et al.*, 2014; Williams *et al.*, 2013). Robert *et al.* (2001) and Zoldos *et al.*

(2010a) reported 13.3% and 67% relative variance in *Gluteus medius* and *Rectus abdominus* for activity-levels, respectively, between individuals. Variability is postulated to relate to differences in muscle fibre type, diameter and distribution between horses (Wijnberg *et al.*, 2003). Interestingly similar patterns are observed in human EMG research, average inter-subject variance is ~60% (Guidetti, Rivellini and Fugere, 1996) although ranges vary between 16-75% (Felici, 2006). Additional research in discipline-based samples could provide data on horses grouped at competition levels, representing performance homogeneity in muscle fibre profiles perhaps facilitating more reliable inter-group analysis.

5.7 sEMG: a relevant performance analysis tool?

Despite research advances, training and management of the equine athlete is still predominately based upon anecdotal success of historic practices (Williams, 2013; Ely *et al.*, 2010; McGreevy and McLean, 2007) and not scientific performance analysis (Smith *et al.*, 1999). Our field-based work demonstrated that sEMG can be used to assess equine performance for a defined event (St George and Williams, 2014; Williams *et al.*, 2013) and to compare muscle activity over time (Williams *et al.*, 2014; Williams *et al.*, 2013) in individual horses. However, further refinement in preparation protocols and generally making the system easier to use will increase practical engagement from riders and coaches (Appendix A1.1, Section A1.1.1). Further studies are required to build an evidence-base and enhance the knowledge and understanding of muscle contribution and adaptation to performance to enable the equestrian industry to value the potential application of the tool within day-to-day analysis of training and competition.

The equine athlete is at high risk of musculoskeletal injury during training and competition (Ramzan and Palmer, 2010; Dyson, 2002) (Section 4.7.5). The ability to analyse muscle performance for a defined event or sequence of events, such as jumping a fence (St George and Williams, 2013), chewing cycles (Williams *et al.*, 2014) or a singular component of a training regimen (Williams *et al.*, 2013), may facilitate assessment of an individual at a specific moment in time and contribute to ongoing monitoring of performance. Establishing muscle recruitment and activity patterns for individual horses provides riders and coaches with information that could be used to improve performance or prevent injury (Williams, 2013). Mechanical loading is believed to be a causal factor in the development of musculoskeletal diseases such as osteoarthritis and tendinopathies (Meyer *et al.*, 2012). EMG data could be used to assess DDF muscle fatigue as a precursor to SDFT injury (Butcher *et al.*, 2007) or to assess muscle during training to ensure sufficient conditioning to meet the physiological demands of competition and prevent fatigue occurs (Ferrari *et al.*, 2009).

sEMG has the ability to test anecdotal training practices and regimens (Section 4.9.4 and 4.10.3), and to evaluate how specific muscle groups adapt in response to clinical and therapeutic interventions (Section 4.11.4). For example, the postulation that jumping strides are extensions of ‘normal’ canter strides (St George and Williams, 2013) could lead to an emphasis on developing the canter during training rather than repetitive jumping, although attaining the same result in more than one subject is required to substantiate the results. The ability to compare muscle performance pre- and post-treatment such as during prophylactic dentistry (Williams *et al.*, 2014) demonstrates potential for the efficacy of other muscular related therapeutic modalities such as massage, to be tested. But perhaps the most exciting outcome of

the research presented is the potential for sEMG to be used within training regimens or at competitions to identify if horses are adequately prepared for the test the event presents. Training should advance skill acquisition and develop required fitness levels to optimise performance and prevent fatigue related injuries (Leisson, Uaakma and Seene, 2008) (Section 4.3). sEMG could be used in field environments to quantify individual muscle contribution to locomotion or assess laterality of muscle performance to assess how balanced equine athletes are (St George and Williams, 2013; Williams *et al.*, 2013) (Section 5.2.2). All equestrian disciplines require horses to be fit enough to complete and hopefully excel in competition. Therefore assessment of fitness and fatigue are key aspects of performance analysis for the equine athlete. sEMG analysis can quickly and easily assess fitness and fatigue, whilst continuing development of mobile telemetric units will increase the scope and range for data collection increasing application throughout training and competition.

5.8 Limitations and challenges within sEMG research

The research presented represents preliminary studies assessing the potential of sEMG as a performance analysis tool in the equine athlete. It could be argued that the technology was taken into the field too soon as there was a lack of standardised laboratory EMG studies conducted into jumping or canter exercise (Section 4.6, Table 19). However, field based research more accurately captured the holistic and multifactorial nature of performance (Atkinson and Nevill, 2001) and facilitated access to a sample of athletic horses (Felici, 2006) that would not have been available for laboratory work.

Conclusions drawn are limited by a number of factors. Sample sizes, although comparable to previous equine EMG research (Section 4.6, Table 19), would ideally be expanded to substantiate the conclusions formed (Grimes and Schultz, 2005; Schultz and Grimes, 2002; Atkinson and Nevill, 2001). The lack of significant results across cohorts suggests that EMG is an individualised measure of performance in horses as it is in humans (Huber *et al.*, 2013). To ensure validity between individual results, coefficients of variance were calculated between participants but further exploration of intra-individual repeatability would have been beneficial (Ochia and Cavanagh, 2007). Practically skin preparation protocols and EMG sensor placement although standardised could also have introduced variability into the data obtained (De Luca, 1997).

An inherent limitation of sEMG is its ability to only record superficial muscular activity (Lopez-Rivero and Letelier, 2000). Data will therefore exert bias towards the superficial portion of muscles being investigated (Sections 3.3 and 4.2.2). Muscle composition can vary with breed, between individuals and according to fitness (Rivero, 2014; Lopez-Rivero and Letelier, 2000). Concurrent evaluation of muscle architecture via biopsy could relate fibre type to EMG data although the technique would be prohibitive to elite equine athlete participation. Superficial muscle supports short duration, rapid propulsive force production (Lopez-Rivero and Letelier, 2000) therefore sEMG is not suitable for assessing the low intensity aerobic or postural activity of the deeper portion of muscles which must be considered during performance analysis (Section 3.9.1). The results represent MU activity under the sensor and not the entirety of the large equine muscles investigated, therefore it may be that differences in activity could be observed in future work utilising different sites upon the same muscles.

The work presented (Williams *et al.*, 2014, St George and Williams, 2013; Williams *et al.*, 2013) was exploratory to determine the best research design, data collection methods and selection of subjects when using sEMG as a tool to assess muscle physiology in the horse (Porter and Carter, 2000). Exploratory research is a valid approach to demonstrate the value of a new technology and can successfully refine project design or guide future research directions (Darke, Shanks and Broadbent, 1998). For instance, identifying that sEMG has more value as a tool to assess individual performance. However, initial selection of discipline and breed specific subjects combined with the small number of participants could potentially guide interpretation and direct future research in a misguided direction (Buchner and Schildboeck, 2006; Atkinson and Nevill, 2001).

Standardisation between subjects in equine research samples is difficult to achieve. Horses are individuals and selecting for age, breed, discipline and other relevant factors may appear to represent a distinct sample but could be misleading. Researchers need to establish transparent and justifiable rationales when selecting study groups (Atkinson and Nevill, 2001). Participant selection should be based on inclusion criteria which consider suitability, accessibility, reliability, validity and ethics (Sections 4.10.2 and 4.11.2). Consider the sEMG racing sample (Williams *et al.*, 2013) where all participants were subjected to the same management routine, trainer, had a similar goal and were the same breed. Wide variability was established in the sEMG traces attributed to the individual muscle composition and unknown clinical history of the horse at that moment in time (Section 4.9.4).

Synchronisation of sEMG data collection with kinematic analysis would increase specificity between muscle recruitment and locomotion (Hug, 2011). For example, the use of the inbuilt accelerometers in Williams *et al.* (2014) enabled digital

synchronisation and eliminated the error found when assessing jumping using manual synchronisation (St George and Williams, 2013). Future work should aim to incorporate simultaneous digital synchronisation of EMG and kinematic analysis to promote accuracy and improve the reliability of sEMG (Hug *et al.*, 2010).

It should be a prerequisite of performance studies that subjects are fit enough for the exercises undertaken and free from lameness to protect *Equid* welfare. In reality competition horses often present with low-grade lameness; for example ‘normal’ Thoroughbreds in race training will average 1/10th lameness on the UK grading system (Appendix 6) (Weller *et al.*, 2006). Acceptable levels of ‘performance or functional soundness’ require validation from industry to facilitate comparison within research but also to clarify that *Equid* welfare has not been compromised. In Williams *et al.* (2013), horses’ health and fitness were validated by the trainer, with no animals undertaking any exercise that they would not have normally completed. An alternative is to use resident equine groups in research environments, unfortunately these often comprise older, leisure horses which may not represent the equine athlete participating in competition. Selecting competition horses managed by professional riders (St George and Williams, 2013; Williams *et al.*, 2013) for research facilitates application to a comparative competitive sample.

