Using Data to Track Racehorse Physiology During Training and Racing

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A thesis submitted to the University of Nottingham for the degree of Doctor of Philosophy

November 2023

Abstract

This thesis investigates multiple aspects of racehorse training, physiology, and performance. The overarching objective of the work is to explore the various factors that may influence the development of racehorses in-training, where a dearth of information exists, historically due to technological limitations. Here, by using a validated fitness tracker, the 'Equimetre™' then multiple aspects of racehorse physiology (heart rate, heart rate recovery), speed (GPS tracked), stride and on-course performance (results-based) could be analysed in large cohorts of racehorses. All studies were retrospective and observational.

In the first study I investigated how training intensity (slow canter to hard gallop) and training surface (sand, fibre, or turf) impacts upon parameters like heart rate, heart rate recovery, stride length/frequency in the racehorses in-training. Additionally, I also explored the influence of horse age and sex on these parameters. The dataset included 509 Thoroughbred racehorses from Australia and France, of varying age, sex (including geldings), and training conditions. In summary, the precision of the Equimetre was excellent (coefficient of variation from 1-5% for locomotory parameters, 3-6% for speed and 5-15% for cardiovascular parameters). The data revealed the marked effect of training surface – sand being mainly used for canters, but markedly shortening stride relative to turf – and how racehorses reach maximum heart rate even at relatively slow speeds (e.g., often at only 'hard canter'). Heart rate recovery was mostly influenced by training intensity and did not appear to 'improve' through the season, as a marker of 'fitness'. There was clearly a zone of maximal cardiac flexibility, at hard canter-to-slow gallop, where responses to training were greatest, perhaps offering the opportunity to use as a basis for setting training zones, as opposed to maximal heart rate, which offered little in terms of between or within horse performance difference. Establishing these data as a reference point, I could then begin to look at training data in a new light; for example, with information on the sex of each training rider, and their experience (professional or non-professional) I could examine whether sex of the rider had any overt influence on racehorse physiology in training or performance on track.

Thus, my second study explored the effect of the sex of rider on racehorse cardiovascular (heart rate, heart rate recovery) and locomotory (stride length and frequency) parameters in training (slow canter to hard gallop) and, ultimately, on the track as race performance in both Australia and the United Kingdom. The dataset consisted of 530 Thoroughbred racehorses that were ridden by randomly allocated work riders of varying sex (male, n= 66; female, n=37) and experience (including registered professionals, n= 43). In training, female riders, on average, participated in more training sessions, but usually at slower intensities (e.g., canter rather than gallop) than their male counterparts. Racehorse speed or the average time taken to cover a furlong (200m) did not differ according to the sex of the rider onboard, nor did stride length adjusted according to training surface (turf or sand). While heart rate and peak heart rate increased with training intensity, as expected, this was not influenced by the sex of the rider. Interestingly, the rate of recovery of heart rate in the horses (from peak to 15 minutes post exercise), appeared to be affected by the sex of the rider, but this depended on the anticipated training intensity vs. the actual training surface: horses recovered slower on turf after slow canters, but faster on sand after fast gallops with male riders, suggesting that the riders either transmitted anticipatory information to the expected training intensity to the horse or the racehorses responded differently according to sex of the rider (i.e. less anticipating a hard gallop on turf with a female jockey). In regard to race data, significantly more male jockeys are represented in the starting gates on race-day (in complete contrast to data during training). However, race-day performance (win percentage) between male and female jockeys was not different. With these aspects considered, I then considered what evidence there was for the race specificities of each racehorse; for example, is a racehorse that only participates in short-distance races, a pre-designated sprinter that can be identified early in its training sessions (e.g., by having a shorter stride) relative to a middle- or long-distance racehorse. With three-generation pedigree information for 421 racehorses, I could then simultaneously explore to what extent the unique characteristics of racehorses are pre-determined by genetics or are developed through the early training sessions.

Therefore, my third study delved into understanding racehorse stride patterns (peak, length, and frequency) by comparing differing distance profiles (‘sprinters, milers, or stayers; according to known race distance). I also investigated the heritability of stride by extracting a comprehensive pedigree database and finally also instigated the correlation of stride with performance prediction through previously collected race-results. The dataset comprised of 421 Thoroughbreds, from a single racing yard in Australia, of varying age, sex (including geldings), and training conditions. Stayers, although fewer and mostly older horses, competed in fewer races but were more successful than sprinters. For the race-pace gallops held on turf, then differences in stride were marked: sprinters presented shorter peak stride length but of higher frequency than stayers. When replicating race-day speeds and conditions from starting gates on turf (‘jumpouts’) over consecutive furlongs, then sprinters were significantly faster than stayers. However, no substantial evolution in stride was reported over the course of continuous training sessions for any individual horse. With everything considered, then colts generally had greater win percentages. Although the effect was relatively small, longer stride length increased the chance of a horse winning and/or finishing in the top three of a race. Peak stride length and frequency were considered moderately heritable, which could theoretically, when coupled to experience and objective data, aid trainer decision-making for the selection of horses. Finally, I explored the extent to which in-training speed and heart rate recovery could differentiate successful racehorses (those that won races, including black-type) from horses that did not.

For this final study, I accumulated sufficiently large training and race data from the same 485 racehorses in Australia in which the training sessions were restricted to race-pace workouts on turf only (i.e., hard gallop and jumpouts) conducted close to and before (within two months) races. Speed, heart rate peak and recovery at maximal running intensities were similar to previously described data in the first chapters. During standard gallops, then the greatest recovery of racehorse heart rate was identified within the first minute following exercise, designated as the early phase of heart rate recovery. Horses completing jumpout sessions, took longer to recover than others during the first three minutes after exercise, as expected for a race-pace simulation exercise. Interestingly, horses appeared to recover better (+/- 5-6 bpm), at any intensity during warmer workouts, relative to cold, with no effect or interaction with humidity. Racehorse speed over the final 600m in-training when designated as 'fast' versus 'slow' was marginally predictive of race performance. Again, as previously described, colts and stayers also tended to win more racehorses in our dataset relative to mares/fillies and sprinters, respectively. I observed very little predictive ability of heart rate measures on race performance. Hence, in-training physiological data is useful for the trainer and/or sports physiologist to monitor the general health and well-being of racehorses and their general condition but does not evidently predict with certainty the chances of a given racehorse winning a selected race.

Overall, these comprehensive, large-scale studies lay the foundation for future research on in-field racehorse exercise physiology. They serve as a valuable resource for trainers and contribute to informed decision-making in the horseracing industry. The findings have the potential to enhance racehorse health and safety, further empowering the future and sustainability of the sport.

Publications & Presentations

Publications

Schrurs, C., Dubois, G., Patarin, F., Cobb, M., Gardner, D.S. and Van Erck-Westergren, E. (2022) Cardiovascular and locomotory parameters during training in thoroughbred racehorses: a multi-national study. *Comparative Exercise Physiology* https://doi.org/10.3920/CEP210037

Schrurs, C., Dubois, G., Van Erck-Westergren, E., Gardner, D.S. (2022) Does sex of the jockey influence racehorse physiology and performance. *PLoS One* https://doi.org/10.1371/journal.pone.0273310

Schrurs, C., Blott, S., Dubois, G., Van Erck-Westergren, E., Gardner, D.S. (2022) Locomotory profiles in Thoroughbreds: peak stride length and frequency in training and association with race outcomes. *Animals 12* (23), 3269 https://doi.org/10.3390/ani12233269

Presentations

Schrurs, C., Dubois, G., Patarin, F., Cobb, M., Gardner, D.S., Van Erck-Westergren, E. *The use of data science to track equine health during training.* School of Biosciences and School of Veterinary Medicine Postgraduate Symposium, University of Nottingham, July 2021.

Schrurs, C., Dubois, G., Van Erck-Westergren, E., Gardner, D.S. (2022) *Does sex of the jockey influence racehorse physiology and performance.* School of Biosciences and School of Veterinary Medicine Postgraduate Symposium, University of Nottingham, December 2021.

Schrurs, C., Dubois, G., Van Erck-Westergren, E., Gardner, D.S. (2022) *Does sex of the jockey influence racehorse physiology and performance.* Horse Tech Conference (online), Cheltenham, United Kingdom, March 2022.

Schrurs, C., Dubois, G., Patarin, F., Cobb, M., Gardner, D.S. and Van Erck-Westergren, E. (2022) *Cardiovascular and locomotory parameters during training in thoroughbred racehorses: a multi-national study.* International Congress on Equine Exercise Physiology, Uppsala, Sweden, June 2022.

3MT presentation: *'Using data to track racehorse physiology during training and racing'.* Annual dinner of the Royal Belgian Benevolent Society, London, United Kingdom, March 2023.

Declaration

Unless otherwise acknowledged, the work presented in this thesis is original. No part of the present work has been submitted for another degree at The University of Nottingham or elsewhere. Any views expressed in the dissertation are those of the author.

Signed:

Date: 22-11-2023

Acknowledgements

I want to extend my heartfelt gratitude to the amazing human beings below, who have been the guiding lights in my doctoral journey as I rode the winds and waves of academia.

First and foremost, I am immensely grateful to my supervisor, Professor David S. Gardner, who has been the steadfast anchor in my kitesurfing adventure on this boundless academic ocean. What a wild ride it has been since the early days of my MSc! Thank you for accompanying me on this memorable research voyage, although at ‘distance’, with the blink of an eye. You always went above and beyond for me, in every aspect, accommodating my crazy hours and lifestyle with enthusiasm, patience, kindness, and relentless sense of humour. You have been the lighthouse guiding me through academic storms and bliss, making the journey immensely enriching, stimulating and fun, as I read, navigated, and tamed my first waves. I am so grateful for your unwavering support in all aspects of my learning, growth, and endeavours. Your guidance, mentorship and friendship have been invaluable, just like a perfect-shaped surfboard beneath my feet, keeping me balanced in the ebb and flow of research.

I would also like to extend my thanks to my collaborators, Dr Emmanuelle van Erck and Dr Guillaume Dubois, who have accompanied me on my crossing over the sea of knowledge. Your insights and expertise were like the favourable winds in my sails, propelling me forward in my academic journey. Emmanuelle, thank you for believing in me since the start. It has been such a privilege to work together and learn from you over the last four years. Guillaume, thank you for making this research possible and for your involvement until the end. Your know-how played a pivotal role in the success of this project. It was such a pleasure to work alongside both of you. Special thanks must also go to Romane and Joshua for sharing their field knowledge and experience throughout all studies.

Peter and Lee, you have been my lifeguards on this academic voyage, ever-vigilant, ready to support and rescue me in times of intellectual shore breaks, like guardians watching over a surfer's safety in the reef. Thank you for your support when things got tough, ensuring I did not wipe out on my academic, personal, or professional waves. Amelia, my PhD surf sister since day one, thank you for the friendship all along.

To my friends, especially Lara, Sam, and Anna, I owe a debt of gratitude to you, who provided encouragement, motivation, and moments of respite throughout this enduring ‘kite-athon’.

You were the currents beneath my kitesurf, keeping me buoyant and propelling me forward as I rode the everchanging waves. Your positive outlook and presence were the steady pull of my kite, keeping me soaring high on this vast ocean.

My dearest Mamy and Sego, your unconditional support was my deep-sea bedrock, unyielding and immovable, like the steady seabed for a surfer to float upon. Thank you for always standing by my decisions and encouraging me to reach the greatest heights.

Damien, my partner in life, I am deeply gifted by your support during this journey. Your kindness and patience sustained me through all the wind seasons. Thank you for riding the wave of life next to me, at times breezy and serene or equally wild and relentless. This achievement would not have been possible without your presence and easy-goingness.

A heartfelt thanks must also go to the institutions and organisations that provided the resources and financial winds that filled my academic kite, including the Royal Belgian Benevolent Society, Arioneo, and the University of Nottingham. You allowed me to explore deeper intellectual currents by materialising my ambition to pursue new academic heights.

And to all the unsung ocean lovers, friends and mentors, near or far, who may not be named here but who, in their own ways, were the hidden currents beneath my kiteboard, I am deeply grateful for you shaping the contours of my horizon.

This journey, much like kitesurfing, has been both a thrilling and enriching ride full of manoeuvres and glides. It would not have been possible without all of you. Thank you for inspiring and encouraging me as I reach the other side of the shore.

With the wind in my sails and the blessing of your support, I continue to surf through the vast sea of life, wherever it will take me, always chasing the next big wave.

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Abbreviations

ATP	Adenosine triphosphate
AUC	Area under the curve
BPM	Beats per minute
CMI	Catastrophic musculoskeletal injury
CT	Continuous incremental training
GPS	Global positioning system
h^2	Heritability
HR	Heart rate
HRR	Heart rate recovery
HR at 15min	Heart rate at 15 minutes after cessation of training
HRV	Heart rate variability
HRM	Heart rate monitor
HR Max	Maximal heart rate
IFHA	International Federation of Horseracing Authorities
IT	Interval training
MSI	Musculoskeletal injury
VO_2 Max	Volume of maximum oxygen uptake
V200	Speed at a heart rate of 200 beats per minute
VLa4	Speed at a blood lactate concentration of 4mmol/l
VLa10	Speed at a blood lactate concentration of 10mmol/l

Chapter 1 Introduction and Literature Review

1.1 Summary

This chapter provides background information on the horse racing sport, including its challenges (i.e., race-day injuries and wastage) and opportunities found in training management, along with the surge of new validated technologies to monitor racehorse performance on the track. The chapter ends with a summary of the aims and research questions of this project, and an overview of the structure of the thesis.

1.2 The Thoroughbred racing industry

1.2.1 Horseracing: nations and global revenue

Thoroughbred horseracing, a globally acclaimed and intensely competitive sport (Wilson et al., 2014a), has shifted from a traditional pursuit into a multi-million dollar industry shaped by both gambling and breeding. The International Federation of Horseracing Authorities (IFHA), established in 2003, now serves as the international governing body. Its overarching mission is to establish a unified framework for horseracing regulations and best practices across member nations.

According to the 2019 IFHA survey, the sport witnessed a staggering total of 148,179 Thoroughbred races (flat and jump races combined) across 50 countries, displaying 239,783 individual runners and offering a total prize money of approximately €3.5 billion (IFHA, 2019). Notably, Australia hosted 19,276 flat races, securing the second position globally after the United States of America (USA) with 36,066 flat races, and preceding Japan with 16,444 flat races. The annual distribution of prize money distributed revealed the following top-ranking nations: Japan (€964,829,380), the USA (€842,570,286) and Australia (€456,662,546) (IFHA, 2019). Given the extensive data available from a single racing yard in Australia, this thesis primarily delves into the intricacies of this particular racing industry.

Australia stands out among racing nations for its high per-capita ownership of Thoroughbred racehorses (Ross, 2003). Moreover, its racing industry significantly contributes to the nation’s economy, serving as a vital source of employment, export income and gambling revenue. In 2019, race-day gambling alone reached a substantial turnover of $AUD 18,254 million. The extensive reach of the industry is evidenced by 454 racecourses hosting 19,276 flat races, with 34,682 different horses participating during the 2019 season (IFHA, 2019).

1.2.2 Racehorse wastage

As mentioned above, the racing sector represents a major driver of the Australian economy. The viability of this particular industry relies directly on the welfare of its horses and thus, their low turnover (Jeffcott et al., 1982), aspects that are intimately associated with public perception and participation (Bourke, 1995). Indeed, if a high turnover is recorded (e.g., many horses unable to race), then racecourses may struggle to fill scheduled races. Unfilled races, in turn, will hinder the ability of venues to attract the betting public. Consequently, this tendency would then cause poor return on owner investment and restrict racehorse owners' pool. Hence, minimising wastage is a priority for most nations, along with the reinforcement of racehorse health and welfare strategies to ensure the sustainability of the sport.

'Wastage' is the term used for a horse that leaves the industry at any stage of its life or career ranging from pregnancy, illness or death in foals, to training or racing related injuries (Bailey, 1998). Within the horseracing discipline, and across other equine sports, a 'one-third' theory continues to be observed: within any given year cohort, approximately one-third of the horses born will not enter the racing sport. Within the remaining cohort, horses will either be intentionally withdrawn from training (e.g. unsuitability for the sport), retire unintentionally (e.g. poor performance-related issues such as musculoskeletal injuries) or will be sent to breeding farms (O'Brien et al., 2005, Friedrich et al., 2011). A study conducted by More (1999) in Queensland, Australia outlined that only 71% of 2- or 3-year-old Thoroughbreds continued to race for at least one more year, and only 46% for at least two more years after their first race. Previous evidence by Bourke (1995) revealed that more than one-third of the Thoroughbred population in Victoria, Australia exited the industry each year. To date, limited information is available to quantify this wastage effect. However, suitable training programs coupled to objective performance monitoring (i.e by means of validated tracking technologies) could lead to overall improved health and welfare, and thus reduced racehorse wastage.