A limitation of working with contemporary equine athletes is access (Sections 2.5.4 and 4.10.2). By the nature of equestrian sport, riders often have multiple horses in training and competition. Routines are dictated by the demands of the horse and the discipline, and often riders have limited motivation to participate in research as it is perceived to be time-consuming, involves wieldy equipment and the results do not relate to their own practice (Williams, 2013; Williams and Kendall, 2007). Researchers need to establish if access and the experimental protocols can be

affiliated to promote successful completion of projects within defined timescales. In St George and Williams (2013) access was required to the coach, rider, horse and arena. Non-athletic horses were not deemed suitable due to the performance level required but access restrictions, suitable horses and timeframes resulted in a single subject. Access to athletic horses will be a challenge to wider implementation of field-based sEMG in the horse and will be dependent on the ease of integration of technology and research protocols into normal management, training and competition regimens (van Weeren & Crevier-Denoix 2006). The selection of horses competed by amateur riders at national level, may prove a viable strategy for future researchers. Horses would satisfy athletic inclusion criteria but reduced economic and time pressures exist compared to elite riders to preclude participation in research.

Affiliated equine athletes constitute a significant financial investment for riders and owners. Practical competence of the research team is therefore essential. Research design needs to consider working practices and competition protocols, which may negate ideal preparation; for example preventing a 0mm skin clip (St George and Williams, 2013; Williams *et al.*, 2013). Undertaking a pragmatic approach to research should not reduce a project's validity (Atkinson and Nevill, 2001). Research designs may require adaptation to meet competition etiquette or the desires of owners/riders without compromising the quality of the research. Ethically, the impact of the research project on participants' welfare and the current and future competition potential of subjects should be considered (Campbell, 2013). Engaging industry partners and combining expertise to refine the research design could prevent issues before they occur (Williams, 2013).

The nature of equestrian sport may pose potential problems for sEMG researchers. Equine athletes regularly change ownership, trainer, and rider or get injured, which could result in the removal of animals from the study. Ideally the numbers involved in projects will embed scope to counteract the impact of participant withdrawal. Research undertaken in controlled environments has the potential to evaluate facets of performance; however it is a challenge for researchers to replicate the extrinsic variables which contribute to performance in either the training or competition environment. Laboratory research can eliminate variability in results; for example sEMG treadmill studies such as Crook, Wilson and Hodson-Tole (2010) control environmental temperature which has been demonstrated to influence muscle activity (Smoliga *et al.*, 2010) but do not reflect competition. Research conducted in the field using ‘real-life’ samples and environments mimics the level peers are competing at. For example, comparison of NH thoroughbreds on an all-weather gallop (Williams *et al.*, 2013) enables knowledge transfer relevant to racehorses but limits application to a more generalised population.

5.9 The future of sEMG research

The preliminary sEMG studies presented provide a foundation for further research. Research can be divided into three key areas (Table 24). Training and competition offer a plethora of opportunities for the sEMG researcher. Expansion of research to consider recruitment and activity patterns in a wider range of muscles and how these interact during locomotion would add to the established biomechanics knowledge base (Ferrari *et al.*, 2009). sEMG has value within diagnosis and clinical evaluation of muscle pathologies and to test the efficacy of treatment and rehabilitation

regimens (Buchner and Schildboeck, 2006). There is also potential to explore the use of sEMG as an adjunct in behavioural work (Appendix 9) to determine non-observational responses to novel objects or environmental stressors. Projects are planned to extend the work presented: repeating the jumping study with a larger sample and evaluation of fatigue from the start of exercise to its conclusion in racehorses.

5.10 Applied equine performance research

Evaluation of performance presents its own challenges. Performance is multifactorial and improvements which contribute to success can be minimal (<1%) and therefore may not always be explicit or reflected as significant within statistical analysis (Atkinson and Nevill, 2001). Performance analysis in equestrian partnerships is complicated further by the inclusion of two sentient partners: the horse and the rider (Visser *et al.*, 2008). Both partners can influence success but only the human is considered to possess the intrinsic motivation to advance and achieve sporting success. The applied equine researcher seeks to identify factors which contribute to performance through a holistic perspective which is more contextualised than traditional experimental research, for example across a training regimen or a specific dressage test. However it is important that academic and industry rigour are retained within study design to optimise the reliability and validity of results obtained (Williams, 2013; Atkinson and Nevill, 2001) to facilitate dissemination and ultimately encourage industry to engage with research.

Table 24: Key target areas for recommended future sEMG research areas

The results obtained by Williams et al. (2013), St George and Williams (2013) and Williams et al. (2014) were reviewed and used as a foundation to propose future directions for how surface electromyography (sEMG) could be used in the horse. Potential research was considered linked to developing the technology, exploring how muscle responds to training and potential clinical applications for sEMG.

Research area	Projects required
1. Advancing the reliability of the technology for use in the horse	<ul style="list-style-type: none"> • erroneous placement of sensors may introduce cross talk and prevent comparison between projects; therefore it would be valuable to create an equine musculoskeletal map creating a reference database for sensor placement in the horse, • equine muscles are notably larger than their human counterparts, future work may wish to utilise multiple sensors sited across the muscle body to assess functional compartmentalisation and the impact of phase lag across the muscle, • evaluating intra-subject reliability of 0mm >5mm skin preparation on data collection efficacy, • determination of the optimum number of sensors to evaluate performance in relation to muscle mass, • establishing valid normalisation protocols for use in the horse, • investigating inter and intra-subject repeatability of sEMG data values, between sessions for amplitude and frequency including determination of standard error and co-efficient of variance, • determination of filtering protocols which maximise sEMG data collection in the horse, • multiple breed studies incorporating larger samples and selected competition related sub-samples to determine if breed patterns exist and if basal data can be related to breeds, or if sEMG is an individualised measurement,
2. Establishing how equine muscle responds to training	<ul style="list-style-type: none"> • determination of which muscles actively contribute to movement and recruitment patterns during locomotion, different gaits, jumping and performance movements such as piaffe, • evaluation of how muscle performance changes in accordance to topographical location and

<p>and the physiological demands associated with performance</p>	<p>compartmentalisation within specific muscles,</p> <ul style="list-style-type: none"> • quantification of muscular fitness and fatigue, facilitating assessment of these variables in relation to training regimens, for example interval training or rollkur, • longitudinal projects assessing fitness and fatigue, using experienced and horses' naïve to across disciplines to provide a valuable insight into how muscle responds to exercise, • measuring muscle adaptation to exercise and post injury, • contribution of muscle fatigue to injury, for example SDFT pathologies, • assessment of the impact of extrinsic variable on muscle performance, for example variable terrain or going categories, • evaluating the role of the warm-up (on muscle) prior to exercise and in equestrian competition would be valuable as no defined protocols exist and variation is observed between and within equestrian disciplines • evaluation of a balanced athlete via determination of lateralisation in muscle recruitment, which could also investigate contribution of laterality to injury and performance, • telemetric units are now available that can be attached to the rider and the horse allowing continuous remote recording enabling data collection for the entirety of an event such as the interval training protocol reviewed • combining gait analysis and sEMG technology to facilitate synchronised data collection to inform evaluation of muscle activity in relation to kinematic variables.
<p>3. Clinical applications of sEMG</p>	<ul style="list-style-type: none"> • Assessment of muscle performance and adaptation during equine rehabilitation regimens, • Evaluation of therapeutic modalities related to muscle, • Integration into lameness evaluation, • Measurement of muscle fasculations associated with neurological disorders, and, • Longitudinal evaluation of muscle workload in athletic horses to assess changes related to acquired injury.

5.10.1 The future of applied equine research

The core objective of equine performance research is to apply research findings to optimise performance and by association improve *Equidae* health and welfare. Yet there remains a lack of application of science within training and management of the equine athlete (Williams, 2013). Research can be theory-driven, contributing to the established knowledge and understanding, or action-centred, applied to derive solutions to practice based problems (von Elm *et al.*, 2007). Human sports scientists feel coaches do not know the correct questions to ask, whilst the coaches consider that the scientists keep answering questions no-one is asking (Williams and Kendall, 2007). A similar scenario exists within the equine sector with riders and coaches questioning the practical applications of scientific research (Williams, 2013).

Equine performance has a solid foundation to draw upon through equine science and veterinary research (Walmsley, 2013; Williams, 2013). However the future needs to build upon the strengths from clinical work and complement these with increased applied research (van Weeren and Back, 2014; Williams, 2013) to answer the practical questions posed by riders and coaches. Emerging technology, such as telemetric sEMG, offer potential bridges between industry and science as results may be interpreted in context by both parties (Section 4.10.3). Increasing applied projects within controlled environments and in the field, in conjunction with industry partners and using horses actively engaged in training and competition will satisfy the requirement of scientists but also increase application to industry. However, the ultimate goal to ‘sell’ the benefits of equine performance research would be the production of an elite equine athlete that attains and sustains competitive success at the highest level achieved via a regimen informed by research.

5.11 Spreading the message

Equine performance researchers aim to inspire industry to engage with science and use the knowledge being generated by applied research to inform training and management regimens for the benefit of the horse. It is essential for progression that research is strengthened by the inclusion of acknowledged equestrian practices utilising competitive horse and rider combinations so industry will embrace rather than dismiss conclusions formed (Williams, 2013). Subsequent dissemination across industry is critical to facilitate practical implementation. Restricted access to peer reviewed forums could limit distribution; therefore ultimately the dissemination of research via practical demonstrations (Appendix 9) and integration of research within lay articles may prove most influential to horses and their owners (Appendix 7).

5.12 Final thoughts

Engagement with performance analysis is commonplace across competitive human sport but uptake is still lacking in equestrianism, potentially due to limited applied research and industry engagement (Williams, 2013). The anecdotal training practices and regimens utilised across the equestrian disciplines continue to produce results and therefore many successful trainers, coaches and riders will not be seeking solutions to problems they do not perceive to exist. Performance analysis provides scope to identify marginal gains which could optimise performance and could also reduce the high wastage and injury levels still reported across the equestrian disciplines (Walker *et al.*, 2014). The practical application of the sEMG work

presented, may offer a potential bridge between science and the equine industry to promote collaboration and ultimately benefit the horse.

CHAPTER SIX

CONCLUSIONS

The research conducted demonstrates that sEMG can be used to assess the physiological responses of muscle within training environments for the equine athlete. Analysis of the data obtained could potentially be used within equine performance analysis to assess how muscles respond and adapt to ‘real-life’ training regimens and competition. However, interpretation should include consideration of related performance factors such as the horse’s health status, fitness levels and muscle profile.

Evaluation of training in racehorses demonstrated that interval canter work did not fatigue horses but exposed a high degree of laterality and individuality in muscle activity suggesting bespoke training regimes would be beneficial to enhance success. Preliminary sEMG appraisal postulates that jumping strides are an extended canter stride therefore jump-training should emphasis the development of a ‘jumping’ canter, although wider evaluation in more horses is required for validation. The benefits of increased understanding of how muscles adapt post dental-treatment has the potential to inform performance through appropriate planning of when prophylactic dentistry occurs in relation to competition. Equine sEMG data are highly individualised therefore the minimally invasive sEMG technique exhibits most potential as a tool to assess and compare muscle performance in the individual equine athlete.

Equine performance is a complex concept. Research should investigate the individual characteristics that contribute to success or the desired outcome, but should also evaluate performance as a holistic entity. Performance research should

optimise potential competition success whilst concurrently promoting the health, welfare and career longevity for the equine athlete. Further applied research is required to increase the understanding of the inter-relationships that exist between psychological, physiological, biomechanical and nutritional variables within the horse, and the impact of the rider, management, training and competition environments upon them. Increased sEMG research is required to fully validate protocols used in the horse. Additional projects to confirm the contribution of muscle to set exercises and evaluating how muscle adapts to training over time have the potential to develop evidence-based equine training regimens. sEMG represents a valuable tool which can increase the knowledge and understanding of the role of muscles during exercise, thus contributing to an evidence-base which could ultimately promote performance and career longevity in the equine athlete.

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APPENDICES

APPENDIX 1: Evidence sources included in the thesis

Evidence source	Title	Page number
1	Williams, J.M. (2013) Performance analysis in equestrian sport. <i>Comparative Exercise Physiology</i> . 9(2), pp. 67-77.	187
2	Williams, J.M., Gundry, P., Richards, J. and Protheroe, L. (2013) A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse. <i>The Veterinary Nurse</i> . 4(9), pp. 566-572. <i>Erratum:</i> Williams, J.M., Gundry, P., Richards, J. and Protheroe, L. (2013) A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse. <i>The Veterinary Nurse</i> . 5(6), pp. 319.	192
3	St George, L. and Williams, J.M. (2013) Electromyographic evaluation of approach stride, jump stride and intermediate stride in selected superficial muscles of the jumping horse: A preliminary study. <i>Comparative Exercise Physiology</i> . 9(1), pp. 23-32.	194

- 4 Williams, J.M., Johnson, C.J., Bales, R., Lloyd, G., Barron, L. 195
and Quest, D. (2014) Analysis of *Temporalis* and *Masseter*
adaptation after routine dental-treatment in the horse via
surface electromyography *Comparative Exercise Physiology*.
(*in press*)

APPENDIX 1.1: EVIDENCE SOURCE 1

Williams, J.M. (2013) Performance analysis in equestrian sport. *Comparative Exercise Physiology*. 9(2), pp. 67-77.

APPENDIX 1.1A REFLECTION ON EVIDENCE SOURCE 1

Williams, J.M. (2013) Performance analysis in equestrian sport. Comparative Exercise Physiology, 9(2), pp. 67-77.

A1.1.1 Rationale

The concept for the review was developed through personal experiences in competitive equine sport and within education. It has been well documented that equine training practices are often based on tradition (Ely *et al.*, 2010), despite the substantial economic profile of the equine industry (Thiruvankadan, Kandasamy and Panneerselvam, 2009). Through debate and observation of horse and rider combinations, literature review and whilst attending ISES conferences, it became apparent that parity existed between the core focus of riders and researchers: to improve equine performance. Despite this parity, an anonymous factor appeared to prevent the establishment of potential synergistic relationships to be established. The majority of riders aim for long and successful competitive relationships with their horse and were often emulating anecdotal fads to try and achieve success. Whilst the researchers were conducting studies to promote the health and welfare of the horse; however riders could not directly relate to these, through lack of contextualisation to specific disciplines.

In human sport, performance analysis has acted as a bridge between the scientific and sporting communities and has helped to overcome the traditional bias observed in equestrian training (McGarry, 2009). An extensive broad and discipline specific sports performance research database exists and informs training across human

sports. For example, the implementation of a research informed development programme within British Cycling has resulted in domination of road and track cycling in recent years (G.B. Cycling, 2012).

The review aimed to establish that pragmatic analysis of equine performance, undertaken with collaboration between the equine industry and the academic community, could facilitate research that relates theory to practical application. Equally the review was also undertaken to underpin the value of future field-based sEMG research using actively competing horses in their normal training environments. Projects which mimic or are conducted in actual competition or during training could thus prove beneficial for all parties including the equine athlete (Felici, 2006). To demonstrate the requirement for contextualisation, showjumping was chosen as an example discipline as although it has the largest participation rate within the FEI equestrian disciplines (FEI, 2012), a systematic, key word search of ScienceDirect and Wiley databases established it was the least researched field with reference to analysis of equine performance.

A1.1.2 Research methodologies and limitations

Theoretically producing the review was a straight forward process, however in practice it proved particularly challenging. A systematic review of relevant research databases was conducted initially using combining the terms ‘equestrian’, ‘equine’, ‘performance’, ‘analysis’ and the names of core equestrian disciplines: ‘showjumping’, ‘dressage’ and ‘eventing / horse trials’ was employed. Database results supported the opinion that there was limited research contextualised to the specific disciplines and identified that although much of the work available could

have practical application to industry, contextualisation may be necessary to promote industry access to the information and for it to relate to individual practice. It was difficult not to focus the review on opinion and the decision to concentrate on one equestrian discipline, showjumping, facilitated the scope to demonstrate how research could be used as an evidence-base for athlete selection, training and performance evaluation through the value of applied projects such as sEMG evaluation of training practices. Application to a specific sport also identified limitations within research which could be attributed to study design perhaps linked to a lack of industry collaboration.

A1.1.3 Contribution to the field of equine performance

The review was designed to highlight how the concept of performance analysis could be used more widely in equestrian sport to both scientific and industry audiences, thereby promoting a more collegiate approach in future work. The results document that research relevant to performance analysis is available but is often undertaken under the umbrella of clinical assessment to promote health and welfare perhaps limiting dissemination to industry. Future research needs to also consider application to the performance field and small modifications in project design, such as selection of participants that mimic competition horses, could enhance its worth (Felici, 2006). Increased collaboration between industry and researchers is warranted at all stages of the research process. One barrier identified to research was the lack of funding streams which the equine performance researcher can access. The piece identifies the diverse range of parameters which may be analysed in relation to performance and supports the wider integration of performance analysis throughout equestrianism.

A1.1.4 Implications and questions generated

Undertaking the review reaffirmed the belief that there is potential for equine scientists to work more closely with industry to promote ‘gold standard’ research which could directly and positively influence the training and management of the equine athlete. An ideology which has been applied across all of the sEMG work presented in the thesis (Williams *et al.*, 2014; St George and Williams, 2013; Williams *et al.*, 2013). However, it became apparent that many barriers potentially exist to prevent research, including funding and access to suitable samples. Due to journal restrictions, there was no scope to fully explore goal setting, periodization and the implementation of the training process which could complement the application of science to the competition rider. Future work could investigate planning and progressive cycling within training regimens beyond the physiological to evaluate their impact on performance.

APPENDIX 1.2: EVIDENCE SOURCE 2

Williams, J.M., Gundry, P., Richards, J. and Protheroe, L. (2013) A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse. *The Veterinary Nurse*. 4(9), pp. 566-572.

APPENDIX 1.2A: Erratum: Williams, J.M., Gundry, P., Richards, J. and Protheroe, L. (2013) A preliminary evaluation of surface electromyography as a tool to measure muscle fatigue in the National Hunt racehorse. *The Veterinary Nurse*. 5(6), pp. 319.

APPENDIX 1.3: EVIDENCE SOURCE 3

St George, L. and Williams, J.M. (2013) Electromyographic evaluation of approach stride, jump stride and intermediate stride in selected superficial Muscles of the jumping horse: A preliminary study. *Comparative Exercise Physiology*. 9(1), pp. 23-32.

APPENDIX 1.4: EVIDENCE SOURCE 4

*Williams, J.M., Johnson, C., Bales, R., Lloyd, G., Barron, L. and Quest, D. (2014)
Analysis of Temporalis and Masseter adaptation after routine dental-treatment in
the horse via surface electromyography. Comparative Exercise Physiology (in press)*

APPENDIX 2: Definition of authorship

Table A2 identifies the methodologies employed and my contribution within each of the evidence sources presented for review in the thesis.