The typical Thoroughbred racehorse is characterised by a height of ~160cm (~16 hands) and weighs ~500 kilograms to perform at maximal speeds of 50-70 km/h depending on the distance to cover (Evans, 2007b, Rivero et al., 2007, Marlin and Nankervis, 2013, Williams and Ashby, 1992, Fleming et al., 2001). Race timings usually span between 1-3 minutes depending on the distance to cover and reflect superior sprinting or endurance aptitude. Running at peak speeds provokes high metabolic rates and exerts substantial impact forces on the horses' limbs.

Such demands only partly justify the particular nature of the horseracing, perceived as a high risk and dangerous sport for its participants including both horses (Hitchens et al., 2016) and professional jockeys (Bailey et al., 1997, Cohen et al., 1997) and its direct association with the high incidence of falls and injuries (Turner et al., 2002, Hitchens et al., 2009, Rueda et al., 2010, Waller et al., 2000, McCrory et al., 2006).

In recent years, the occurrence of catastrophic incidents on the racetrack has become more visible to the greater public through wider media coverage. In both Thoroughbred flat and jump racing, the percentage of sudden death was estimated to be 19% in Australia between 1989-2004, 12% in the UK and 9% in California between 2000-2009 (Lyle et al., 2011, Boden et al., 2006). Some more recent events include the death of horses during or shortly after participating in the Kentucky Derby in 2023, the Melbourne Cup in 2020 and the Cheltenham Festival in 2023. Social media now, more than ever, significantly contributes to the rapid dissemination of negative news, further serving lobby groups (Graham and McManus, 2016). Triggering substantial criticism and debate, these incidents further question both the ethics and future of the sport. The origin of such accidents is often reported as ‘anomalies’ (i.e. a rare physical condition or accident-related injury) (Markwell et al., 2017), pressing the need for both evidence-based research and clear jurisdiction strategies to improve racehorse health and welfare. Recently, large epidemiological studies have been on the rise in effort to identify recurring racehorse conditions associated with track-related injuries (Clegg, 2011). These included musculoskeletal damage (Boden et al., 2006), exercise-induced pulmonary haemorrhage (Morley et al., 2015) and gastric ulcers (Orsini et al., 2009).

Racehorses may initiate their training from the age of one to ultimately start racing at the age of two. Some trainers follow a practice of "training by the calendar" for their yearlings: that is, they set a specific target date for their horses to be race-ready, even if it requires sacrificing periods of rest in the paddock. For racing and bloodline purposes, Thoroughbred age is determined by the calendar (i.e., 1st of January for the Northern Hemisphere and 1st of August for the Southern Hemisphere) and not the individual’s birthdate. As a result, buyers tend to shy away from horses born late in the year, as they will present less training experience and maturity, thus increasing their likelihood of average race performance. This raises a significant controversy within the racing community: whether commencing Thoroughbred training at two years of age is detrimental or beneficial to a racehorse's career and growth. Contrasted opinions fuel the debate amongst equine professionals, as this practice engages relatively immature horses to high work demands early on in their development phase and may therefore increase the risk of injury. Evidence in the literature on both the training and racing of two-year-olds is conflicting. For instance, Mason and Bourke (1973) evaluated 74 Thoroughbreds in

Australia during their two-year old racing season and reported that 40% were unsound at the end of the season. Similarly, Hernandez and Hawkins (2001) observed that 45% of horses presented lameness over a 6- to 8-month period for a median of 26 lost days. In contrast, a more recent epidemiological review by Stover (2003) outlined that two-year-old racehorses were not at greater risk of injury as opposed to 4-year-olds and age categories above. For two-year old horses, it is indispensable for trainers to carefully balance workload, distance, and frequency. Indeed, regular, low intensity canter exercise is necessary and considered beneficial as contributes to overall joint health (Tanner et al., 2013). However, it should be coupled to the right amount of high-speed exercise, as excessive accumulation has the potential to damage meta-carpo- and meta-tarso-phalangeal joints (Reed et al., 2013). Interestingly, Stover (2003) also highlighted that horses appropriately exercised at high speeds over short distances presented lower injury incidence as opposed to those that completed single, long-distance high-speed work. Early onset of suitable training provides a positive stimulus and equally offers racing advantages for two-year-olds compared to those initiating training at a later date (Rogers et al., 2012) including prolonged careers (Velie et al., 2013a), more race starts and greater earnings (Santschi et al., 2017).

In racehorse training, when a locomotory issue arises (e.g., lameness in a limb or other musculoskeletal concern), then it is common practice for trainers to administer pain-mitigating medications to their horses instead of prescribing rest or reducing the workload. Corticosteroids, regardless of their anti-inflammatory effects, when injected in joints repetitively alter the integrity of articular cartilage leading to increased risk of racehorse injury (Murray et al., 1999). Similarly, hyaluronic acid, injected to provide lubrication and cushioning to the targeted joint, can also cause training injuries (Hitchens et al., 2018). In California, USA for instance, it is estimated that 70% of the in-training Thoroughbred population is routinely under medication (Hitchens et al., 2018). The reason behind this widespread practice lies in the substantial amount of financial pressure placed on trainers: the high expectations to produce exceptionally performing horses, a strong push to maximise race-entries and above all, to ensure that high-paying owners and shareholders secure their return on investment.
Such factors have long been major contributors to the persistent doping issues that blemish the horseracing industry (Tobin, 1981). ‘Doping’ refers to the unethical practice of administrating prohibited substances to horses to enhance their performance or obtain a competitive advantage. It is interesting to note that racing authorities equally prioritise the detection of substances that can impair a horse's performance. That is, in certain circumstances, individuals may intentionally reduce a horse's performance, not to win the race, but rather to manipulate betting outcomes. The motivation behind this practice lies in the fact that the financial gain from betting on a race with impaired performance may, in certain

contexts, outweigh the potential prize money on offer from winning a race legitimately. In human sports, a unified approach for rules and regulations is implemented for most elite sport events worldwide under the World Anti-Doping Agency. The horseracing sport is currently hampered by the lack of global governance that would streamline both rules and regulations. However, several racing authorities have gradually adopted the guidelines and best practices advocated by the IFHA. The following principle has drawn particular attention: no prohibited substance should be present in official samples (i.e., urine or blood) collected from any horse following racing, with testing and screening conducted by officially registered racing chemists or regulatory veterinarians.

In addition to the variations in doping control programs, the vast scope of substances to control continues to pose considerable challenges (Wong and Wan, 2014). Indeed, the ongoing surge of new drugs on the market, whether legal or illegal, outpaces the development of testing methods by racing chemists, creating a barrier in effectively detecting their use and abuse. Various global initiatives have been developed in attempt to address racehorse doping and its related risks. One example is the Californian Horseracing Board that tested the implementation of a 30-day drug cutoff prior to races along with a 10-day cutoff prior to training on intra-articular injections of corticosteroids. The results led to a marked decrease in catastrophic injuries on major racetracks such as the Santa Anita course (Horse Racing News, 2020). Hence, medical administration and other management-related factors can play a direct role in mitigating race-related injuries on the track.

Whilst racing injuries must officially be recorded by veterinarians, there is no current obligation to register training related injuries. This is somewhat surprising, considering that the majority of musculoskeletal injuries (MSI) are reported to occur during training (Verheyen and Wood, 2004, Robinson et al., 1988) and not racing (Perkins et al., 2005, Verheyen and Wood, 2004, Estberg et al., 1995, Jeffcott et al., 1982). Characterised as repetitive stress, MSI is the leading cause behind lost training days in Thoroughbreds (Cogger et al., 2006). Johnson et al. (1994) reported that in-training MSI mainly occurred in both the forelimb and hindlimbs (i.e., humerus, fetlocks, and pelvic joints). A series of countries have explored this topic. In the UK, 20% of horses presented serious lameness issues that impeded return to race training between 1977-1980 (Jeffcott et al., 1982). During similar years, 19% to 33% of racehorses terminated training within a 3-month-or-less period in the USA (Kobluk et al., 1990). While later, in Germany, 26% of racehorses finished training within a 9-month period (Lindner and Dingerkus, 1993).

From a racing perspective, MSI account for 70% of racehorse fatalities (Wood et al., 2000). According to post-mortem investigations, they are seen to predominantly affect the forelimb, including the proximal sesamoid bone (i.e., navicular bone), suspensory apparatus and the

third metacarpal bone (i.e., commonly referred to as the cannon bone). An analysis of the literature relating to racehorse injury between 1990-2017 compared the numbers of catastrophic musculoskeletal injuries (CMI) happening on the racetrack between countries (Hitchens et al., 2019). Findings outlined that the pooled incidence for racehorse CMI was 1.17 per 1000 race starts. For Australia and New Zealand, the pooled incidence of CMI were substantially lower than the findings observed in the United States ($P < 0.001$) and Canada ($P = 0.011$) but did not differ significantly from Hong Kong ($P = 0.608$) and the United Kingdom ($P = 0.091$). The following factors are believed to mitigate CMI occurring on the racetrack:
(1) Horse-level indicators: older horse age and age at first race start, male sex, and higher race class or lower claiming price.
(2) Race-level indicators: harder track conditions on turf and wetter conditions on dirt, prolonged race distance, and a greater number of racehorse starters.
(3) Management-related indicators: more days since previous race start, greater number of starts, longer career, issues found at pre-race examination, previous recorded injury, and recent administration of medication or injections.

Overall, the prevalence of MSI and racehorse mortality (Maron et al., 2009, Lyle et al., 2012) raises substantial ethical, welfare, safety and economic concerns across the racing industry. Racing jurisdictions have gradually created monitoring programmes to track, monitor and investigate this particular topic (Arthur, 2011), such as the 2023-2027 Equine Welfare Strategic Plan of Racing Victoria in Australia. Studies objectively tracking racehorse training, whether in small or larger size cohorts, are needed to guide existing racehorse health and welfare efforts.

1.3 Thoroughbred flat racing

Thoroughbred racing is largely subdivided into two forms known as flat and jump racing (i.e., National Hunt racing in the United Kingdom, steeplechasing in the USA). This thesis will exclusively focus on flat racing. Flat races are usually held on oval tracks deprived of obstacles (i.e., hurdles or fences), where typical distance varies between 1000 - 4400m. Largely of similar nature across all nations, some differences are found in terms of flat racing rules, regulations (i.e., the use of the whip by the jockey) and race-day conditions (i.e., distance and track type).

1.3.1 Race distance and tracks

In Australia, flat races are mainly run on turf surfaces (i.e., grass) over distances of 800 - 3375m. For instance in Victoria, during the 2016/2017 racing season (1 August 2016 - 31 July

2017), 91.6% of the flat race starts were conducted on turf, with the remainder performed on synthetic tracks (Racing Victoria, 2017). In the United Kingdom and France, with the racing season running from March to November, common flat race distances range between 1000 - 4400m and occur on turf tracks. However, during the colder and wetter months of winter, then it is frequent to leverage all-weather tracks (i.e. a mixture of sand/fibre/binder) (Turner et al., 2002, McCrory et al., 2006).

Five race distance categories have been established by the IFHA:
Sprint (5-6.5 furlongs (f), ≤ 1,300 m)
Mile (6.51-9.49 f, 1,301-1,900m)
Intermediate (9.5-10.5 f, 1,901-2,112m)
Long (10.51-13.5 f, 2,114-2,716 m)
Extended (> 13.51 f, > 2,717m) races (IFHA, 2022).

Note that one furlong equals 200 meters. Horses that compete in these races are commonly referred to as ‘sprinters’ (<6 furlongs; 1200m), ‘middle distance’ or ‘milers’ (7–8 f; 1400-1600m) or ‘stayers’ (>8 f; >1600m).

1.3.2 Race categories

In Australia, flat racing encompasses various categories of races. The classification system is designed to group horses of similar abilities, allowing for fair and competitive racing. In some circumstances (i.e., condition races), a racehorse’s eligibility to enter a race will depend on its performance level (i.e., number of wins), sex, age, prize money won, etc. The common flat racing categories found in Australia are described below (Morrice-West et al., 2021).

Group and Listed races
Group races, also called ‘Stakes’ races, are at the top echelon of races. Considered the highest level attainable in Australia, such meetings attract only elite horses. To be entered in such races, horses must accumulate a certain level of winnings. These prestigious meetings include classic races (e.g., Coxe Plate and Golden Slipper) and those of major international importance (e.g., the Melbourne Cup). The prize money offered is often significant, with a starting minimum of $250,000. Group 2 races, the next tier below Group 1, still feature high-quality competition. While the prize money is slightly lower (i.e., at least $125,000 per race) than in Group 1 races, these events are also prestigious (e.g., Makybe Diva Stakes and the AAMI Vase) as they attract quality horses. Group 3 races, the third tier, offer competitive fields and decent prize money (i.e., a minimum of $75,000). They are essentially domestic races, with examples

including the Victoria Handicap and the Caulfield Guineas Prelude. Listed races are just below Group level in terms of prestige and prize money (i.e., $50,000 per race). They offer horses the chance to improve and develop their racing before entering the higher-level events. Examples include the Winterbottom Stakes and the Blue Diamond Prelude.

Maiden and Class 1 races

These races are for starters that have not previously won a race and have not won more than one race respectively. With different races applied to different age groups, this category carries the lowest prize money and provides opportunities for less experienced horses to break their maiden status.

Class 2-5 races

These races target starters that have won no more than the respective number of races.

Restricted races

Such events include both Benchmark and Handicap, that is, races in which horses are assigned weights based on their rating. Benchmark races are classified based on a horse's benchmark rating, which reflects its recent performance. Horses compete against others with similar benchmark ratings, ensuring more evenly matched fields. Handicap races require horses to carry a weight determined by their previous performances in other races. Horses are instructed to carry different weights based upon their ability and race performance history, with the aim of equalising the chances of all horses. The amount of weight horses carry is predetermined by specialists referred to as ‘handicappers’ (Langlois, 1980, Bokor et al., 2006). On race day, the handicapper or racing steward allocates a specific weight to each jockey for a particular race in comparison to its opponents. To supplement the combined weight of the jockey and saddle up to the assigned weight (referred to the ‘impost’), lead weights are placed in the pockets of the saddle pad (referred to lead pads). A better-performing horse will carry a heavier weight, to give it a disadvantage when racing against slower competitors. During handicap race betting, the skill lies in predicting which horse can overcome its handicap. Most handicap races are run for older, less valuable horses. However, some famous meetings are handicap races with examples of the Grand National steeplechase (UK) and the Melbourne Cup (Australia). Open handicap races welcome horses of various ages and abilities, and the weights are assigned to level the playing field. Quality handicaps are similar but are restricted to horses of a certain quality or rating. The weights are assigned based on a horse's handicap rating.

Open races

Open races impose no special conditions or restrictions.

Altogether, understanding the categories that revolve around flat racing in Australia is crucial for participants, punters, and racing enthusiasts to appreciate the level of competition and make informed decisions both on and off the track. The classification also system ensures that horses of similar abilities compete against each other, making races more thrilling and fairer.

1.4 The training environment

Racehorse exercise sessions occur in a controlled and safe environment of purpose-built tracks, commonly referred to as ‘gallops’. Usually between 3-4 metres wide, they are designed to ensure sufficient distance for both the initial warm-up and final pull-up (i.e the last phase of cooling down and bringing the horse to a complete stop after a workout) of horses during exercise. Track layouts may vary including oval, circular, or irregular shapes. However, the most common shape is an oval. The bends (i.e left/anti-clockwise or right-handed/clockwise direction), straightaways and inclination will be different from one training ground to another. Each track presents its own unique characteristics and understanding these features is essential for all those gravitating around the racehorse athlete.

1.4.1 Track surfaces

Various surfaces compose racetracks, each with their own characteristics that can significantly affect the performance of horses. The main types of racetrack surfaces include dirt, turf, synthetic and sand. The choice of surface depends on factors such as climate, location, and the preferences of racing authorities.

Dirt tracks are commonly used in the United States and consist of a mixture of sand, clay, and soil. They are often treated with additives to improve both stability and drainage and provide a loose surface that becomes compact over time. Their offer a cushioning effect reducing impact on racehorses’ limbs while remaining weather dependent (i.e., muddy with rain, dusty when dry).

Turf tracks are made of grass and are commonly used in Europe, Asia, and some parts of the United States. Turf racing is often associated with long distance races and is favoured by horses with a preference for grass surfaces. Turf tracks are generally firmer than dirt tracks, providing a consistent and stable surface. The disadvantage of turf tracks lies in the slow draining of the ground. Grass provides a softer surface, reducing the impact of racehorse running forces, which can be beneficial for horses' joints.

Also known as all-weather tracks, synthetic tracks are artificial surfaces designed to provide a consistent and stable surface, good drainage properties and resist to extreme weather conditions. Made from artificial materials such as polytrack, or other proprietary blends (e.g., wax or polymeric binder on a hard porous base), they replicate the properties of natural surfaces (e.g dirt and turf), providing a reliable racing surface that can withstand heavy rain or dry spells.

Some racetracks use sand tracks, consisting of a mixture of sand and other materials. Man-made sand tracks tend to be composed of pure sand over a non-porous base, to offer drainage and cushioning. When used in training, they provide a soft and 'forgiving' surface for conditioning work. In Australia for example, location dependent, it is not uncommon for trainers to exercise their horses on the beach on firm or soft sand (Morrice-West et al., 2018). Sand tracks are less common in major racing circuits but may be found in certain regions where other surfaces are not practical due to climate or cost considerations.