Table A2: Overview of methodologies and author contribution within the evidence sources

Evidence source	Collaborative project	Lead Researcher	Research team	Research method	Data collection		Analysis		Interpretation of results		Dissemination			
					Pilot	Main dataset	Lead	Team	Lead	Team	Journal	Presented oral	Poster	Lay article
1	N	Y	Y	REV			Y		Y		Y			
2	Y	Y	Y	OBS	Y	Y	Y		Y		Y	Y/C		Y
3	Y	Y	Y	OBS	Y	Y	Y		Y	Y	Y	Y/C	Y	
4	Y	N	Y	OBS	Y	Y	Y	Y	Y	Y	Y			
ISES EMG Demo	N	Y	Y	PRAC		Y	Y		Y		Y	Y; PRAC		

N; no; Y: yes, confirming personal contribution; REV: Review; OBS: observational analysis; PRAC: practical workshop; C presented at conference

APPENDIX 3: Collaborative Relationships

Throughout the course of my research practice I have worked with a number of colleagues from other institutions and industry partners. Details of my key collaborative relationships are outlined below and their roles in the evidence presented in the thesis are provided in Table A3.

Dr David Marlin, David Marlin Consulting Ltd., Science Supplements

It was serendipitous that at the start of my research journey Dr Marlin was the Associate Dean of Research at Hartpury. I was fortunate that my research interests aligned with projects that he was commencing and my decision to participate in them exposed me to individuals with whom I have subsequently established productive collaborative relationships and have developed my research skills. We have worked together to design a number of projects predicting success and risk factors in equine sport.

Dr Tim Parkin, Senior Research Fellow Large Animal Clinical Sciences and Public Health, University of Glasgow

I was introduced to Dr Parkin via the projects undertaken in collaboration with Dr Marlin. The support of colleagues as mentors has exposed me to statistical analysis techniques that previously I would not have had the confidence or expertise to utilise. Dr Parkin has particularly enabled me to progress to take more of a lead role in statistical analysis and we are now working in partnership to analyse data within other research groups. Having a mentor available to discuss the most appropriate statistical direction and to provide reassurance that my approach was suitable was invaluable. I now routinely use analysis software to inform sample size in

conjunction with hypothesis led inclusion criteria to define start and end periods for data collection.

Professor Jim Richards, Professor of Biomechanics, University of Central Lancashire

During initial investigation of potential EMG systems, Delsys® suggested I contact Professor Richards to review their system in situ. Having access to Professor Richards as a guide during practical familiarisation with the Trigno™ system and EMG Works™ enabled me to progress more rapidly than anticipated; his experience with the system and knowledge of the human field has proved invaluable to help me resolve problems encountered and with interpretation of data obtained.

Dr Hayley Randle, HE Manager, Duchy College

Dr Randle has provided a critical voice to guide my work, a sounding board for ideas and her statistical expertise has been useful when I have needed support in this domain.

Dr Kathryn Nankervis, Equine Therapy Centre Manager, Hartpury College

Dr Nankervis was my research mentor when I was employed at Hartpury. Her approach has helped me to refine projects and clarify the research question, aims and objectives within them.

Fernando DaMata, Senior Lecturer Statistics, Hartpury College

Fernando has provided statistical advice and support within the epidemiological studies undertaken at Hartpury College.

Claire Johnson, Senior Lecturer Equine Dental Science, Hartpury College

Claire is a qualified B.A.E.D.T. Equine Dental Technician and colleague from Hartpury. We have worked together on a number of dentistry projects centred on her research to identify the effects and impact of prophylactic dentistry on the horse. Claire's practical experience and enthusiasm provided expertise and support for myself, and the students involved in data collection, for the EMG dental project.

Delsys® Limited

Delsys® are the manufacturers of the EMG data unit and system used for the the work presented. Since my initial enquires regarding the Delsys® sEMG system, the company has supported my work in horses and we have developed a beneficial working relationship.

Polly Gundry, National Hunt Trainer, Devon

Ms Gundry is a progressive trainer, with whom I have forged a beneficial working relationship which has facilitated access to N.H. racehorse samples within my research.

Table A3: Overview of collaboration within the research presented in the thesis

Evidence source	Collaborative partners	Role in Project			Manuscript preparation	
		Design / planning	Data collection	Data analysis	Production	Editing
1	Jane Williams	100%	100%	100%	100%	100%
2	Jane Williams	60%	100%	60%	80%	50%
	P. Gundry	10%	0%	0%	5%	0%
	J. Richards	20%	0%	25%	10%	30%
	L. Protheroe	10%	0%	15%	5%	20%
3	L. St George	30%	50%	40%	50%	50%
	Jane Williams	70%	50%	60%	50%	50%
4	Jane Williams	60%	50%	50%	50%	50%
	C. Johnson	40%	50%	50%	50%	50%

APPENDIX 4: Attainment of Doctoral learning criteria

Table A4 outlines where to find evidence of achievement of the required Doctoral learning criteria and should be considered in conjunction with the published evidence sources presented in Appendices 1.1 to 14.

Table A4: Evidence presented mapped to the Doctoral learning criteria

Criteria:	Evidence	Page number
<i>(i) has conducted enquiry leading to the creation and interpretation of new knowledge through original research or other advanced scholarship, shown by satisfying scholarly review by accomplished and recognised scholars in the field;</i>	4.9 Evidence source 2	97
	4.10 Evidence source 3	107
	4.11 Evidence source 4	114
	5 Discussion	121
	6 Conclusions	147
	Appendix 1.1: Evidence source 1	187
	Appendix 1.1A: Reflection on evidence source 1	188
	Appendix 1.2: Evidence source 2	192
<i>(ii) can demonstrate a critical</i>	1 The research journey: an introduction	1

<i>understanding of the current state of knowledge in that field of theory and/or practice;</i>	2 Equine performance	9
	3 An introduction to surface electromyography	21
	4 Surface electromyography and the equine athlete	47
<i>(iii) shows the ability to conceptualise, design and implement a project for the generation of new knowledge at the forefront of the discipline or field of practice including the capacity to adjust the project design in the light of emergent issues and understandings;</i>	4.9 Evidence source 2	97
	4.10 Evidence source 3	107
	4.11 Evidence source 4	114
	5 Discussion	121
	Appendix 1.1: Evidence source 1	187
	Appendix 1.1.1: Reflection on evidence source 1	188
	Appendix 1.2: Evidence source 2	192
	Appendix 1.3: Evidence source 3	194
Appendix 1.4: Evidence source 4	195	
<i>(iv) can demonstrate a critical understanding of the methodology of enquiry;</i>	4.9 Evidence source 2	97
	4.10 Evidence source 3	107
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<i>(v) has developed independent judgement of issues and ideas in the field of research and/or practice and is able to communicate and justify that judgement to appropriate audiences;</i>	2 Equine performance	9
	4 Surface electromyography and the equine athlete	47
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<i>(vi) can critically reflect on his/her work and evaluate its strengths and weaknesses including understanding validation procedures.</i>	4.9 Evidence source 2	97
	4.10 Evidence source 3	107
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APPENDIX 5: Training and Continuing Professional Development (CPD)

The training requirement for the Doctoral award was met via accreditation of prior learning from previous study as outlined below:

UIN X43-10-M Research Methods and Experimental Design (10C) achieved:
3/7/2009

UIE X33-20-M Applied Equine Exercise Physiology (20C) achieved:
3/7/2009

UIE X35-20-M Therapy and Rehabilitation of the Equine Athlete (20C)
achieved: 3/7/2009

UIE X36-20-M Welfare of the Horse (20C) achieved: 3/7/2009

Additionally, during the period encompassed by the thesis I have also actively participated in CPD to develop my research skills (Table A5).

Table A5: Continuing Professional Undertaken 2011 to 2014

Name of event	Date
British Equine Veterinary Association Conference	2011
International Society of Equitation Science Conference	2011 / 2012 / 2014
International Conference of Equine Exercise Physiology: Interim meeting	2012
ICEEP 9	2014
Alltech Hartpury Equine Performance Conference	2011 / 2012 / 2013
The part-time researcher, University of the West of England	2011
Managing long documents in Excel, University of the West of England	2012
Multivariate statistics 1, University of the West of England	2012
Advancing Equine Scientific Excellence: Meetings including: - Research Design - Review of inferential statistics - Guide to publication	2012-2013