Thus, appropriate track surface and condition are fundamental aspects of the daily decision-making of any trainer prior to racehorse routine workouts. Influenced by weather and maintenance, tracks can be fast, firm, slow, or muddy, impacting the speed and performance of horses. The choice of suitable surface for the training of any individual horse will largely depend on the maximal speed targeted by the trainer. However, training programs are rarely restricted to a single type of track, but rather a combination of two or three (e.g., sand, turf, or wood pellets/all-weather).

When leveraged appropriately, such surfaces can be maximised to build racehorse fitness and reproduce race-day conditions. Morrice-West et al. (2018) in their survey, interviewed 66 registered trainers in Victoria, Australia. The results of their study showed that track surfaces were variable from one trainer to another, with the most common surfaces including turf (grass), sand, synthetic or dirt. The study outlined that for slow-workouts, 97% of trainers used sand while 36% preferred synthetic surfaces. For fast workouts, 82% of the trainers directed gallop training on turf tracks compared to 58% on synthetic. Evidence showed that 90% of trainers also integrated alternatives to flat ridden exercise such as treadmill and swimming.

That same study described that 80% of the trainers adopted turf surfaces, with only 34% accounting for gallop exercise. The reasons behind this observation included 1) limited access or availability of turf tracks, 2) synthetic surfaces being more practicable in wet conditions 3) sand tracks providing less concussion 4) synthetic surfaces being too compact (Morrice-West et al., 2018). The use of track surfaces contrasts greatly with what has been described in the United Kingdom by Verheyen et al. (2006a). The study assessed the risk of tibial and pelvic fractures in horses and found that 81% of individuals completed a minimum of 70% of their high-speed work on turf or peat-moss soil tracks. 36% of trainers surveyed in Victoria raced their horses on surfaces they were exposed to in training (i.e., sand or turf) (Morrice-West et al., 2018). While a proportion of 34% of trainers did the opposite by using a specific surface only for an occasional gallop (i.e., pre-race trial) or exposed their horses to a new or different surface on race-day. This can occur when certain training facilities restrict easy access to turf tracks for gallops, thus making the tracks exclusively accessible to given horses participating in planned races that same week. This aligns with the findings of Morrice-West et al. (2018), whereby 29% of trainers declared no prior exposure to the surface used on race day for their horses, or only occasionally, in context of a preparatory gallop or trial.

1.4.2 Ground condition

The track rating (AUS), also referred to the ‘going’ (UK) or track condition (USA), has the potential to significantly alter and influence racehorse performance. Reflecting either the firmness or softness of a track, the track rating plays a crucial role in determining how horses will perform. Often described as "fast," "good," "firm," "soft," or "heavy" it can be measured by means of a penetrometer, an iron rod instrument with a one-kilogram shell-shaped point. The instrument, used by racing stewards, is dropped from a specific height (i.e usually 1 meter), and measures the depth (i.e in centimetres) it reaches upon penetration. Ground measurement involves three consecutive impacts at ten designated locations on the track, typically 2 to 3 meters apart. The collected data provides an average numerical value, typically measured in newtons (N), with an established range from 2.2 to 6 or higher. Measurements are conducted the day before racing and on race-day to inform a report that publishes the track rating for punters and trainers. Racing authorities may use various methods to assess and communicate the condition of the track, including penetrometer readings, visual inspections, and reports from jockeys. The track rating may evolve throughout a racing event, especially with precipitation or significant weather variations. Racecourse stewards monitor tracks and signal any improvements or deterioration with a siren for on-course punters. While broadcasters and betting agencies relay the information to punters of any track rating changes. Race-callers also announce any track rating changes before the next race.

Racing Victoria, one of the racing jurisdictions in Australia, suggests the following track rating benchmarks as a reference guide (Racing Victoria, 2022):

1-2 firm: a firm track is hard but not excessively dry or abrasive, thus doesn't cause excessive wear or discomfort to the horses. Additionally, a firm track typically has less 'give' in the ground compared to softer tracks and therefore may be less forgiving in terms of cushioning and shock absorption.

3-4 good: a good track is slightly softer and balances firmness and cushioning. Horses generally perform well on good tracks. A good track rating is usually considered the optimum surface to race on, as it provided the safest and fairest racing conditions for the majority of horses.

5-7 soft: a soft track shows more flexibility in the ground. It often results from recent rainfall or irrigation. Horses that handle softer surfaces well may have an advantage in soft conditions.

8-10 heavy: a heavy track is wet, thus contains a significant amount of water. Resulting from prolonged rain or poor drainage, a heavy track can be physically demanding, thus may tire horses more quickly.

The track rating is an important consideration for trainers, jockeys, and punters as horses have unique preferences for specific track conditions: some will perform better on firmer surfaces, while others will excel on softer ones. Therefore, trainers include the track rating in their decision-making for race entries to select events that are best aligned with their horse's preferred track conditions.

Racehorse performance is further influenced by surface-related factors including maintenance, temperature, moisture and hardness (Peterson et al., 2010, Peterson and McIlwraith, 2008). As a result, the track rating may significantly impact race times, with firm ground delivering the best race times. The suitability of a horse to a particular sort of going can be explained by its conformation or locomotion (i.e. speed) (Marlin and Nankervis, 2013). For example, a horse showing a pronounced upright forelimb conformation may be more likely to suffer concussion-related injuries on firm ground, while a horse with a higher, rounder action may have a race advantage on soft ground.

1.4.3 Racetrack surface and relevance to injuries

Thoroughbred races predominantly take place on turf in Europe, South Africa, Australasia, and South America, whereas dirt racetracks are more commonly found in North America, Japan and the Middle East. Regardless of the type of racing ground, racetrack surface was shown to alter limb loading, hoof acceleration and ground reaction forces of horses (Chateau et al., 2009, Setterbo et al., 2009). Track surface properties may therefore lead to the development of bone fatigue injuries (MacKinnon et al., 2015). Hard tracks, particularly firm surfaces, offer reduced cushioning effect, which may increase the risk of racing injuries (Oikawa and Kusunose, 2005).

Publications on safety considerations related to racetrack surface remain somewhat contradictory. Work by Hernandez et al. (2001) explored the association between race-start characteristics and catastrophic MSI injuries in Thoroughbred racehorses in Florida, USA. The findings showed that incidence of injury was significantly higher during turf races (2.3/1,000 starts) compared to dirt races (0.9/1,000 starts). While a case-control study in New York evidenced that horses racing on turf tracks had a lower risk of MSI compared to dirt (Mohammed et al., 1991). More recently, a five-year cohort study (2009–2013) in North America including all flat racing starts, deducted that horses racing on a dirt surface were at a higher risk of fatality, compared to horses racing on turf or all-weather surfaces (Georgopoulos and Parkin, 2017).

During training, then a correlation was identified between gallops on turf and lower odds of lateral condylar third metacarpal/metatarsal fracture has previously been evidenced (Parkin et al., 2005). All-weather, synthetic training tracks have proven to associate with increased risk of pelvic and tibial stress fractures compared to both turf (Verheyen et al., 2006a) and dirt surfaces (MacKinnon et al., 2015). In another study, gallop work conducted on both sand and dirt surfaces lead to a higher risk of catastrophic MSI compared to turf-tracks (MacKinnon et al., 2015, Parkin et al., 2004a). When the same type of surface is found at two different racetracks, the performance on that surface may vary significantly, because of the influence of factors such as maintenance, temperature, moisture, and hardness (Peterson et al., 2010, Ratzlaff et al., 1985, Peterson and McIlwraith, 2008). The North American horseracing industry has witnessed a surge in the recent years of synthetic tracks, as it was believed that overall, they were safer and similar to turf (Clarke, 2009). The shift of trainers from dirt to synthetic track surfaces, led to speculation that hindlimb lameness and tibial stress fractures became more prevalent (Arthur, 2010). Dimock et al. (2010) demonstrated a change in the distribution of humeral stress remodelling lesions to the distal cranial aspect, rather than the proximal caudal aspect, following a transition from dirt to synthetic tracks. Other, less evident aspects contributing to MSI during racing and training include horse (age, sex, return to training following rehabilitation, specific shoes and previous injury), trainer (work regimens), racetrack (surface, maintenance, temperature, moisture, hardness, racing class and race length) and jockey-related (experience) factors (Verheyen and Wood, 2004, Carrier et al., 1998, Verheyen et al., 2006a, Parkin, 2011, Peterson and McIlwraith, 2008).

Nonetheless, the impact of both training and track surfaces has consistently been proposed as more influential in causing injuries compared to other factors, although there is limited research on this topic (Verheyen and Wood, 2004, Verheyen et al., 2006a, Parkin et al., 2004b). Both aspects of racehorse management are considered modifiable risk factors (Georgopoulos and Parkin, 2017). The adoption of alternative training approaches has become widespread in Australia and may also contribute to lowering the risk of injury. Both treadmill and swimming training methods specifically target reducing the cumulative load from ridden exercise while simultaneously improving cardiovascular fitness and oxidative muscle capacity (Misumi et al., 1994, Misumi et al., 1995). The evidence on high-speed treadmill exercise supports adaptive bone modelling and shows a positive correlation with enhanced racing performance when compared to horses exercising on the ground (Kobluk et al., 1996). In the context of swimming, the intensity of exertion was described as similar to that of a fast trot or slow canter rather than gallop, resulting in reduced stress on the skeletal system, offering a less adaptive loading (Murakami et al., 1976). There is limited research on the relationship between walking distance and injury occurrence. However, Bolwell et al. (2012) demonstrated that an increase in time spent on mechanical walkers resulted in a higher risk of involuntary interruptions to training (including MSI and dorsal metacarpal disease).

1.5 Training practices

Racehorses undergo daily training in cohorts organised by age, experience, and fitness level. A horse in full race training would typically engage in slow workouts at canter pace 6 days per week and perform high-speed or 'breeze' workouts at gallop pace 2-3 times a week, depending on its racing schedule. Thoroughbreds initiate their training at the age of one, focusing primarily on canter work to promote physical development. The race preparation phase spans from the yearling sales in October of the horse's first year until a few months into their second year. Thoroughbreds are universally considered one year older on the first day of January each year in the Northern Hemisphere (or first day of August in the Southern Hemisphere). This practice is intended to align with the breeding season, aiming to produce foals as early as possible in the year to ensure physical maturity before entering the racetrack as 2-year-olds. Following the completion of their foundational training and adequate exposure to starting stalls, Thoroughbreds begin racing at the age of two.

Training programs vary among different yards, but they all have a shared objective: to optimise and develop specific physiological capabilities necessary for a particular type of exercise, with the ultimate goal of winning races (Bayly, 1985). Whether focused on long-distance or short distance horseracing, the physiological demands differ significantly.

Exercise programs generally aim to achieve four key objectives:
(1) Increase stamina/endurance
(2) Increase speed
(3) Increase muscular strength
(4) Delay the onset of fatigue due to exercise (Marlin and Nankervis, 2013)

Racehorse training stands apart from other equestrian sports (e.g. endurance, eventing, show jumping, dressage, reining etc) due to variations in energy demands, biomechanical function, thermoregulation, and training strategies, particularly in terms of aerobic energy utilisation. Each exercise session is customised by the trainer to consider factors such as the optimal age to initiate training, the specificity of workouts (e.g. speed versus stamina), the selection of horses and the progression of individual racehorse fitness (Hodgson and Rose, 1994).

Racehorses require substantial energy for both efficient gait and high-speed sprinting. This energy is derived from two distinct metabolic pathways: aerobic and anaerobic. The utilisation of such pathways contributes to the horse's explosive power and stamina (Williams, 2015). These pathways differ in terms of the availability of oxygen and the efficiency of energy production.

The aerobic pathway relies on oxygen to break down nutrients, primarily fatty acids and carbohydrates, to produce energy in the form of adenosine triphosphate (ATP). In racehorses, the aerobic pathway is primarily responsible for providing sustained energy during moderate-intensity exercise, such as long-distance gallops and endurance rides. During aerobic metabolism, fatty acids are broken down in the mitochondria of muscle cells through a process called beta-oxidation, while carbohydrates are metabolized through glycolysis and the citric acid cycle. The aerobic pathway yields a large amount of ATP per molecule of nutrient, making it an efficient energy source for prolonged activities.

While the anaerobic pathway operates in the absence of sufficient oxygen and is utilised during high-intensity, short-duration efforts, such as sprints or intense bursts of speed. In racehorses, the anaerobic pathway primarily relies on the rapid breakdown of stored carbohydrates (glycogen) in muscle cells to produce energy. Anaerobic metabolism involves glycolysis, where glucose is converted into pyruvate in the cytoplasm of cells, followed by the conversion of pyruvate into lactate or lactic acid. While the anaerobic pathway produces ATP quickly, it is less efficient than aerobic metabolism and generates lactate as a byproduct. Accumulation of lactic acid in muscles leads to difficulties in sustaining physical exertion, commonly referred to muscular fatigue or 'heaviness' in human physiology (Sahlin, 1986). The ability to maintain high-intensity exercise is thus associated with the capacity to either prevent the production of lactic acid or enhance its metabolism to minimise accumulation.

1.5.1 Continuous versus interval training

Various training models offer guidance to trainers for conditioning their horses for specific disciplines, such as flat racing, and optimising performance in particular events including short and long-distance flat racing. The racing industry primarily employs two main training protocols: continuous training (CT) and interval training. These protocols differ in intensity, duration, and frequency, with the resulting "training effect" arising from a combination of these factors (Bayly, 1985).

Continuous training (CT), the traditional form of training, involves prolonged workouts at low intensity or submaximal speed. Often associated with "endurance training", CT is implemented during the preparatory period of an equine athlete to enhance fitness and stimulate metabolic, cardiovascular, and musculoskeletal adaptations. The goal of CT is to improve the horse's aerobic capacity, measured as cardiorespiratory fitness by VO_2max. VO_2max (ml/min/kg) represents the optimal rate at which heart, lungs and muscles can efficiently use oxygen during exercise. The intensity and duration of CT vary day-to-day, that is, ranging from walking or galloping over longer distances than races to completing a single fast gallop or "breeze" at or above racing speed over a shorter distance than that of race-day. This variety aims to develop or enhance the horse's anaerobic capacity (Bayly, 1985).

Advancements in human sports physiology have gradually introduced interval training (IT) to equine conditioning (Derman and Noakes, 1994). IT entails exercise sessions with alternating segments of high intensity and periods of recovery at slower speeds. Previous research indicates that short recovery periods (i.e. less than 2 minutes) enhance oxidative recovery within the muscles (Eto et al., 2004a). The advantage of IT lies in enabling athletes to perform multiple bouts of strenuous exercise at a specific intensity and cumulative time, unlike CT, which may lead to a quicker onset of fatigue. The primary goal of IT is to enhance both aerobic and anaerobic performance, benefiting cardiorespiratory, muscular, and metabolic functions. Anaerobic capacity is defined by the total energy output from anaerobic (without oxygen) systems, combining ATP, phospho-creatine, and lactic acid systems. Additionally, Stover (2003) found evidence that breeze work, a short high speed gallop, possibly better prepares racehorses for the skeletal stresses involved in racing. However, few studies have compared Thoroughbred fitness following IT with other training types (Knight et al., 1991). In conclusion, both IT and CT contribute to equine fitness, provided both approaches are conducted at the same workload, considering fewer galloping strides for CT (Bronsart et al., 2009).

1.5.2 Example of training model

Thoroughbred trainers tailor their exercise routines to enhance both racehorse endurance and speed, focusing on the appropriate utilisation of aerobic and anaerobic energy pathways. Derman and Noakes (1994) proposed one of the first training models that incorporates the following three phases, a framework still widely adopted by Thoroughbred trainers globally.

Phase 1: Endurance training

This initial phase, spanning several weeks, involves workouts at slow speeds (i.e. trot 14-25km/h (Starke et al., 2013), canter ~40 km/h (Verheyen et al., 2006b)) over varying long distances, depending on individual trainer preferences. In Australia, this slow-speed training spans 4-5 weeks, with horses trotting and cantering over 3-5km on a typical training day, followed by faster work at speeds of 20 seconds per furlong. Early training preparation for 2-year-olds in Australia is a sensitive topic, as prolonged exercise distances over short periods of time correlated to the increased risk of developing joint pathologies such as dorsal-metacarpal disease (Verheyen et al., 2005). Most Thoroughbreds then typically canter over 10km at about 30km/h in one bout, six days a week, following a suitable 3- to 5-month pre-training and adaptation period. Balancing adaptive advantages and the financial cost of prolonged training duration is crucial. In hot and humid environments, endurance training is divided into 10- to 15-minute sessions to mitigate the risk of exhaustion from hyperthermia or heat stroke.

Slow-speed training usually also includes a phase at a faster speed to provoke physiological adaptations in the racehorse. The duration and intensity of this approach vary based on the trainer, horse, track and climate. Prolonged exercise at such speeds, with gradual intensity increases every few weeks, is likely the most physiologically appropriate. Endurance training triggers a rapid increase in maximal oxygen consumption (VO_2max) within the initial weeks, along with improvements in maximal aerobic capacity. During this period, bone strength and soft tissues also develop in the racehorse’s limbs, although the optimal duration or intensity of exercise for adaptive responses in bone or soft tissue remains unknown.

Trainers employ various methods for racehorse endurance training, including treadmill exercise at trot and canter, jogging behind trucks or swimming. However, sufficient ridden work is essential to shape the horse’s behaviour and physical adaptations. For instance, a 14-week treadmill program has shown effects on the third metacarpus bone quality in 13- to 14-month-old Thoroughbred horses (McCarthy and Jeffcott, 1992), indicating adaptive responses in the cortices of the metacarpal bones compared to unexercised controls (i.e. increased subcortical bone, bone mineral content and bone stiffness). The “overload” principle supports optimal bone adaptation, emphasizing a gradual increase in the training stimulus every 2 to 3 weeks to allow for adaptation before introducing further stress. Common issues like bucked shins and periodic inappetence are often associated with Thoroughbred training and may result from a rapid increase in training intensity, causing stress without sufficient time for necessary adaptation.

Phase 2: Combined aerobic and anaerobic training.

This phase involves training at 70-80% of the racehorse’s maximal speed (i.e. a gallop up to ~60km/h (Verheyen et al., 2006b)). During this phase, there is an accumulation of lactate in both the muscles and blood of racehorses, as muscle cells employ anaerobic glycolysis to promptly supply ATP in response to the need for energy. Exercise at speeds generating high blood lactate concentrations (i.e., 5-20 millimoles per Liter; mmol/L), values comparable to those observed after racing, cannot be sustained for extended periods or reproduced daily. Frequent attempts to replicate such exercise can lead to various states of overtraining including lameness, weight loss, inappetence, loss of interest in racing and/or poor performance (Morrice-West et al., 2020). However, this training is essential for initiating muscular adaptations, enhancing the capacity for anaerobic ATP resynthesis, and likely increasing the percentage of type II fibres and enzyme concentrations involved in anaerobic metabolism.

Australian racehorse trainers employ a strategy of alternating between slow and fast workouts. Slow workouts entail horses exercising over 5.5km at speeds ranging from 14-25km/h, corresponding to trot and slow canter. Fast workouts are conducted at velocities of 43-57km/h over 1-2km after a warmup of approximately 1km. Training strategies aim to increase the volume and intensity of exercise to stimulate anaerobic glycolysis while avoiding fatigue and overtraining. Some training sessions may include increased training distance or frequency, as well as the use of terrain inclination at 5-10% (e.g., a hill or treadmill). Many horses in Australia train on distances shorter than those during races. The assumption is that Thoroughbreds can successfully perform at top speeds over 1km at least once a day for five days per week, in addition to daily treadmill exercise. Treadmill exercise typically involves 1.6km of trot and slow canter, with 3-minute rest periods, followed by a fast canter workout over 1.2 – 1.6km (blood lactate concentrations of about 4 mmol/L).

Phase 3: Anaerobic training

In horseracing, achieving peak speed requires significant acceleration, regardless of the race distance (Hodgson, 2014). Traditionally, the training of Thoroughbreds has given minimal attention to aspects of speed and acceleration. The majority of high-speed exercise follows workouts at submaximal speeds. For instance, horses may cover distances of 600-1600m at 14-16 seconds per furlong and then gallop over 200-600m at 95%-100% of their peak speed. Employing 'interval-training' techniques, which may include even shorter sprints lasting around 40-45 seconds duration, is considered most effective for improving anaerobic capacity and lactate threshold. Trainers gradually increase the number of these intervals every 2 to 3 weeks, with intensive training days limited to two sessions per week.

1.5.3 Alternative approaches to track work

Many trainers have incorporated alternative approaches to traditional ridden track work into their exercise programs. Land treadmills, for instance, offer a consistent and firm surface for the exercising horse, eliminating the constraint of the rider's weight. This setup allows the trainer to control climatic conditions and the speed of the workout effectively (Kobluk et al., 1996, Harkins and Kamerling, 1991). Swimming is another modality that can be integrated into a horse's training program. Swim training, by virtue of the buoyancy of water counteracting the effects of gravity, reduces the frequency of limb injuries associated with weight bearing forces (Misumi et al., 1994). Additionally, hill work or inclined treadmill exercises reduce the speed at which horses exercise, contributing to strengthening efforts and lowering the risk of injuries (Self et al., 2012).

In a survey conducted by Morrice-West et al. (2018) with 66 registered Thoroughbred trainers in Victoria, Australia, results indicated that swimming, followed by mechanical walkers, were the most commonly used alternative exercises. These findings align with observations by Walmsley et al. (2011), emphasizing their widespread use in Australasia. Bolwell et al. (2013) described the practices of 14 New-Zealand trainers, revealing that horses entering races complete a median of one swim per day before racing starts, with a median session of 40 minutes on mechanical walkers.

1.6 Equine exercise physiology

Exercise physiology encompasses the study of all systems within an individual including cells, tissues, organs and whole systems, involved in exercise (Marlin and Nankervis, 2013). These have been explored in various athletic species including humans, dogs and camels. Among mammals, horses and specific canine breeds (i.e greyhounds) present evolved superior athletic capabilities (Poole and Erickson, 2011, Derman and Noakes, 1994).

1.6.1 Exercise testing

Exercise testing is a method that evaluates the physiological and biomechanical responses to exercise, as well as the physical ability of an individual, typically during a standardised exercise or benchmark test (Galik, 2013). Two forms of exercise testing can be performed for any athlete: clinical exercise testing and performance exercise testing. In horses, clinical exercise testing allows veterinarians to assess vital organ function, particularly the cardiorespiratory system, and make corresponding diagnostic evaluations (Hinchcliff et al., 2013). Performance testing, on the other hand, assesses both the fitness and performance of athletes. On the rise in the equine racing industry, these tests are usually conducted in apparently healthy horses and aim to guide trainers in evaluating fitness and refining training programs. In elite human athletes, continuous performance testing aims to optimize training program design, mitigate injury or illness risks, extend career longevity, and enhance overall sports performance (Newton et al., 2008).

The motivations behind applying performance testing for racehorse trainers are diverse and include:

(1) Comparing horses within a cohort for performance prediction.

(2) Monitoring individual horses over time to assess responses to training.

(3) Verifying the effectiveness of a set training program in preparing the horse for racing.

Studies have identified that certain routine training programs in racehorses and eventers may ‘overprepare’ the horse for racing or competition (Serrano et al., 2002, Kingston et al., 2006), potentially leading to injuries (Evans, 2007b).

1.6.1.1 Treadmill versus track testing

Exercise testing can take place in various settings, either to assess fitness or to identify underlying clinical pathologies. In human athletes, exercise testing is commonly conducted in controlled environments, such as a laboratory, treadmill or on an ergometer machine resembling an indoor fitness bike. These controlled settings facilitate the comparison of a broader range of physiological parameters, allowing for referencing against previous benchmark tests conducted in the same environment. Outdoor testing can also be conducted on specific training tracks and typically involves equipment such as a backpack with an integrated, connected mobile device. The use of different settings offers unique advantages and disadvantages, which will be further discussed (Barker and Armstrong, 2011).

1.6.2 Introduction of physiological tracking devices to racehorse training

In the past three decades, advancements in high-speed land treadmills and techniques for recording physiological function during exercise have significantly enhanced the study of equine exercise physiology. The first equine treadmill, developed in the 1960s to study Swedish trotter horses, marked a significant milestone (Hodgson and Rose, 1994). Since then, the popularity and use of high-speed treadmills has grown among veterinary research institutions and other equine training settings (Nankervis et al., 2017). Treadmill research has expanded the understanding of physiological responses to exercise, encompassing cardiovascular, respiratory, metabolic, thermoregulatory, hematologic, and hormonal functions at various distances and intensities (Hodgson and Rose, 1994). From a practical perspective, measurements including arterial blood gases, blood lactate concentrations and heart rate obtained different sub maximal treadmill speeds offer insights into training responses.

Land treadmills provide a controlled environment for precise measurement of various physiological variables during specific exercise protocols. The controlled setting allows for the repetition and reproducibility of speeds and durations for each exercise step. Easy access to horses during and after exercise facilitates cardiorespiratory measurements and blood collections. However, treadmills present limitations in contextualising racing conditions and require prior acclimatisation of the horse to the treadmill and environment. Treadmills also reproduce an artificial and mechanical setting, thus lack elements pertaining to air movement, ground surface variations (i.e. grass or dirt), momentum and the impact of the rider (Hodgson and Rose, 1994). Therefore, treadmill work cannot be precisely extrapolated to outdoor track work or race conditions.

Persson (1967) developed the first standardised exercise protocol for assessing exercise capacity in horses, incorporating measurements of heart rate, oxygen uptake, blood lactate levels and total red cell volume. This study, conducted on Swedish trotter horses in both track and treadmill conditions, laid the groundwork for subsequent research analysing cardiovascular responses during treadmill exercise tests. Two standard protocols emerged, one utilising an incremental velocity test and the other focusing on a single step exercise test (Evans, 2007a). These protocols have widely been adopted for evaluating exercise programs in Thoroughbred and Standardbred racehorses. Initially designed for endurance horses, these tests aimed to optimise training regimens for peak performance in races (Fraipont et al., 2012).

Subsequently, physiological responses such as HR on both track and treadmill were studied, standardised and associated with specific equine disciplines (Navas de Solis, 2019). The measurement of standard variables such as HR and blood lactate concentration at various submaximal treadmill speeds allows for the identification of training responses and the calculation of derived values such as the speed at a HR of 200 beats per min (V200) and the speed at a blood lactate concentration of 4 mmol/l (V). While variables like stride length and stride frequency can be extrapolated, their correlation with training and performance remains unexplored (Couroucé, 1999).
In the early 1980s, the introduction of human radio telemetric heart rate monitors and portable lactate analysers validated their suitability for exercise testing in human athletes (Foster et al., 2017, Larsson, 2003). These portable devices rapidly found applications across various equine disciplines, providing insights into exercise capacity and track conditions (Fraipont et al., 2012, Hodgson, 2014).
In recent years, significant technological advancements have led to increased availability of portable diagnostic equipment for assessing athletic performance. Vermeulen and Evans (2006) emphasized that parameters such as heart rate (HR) and real-time velocity offer a method for routine fitness studies in the field. Alongside the proliferation of portable diagnostic equipment, field investigations offer the primary advantage of reflecting the natural environment and daily exercise routine of the horse. Surface variations, gaits and speeds closely mimic the demands of the sport, enabling the evaluation of jockey interaction and track modifications. Field tests also provide cost advantages over treadmill tests and do not disrupt routine training schedules, contributing to greater owner acceptance. However, the main limitation of field tests is the challenge of standardising conditions (e.g., track going, surrounding environment), which may introduce potential confounding factors that could bias interpretation.

Traditionally, trainers assess the physical condition and readiness of their horses on the track through a combination of visual observation, feel, rider feedback and expertise (De Maré et al., 2017). However, this subjective monitoring approach may reveal inconsistencies and lacks objectivity. With the evolution of the equine industry and ongoing scientific research, there has been a transformative shift in the training and health management of equine athletes. Traditional practices, rooted in tradition, experience and rider feedback (Ely et al., 2010), are now gradually being supplemented with scientifically proven, objective measures across various equine disciplines (Bitschnau et al., 2010, Rogers and Firth, 2004, Williams, 2013). The introduction of the Kruuse Televet 100 system marked a significant milestone as the first commercially available device capable of recording electrocardiogram (ECG) parameters during field testing (Fraipont et al., 2012, Hodgson, 2014). This system required an additional

Global Positioning System (GPS) for recording speed and distance travelled. Lactate analysers also emerged as a simple method to investigate the effects of different exercise intensities and the training response in equine athletes. Evans et al. (1993) demonstrated the correlation between blood lactate concentrations and Thoroughbred performance quality. Subsequently, devices with integrated GPS, such as the Polar Equine system, replaced traditional stopwatches. Validation studies, albeit relatively small (n=10 horses), confirmed their utility in measuring speed during training (Kingston et al., 2006, Williams et al., 2019). Several equine studies provided satisfactory evidence of their usefulness in assessing fitness (Kingston et al., 2006) and performance (Gramkow and Evans, 2006) based on the linear relationship between heart rate and exercise intensity (Fonseca et al., 2010). Ille et al. (2014) affirmed the appropriateness of combining both systems for accurate recording measures in horses. Most of these HR devices offer storage mechanisms (with the capacity to review the effect of training on heart rate after exercise), transmission capabilities (i.e. telemetry from the monitor to a recorder or screen), records of distance travelled, practical designs (e.g. wristwatches) and effective application to the horse through electrodes placed over the withers and ventral midline under the girth, utilising electrode gel or concentrated saltwater solution to improve electrical transmission of heart rate signals.

The below table by Kee et al. (2023) provides an overview of the commercially available technologies for racehorses and their reported capabilities (Table 1).

Table 1 Summary of commercially available technologies for racehorses and their reported capabilities (Kee et al., 2023)

	Cardiovascular biometrics				Respiratory biometrics			Thermometry	Locomotor profile			Movement tracking		Device features					
Devices	HR[c] (bpm)	HRV[d]	ECG[e]	Heart sounds	Respiration frequency	Blood oxygen saturation	Lung sounds	Body temperature	Stride length	Stride frequency	Sectional times	GPS[f]	Accelero-meter	Wearable	Wireless	Real-time measure-ments	Remote monitoring	Scientifically validated	Battery life
E-Trakka	✓								✓		✓	✓	✓	✓	✓	✓	✓	✓[g,h,i,j,k]	10 h
EKuore 1-lead digital cardiac monitor	✓	✓	✓													✓	✓[a]	✓[g]	Not stated
Equimetre by Arioneo	✓	✓	✓						✓	✓	✓	✓	✓	✓	✓	✓	✓	✓[g,h,i,j,k]	20 h
Equinity by Equinity Technology	✓								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓[g,h,i,j,k]	16 h
Motion sport by Equisense	✓								✓	✓		✓	✓	✓	✓	✓[b]			30 h
Nightwatch	✓				✓							✓	✓	✓	✓	✓	✓		12 h
Smart Bit by Equine Smart Bit	✓				✓	✓		✓					✓	✓	✓	✓	✓		40 h
Stridemaster									✓	✓	✓	✓	✓	✓	✓	✓	✓	✓[g,h,i,j,k]	Not stated
Tail Tab by Epona Biotec								✓						✓	✓	✓	✓[a]		480 h
VetCheq by PonyUp Technologies	✓				✓									✓	✓		✓[a]		Not stated

Wearable fitness tracking devices, validated to measure physical activity, physiological and biomechanical variables, have gradually been incorporated in horses at rest (Williams et al., 2019). Another innovative device, the ‘Equimetre™’ (Arioneo Ltd, Paris, France), integrates heart rate, GPS, ECG and provides additional information on heart rate variability (ter Woort et al., 2021) and locomotion. The increased availability of connected monitoring devices enhances the expertise of trainers and veterinary professionals. A more integrated interpretation of generated data allows for tailored training regimes, optimising performance while minimising injuries. These systems undeniably aid the decision-making regarding appropriate training regimes and the selection of suitable race entries.

1.7 Performance indicators

Race performance is a key factor determining a horse’s value and influences decisions related to future career plans, breeding and retirement. Training methods have evolved to include quantitative assessments aimed at evaluating the athletic potential of racehorses. Physiological indicators of athletic performance include muscle fibre and enzyme activity (Ronéus et al., 1999), blood lactate concentrations, heart rate and oxygen consumption (Harkins et al., 1993, Evans, 2007a).

1.7.1 Maximal oxygen uptake

Brandon and Boileau (1992) established a correlation between VO_2 max and athletic performance, with VO_2 Max representing the maximum volume of oxygen a horse can utilise during exercise. In a laboratory setting (e.g. overground treadmill), maximal oxygen consumption is measured in horses undergoing submaximal tests using open or biased-flow systems (Bayly et al., 1987) or breath-by-breath systems (Curtis et al., 2005). Few commercialised systems are suitable for measuring high flow and respiratory rates in the field. One portable breath-by-breath gas analyser was employed for VO_2 measurement in horses exercising in the field (Art et al., 2006, Van Erck et al., 2007). However, the resistance of the mask decreased ventilation during exercise, hindering horses from reaching maximal exercise (Van Erck et al., 2007). An alternative system used by Sides et al. (2014) produced results similar to those of an open-flow system. Expressed in ml/min(/kg), horses reach VO_2 Max at their maximum speed (Harkins et al., 1993). A higher VO_2 Max indicates the horse’s ability to endure physical effort for a more extended period. VO_2 Max varies with genetics, age, sex, training level and time of the year. Incorporating VO_2 Max into longitudinal monitoring routine provides insights into the horse's progression over time, quantifying the energetic cost of each effort.