APPENDIX 6: Glossary of terms and list of abbreviations

Terms	Definition
Action potential	Electrical charge which generates contraction in individual sarcomeres
Affiliated competitor	Horse and rider combination participating in competition accredited by Awarding Bodies which fall under FEI governance and for which an annual membership or affiliated subscription is paid
Band-pass	a device that passes frequencies within a certain range and rejects (attenuates) frequencies outside that range
Brought down	Horse which has fallen as a result of direct interference from another horse participating in the same event
Cross talk	Erroneous electrical signals which may be related to activation of multiple muscles, movement or interference from electrical equipment
Cut off frequency	Frequency (Hertz) at which data are eliminated from analysis during filtering
Epidemiology	Branch of medicine that investigates incidence, distribution and control of diseases; can be applied to analyse risk factors related to injury, disease or performance.
Equine athlete	Horse actively participating in or retired from equine competition
Equine industry	Overarching term referring to all businesses, organisations, riders: professional, amateur and recreational, coaches, trainers, associated industries such as farriery and veterinary medicine associated with the management of all horses and ponies in the UK
Filter	System/s to refine the frequency range within collect electromyography data; variable types exist
Frequency	Number of sine waves per unit time in the EMG signal
Frequency domain	Analysis of sEMG signals with respect to their

	frequency components, rather than time
Frequency spectrum (spectral frequency)	Range of frequencies relating to motor unit activation within the EMG signal
Going	Condition of the ground; usually related to moisture content
Grassroots	Horse and rider combinations engaged in leisure riding and / or unaffiliated competition
Hyperflexion	Hyperflexion of the neck is a technique of working/training to provide a degree of longitudinal flexion of the mid-region of the neck that cannot be self-maintained by the horse for a prolonged time without welfare implications
Impedance	The effective resistance within an electrical circuit or generated due to interference such as electrical noise
Kinesiological EMG	Study of dynamic movement using EMG
Lateral excursion	Sideways movement of the mandible during chewing
Leisure horse	Horse used for hacking and / or unaffiliated competition
Mean MUAP	Measure of the average MUAP amplitude during contraction: broadly representative of muscle workload
Mean (MUAP) frequency	Measure of the average MUAP frequency; alternative measure of muscle workload considered less reliable than MUAP amplitude
Motor unit action potential (MUAP)	The sum electrical charge which generates contraction of a motor unit (sum of all active fibres)
Muscle twitch	Muscle contraction within a small and defined area
Noise	Interference in data; can be related to skin preparation, electrical activity or movement in skin: sensor interface
Order (filter)	A number describing the highest exponent in the numerator or denominator of the z-domain (transfer function time phasing) of a digital filter
Pass-band	a frequency band within which signals are transmitted by a filter without attenuation

Peak amplitude	Maximum contraction or maxima of the sine waves within a defined period of EMG activity
Peak to peak	Measure of minima and maxima EMG amplitude for a defined period of activity
Pessoa	A commercial training aid used in horses to develop muscle topline by encouraging the horse to work on the bit using the hindquarters. The Pessoa engages the horse's back muscles by connecting the tail to the head via a series of pulleys and elasticated reins to develop epaxial muscle condition or 'topline'.
Pulled up	Horse which has been selectively removed from competition by the rider during the competition
Power stroke	Movement from the laterally deviated position of the mandible back to the midline which allows attrition i.e. when the teeth grind food
Sound (horse)	Horse which is free from lameness; commonly measured on a scale of 10 or 5 e.g. 1/10 th or 1/5 th lame
Surface electromyography	A system to measure motor unit action potential in surface musculature
Sports performance analysis	Analysis of data or information to help in the acceleration of athlete performance.
Stopband	a band of frequencies which are attenuated by a filter
Telemetry; telemetric	Automatic transmission and measurement of data from remote sources by wire or radio or other means
Topline	Equestrian industry slang term for development of the epaxial spinal muscles: specifically the <i>Longissimus dorsi</i>
Transition zone	Area of change from one type of filter to another, or from one type of muscle contraction to another
Unaffiliated competitor	Horse and rider combination participating in competition which is normally not accredited by an FEI governed Awarding Bodies and for which an affiliated subscription is not paid

UK Lameness grading system Observational method of equine lameness assessment; graded on a likert scale 0 (no lameness) to 10 (will not place foot to the floor) and expressed as a fraction x/10

Abbreviation	Definition
AESE	Advancing Equine Scientific Excellence
AP	Action potential
ATP	Adenosine tri phosphate
BEF	British Equine Federation
BETA	British Equestrian Trade Association
BF	<i>Biceps femoris</i>
BHA	British Horseracing Authority
BHIC	British Horse Industry Confederation
BHS	British Horse Society
EDT	Equine dental technician
EN	Endurance training
EMG	Electromyography
f_c	Cut-off frequency
FEI	Federation Equéstre Internationale
GM	<i>Gluteus medius</i> muscle
HI	High intensity training
Hz	Hertz: SI unit of frequency
ICEEP	International Conference for Equine Exercise Physiology
ISES	International Society of Equitation Science
LD	<i>Longissimus dorsi</i>
m	Metres: SI unit of distance
mm	Millimetres: SI unit of distance
mpm	Miles per metre; unit of speed in equestrian jumping competitions
MEP	Motor end plate
MU	Motor unit

MUAP	Motor unit action potential
mV	Millivolts: SI unit of electricity
MVC	Maximum voluntary contraction
PC	Pony Club
RC	Riding Clubs
sEMG	Surface electromyography
SC	Strength and conditioning training
SENIAM	Surface electromyography for the non-invasive assessment of muscles
SG	<i>Superficial gluteal</i> muscle
TB	<i>Triceps brachii</i>
TBA	Thoroughbred Breeders Association
μv	Microvolts: SI unit of electricity
V	Volts: SI unit of electricity
VL	<i>Vastus lateralis</i> muscle
Ω	Omega; SI unit of electrical resistance
°	Degrees of arc or temperature

APPENDIX 7: *Curriculum Vitae*

Qualifications:

1987 O-levels: English Language (A), Mathematics (B), English Literature (B),
Biology (A), Chemistry (A), Physics (A), French (A), History (A)

1999 Royal College of Veterinary Surgeons (RCVS) Veterinary Nursing Certificate

2000 TDLB D32 / 33 Assessor Award

2002 TDLB D34 Internal Verifier Award

2004 Certificate of Education Pass A*

2005 Post graduate Certificate in Learning and Teaching in Higher Education –
General Teaching Assistants Course Pass A*

2009 MSc Equine Science Distinction

Employment History:

Field Leader Higher Education Equine Science; Hartpury College

Main duties:

- Management of the field of HE equine science
- Senior lecturer predominantly level 3 (level 6 UG) and M level; UG and PG
dissertation supervisor
- UG dissertation module leader
- Programme Manager MSc / MRes Equine Science

- Member / Chair of various management, teaching and learning, quality and research focused committees (UWE, Hartpury and cross faculties) including regular attendance at FE equine team meetings and Chair / Lead of Equine Research Centre for Performance in Equestrian Sports
- Member of HE lesson observation team
- Member of HE strategic management team

Section Head Environment and Land based Studies; South Devon College

Main duties:

- Management of section including animal, equine, horticulture and environment FE and HE curriculum and work based learning qualifications
- Management of animal and equine units and land based resources
- HE Lecturer animal and equine science

Head of Centre Veterinary Nursing Approved Centre / Senior Lecturer / Internal Verifier Veterinary Nursing; Hartpury College

Main duties:

- Regulation of associated veterinary practices and student veterinary nurse training
- Senior lecturer HE / FE Equine Veterinary Nursing / Animal Nursing Assistants
- Internal Verifier FE / HE Equine & Companion Animal Veterinary Nursing

Director of Veterinary Nursing; University College Dublin

Main duties:

- Management of veterinary nursing curriculum, students and partner veterinary practices
- Curriculum development – production of BSc Veterinary Nursing and postgraduate provision
- Production of funding bids / proposals to Irish Higher Education Authority
- Quality management for teaching and learning for the department including lesson observation and peer review; member of University Teaching and Learning Committee
- Academic lecturer (80 hours per annum); subjects included all species anatomy and physiology, large animal reproduction and parturition, equine nursing, diagnostic techniques and anaesthesia
- Research – initial exploration within field of equine behaviour and biomechanics

Animal Care Co-ordinator Stoke Climsland; Programme Manager Advanced National Certificate Animal Care; Duchy College

Main duties:

- Lecturing, marking and assessment (FE/HE equine and animal curricula)
- Course management
- Curriculum planning and development

Programme Manager HND Veterinary Nursing & Management; Programme Manager Foundation Degree Animal Science; Programme Manager Student Veterinary Nursing Day & Block Release (Maternity Cover); Lecturer Further

Education (FE) and Higher Education (HE) programmes in Veterinary Nursing, Animal Management, Horticulture and Equine Science; Head of Centre Veterinary Nursing Approved Centre and Lead Internal Verifier; Bicton College

Main duties:

- Course management and lecturing predominately HE
- Development of new HE provision
- Management of Veterinary Nursing Team

Head Nurse; New Street Veterinary Centre, Devon

Small animal, equine and large animal practice.

Head Nurse / Practice Manager; Ark Veterinary Centre, Liverpool

Small animal / exotic practice.

Emergency Night Duty Nurse – Part-time; Alder Veterinary Centre, Liverpool

Small animal practice.

Veterinary Nurse; Mews Veterinary Centre, Liverpool

Small animal practice.

Stable Manager; West Derby Livery Stables, Merseyside

Hunting and competition livery and hireling yard.