During racing, horses surpass the speeds which VO_2 Max is reached, leading to a build-up of blood lactate. Research by Mercier and Aftalion (2020) suggests that VO_2 Max is attained within 20 to 30 seconds of a race's start. They emphasize the importance of maintaining VO_2 Max throughout the race for optimal performance, particularly during sprint starts in long races. In training, considering VO_2 Max aids in establishing race strategies. For instance, a soft canter typically requires about 50% of VO_2 Max, while galloping requires 90 to 100%, reaching up to 115% during a sprint (Bermann, 2010). The challenge for trainers lies in enhancing the speed at which VO_2 Max is reached, as trained horses exhibit lower VO_2 values for the same exercise compared to undertrained horses with higher VO_2 Max. Routine measurement of VO_2 Max in athletic horses is impractical due to the controlled environment requirement (e.g., land treadmill), making indirect measurements preferable.

1.7.2 Heart rate

Assessing HR responses in the field, depending on the equine discipline, provides valuable insights into fitness and exercise intensity. HR responses to exercise may be influenced by health status and inherited factors like breed and body conformation (Marlin and Nankervis, 2013). Horses with superior athletic capacity tend to reach HR Max at faster speeds. Comparable to findings in highly trained human endurance athletes exhibiting faster heart rate recovery (Hagberg et al., 1980), simultaneous measurement of HR and speed, such as through HR and GPS monitors, enables the calculation of variables such as the speed at which maximal HRmax is reached (VHRmax) and the speed corresponding to a heart rate of 200 beats/min (V200).

Contrary to VO_2 Max, no direct correlation has been established between VO_2 Max and HRmax, but a relationship exists between %VO_2 Max and %HR Max (Evans, 1987). In situations where VO_2 Max measurement is impractical, VHRmax serves as a useful fitness indicator correlated with VO_2 Max (Evans, 1987). Notably, horses with superior athletic capacity tend to reach HRmax at peak speeds, with studies indicating that VHRmax correlates with race earnings (Gramkow and Evans, 2006). Another indicator, V200, is easily measured during submaximal exercise tests, although its utility is limited to the variability in HR max among individual horses. For instance, in sport horses, V140, V170 or V180 are recommended when HR as high as 200 beats/min is not achieved, and consecutive measurements of these

VHR variables over time can evidence fitness improvement during a training regime (Vermeulen and Evans, 2006).

Traditionally, speed and HR assessments involved standardised stepwise exercise tests, allowing HR to reach a steady state at each speed. While such tests are common in treadmill settings and with Standardbred racehorses on the track, replicating them in Thoroughbred flat training poses challenges due to shorter distances. Vermeulen and Evans (2006) explored the pairing of HR and speed measurements during continuous exercise, which is more applicable and can be integrated into typical ‘fast’ Thoroughbred workouts. GPS measurements of speed and distance may not be ideal for confined spaces such as arenas, especially at peak speeds (Coutts and Duffield, 2010, Duffield et al., 2010).

1.7.3 Blood lactate

Blood lactate, a byproduct substance of anaerobic muscle metabolism, serves as a key indicator of a horse’s aerobic and anaerobic capacity. Its measurement in field training is crucial for assessing training intensity and performance (Eto et al., 2004b). This parameter is paramount in evaluating the onset of lactate accumulation, identifying the anaerobic threshold, and measuring overall fitness in equine athletes (Williamson et al., 1996). When horses engage in high-intensity workouts or sustain maximal effort for 20–120 seconds, blood lactate levels reach the anaerobic threshold, indicating the point at which energy production becomes anaerobic (Clayton, 1991). Short-term supramaximal exercise induces intramuscular lactate production in racehorses, and the onset of fatigue, marked by a rapid rise in blood lactate post exercise (Hinchcliff et al., 2008), becomes a performance-limiting factor (Hodgson and Rose, 1994).

At rest, blood lactate levels range from 0.5 – 1 mmol/l. During exercise, the relationship between blood lactate and speed forms an exponential curve (Kronfeld et al., 1995), and deviations from this curve indicate an imbalance between lactate production and metabolism in the horse’s body. This imbalance typically occurs at blood lactate concentrations of 2–4 mmol/l, with 4 mmol/l commonly designated as the onset of blood lactate or anaerobic threshold (Campbell, 2011). Peak blood lactate concentrations in horses can be significantly higher than those in human athletes, reaching values of 25–30 mmol/l in Thoroughbred horses after maximal workouts (Harris et al., 1987). Peak lactate levels are typically observed around 5 minutes after exercise due to the outward flow from muscles (Marlin, 1991).

When comparing measures between a cohort or individual horses, standardising the methodology and sampling site is crucial to avoid influencing the results (Lehnhard et al., 2010). Differences exist between whole blood and plasma lactate concentrations, with plasma lactate approximately 1.5 times greater than whole blood lactate. While jugular venepuncture is the conventional method for sample collection, portable hand-held lactate, though relatively expensive, offer immediate analysis in the field (Lehnhard et al., 2010). Two approaches are commonly applied for blood lactate assessment. The first involves calculating the speed at which a lactate concentration of 4 mmol/l is reached (VLa4), providing insights into aerobic capacity and performance potential. The second approach measures lactate concentrations after a single bout of submaximal exercise or during intense exercise fatigue, serving as an indicator of anaerobic capacity (Davie and Evans, 2000, Lehnhard et al., 2010). Routine monitoring of VLa4 during a training program helps trainers assess their horses' fitness, with incremental exercise tests on both treadmills and field conditions providing valuable data (Couroucé, 1999, Lindner, 2007). The suitability of these tests depends on factors like step duration, emphasizing the importance of controlled conditions for accurate blood sampling (Lindner, 2007).

1.8 Physiological data recorded by the Equimetre fitness tracker

The table below presents an overview of the parameters analysed in the subsequent chapters of this thesis; providing a summary of data collected from the Equimetre fitness tracker (Table 2).

Table 2 Overview of racehorse speed, stride and heart rate parameters collected through the Equimetre fitness tracker

Parameter	Description	Unit	Source type
200m	Time taken to cover the distance of 0-200 meters	seconds	derived
400m	Time taken to cover the distance of 200-400 meters	seconds	derived
600m	Time taken to cover the distance of 400-600 meters	seconds	derived
800m	Time taken to cover the distance of 600-800 meters	seconds	derived
1000m	Time taken to cover the distance of 800-1000 meters	seconds	derived
1200m	Time taken to cover the distance of 1000-1200 meters	seconds	derived
1400m	Time taken to cover the distance of 1200-1400 meters	seconds	derived
Best 1000m	Fastest time recorded for covering 1000 meters	seconds	derived
Best 800m	Fastest time recorded for covering 800 meters	seconds	derived
Best 600m	Fastest time recorded for covering 600 meters	seconds	derived
Best 400m	Fastest time recorded for covering 400 meters	seconds	derived
Best 200m	Fastest time recorded for covering 200 meters	seconds	derived
Max Speed	Maximum speed recorded	km/h	derived
HR peak	Maximum heart rate recorded	BPM	derived
HRauc	Area under the curve of heart rate or overall HR	BPM	calculated
Delta HR	Rate of recovery	value	calculated
HRR	Heart rate recovery	BPM	calculated
HR at 15 min	Heart rate during recovery at 15 minutes, estimated based on a model	BPM	derived
Cardiac flexibility	The ability of the horse's cardiovascular system to quickly adjust heart rate during recovery from exercise, with higher values indicating a greater ability to return heart rate to baseline	value	n/a
Peak Stride Frequency	Highest recorded stride frequency	strides/sec	derived
Peak Stride Length	Maximum recorded stride length	meters	derived

The validity of the Equimetre for heart rate monitoring, thus ECG, was evaluated against the Televet system in 49 exercising horses and was concluded reliable including for arrythmia detection (ter Woort et al., 2021).

As far as locomotion is concerned, the company has integrated algorithms developed in the 90s by Barrey et al. (1995). There are also internal validations which the company could not disclose to include in this thesis, for obvious intellectual property reasons. Stride information is captured by gyroscope (i.e a device that measures orientation and angular velocity) and accelerometer sensors. The stride length calculation combines data from both sensors. The tracker can provide a stride length estimate by analysing the time taken for a full stride cycle and the associated acceleration/deceleration.

Speed measurements rely on a commercially available integrated system, combining GPS (USA), GLONASS (RUS) and GALILEO (EU) constellations. This network of satellites is used to determine the precise location of the tracker and thus the horse. Speed calculation can then be deducted by tracking the horse’s position on the track at regular intervals and the change in location over time. The device constructor reported a high accuracy of < 2.5 meters for distance in 50% of the trials and a high accuracy of 1.5meters @CEP (Circular Error Probable), open sky conditions for 24 hours. Thus, there is a high probability that the actual location or measurement will fall within a circle with a radius of 1.5 meters around the target or intended position, indicating the precision or reliability of the Equimetre system in determining locations or measurements.

1.9 Data collection

For the Chapters 2-5, data collection occurred retrospectively for all the available parameters, as part of the company’s database. The trackers were fitted to the horses by trained stable personnel and thus, data was directly collected by users of the Equimetre (i.e riders or racehorse trainers). As the individual studies developed over time, the parameters and algorithms of the company’s database were constantly upgraded and refined. Therefore, separate databases were provided for each study.

The Equimetre comprises of two fixing systems, the first is an all-in-one system. One electrode is placed under the girth, close to the heart, and the other electrode is positioned under the saddle pad. The second system consists of a strap with two electrodes, one close to the heart and the other to the right of the withers. The girth is connected to the device unit secured at the right rear of the saddle pad by a wired cable. The electrodes are positioned as previously illustrated below, by ter Woort et al. (2021) (Figure 1a).

Figure 1 The Equimetre fitness tracker set up on a horse (ter Woort et al., 2021)

A **B**

The patented electrodes (patent number PCT/FR2017/053028) allow a sampling frequency of 500 Hz. Their design consists of large rectangles of conducting small soft rubber spikes and a foam (Figure 1b). The soft spikes at the surface of the electrode, penetrate the hair and maximise the contact surface also reducing movement over the horse's skin. While the foam collects sweat to improve overall electrode conductivity.

1.10 Statistical models

When comparing large datasets of animals retrospectively, various statistical models may be employed depending on the specific research questions and characteristics of the data. Commonly used models are briefly described below along with their main advantages and disadvantages.

Cox proportional hazards regression, or Cox regression, is a statistical method used in survival analysis to examine the association between covariates and the time until a specific event (e.g., death or disease) occurs. It allows for the incorporation of time-dependent covariates and censoring. However, interpretation can be challenging for individuals not familiar with survival analysis concepts. Assumptions such as proportional hazards need to be assessed and, if violated, may lead to biased results.

Logistic regression is another statistical model used to analyse the association between a binary outcome (e.g., alive/dead, success/failure) or categorical (e.g., disease/no disease) and one or more predictor variables, estimating the probability of the outcome. It provides interpretable odds ratios that quantify the association between predictor variables and the outcome. However, it may not capture time-to-event data directly and may not be suitable if the outcome is not binary or categorical.

Generalised linear models adopt a more flexible approach, involving linear regression to handle non-normally distributed response variables by specifying a link function and a probability distribution. Such models can accommodate various types of outcome variables (e.g., continuous, binary, count data) by specifying different distributions and link functions. However, model selection and interpretation can be complex, particularly with large datasets and many potential predictors.

Propensity score matching method can be used to reduce selection bias in observational studies by matching treated and control subjects based on their propensity scores (i.e., the probability of receiving the treatment given covariates). It can be useful for comparing outcomes between treated and control groups in retrospective studies. However, it requires careful selection and matching of covariates, and the validity of the results depends on the adequacy of the propensity score model and the quality of the matching.

Time series analysis techniques can be used to analyse longitudinal data collected over time, such as repeated measurements on the same animals. However, such models may require a large number of observations to accurately estimate parameters, and they assume stationarity and independence of observations, which may not always hold in animal data.

Machine learning techniques like random forests, support vector machines, or deep learning can handle complex, high-dimensional data and capture nonlinear relationships between predictors and outcomes. However, such models may require a large amount of data for training and validation, and they can be computationally intensive. Interpretability may also be a concern with some machine learning models.

The choice of statistical model will depend on the specific research question, the type of outcome variable, the structure of the data (e.g., longitudinal, time-to-event), and considerations regarding model assumptions, interpretability, and computational resources. It is necessary to assess the performance of different models using measures such as predictive accuracy, goodness-of-fit statistics, and interpretability of results. Additionally, sensitivity analyses and validation techniques can help assess the robustness and generalisability of the findings.

1.11 Conclusions

The integration of connected technologies in equestrian disciplines mark a new turn for the monitoring of equine exercise physiology. Over the last decade, commercially available fitness trackers have been integrated in routine work across leading racing yards globally, complementing the trainers' 'eye' for racehorse health and performance management. These tools facilitate the live recording of racehorses' responses to routine exercise on the track, capturing cardiovascular (e.g., peak HR, HR recovery, ECG) and locomotory parameters (e.g., speed, stride length or frequency). The purpose is to monitor an individual racehorse's performance over time or compare multiple horses amongst each other. This data tracking approach can provide valuable information for the detection of racehorse injuries, assessment of physical preparedness including responses to exercise intensity or workload (referred to as 'fitness') and determining readiness for racing. The acquisition of such quantitative data has the potential to bring racehorse training into the 21st century, embracing the era of 'Big Data'. However, a vast majority of the existing literature on equine exercise physiology has focused on small cohorts of horses (~15-20 horses), often exercised in controlled laboratory conditions such as a treadmill, with no jockey aboard. To establish comprehensive insights into physiological patterns and characteristics at a population level, particularly factors influencing race-day preparation and performance, large-scale observational studies involving hundreds of horses are essential. These studies would contribute to a more holistic understanding of equine exercise physiology in real-world scenarios, encompassing the diverse variables encountered during actual race conditions.

1.12 Study aims and research questions

The aim of this thesis was to explore the application of data science to track racehorse physiology and performance. Data science involves extracting insights from data using a combination of statistical analysis, machine learning, and visualisation techniques to ultimately inform decision-making. The present research primarily used a single dataset (a 'convenience sample') in Victoria, Australia, but was also compared against other available datasets using the same technology. Our approach involved the completion of large retrospective, descriptive studies to explore racehorse physiological patterns and other relevant factors relating to training and racing. Four separate studies were conducted, each comprising different research questions that will be briefly outlined below:

The **first study** described physiological patterns recorded during training in two large racehorse cohorts, based in Australia and France respectively. It reported the effect of increased training speed and intensity, on racehorse heart rate, heart rate recovery and stride length and frequency. This research also demonstrated the effects of varying track surface, horse age and sex (*see Chapter 2*).

The effect of the sex of the jockey on racehorse physiology and performance was investigated in the **second study**. The primary research questions of the project were: (1) whether racehorse cardiovascular (heart rate, heart rate recovery) and biomechanical (stride length and frequency) parameters at various exercise intensities varied according to sex of the rider in Victoria, Australia and (2) what effects may sex of jockey have upon win percentage and chance of a top-three placing in both UK and Australia (*see Chapter 3).*

The **third study** investigated locomotory profiles (stride length and frequency) during training and association race performance in Victoria, Australia. The study also asked whether locomotory characteristics had high heritability i.e., is a sprinter born a sprinter? The primary hypothesis of the study was: (1) racehorses categorised according to race distance (sprinter/miler/stayers) may be distinguished in training by having relatively short, medium or long stride, respectively when analysed at race speed (soft-medium-hard gallop session or 'jumpout'). Secondary hypotheses were: (2) sprinters-milers-stayers with relatively short or long stride within each category are more successful in their respective races, and (3) that locomotory parameters have moderate-to-high heritability. Finally, since many racehorses compete in different types of races (e.g., sprint, mile and/or staying race), an analysis was conducted on the extent to which locomotory profiles (e.g., peak stride frequency, length) in training evolved over time within individual horses throughout the race season (*see Chapter 4).*

The **fourth study** examined whether measures of speed (i.e., speed over the final 600m), heart rate peak and recovery during race-pace workouts on turf (hard gallop and jumpout) and other factors (sex, age and locomotory profile) were predictive of race performance (i.e., 'win' or 'lose' as primary outcome) (*see Chapter 5*).

Ultimately, this project should provide a better understanding of how data can be used and applied in the context of the training of racehorses in order to further explore racehorse physiology and performance. Such quantitative data could be used as a reference point from which, in the future, potential impacts on racehorse health and welfare and improved decision-making for all participants involved in the sport, can be determined. Given that the most common reported reason for Thoroughbred horses leaving racing stables in Australia is poor performance and illness/injury, the results from this project could have substantial implications for racehorse management and future of the sport (Thomson et al., 2014).

1.13 Thesis structure

***Chapter 1*:** A general introduction to the thesis, including a literature review on the horseracing industry, sport and performance assessment.

***Chapter 2*:** Study 1, Cardiovascular and locomotory parameters during training in Thoroughbred racehorses. Published as "Schrurs, C., Dubois, G., Patarin, F., Cobb, M., Gardner, D.S. and Van Erck-Westergren, E. (2022) *Cardiovascular and locomotory parameters during training in thoroughbred racehorses: a multi-national study*. Comparative Exercise Physiology https://doi.org/10.3920/CEP210037."