Publication Record

Journal manuscripts

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Williams, J.M. (2012) The Grand National: a test too far?. *Horse and Rider*. May, pp. 25

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Research consultancy:

EMG / Delsys® workshop delivery to internal and external clients

Gait analysis workshop delivery internal and external clients (Pegasus systems)

Current research projects:

Epidemiological review of Thoroughbred growth data in relation to sales price and racing career performance (In collaboration with Rosssdales and University of Glasgow)

Activation of Rectus abdominus during trot poles (in collaboration with Royal Veterinary College / UWE Hartpury)

Activation of Rectus abdominus during carrot stretches and physiotherapy (in collaboration with UWE Hartpury)

Surface EMG analysis of muscle recruitment during showjumping (in collaboration with UCLan / Delsys®)

Surface EMG analysis of muscle recruitment and fatigue during equine warm up periods

Sleep duration and patterns in crib biting horses; impact on learning (in collaboration with Royal Agricultural University)

Impact of chelated calcium calmers on equine performance (in collaboration with industry)

Heart rate analysis in training and competition in 2* and 3* eventers (in collaboration with advanced event rider)

Epidemiological analysis of team and individual performance in rugby (in collaboration with Cambridge RUFC and DM Consulting)

Epidemiological analysis of causal factors associated with equine Head shaking (in collaboration with DM Consulting and University College Davis, USA)

Investigation of equine personality versus non-equine / sporting personality types (in collaboration with DM Consulting and Van Hall Larenstein, University of Applied Sciences)

Grant and funding applications

I have had experience preparing funding applications as outlined below:

- Horse racing betting levy board 2011: analysis of racehorse performance via EMG unsuccessful,
- Petplan Start-up fund 2010 as above: unsuccessful,
- ELBS Diploma bid 2009: successful £20000 plus matched CPD funding,
- Modern Apprenticeship Equine Dentistry bid 2011: successful £84000, and,

- Seale Hayne Educational Trust Fund 2009 successful: £5000.

Reviewer contributions

I have undertaken the role of peer reviewer for the following journals and conferences:

- Journal of Veterinary Behaviour,
- The Veterinary Times,
- The Veterinary Nurse,
- Comparative Exercise Physiology,
- Livestock Science,
- Iranian Journal of Animal Science,
- Alltech-Hartpury Equine Performance Conference: member of scientific committee 2011, 2012 and 2013, 2014; Editor of Proceedings 2011 and 2012
- ISES 2012 Co-editor of Proceedings and reviewer, and,
- BEF AESE HE institutional representative 2012-2013

Committee and professional body membership

I am, or have been, a member of the following professional bodies and committees:

- H.E. Representative B.E.F. A.E.S.E. Board 2012-2013,
- International Society of Equitation Science,
- British Society of Animal Science,
- British Horse Society, and
- British Showjumping.

APPENDIX 8: Reflection on the research journey

A8.1: Developing a research philosophy

My career commenced in the equine industry where I progressed from groom to running a competition yard managing hunters and sports horses. My experiences initiated an early interest in equine sports medicine which developed further as a result of career change into the veterinary field; the remit of the Head Nurse role in mixed practice brought with it increased exposure to all levels of horses, from those kept as companions through to elite level equine athletes. Throughout this period, I was also competing regularly in affiliated showjumping and involved in schooling young horses for the start of their competitive careers. Initially my interest developed around competition, specifically questioning the reliability of the evidence-base for the training practices employed and witnessed, as some aspects appeared to be detrimental to the horse's immediate welfare (Ely *et al.*, 2010; McGreevy and McLean, 2007). It was also observed that, anecdotally, owners and riders were often frustrated by unexpected set-backs related to injuries within training regimens or deviation from their perception of the potential their horse/s should attain. Personal experience of horses which were injured not through neglect but through lack of knowledge on how to prepare them for the requirements of their discipline, or who with more careful management may have had longer careers, substantiated the requirement for further research to explore why this was the case.

I embarked upon a career in education and started to accumulate the professional and research skills to explore the field of equine science and performance to ascertain if answers existed to explain the lack of progression in equine training. The achievement of the Masters in Equine Science facilitated further exploration of

concepts and provided the opportunity to engage in debate with academic and industry peers to glean their viewpoints. I studied the relationship between dermatoglyphs, stereotypy expression and performance in racehorses for my dissertation, and the project fuelled my desire to research establishing my main research interest was the diverse sphere of equine performance. It was therefore logical that my teaching practice and subsequent research activity moved more distinctly into the performance field. I believe as a tutor it is my responsibility to develop students who will question the academic worth of research and be able to triangulate concepts within research to propose solutions to problems in the 'real-world'. Through experience during discussions when teaching both Undergraduate and Postgraduate students, I realised that students struggled to contextualise research papers to demonstrate their application in the equine disciplines and needed the tutor's input to make these links. Interestingly, a similar reaction occurred during discussions with industry peers engaged in competitive equine sports, as they were not aware or demonstrated limited awareness of what research based knowledge was available which could underpin their training practices.

The result was the development of a personal research philosophy which aims to produce quality pragmatic research informed by industry requirements that promotes equine health, welfare and performance through clear strategic objectives which must include the capacity to inform actual practice in the equine industry. My own research interests continue to mirror my teaching practice and I have focused supervision of undergraduate and postgraduate research to facilitate data collection. I also believe in the promotion of collaborative projects and have engaged with other academic institutions, veterinary practices and industry practitioners to facilitate project completion. I am passionate that research should not just be the prerogative

of academics and am proactive in my commitment to knowledge transfer to industry, often translating research into magazine articles to promote dissemination to the lay equine audience (Appendix 7).

A8.2: Reflection on personal development during the research journey

By nature I am predisposed to work independently to achieve goals; one outcome of this experience has been the realisation of how working within a peer group can foster a collegiate culture of support and also be beneficial to idea generation, project design and subsequent completion. The worth of utilising peer support as a discussion forum for ideas has become an integral component of my research approach and I am now more confident to approach colleagues I hold in esteem to discuss conceptual ideas or their research, where previously I would not have had the confidence to do this. Through the research process I have gained a greater appreciation of importance of planning all aspects of a study especially in the sEMG field. It is also optimised time management as colleagues have highlighted pitfalls and strategies to prevent them from their personal research experiences which would not have been exposed when reviewing published literature. My role within research teams has also evolved over time from a team member predominately responsible for data collection to the role of principal researcher investigating new applications of technology in the equine performance field.

The process of publishing research resulted in exposure to peer review for the first time and this has been an aspect of the research process which, on reflection, I do not believe professional practice had fully prepared me for. In some ways the research journey documented has been a cathartic experience and although already self-

critical it prompted the realisation that self-investment and familiarity in projects could conceal flaws which were present within them. As a result, I developed an approach, subsequently applied in projects, whereby proactive consultation with colleagues and peers is used effectively throughout the research process to promote best practice. The outcome of the research journey undertaken to date is the formulation of a realistic appreciation of my own capabilities to '*get the job done, well*'; a concept which interestingly is often defined as self-confidence when appraising athletic performance (Feltz, 1998).

APPENDIX 9: Practical sEMG demonstration ISES 2012

Williams, J.M., Randle, H. and Hall, C. (2012) Practical demonstration of equine eye tracker, rein tension and EMG assessment of driving horses. In eds. Randle, H., Waran, N. and Williams, J. *Proceedings of the 8th International Equitation Science Conference: The Road Ahead. 18th – 20th July 2012. Edinburgh: BSAS & Duchy College Print, pp. 52.*

SHOW-AND-TELL BACKGROUND INFORMATION



Surface Electromyography Delsys Trigno™ EMG Lab and Mobile Systems

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Surface electromyography (sEMG) systems are routinely utilised in human physiological research laboratories for functional monitoring during rehabilitation programmes and for performance analysis. Modern sEMG systems can assess muscle activity by measuring motor unit action potentials (MUAP) in 'real-time' telemetrically, thus facilitating objective analysis of equine performance and training practices. Analysis of sEMG data can be used to establish onset and offset of muscle contraction, and also determine when muscle performance is eccentric, concentric or isometric. Further analysis of the mean EMG frequency can provide an objective measure of fitness levels whilst a left shift in the median EMG frequency over time illustrates fatigue. The Delsys Trigno™ systems on display combine telemetric sEMG sensors with integrated 3d accelerometers and offer a viable research tool for field and laboratory based equine research. During this session, the laboratory based system will be used to demonstrate the impact of carriage driving on activity in *Longissimus dorsi* and the superficial gluteal muscles. There will also be the opportunity to test the system on yourself and to discuss its potential for research.

A9.1 Rationale

An invitation was received from the International Society of Equitation Science (ISES) conference 2012 to present and demonstrate to delegates the potential application of sEMG for analysis of performance in research and training in equine sport using a pair of driving horses. The practical day of the ISES conference was an excellent forum for dissemination of research utilising the sEMG system as it brought together equine researchers, riders, coaches and other equine industry professionals to showcase emerging technology. The aim of the session was to provide an overview of what sEMG could measure, evidenced by the visualisation of live data streaming, with accompanying presenter interpretation, from the demonstrator horses.

A9.2 Research methodologies and limitations

The time constraints negated any live data analysis and required a simplified approach to prevent raw data streamed to viewing screens from being too complex. The driver of the pair of horses participating was competing at a National level and had other horses to exercise, and therefore could only attend for 1 hour prior to the start of the demonstration. Time constraints resulted in a limited window to set up equipment due to the schedule. Because of the lack of preparation and acclimatisation time available with the horses, it was decided to only review activity in one easily accessible muscle which could be palpated accurately. The main worry was the quality of the connection between the sensor electrodes and the skin surface, as the demonstrator horses could not be clipped and current length of their coat was unknown. Prior experience also produced concerns that as the horses' activity-levels

increased, sweat production could reduce the efficacy of the adhesive holding the sensors in situ and they could fall off mid-performance. To avoid sensor displacement, consultation occurred with veterinary colleagues, prior to the event, to determine if any adhesive dressings on the market could be employed over the sensor to increase its immobility without compromising performance or data collection. Subsequently three dressing types were tested on horses of variable coat length and established a new adhesive protocol: sensor plus adhesive interface, overlaid by a Tegaderm™ Film dressing (3M, Berkshire, U.K.). On the day, the horses were clipped (but not to 0mm which is ideal) and the addition of the dressing ensured the sensors were secure and collected data for the duration of the display. The right and left *Gluteus superficialis* of each horse were selected for the demonstration due to prior experience in sensor placement for SG muscle and their visible location from the audience's perspective.