Chapter 3: Study 2, Does sex of the jockey influence racehorse physiology and performance? Published as "Schrurs, C., Dubois, G., Van Erck-Westergren, E. and Gardner, D.S. (2022). *Does sex of the jockey influence racehorse physiology and performance* PLoS ONE 17(8): e0273310. https://doi.org/10.1371/journal.pone.0273310."

Chapter 4*:* Study 3, Locomotory Profiles in Thoroughbreds and association with race success. Published as "Schrurs, C., Blott, S. Dubois, G., Van Erck-Westergren, E. and Gardner, D.S. (2022) Locomotory *profiles in Thoroughbreds: peak stride length and frequency in training and association with race outcomes*. Animals 2022 12(23) 3269 https://www.mdpi.com/2076-2615/12/23/3269."

Chapter 5: Study 4, Cardiovascular fitness and stride acceleration in race-pace workouts for the prediction of performance in Thoroughbreds.

Chapter 6: Overall discussion and implications of the work. Study limitations and future work.

Chapter 7: Bibliography.

Chapter 8: Published Papers.

Chapter 2 Study 1: Cardiovascular and locomotory parameters during training in thoroughbred racehorses: a multi-national study

2.1 Abstract

Studies assessing concurrent speed, cardiovascular physiology and biomechanical parameters in racehorses during training have been rarely reported, mostly due to a lack of available comprehensive technology. Here, using a validated device (the ‘Equimetre’™) that records all parameters simultaneously, we report the effect of increased training speed and thus intensity, from slow canter to hard gallop, on racehorse heart rate, heart rate recovery and on biomechanical parameters such as stride length and frequency. We also demonstrate the effects of varying track surface, horse age and sex. Cohorts comprised a total of 509 Thoroughbred racehorses in-training in either Australia or France, completing a total of 1,124 and 6,016 training sessions, respectively. Horses varied by age (2-9 years old) and sex (including geldings) and were trained by either a single trainer (Australia) or two trainers (France); both using multiple training centres that varied by track surface (sand, turf or fibre). Data were analysed using Analysis of Variation (ANOVA) or linear mixed-effect models as appropriate. Racehorses increased speed predominantly by an increment in stride length, then frequency, both of which varied according to track surface (shorter stride on sand; P<.001). Cardiovascular parameters (peak, and recovery of, heart rate) increased with training intensity, but not linearly (P_{trend}<.001). Older horses recorded lower heart rate at 15mins after training (P=0.002), often due to lower achieved peak heart rate at most training intensities (P<.001 for the cohort in Australia). In conclusion, this immersive field study demonstrates the value of comprehensive technology for recording physiological and biomechanical parameters of racehorses-in-training. The data could inform trainers, jockeys and owners on aspects of individual racehorse health, welfare and suitability for certain races.

2.2 Introduction

Thoroughbred racehorses have evolved, comparatively, as elite athletes. By any measure, they have superior speed, oxidative threshold and exhibit greater circulatory responses to exercise such as release of red cells from the splenic reservoir, when compared to Man (Allen et al., 2016b). Racehorses are trained consistently from two years of age to race and ideally win against other racehorses at ages two, three or older. Despite much progress in the understanding of equine sports performance, training practices remain predominantly grounded in tradition, experience, observation and the rider’s feedback (Ely et al., 2010) rather than evidence-based principles of performance (Williams, 2013). In contrast, development of human elite performance toward readiness for competition has been influenced and informed by objective feedback from a variety of training aids such as monitoring of heart rate (HR) or of recovery (HRR), or power output (particularly for cycling) for decades. Indeed, relatively recently, incorporation of variations in training intensity (e.g. high-intensity intervals during a training session) and variations in training patterns over time (e.g. periodisation of training over the racing season) have been introduced with significant gains in peak performance, accompanied by a reduction in the proportion of athletes reporting symptoms of 'over-training' or of injury (Seiler, 2010).

In part, the relatively slow adoption of training devices to monitor performance in equine athletes has been due to lack of available, validated, and accurate technology. Treadmill exercise testing is relatively straight-forward to perform, as the horse is in a fixed position and has been used for assessing cardio-respiratory responses to set testing regimes in set environments (Marlin et al., 1996). However, an individual horse galloping on a treadmill with no jockey aboard will perform significantly differently to a racehorse working on an outdoor training gallop or in a race (Bitschnau et al., 2010). Thus, to ascertain cardiovascular fitness in racehorses and increase the number of horses able to be assessed, it is important and preferable to record them working in their natural training environment. Over the last decade, a few devices have been developed for use on the freely moving, exercising racehorse. After overcoming technological difficulties associated with loss of body contact, interference and movement, the Kruuse Televet 100 system was the first device able to record ECG parameters during field exercise testing (Fraipont et al., 2012, Hodgson, 2014), but required an additional GPS device to also record speed and distance travelled. Shortly after, devices with integrated Global Positioning Systems (GPS) became more standard such as the Polar Equine system. Similar technologies were able to measure speed whilst training, albeit in relatively small studies (e.g. n=10 horses; (Kingston et al., 2006, Williams et al., 2019). A device has recently been developed that can integrate all these measures (heart rate, GPS, ECG) plus additional information on heart rate variability (ter Woort et al., 2021) and locomotion. The 'Equimetre™' (Arioneo Ltd, Paris, France) has been validated to accurately record heart rate at rest and during high-intensity training sessions and, when used in conjunction with an electrocardiogram (ECG), can also provide information on heart rate variability (ter Woort et al., 2021). Hence, the technology is now available to objectively monitor several aspects of a racehorse's cardiovascular response to a given exercise together with their rate of recovery, characteristics of locomotory function and speed before, during and after exercise. To date, however, no large observational studies have been conducted to report how such parameters may change for individual racehorses over multiple training sessions nor how they compare to horses training on different track surfaces (turf, fibre or sand) or how responses may effectively vary according to sex or age of the horse.

Racetrack surface has been shown to influence the level of training effort in racehorses (Crevier-Denoix et al., 2010) but the effect on cardiovascular physiology is unknown. Similarly, racetracks of differing surfaces may alter locomotion by affecting hoof movement, stride length and/or frequency (Burn and Usmar, 2005, Crevier-Denoix et al., 2010, Symons et al., 2014). No study has reported how differing training regimes on various surfaces may influence racehorse locomotory function including stride length and frequency. Equines, much like canines, can only breathe in synchrony with their stride during canter and gallop, due to a 1:1 respiratory-locomotory coupling (Ainsworth et al., 1997). Therefore, it could be expected that variation in stride rate may have an effect on cardio-respiratory parameters.

In the present study, the largest of its kind to date, we have conducted a multi-national, observational study, using a validated fitness tracking device to report on racehorse cardiovascular (e.g., heart rate [HR] and heart rate recovery [HRR]) and locomotory (stride length and frequency) responses to in-field training at three renowned training yards. Horses of varying age and sex were tracked longitudinally as they trained on varying surfaces throughout the year. The primary outcome of the study was to report the effect of increasing speed (slow canter to hard gallop) on heart rate, heart rate recovery after exercise and on stride length and stride frequency in racehorses-in-training, considering varying track surfaces, horse age and sex.

2.3 Material and Methods

2.3.1 Horses

Ethical approval for this study was obtained from the University of Nottingham (School of Veterinary Medicine and Science) Research Ethics Committee (REC code: 3270 201029). The study is a retrospective, observational study using datasets collected from racing stables in two countries (Australia and France), training racehorses according to the established practices of each trainer. Both study populations represented convenience samples.

Study population 1 included 275 Thoroughbred racehorses that were recruited from the same racing yard in Australia. The horses were 2 – 7 years of age. However, date of birth and thus racing age were only partially available (two; n=56, three; n=28, four; n=19, five; n=11, six;

n=6, and seven-year-olds; n=3). When recorded, the sex of the horse was coded as male (colts/stallions; n=38), female (fillies/mares; n=76) or gelding (n=52).

Study population 2 comprised 234 Thoroughbred racehorses, trained at two different racing yards in France. The horses were 2 – 9 years of age and included males (colts/stallions; n=13), females (fillies/mares; n=38), geldings (n=21) or unrecorded individuals. The respective trainers regarded all horses as race fit; that is, horses that were actively in training to sustain their fitness levels and competing in races during the study period. Each training session was evaluated based on the trainer's observation on the track, riders' feedback following exercise and the fitness tracker recordings ('Equimetre'™, Arioneo Ltd, France). Prior to the study, all trainers had integrated such systems into their work regimes. For the subsets of each cohort where age and sex were known, these were cross-checked against data available on the Racing.com and France-Galop websites.

2.3.2 Equipment

All horses were equipped with a commercialised equine fitness tracker ('Equimetre'™, Arioneo Ltd, France) during and after exercise. Horses wore their regular tack and were exercised by their usual work rider. The device was fitted prior to training by persons accustomed to the system. An electrode was fastened at the girth and the second secured under the saddle pad in the natural dip of the back, as previously described (ter Woort et al., 2021). The Equimetre uses an algorithm based upon the accelerometric recordings to detect and measure parameters associated with speed and stride (Barrey et al., 1995).

2.3.3 Training

During the study, horses were trained according to an individual and tailored programme established by the trainer. Trainers considered the most appropriate type of work and track to meet their objectives for each horse in relation to age and stage of career. In Australia (study population 1), the trainer gave target timings, to their discretion, for set distances to the riders during each type of training. A sound and light system fixed to the riders' helmet signalled the time taken to cover each furlong. Training usually occurred before daylight, with the trainers monitoring the horses from a distance, often from a watchtower, using binoculars. Subsequently, recorded Equimetre sessions were downloaded and retrospectively reviewed on a computer by the trainer. When appropriate, trainers would also time the horses' performance on the track using a manual stopwatch. Following exercise, all horses were systematically placed on a horse walker or walked in hand to recuperate. This approach formed the trainer's own exercise categorisation (e.g., soft canter to hard gallop). With target timings to cover set distances, speed could be known at any point along the track during each session, but to an extent was dependant on the jockey following the instructions of the trainer. Speed was categorised as soft canter, medium canter, hard canter and soft gallop, medium gallop and hard gallop (see Figure 2a). The training locations were on racetracks or training centres with a choice of surface including sand, turf or fibre. These latter aspects were also recorded for each training session. Using the Equimetre, data were available on speed (i.e., time taken to cover 200m in seconds) recorded for each 200m segment (at 200, 400, 600, 800, 1km, 1.2 and 1.4km using GPS satellite data). From this data, the Equimetre also calculated the fastest 200, 400, 600, 800 or 1000m segment. Using such data from the device allowed for a data-driven categorisation of speed from slow-canter to hard-gallop by taking the value for the 'fastest 200m' recorded for each individual training session following a progressive increase of speed, as opposed to an explosive sprint (see Figure 2b). This markedly reduced variability in classification of training sessions (compare Figure 2b with Figure 2a). This 'data-driven' classification of training intensity was used thereafter for all other analyses and comparisons.

For study population 2 in France, horses were exercised daily in groups according to age and level with the aim of developing their racing experience and to gradually build their fitness. The trainer would watch the horses train on the track and review the recorded sessions a posteriori on a computer. Once mounted, horses were walked to the gallops or training centres nearby (approximately a 1km walk), then "warmed up" by completing two 800-meter (4 furlongs) sessions in trot (10.1 ± 1.3 kph) or soft canter (19.6 ± 5.1 kph). After this warm-up, horses would walk 150-200m before being instructed to complete a given 'work' session at trainer defined speed for a given duration (on average, a distance of 1,765 ± 701 metres). Horses would then walk a further 150-200m before completing, if instructed to do so, a final work session, often faster than the first. Once a week, trainers would exercise individual horses "harder" by warming up as before, followed by 1500m at a medium canter (24.3 ± 1.8 kph) and a final 1000m at medium (53.8 ± 2.1 kph) to hard (58.9 ± 1.7 kph) gallop, increasing speed toward the final 500m. Similar to the Australian cohort, for analysis purposes, training sessions were divided into six categories (Canter, soft/medium/hard; Gallop, soft/medium/hard) based upon the fastest 200m achieved during each session. This enabled direct comparison to dataset 1 (Australia). In the French cohort, track surface was also recorded (sand or turf) for many of the sessions, but no training was conducted on all-weather or fibre tracks.

2.3.4 Data collection

All data collection occurred between March and December 2020 for Study population 1 and from May 2018 to June 2020 for Study population 2. Study population 1 (Australia) recorded a total of 1,124 training sessions. Each horse completed n=4 (2-7), median (first-third interquartile range [IQR]) training sessions. Study population 2 (France) recorded a total of 6,016 training sessions. Each horse completed n=20 (8-48) median (IQR) training sessions. Month of training session was recorded and from the exact date of training then the number of training sessions, and the interval between them, could be recorded for each horse. The Equimetre recorded aspects of each horse's cardiovascular responses to exercise (e.g., heart rate, HR) during trot, canter, gallop, peak heart rate (HRpeak) and HR during recovery (HR at 15 or 30 mins or at the end of training session) and aspects of locomotion (speed, stride length and stride frequency). From these live data that were instantly recorded by the device, further analyses were able to be conducted post-hoc that pertained to each training session such as the deltaHR (HRpeak – HR at 15min recovery) or overall HR area under the curve (HRauc; ([HRpeak +HR at 15min]/2)+([HR at 15min+HR at 30min]/2)+ ([HR at 30min+HR at end of session]/2)) or the recovery response (i.e. only including values to 15min). All AUC were calculated according to the trapezoid rule in Graphpad Prism (Graphpad Prism 9, Graphpad Software, La Jolla, USA). Final datasets were cleaned and checked for artifacts in MS Excel. Further data collected but not found to contribute to variability in outcomes and thus not considered here were environmental temperature and precipitation.

2.3.5 Data analysis

Any descriptive data (e.g., continuous variables) that were normally distributed (e.g., speed, stride length, stride frequency) are presented as mean (± 1 standard deviation [SD]). Similar data that were not normally distributed or categorical are presented as median (1st - 3rd interquartile range) or as percentage (of total number) for categorical variables. Data distribution was checked either by standard tests (e.g., Shapiro-Wilk test) or checking of residuals post analysis. If necessary, data were log-transformed (log10) to normalise the distribution of the data prior to analysis. For some analyses, where assumptions for analysis of variance could not be met (e.g., differing sample size for some factors (mare/stallion/gelding) or missing data, then a different approach was taken so as not to exclude that individual from all analyses. These data were analysed by linear mixed models (restricted maximum likelihood; REML), which adopts a flexible approach to estimating treatment effects (e.g., assumes 95% CI for small sample sizes and adjusts accordingly), and assumes that any missing data were randomly distributed amongst treatment groups. Such a technique means all data can be used and any estimates are not biased by an uneven dataset. Any factors that were not part of the design but may influence outcome were included as co-variates in any analysis (e.g., interval between training session in days, training month). Where data for the same horse were repeated, then either a repeated measures analysis was conducted with training session (i.e. 1 to ≤21) included as a fixed effect (if the effect of time was of interest) or with each horse fitted as a random effect in the model, to account for the reduced within-animal variation (where the effect of repeated sessions is averaged over all fixed effects in the model). Similarly, training centre/location were added as a further random effect, as many had tracks of differing surfaces at the same location. All data were analysed using Genstat v21 (VSNi Ltd, Rothamsted, Harpenden, UK). Statistical significance was accepted at $P<0.05$.

2.4 Results

2.4.1 Variation associated with recordings from the Equimetre.

In live recording of the same horses (n=21) completing at least eight or more (average = 10) different training sessions, where the training interval was not >30 days and was conducted on the same surface (sand) at a similar training speed for each horse (n=330 sessions available for comparison), the coefficient of variation ([SD/mean] × 100) for data on speed, cardiovascular and locomotory data were excellent (Table 3). An example of real data for an individual horse are given in (Table 4).

Table 3 Percentage coefficient of variation of the Equimetre

Training type…	Soft Canter	Med Canter	Hard Canter	Soft Gallop	Med Gallop	Hard Gallop
Speed parameters…						
Best 200m (secs) Turf	-	-	-	-	4	3
Sand	14	8	10	6	5	-
Best 600m (secs) Turf	-	-	-	-	4	3
Sand	12	8	-	5	4	-
Cardiovascular parameters…						
HRpeak (bpm) Turf	-	-	-	-	3	5
Sand	9	11	10	1	7	-
HR at 15min (bpm) Turf	-	-	-	-	11	15
Sand	14	16	20	12	16	-
Locomotory parameters…						
Stride frequency (strides/sec) Turf	-	-	-	1	2	1
Sand	4	3	3	3	2	-
Stride length (metres) Turf	-	-	-	2	3	2
Sand	8	7	4	5	4	-

Values are mean coefficient of variation from live recording of n=21 racehorses completing at least ten different training sessions in which the training interval was not >30 days apart. Sessions were conducted on sand at the same track. Values for differing surfaces training speed are given. In total, n=265 sessions were available for comparison. Coefficient of variation calculated as ([SD/mean] × 100), expressed as percent.

Table 4 Validation of the fitness tracker device (Horse A exercised at 'Hard Canter' on the same track and surface [sand])

Individual example, Horse 'A'	Best 200m (secs)	Best 600m (secs)	HR Peak (beats/min)	HR at 15min (beats/min)	Stride Frequency (stride/sec)	Stride Length (m/stride)
Training session 1, 23/03/2020	19.5	59.5	195	66	2	5.3
Training session 2, 25/03/2020	21	64	185	40	1.92	5.2
Training session 3, 26/03/2020	18.5	57	200	55	2.02	5.5
Training session 4, 30/04/2020	19.5	59.5	190	45	1.98	5.35
Training session 5, 01/04/2020	20.5	62	184	43	1.92	5.25
Training session 6, 03/04/2020	18.5	57.5	180	53	1.94	5.8
Training session 7, 17/04/2020	20.5	63	190	52	1.94	5.25
Training session 8, 11/05/2020	21	65	193	43	1.96	5.45
Mean	19.88	60.94	189.6	49.6	1.96	5.39
Standard deviation	1.02	2.99	6.47	8.58	0.03	0.20
Coefficient of variation	5%	5%	3%	17%	2%	4%
Intraclass correlation coefficient (ALL)	0.87 (0.78-0.94)	0.87 (0.78-0.94)	0.18 (0.02-0.44)	0.61 (0.2-0.80)	0.90 (0.83-0.96)	0.94 (0.90-0.98)

Recorded values by the fitness tracker device for an individual horse over eight training sessions, conducted on sand at the same track and at hard canter. The intraclass correlation coefficient (3,1) was used to assess the reliability of the Equimetre to record a similar value for each training parameter on the first five occasions for each horse training under the same conditions (i.e., pace and surface). The output quantifies the agreement between two independent scores of the same parameter (0 = no agreement, 1 = perfect agreement). A value ≥0.75 is considered as very strong agreement and 95% confidence intervals are used to represent the experimental variability around each score.

2.4.2 Descriptive characteristics of each cohort

Training practices varied from trainer-to-trainer within and between countries. The use of a fitness tracker provided equivalent data for the comparison of speed, cardiovascular response, recovery and locomotory parameters in racehorses in training. During warm-up, average HR during trot and canter was: 93 ± 24 and 169 ± 30 beats/min, respectively for Australia; and 99 ± 27 and 134 ± 32 beats/min, respectively for France. Thereafter, HR increased progressively with pace of the training session from soft to hard canter, where, on average, the peak heart rate (HRpeak) was achieved for each horse (249 ± 20 [1 SD], 237-260 [IQR] beats/min). As pace increased from soft to hard gallop, the HRpeak did not change significantly (Table 5). At hard gallop, the fastest 200m (or 'furlong') was covered in 11.0 ± 0.2 secs, in contrast to soft canter, covered in 24.7 ± 5.2 secs (Table 5). Despite many different horses and training sessions, there was good consistency between the differing paces; however, it was clear that based on the trainer-determined session, dependent on jockey compliance, versus a data-driven session based on the best 200m achieved and recorded during that session, then some variability existed with the former (Figure 2a,b). Consequently, for equivalence and comparison, we adopted a data-driven designation of training sessions (split into six categories; Figure 2a, b) based upon the fastest 200m for any training session. Highest variability was only in the slowest 'soft canter' category. Comparison between countries and training strategies, at each training intensity, suggested that racehorses in Australia had similar maximum stride frequency but consistently longer maximum stride length (Table 5), and were exercised at a higher intensity for shorter intervals based upon indicators of speed and time within each training category coupled with the HRpeak during each session. However, in France, the training sessions appeared to have a greater overall cardiovascular stimulus with higher and longer indices of recovery (e.g., HR at15min, HRauc) within each training category (Table 5). At higher speeds (medium to hard gallop) the differences in training strategies were largely eliminated (Figure 2c, d). Horses increased speed by both increasing stride length and frequency, although the increment in stride length from soft canter to hard gallop was much greater (~ 63% increment) than frequency (~ 25% increment; Table 5).

Table 5 Descriptive characteristics of the Australian and French racehorse training datasets

Training type…	Country	Soft Canter	Med Canter	Hard Canter	Soft Gallop	Med Gallop	Hard Gallop	'Jumpout'
Best 0-200m	Australia	24.7 ± 5.2	19.9 ± 0.8	15.6 ± 1.	12.6 ± 0.4	11.7 ± 0.2	11.0 ± 0.2	11.2 ± 0.6
	France	43.0 ± 14.0	30.7 ± 1.5	23.2 ± 2.	16.4 ± 1.2	13.5 ± 0.4	12.2 ± 0.3	–
Time, 400-600m	Australia	26.1 ± 5.4	21.3 ± 1.3	16.9 ± 1.	14.1 ± 0.9	13.2 ± 0.8	12.7 ± 0.8	11.5 ± 0.78
	France	42.8 ± 13.3	33.0 ± 2.6	25.5 ± 3. 1	18.4 ± 2.3	14.9 ± 1.6	13.5 ± 0.9	–
Max speed	Australia	31.6 ± 5.2	37.1 ± 1.8	47.3 ± 4.	58.1 ± 2.5	62.3 ± 1.2	66.0 ± 1.6	64.5 ± 3.7
	France	19.6 ± 5.1	24.3 ± 1.8	32.2 ± 3.	44.9 ± 3.5	53.8 ± 2.1	58.9 ± 1.7	–
Peak heart	Australia	178 ± 31	195 ± 21	212 ± 27	221 ± 26	214 ± 18	216 ± 15	215 ± 18
	France	152 ± 42	166 ± 33	182 ± 35	206 ± 33	217 ± 23	219 ± 23	–
Percent max HR	Australia	76 ± 14	83 ± 12	87 ± 15	92 ± 11	92 ± 11	93 ± 10	94 ± 8
	France	62 ± 16	66 ± 15	75 ± 15	85 ± 13	90 ± 10	92 ± 9	–
Heart rate at15min	Australia	59 ± 14	63 ± 29	70 ± 23	90 ± 24	92 ± 17	97 ± 20	94 ± 27
	France	71 ± 24	73 ± 20	74 ± 20	81 ± 20	96 ± 19	102 ± 17	–
HR recovery auc	Australia	119 ± 18	130 ± 18	141 ± 20	156 ± 19	154 ± 11	157 ± 13	155 ± 17
	France	220 ± 75	233 ± 59	244 ± 59	268 ± 64	318 ± 56	339 ± 56	–
Stride frequency (strides per sec)	Australia	1.96 ± 0.11	2.03 ± 0.07	2.17 ± 0.	2.31 ± 0.0	2.34 ± 0.0	2.41 ± 0.0	2.40 ± 0.10
	France	1.90 ± 0.25	1.97 ± 0.18	2.11 ± 0. 18	2.28 ± 0.1 6	2.38 ± 0.1 2	2.41 ± 0.1 2	–
Stride length (meters)	Australia	4.58 ± 0.58	5.19 ± 0.25	6.17 ± 0.	7.10 ± 0.3	7.49 ± 0.2	7.71 ± 0.2	7.63 ± 0.41
	France	3.09 ± 0.60	3.62 ± 0.35	4.44 ± 0. 45	5.60 ± 0.4 7	6.41 ± 0.3 6	6.88 ± 0.3 3	–

Values are Mean ± 1SD for continuous data recorded by 'Equimetre' in Australia (n=275 different racehorses, n=1124 different training sessions) and in France (n=234 different racehorses, n=6016 different training sessions). Data were available throughout the year. Training intensity (soft/med/hard canter; soft/med/hard gallop) was calculated from both cohorts based upon the fastest furlong (200m interval) for each session, excluding 'jumpout' as in France, horses were not started from the starting gates. In Australia, there were n=163 racehorses that had trained from out of the starting gates ('jumpout'). Data are described and not formally statistically analysed.

Figure 2 Classifying intensity of racehorse training sessions

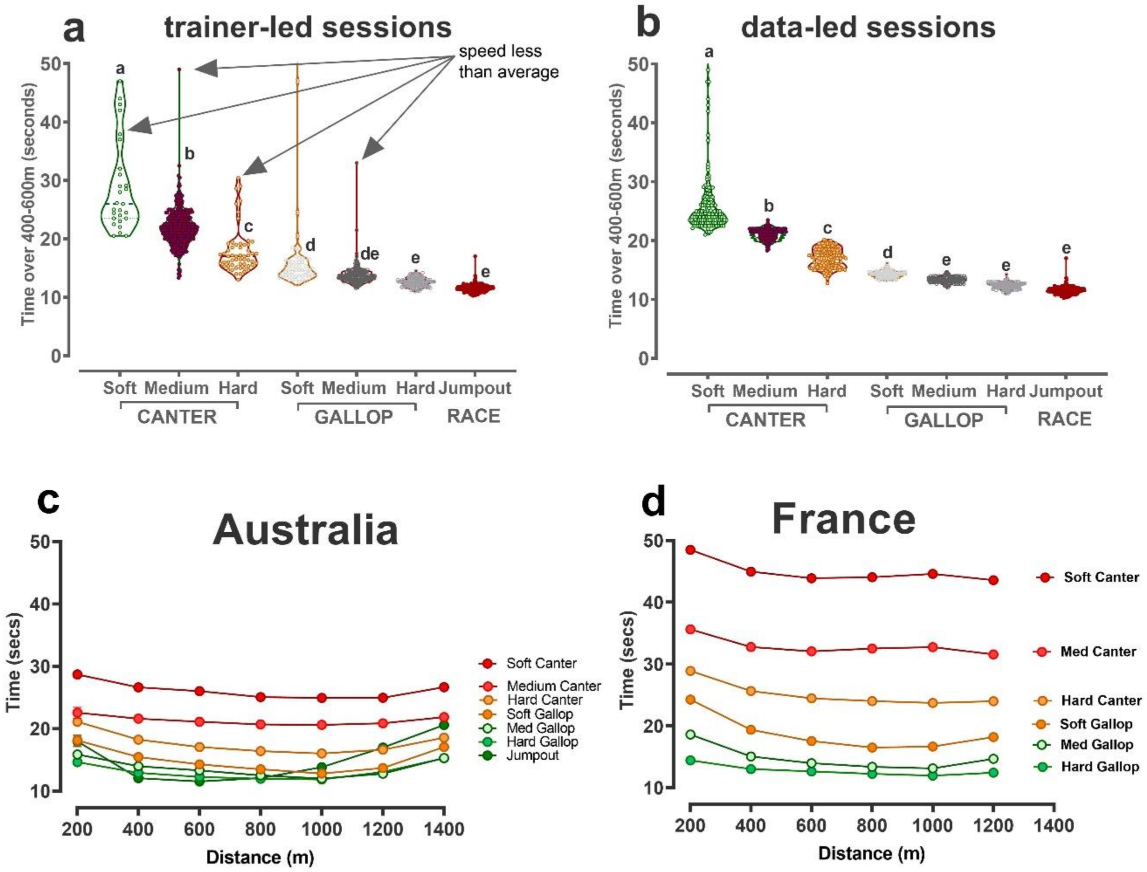


Figure. **a, b**: Individual data points are time to complete a 200m segment from 400-600m (i.e., mid-session) at varying training intensity (soft/med/hard canter; soft/med/hard gallop). Training intensity was calculated from both cohorts based upon the fastest furlong (200m interval) for each session, excluding 'jumpout', for which there was no equivalent in France. Values were recorded by a fitted 'Equimetre' on horses in Australia (n=275 different racehorses, n=1124 different training sessions) and in France (n=234 different racehorses, n=6,016 different training sessions). **c, d:** Data are predicted means (S.E.M.) for racehorses in Australia (including a further n=163 that had trained from out of the starting gates, 'jumpout'). Predicted means were calculated from continuous data recorded for each horse every 200m, with training intensity as the fixed effect in a repeated measures design. HorseID, track and racehorse trainer (two in France) were included as random effects in the model. All data analyses were conducted using Genstat v20 (VSNi, UK). Different superscripts indicate statistical significance at P<0.001, after *post hoc* analysis (Bonferroni correction).

2.4.3 Effect of track surface

Notably, track surface had an independent effect on racehorse speed, stride and the racehorse cardiovascular system during a given training session. Regardless of the intensity of the training session, speed was slower (P<.001; Figure 3a,b) and stride length was reduced (P<.001; Figure 3c,d) on sand versus turf (and fibre, where data were available for in the

Australian cohort); but recovery of heart rate at 15min was not different (Figure 3e,f).

Figure 3 Track surface influences racehorse training characteristics

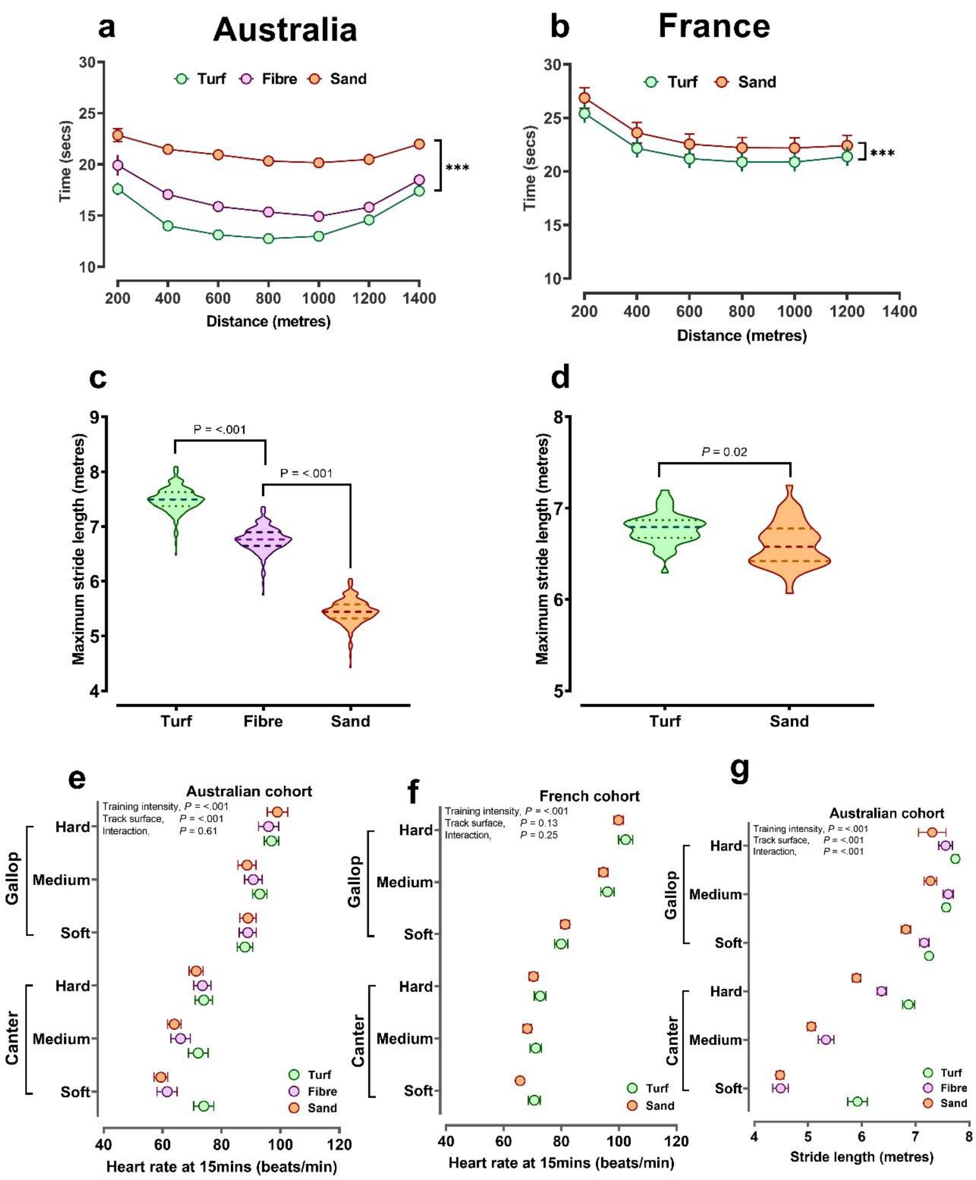


Figure. **a,b,e,f,g:** Data are predicted mean ± S.E.M. as recorded by 'Equimetre' in Australia (n=275 different racehorses, n=1,124 different training sessions) and in France (n=234 different racehorses, n=6,016 different training sessions). **c,d**: violin plots are all data with median and IQR indicated by solid and dashed lines, respectively. Training intensity (soft/med/hard canter; soft/med/hard gallop) was calculated from both cohorts based upon the fastest furlong (200m interval) for each session, excluding 'jumpout', for which there was no equivalent in France. Predicted means were calculated with training intensity fitted first, adjusted for sex of the horse and with track surface fitted last in the model. HorseID, racetrack and racehorse trainer were included as random effects in the model. All data analyses were conducted using Genstat v20 (VSNi, UK) and graphs produced using Graphpad Prism v9.0 (La Jolla, USA). ***, P<.001.