A9.3 Summary of demonstration and results

During the demonstration surface EMG sensors were located on:

- Right superficial gluteal: Tango (right horse in the pair);
- Left superficial gluteal: Tango;
- Right superficial gluteal: Jed (left horse in the pair); and;
- Left superficial gluteal: Jed.

Data were recorded in real time to be able to assess:

- Timing of muscle recruitment; for each horse and between the left and right sides; and;
- Estimate how active the muscles were during exercise.

A9.3.1 Visual assessment of muscle activity

Upon entry into the main arena, both horses' recorded high levels of activity in the superficial gluteals whilst standing still, with short firing durations; which suggests that the horses were tense or excited and that their muscles were prepared for activity. Once they began to move the mean frequency of activation dropped by 50%. Within the horses, each presented with a lead or dominant leg whilst working which varied in accordance with the direction of travel. Tango and Jed both exhibited lateral variability between muscle activity-levels in the right and left superficial gluteals (range of 15-47% variance). Lateralisation could relate to the work of the individual horse but also could correspond to which horse was the lead within the pair. It appeared from the data that Tango was working harder than Jed.

A9.4 Contribution to the field of equine performance

The session demonstrated effectively the practical application of the technology and improvements made between the sensor-skin interface. The live data stream worked well to visualise lateral recruitment and generalised muscle activity-levels for each horse, and within the pair. Initially the potential of sEMG as a measurement tool was

reviewed and then illustrated practically via verbal instructions to the driving pair to perform set movements accompanied by interpretation of the raw data for the audience. Two aspects within the data were of particular interest. When the carriage and horses first came into the arena and halted, both of the horses recorded their highest muscle activity-levels; which suggests that their muscles were prepared for activity which could be seen as a stress or anticipatory response to their environment. The demonstration highlighted an application for the sEMG system which to date had not considered, as it could be incorporated into novel object testing to add a quantitative measure of response. The second area which was intriguing was the contribution each horse made, in simple terms, to pulling the carriage; the raw data were supported by subsequent analysis which identified an imbalance in the distribution of work between the horses. Workload was subsequently discussed with the driver and both parties agreed that both horses appeared apprehensive and to be anticipating their work at the start of the demonstration, and that the more experienced horse was taking the lead in terms of the workload conducted during the performance.

A9.5 Implications and questions generated

The conference produced unexpected outputs. The potential of the technology within behavioural research emerged from debate during the practical demonstration. Whilst the opportunity to expose the equipment to a broad audience research, led to the development of collaborative projects integrating complementary technology which have the potential to contribute significantly to the body of research.

APPENDIX 10: Skeletal muscle

Skeletal muscle is a heterogeneous tissue, which is composed of diverse fibre type with distinct and varied functional characteristics (Choi and Kim, 2009). The main function of skeletal muscle is to facilitate movement under neural coordination; motor neurons innervate muscle fibres at motor units (Rivero and Piercy, 2008). Muscles attach via tendons to the skeleton and once innervated, they contract to produce movement (Marlin and Nankervis, 2002). In this way, muscles effectively function as motors and when recruited strive for equilibrium at any given instant (Winter, 2009).

A10.1 Anatomical hierarchy

Skeletal muscle has a complex structure organised into a distinct anatomical hierarchy (Crook *et al.*, 2002) (Figure A9.1). The muscle is the gross unit; 90% of its structure consists of muscle fascicles which are bundles of muscle fibres. The entire muscle is encompassed within an outer connective tissue fascia, the epimysium, which evolves to form the tendons of insertion and internal tendons in compartmentalised muscles such as the *Biceps brachii*. Individual muscle fibres consist of myofibrils, whilst each myofibril contains multiple myofilaments. Further connective tissue separates and effectively insulates the individual muscle fibres, the endomysium, and the fascicles, the perimysium. The perimysium also houses the muscle's capillary network; some capillaries circumvent the muscle fibre but the majority are found in multiple numbers running parallel to individual myofibrils to optimise oxygen uptake during exercise. Motor nerves also intersperse the

perimysium terminating in the motor end plates of the individual muscle fibres
 (Rivero and Piercy, 2008; Purslow, 2002).

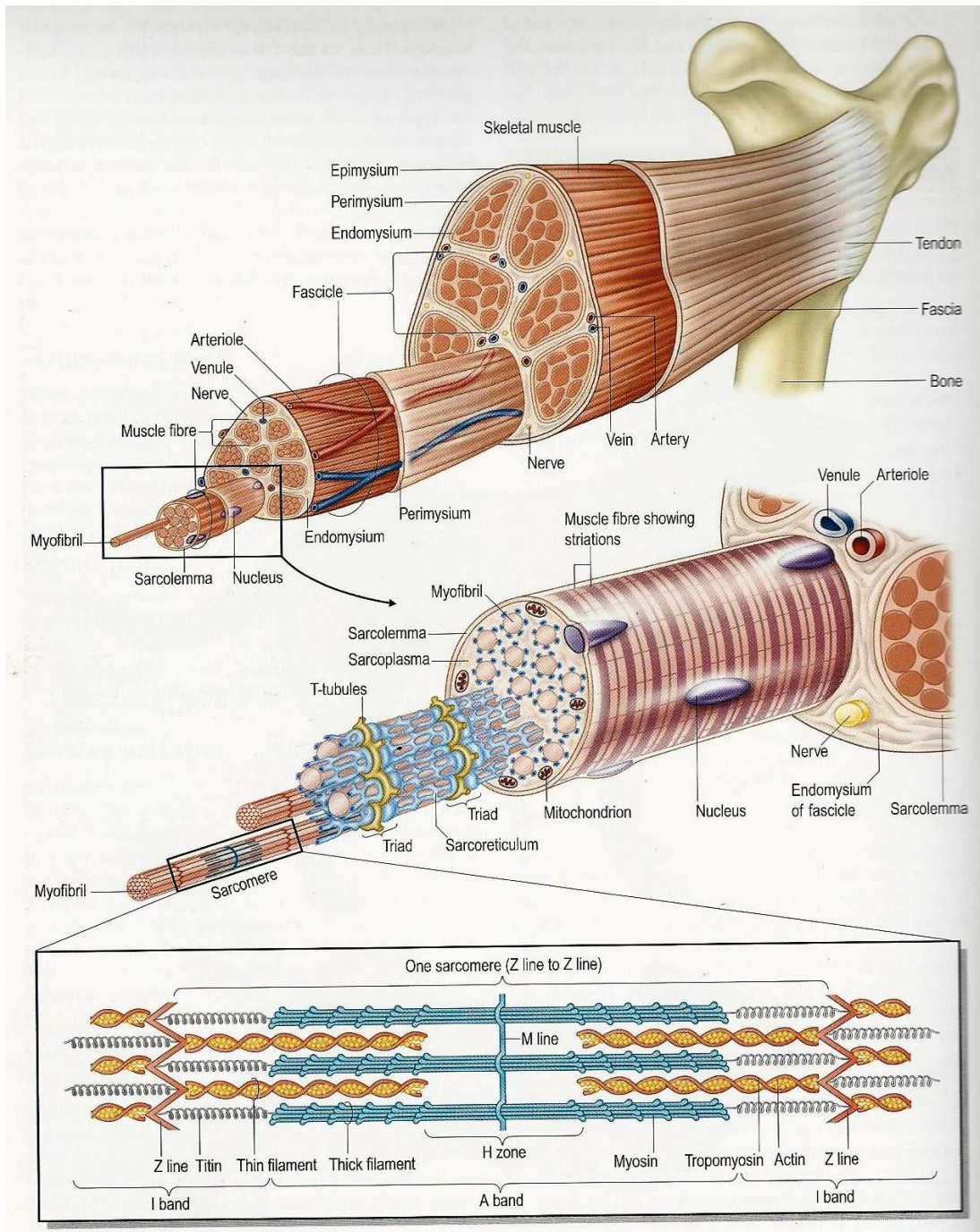


Figure A10.1– Muscle hierarchy reproduced with kind permission from Elsevier.

A10.2 Functionality

Due to the size and energy demands of the horse, muscle has to be able to function efficiently and effectively (Rivero and Piercy, 2008). The architecture and physiology of individual muscles influence their function. Core functional components include muscle belly length, associated tendon length, the physiological cross-sectional area (CSA) of muscle fibres, muscle fascicle length, fascicle pennation and pennation angle, and fibre composition (Crook *et al.*, 2002). Muscle and tendon work collectively to produce energy and drive resultant activity (Rivero and Piercy, 2008). Muscle belly size has been related to individual breeds and to exercise type undertaken in individual horses, for example Arabian endurance horses have longer muscle bellies in the *Gluteal medius* and *Biceps femoris* muscles than Quarter-horses whose function is to sprint over short distances (Crook *et al.*, 2002). Fascicle length is indicative of the number of sarcomeres present in the muscle fibres within it and is directly related to force production within the muscle (Crook *et al.*, 2002). Therefore the longer the fibre, the faster it can contract (Kearns, McKeever and Abe, 2002). Fibres can be unipennate, bipennate or fusiform in nature and angles between fibres also vary (Butcher *et al.*, 2007). As the pennation angle increases within muscle fibres, force generation decreases (Butcher *et al.*, 2007), therefore muscle fibre type combined with fascicle length and cross-sectional area will determine force output (Payne *et al.*, 2005). Specialisation and resultant efficient muscle function is a combination of pennation angle, fascicle dimensions and profile (Crook *et al.*, 2002; Hearn, McKeever and Abe, 2002).

A10.3 Muscle fibre characteristics

Muscle fascicles contain the muscle fibres. Fascicle length is indicative of the number of sarcomeres present and relates to the range of motion, force and contraction potential of the muscle (Crook *et al.*, 2002). Equine muscle fibres vary in CSA between 30-100 μm in diameter and from a few millimetres to >30 centimetres in length (Choi and Kim, 2009). Individual fibres contain multiple nuclei, storage capacity for lipids and glycogen (energy stores for activity), myoglobin, (which facilitates oxygen uptake and transfer across the cell), mitochondria and hundreds of myofibrils (the contractile unit of the cell) (Rivero and Piercy, 2008). The myofibrils have a diameter of $\sim 1\mu\text{m}$ and are formed from bundles of myofilaments, with diameters of $\sim 100\text{\AA}$ (Choi and Kim, 2009). The entire fibre is enclosed within a connective tissue membrane; the sarcolemma (Rivero and Piercy, 2008). Skeletal muscle fibres are characterised via their organised striated myofibrils, which are formed from repetitions of contractile and regulatory proteins arranged in series with a periodicity of ~ 2 to $3\mu\text{m}$, known as sarcomeres (Choi and Kim, 2009).

A10.3.1 The sarcomere

The sarcomere is the functional mechanical structure and unit of contraction within the muscle fibre. It is characterised by its cross-striated appearance and is a complex structure containing at least 28 different proteins in mammals (Craig and Padron, 2003). The ultrastructure of individual sarcomeres is generally consistent across muscle fibre types (Choi and Kim, 2009); however the molecular composition can vary due to the existence of multiple isoforms of each molecular component (Clark *et al.*, 2002). Histological examination of the myofibril, via longitudinal section,

exposes light and dark bands along the myofibril; darker A bands alternate with lighter I bands which also contain areas of denser striations known as Z discs. The functional sarcomere is located between two adjacent Z discs and contains half the I band on each side of the A band. The basic length of the sarcomere is the distance between the Z discs and varies between 1.5 μ m at full shortening to 2.5 μ m at rest and ~4 μ m at maximum lengthening of the fibre (Winter, 2009). I bands contain thin myofilaments (~5-8nm in diameter and 10000nm in length), whilst A bands have both thin and thick filaments (15nm in diameter and 1600nm in length) (Rivero and Piercy, 2008; Marlin and Nankervis, 2002). The thick myofilaments contain predominately myosin and myosin-binding proteins; each myosin II protein has two heads, a long tail and two heavy chains and two light chains. The heads are the primary location for A.T.P. synthesis and the designation of the myosin chain isoform relates to fibre type (Rivero and Piercy, 2008).

The thin filaments are formed from three main proteins: tropomyosin, the troponin complex (T, C and I) and actin, with the latter the main constituent. Actin is a polymer of G-action which acts to form an alpha helix. Within the A band there is an H band found at the junction of the thick and thin filaments; here no overlapping is observed, but each thick filament is surrounded by a hexagonal arrangement of six thin filaments linked by cross-bridges formed from the helical organisation of the thin filaments (Grazi and Di Bona, 2005). The tension which drives lengthening and shortening of the muscle fibre, and by default movement in the gross muscle, is achieved through changes within the cross bridge structure of the series of sarcomeres present in parallel filaments within the muscle fibre to form the contractile element (Grazi and Di Bona, 2005; Winter, 2009).

A10.3.2 Force-length curves

Muscle, and thus fibre, length vary depending on function. The changes in the structure of the myofibril at the sarcomere level can be plotted to analyse the shape of the force-length curve produced (Winter, 2009). At rest, there are a defined number of cross-bridges between the filaments of the muscle fibril, therefore there will always be a maximum tension that fibril can produce (Piazzesi *et al.*, 2014). The combination of fibrils acting together give a maximum tension that the complete muscle unit can generate. When muscles lengthen, the filaments are pulled apart, reducing the quantity of cross-bridges and reducing the maximum tension which can be generated i.e. a lower intensity contraction is produced. If the muscle achieves its maximum or full length, there will be no cross-bridges remaining resulting in zero tension in the muscle. In muscles which shorten to function, as their length reduces, the number of cross-bridges decrease and overlapping between bridges is observed which results in interference in tension generation, reducing the overall output. However, even if maximum shortening is attained, an element of tension will always remain (Huijing, 1998; Winter, 2009).

A10.4 Muscle twitch

Muscle fibres will fire at different rates with variable tension levels depending on the type of fibre present producing a unique tension or force signature (Winter, 2009). Action potentials stimulate MUs to fire (Konrad, 2005). The initial response to generation of an action potential has a short duration and can be classified as an electrical impulse also known as the twitch. Within the MU a second, long duration mechanical response occurs after the initial impulse, building to maximum tension

generation or the contraction (Winter, 2009). No work has evaluated twitch times in equine muscle probably due to the inability to generate a maximum voluntary contraction from a horse. However in human studies, twitch has been shown to vary. Generally, slow twitch fibres require an increased contraction time and produce lower MU action potentials than fast twitch fibres. For example in the medial *gastrocnemius*, predominately slow twitch fibres, mean twitch time has been recorded at 79.0ms with a range of 40-110ms; in contrast in the *Triceps brachii*, containing a higher percentage of fast twitch fibres, mean twitch time was 44.5ms, with a range between 16-68ms. Twitch times are approximately four times shorter than the contraction they initiate (Yousefi and Hamilton-Wright, 2014; Winter, 2009). Similar patterns would be expected in the horse relative to fibre type.

A10.5 Excitation - contraction coupling

During muscle contraction the MUAP stimulate each sarcomere in the myofibrils within the muscle fibre to contract in turn (Kamen and Gabriel, 2010). The action potential is transferred deeper into the muscle fibre via invaginations of the sarcolemma, the transverse tubules. These lie in close proximity to the sarcoplasmic reticulum. The arrival of the action potential activates voltage-gated channels, dihydropyridine receptors (DHPR) and opens the Ca^{2+} channels and releasing calsequestrin bound Ca^{2+} within the sarcoplasmic reticulum, increasing the concentration of calcium in the cytoplasm of the muscle fibre (Rivero and Piercy, 2008). Next Ca^{2+} ions bind to troponin C forming troponin I which facilitates the myosin head to bind with the actin in the sarcomere, forming the cross bridge (Rivero and Piercy, 2008). The process provides sufficient ATP to drive the

movement of the bound actin and myosin II through 90° towards the centre of the sarcomere (Marlin and Nankervis, 2002). In effect, the thin actin myofilaments slide over the thick myosin filaments bringing the Z disks together, shortening the I band and causing the H band to disappear, forming cross bridges which shorten or contract the sarcomere. The process is reversed as the wave of depolarisation is transferred along the sarcolemma altering the membrane potential (Kamen and Gabriel, 2010). The cycle continues for the duration of muscle stimulation. Force is generated when the head of the motor protein myosin II forms cross-bridges from the thick filament to the thin filament, pulling the latter towards the centre of the sarcomere using ATP as energy (Piazzesi *et al.*, 2014).

A10.6 Energy requirements of contraction

The processes of contraction and relaxation require energy. ATP is needed to drive the binding of myosin to actin to stimulate sarcomere contraction. As excitation ceases, the muscle cell needs to reduce the concentration of Ca^{2+} ions to prevent myosin and actin interaction, and requires further ATP to divide the myosin and actin, and pump the Ca^{2+} back into the sarcoplasmic reticulum, enabling the muscle cell to relax and recreate the cross links in the sarcomere. As muscle functions as a dynamic unit, during recruitment the process of contraction and relaxation is repeated until a resting state is returned to or the animal fatigues (Rivero and Piercy, 2008; Marlin and Nankervis, 2002).

The energy required (ATP) to support muscle function can be provided by aerobic or anaerobic pathways. ATP can be synthesised aerobically in the mitochondria of muscle fibres by β -oxidation of free fatty acids, the tricarboxylic acid cycle and

oxidative phosphorylation of carbohydrates within the electron transfer chain. Additional anaerobic energy pathways exist in the horse; anaerobic phosphorylation of high energy phosphate and / or carbohydrate stores (glycolysis) from within the muscle. Aerobic energy production is efficient but relatively slow compared to anaerobic energy production which is fast acting but inefficient. In reality, both energy pathways are usually active during exercise in the horse and the predominant pathway will relate to the intensity and duration of exercise, and the nutritional and fitness status of the individual. Low-speed exercise is predominately aerobic whilst high-speed or intensity exercise such as the effort required to jump an obstacle are considered anaerobic activities (Rivero and Piercy, 2008; Marlin and Nankervis, 2002).