2.4.4 Cardiovascular responses to training in thoroughbred racehorses

During warm-up in trot, HR was 97 ± 27 and 92 ± 23 beats/min in France and Australian datasets, respectively. During canter, HR rose to 133 ± 32 and 169 ± 29 beats/min, respectively. These values were on average 40 ± 11 and 54 ± 13 percent of peak heart rate calculated for each individual horse. At the end of any recorded training session i.e., during cool-down, HR decreased to an average of 63 ± 18 beats/min across the two datasets. The average overall HRpeak recorded was 249 ± 20 and 238 ± 43 beats/min in France and Australian horses, respectively. As the intensity of the training session increased, so did the recorded HRpeak, but the response was not linear and HR appeared to plateau during soft gallop in France, versus hard canter in Australia (Figure 4a,b), where the average time to cover a furlong from 400-600m was 18.3 ± 2.3 and 14.1 ± 0.9 secs in France and Australia, respectively. These data corresponded to training intensities (percent of HRpeak) of between 62-75% and 76-87% for canter in France and Australia, respectively. In gallop, most horses were working at or above 85% HRpeak (Table 4). Recovery of HR toward baseline after each training session took longer after gallop than canter (Figure 4c,d), with some variability in recovery within training intensities (e.g. soft, medium, hard) between countries (Figure 4c,d). Analysis of rate of change in HR during recovery, with higher values indicating greater rate of return of HR toward baseline, suggested horses achieved greatest ‘cardiac flexibility’ during hard canter in Australia and soft gallop in France (Figure 4f,g).

Figure 4 Cardiovascular responses of racehorses to differing training intensities

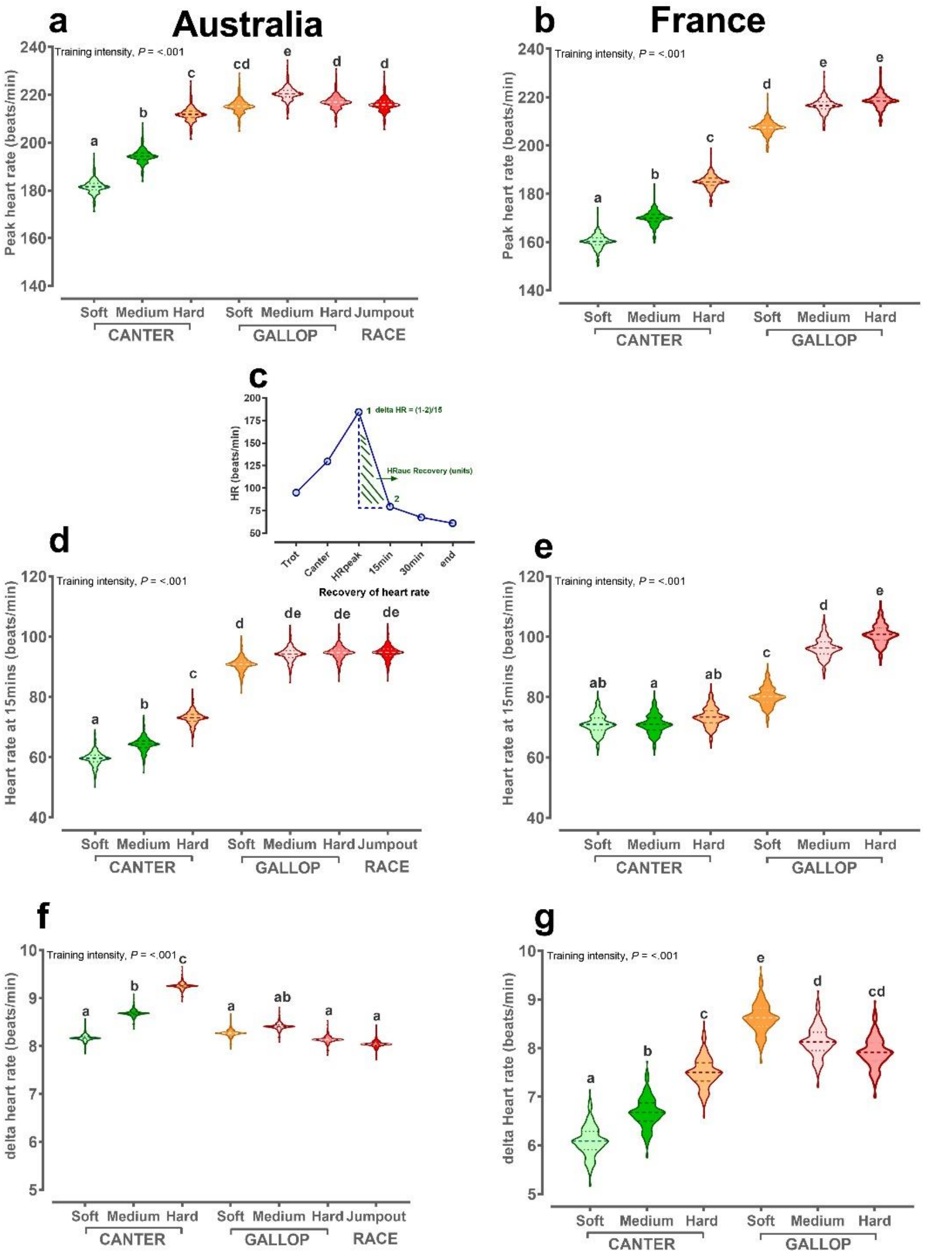


Figure. **a,b,d,e,f,g:** Violin plots are all data for each individual horse at differing training intensities. Median and IQR are indicated by solid and dashed lines, respectively. Training intensity (soft/med/hard canter; soft/med/hard gallop) was calculated from both cohorts based upon the fastest furlong (200m interval) for each session, excluding 'jumpout', for which there was no equivalent in France. 'Equimetre' recorded n=275 different racehorses in the Australian cohort (n=1124 different training sessions) and n=234 different racehorses in France (n=6016 different training sessions); **c**) figure illustrates calculation of area-under-the-response-curve (AUC). Statistics are by REML with horse ID included as a random effect and 'training intensity' fitted last in the model after correction for sex of the horse, track surface and number of training sessions completed. Differing superscripts indicate statistical significance at P<0.01, adjusted appropriately for multiple comparisons (6 groups, Bonferroni correction). Data analyses were conducted using Genstat v20 (VSNi, UK) and graphs produced using Graphpad Prism v9.0 (La Jolla, USA).

2.4.5 Effect of age on training parameters

In both countries, age appeared to limit, to some extent, the peak HR achieved during a given intensity of training session; that is, at any given intensity of training younger horses achieved higher HRpeak than older horses (Figure 5a,b). These effects were more apparent in Australia than in France, where such effects were only noted at the higher speeds recorded during gallop. Equally, these effects, albeit biologically small, were also reflected in HRR where older horses appeared, to some extent, recover better (Figure 5c,d).

Figure 5 Effect of age, training month or training session on racehorses

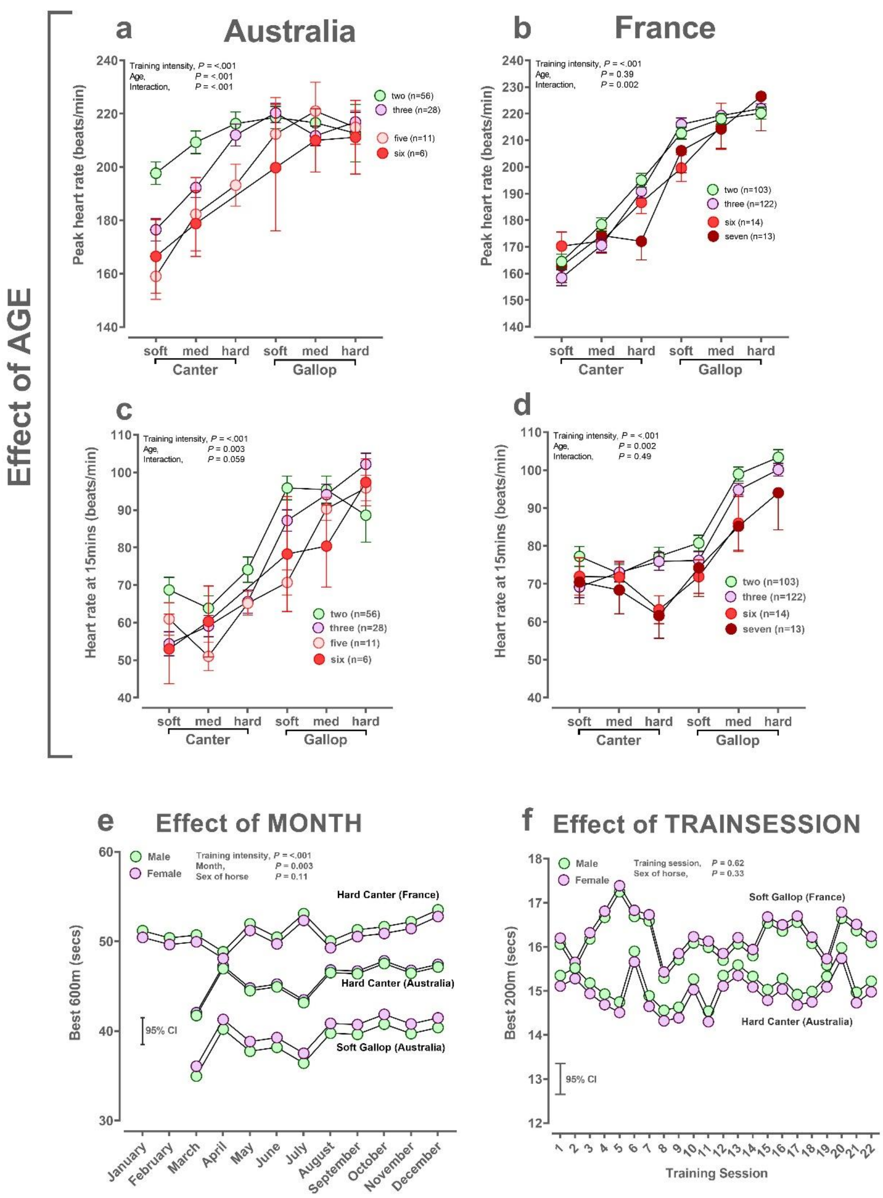


Figure. **a,b,c,d:** Data are predicted mean ± S.E.M. as recorded by 'Equimetre' in Australia (n=275 different racehorses, n=1124 different training sessions) and in France (n=234 different racehorses, n=6016 different training sessions). **e,f**: Data are predicted mean ± S.E.M (95% CI shown for comparison) for repeated data on individual two- or three-year old horses training on sand at only the paces shown (Hard Canter or Soft Gallop). All data were generated with individual horseID fitted as a random effect and after adjustment for track surface and age. Racetrack and racehorse trainer were also included as random effects in the model. All data analyses were conducted using Genstat v20 (VSNi, UK) and graphs produced using Graphpad Prism v9.0 (La Jolla, USA).

2.4.6 Effects of sex of horse and month on training outcomes

In both countries, horses were trained throughout the year and many individual horses completed multiple, repeated training sessions over the span of the study. When analysing all data for two and three-year olds training on sand (most data available for these categories) there was no effect of sex of the horse (i.e. whether male [including geldings] or female) on the time taken to complete 600m (Figure 5e) or 200m (Figure 5f) - two standardised training metrics. There was some variability observed for training month, but no consistent effect.

2.5 Discussion

Digital progress has been increasingly embraced by those working in sports performance. Human performance analysts were early adopters of many types of wearable technologies (Jin et al., 2020). Within the equine sports industry, racehorse trainers are looking beyond subjective tradition, to incorporating more objective advice from veterinary specialists to help improve performance and conditioning of horses and getting them “race-ready”, but also to reduce wastage and injury. Various wearable technologies are now much more mainstream in elite racehorse training, allowing real-time monitoring of performance in their natural environment, with little to no interference with their usual work routine. Data analysts are helping to interpret the signals and drive progression towards better performance and welfare. Nevertheless, among the fitness devices that have been commercialised to date for the equine market, few have been scientifically validated. For example, both the Polar S810i (Polar Ltd, Kempele, Finland) and Televet ECG system (Televet 100 v4.2.3) (Kruuse Ltd, Marslev, Denmark) have only explored their appropriateness for the measurement of heart rate and heart rate variability in horses at rest (Ille et al., 2014). A standard GPS device (Forerunner 205/305; Garmin Ltd, USA) was used to measure speed and distance in a small number of actively, exercising endurance horses (in the field and on a treadmill) (Fraipont et al., 2012). More recently, the Equimetre device, as used in this study, was validated against the Televet ECG system to accurately record heart rate (HR) and heart rate variability (HRV) during high-intensity exercise in twenty thoroughbred racehorses (ter Woort et al., 2021). The size of the sample evaluated in the present study was particularly large (i.e., hundreds of horses across different countries and training regimes) allowing an analysis to be undertaken with greater sensitivity on the cardiovascular and locomotory changes of racehorses in training. The tracking device ‘Equimetre ©’ was shown to objectively discriminate training intensity by measuring racehorse speed, locomotor and cardiovascular responses. Categorising training intensity by speed within each country, and thus normalising the training impulse offered by incremental speed categories, this study has shown how the cardiovascular (heart rate) and locomotory (stride length and frequency) functions of an individual racehorse respond to bouts of exercise and be influenced by under-appreciated other factors such as the training surface.

The precision and reliability of the Equimetre was initially considered over a total of 330 sessions, performed at the same speed, on the same track and same surface: at faster paces, where most training occurs the device had coefficient of variation from 1-5% for locomotory parameters, 3-6% for speed and 5-15% for cardiovascular parameters. The latter being subject to much greater within-individual variation. Hence, the device when fitted correctly can offer good reliability and repeatability for recording of speed, cardiovascular and locomotory data in situ allowing individual racehorse responses and progression to be followed throughout the year. Such individual data in a large cohort can reveal more subtle and unforeseen effects of differing training environments on the physiological adaptation and biomechanics of the racehorse. For example, one variable drawn out in our analyses to have marked effects on most measured parameters was the racetrack surface: whether turf, fibretrack or sand.

Historically, some prestigious races have always been run on either turf (e.g., the English Derby) or 'dirt'/sand (e.g., the Breeders' Cup Classic). Fibre track or synthetic surfaces evolved as an all-weather option allowing racing to continue through poor atmospheric conditions and was adopted by many racehorse trainers as it allowed a consistent training surface throughout the year. Trainers can now choose where, and on what, to train or race their horses; nevertheless, many trained on a different surface to what the horse eventually raced on, perhaps contributing to racing-induced injury (Morrice-West et al., 2018). Indeed, track surface properties such as temperature, moisture and hardness can alter limb loading and lead to bone fatigue injuries (MacKinnon et al., 2015). Initial studies found that injury rates of limb fractures were the highest on dirt surfaces compared to turf and synthetic tracks. Regardless of the surface, fractures occurred predominantly in forelimbs. While forelimb injuries were mainly reported on dirt surfaces, horses were more likely to experience fatal hindlimb fractures on turf (Peterson et al., 2021); (Crevier-Denoix et al., 2010); (Symons et al., 2014). In more recent studies, some contradictions exist regarding injury rates on synthetic surfaces. Some studies suggested less injury rates (Setterbo et al., 2009), while others found greater musculoskeletal injuries such as pelvic and tibial stress (Verheyen et al., 2006a, MacKinnon et al., 2015). This study demonstrates an effect of track surface (e.g., turf vs. sand) on the racehorse's speed, stride and cardiovascular responses during training. However, we acknowledge that without any information on structural properties of each surface (e.g., porosity, granular composition, depth) or any knowledge of track gradient, then the data could be influenced by these factors. In both countries, speed was lower on sand, stride values (stride length and stride frequency) were reduced, but horses appeared to recover better when compared to turf. This could be explained by the use of each respective training ground for a given workout; for example, in France trainers conduct most of their "slow" workouts on sand. Fast workouts, during which horses reproduce racing conditions, tend to occur on turf. Previous work has shown that deformable racetrack surfaces decrease stride length (Burn and Usmar, 2005). The importance of this finding lies in the fact that, knowing the effect of each type of track on the horse's biomechanical and cardiovascular function (i.e., recovery), trainers can adapt the type of exercise and the rate at which the horse reaches different cardiac training zones.

Heart rate measures in the present study rose with increasing exercise intensity, corresponding to the different paces (trot, canter, gallop) in both cohorts of racehorses, with some slight but significant differences between countries in the slope of HR increase with increasing work intensity. This is perhaps due to the differing training strategies in each country. Previous studies have demonstrated that horses exhibit a linear relationship between heart rate and submaximal exercise intensity (Hinchcliff et al., 2013). However, when measured in situ with a rider aboard, and with racehorses taken to their cardiovascular peak (e.g., hard gallop), then heart rate measures were linear and tailed off at higher speeds (see Figure 4a,b). Hence, estimated HRpeak or within 90-95% of it, was often achieved at relatively slower speeds; 'hard canter' in Australia or 'soft gallop' in France. This means that the cardiovascular system of racehorses, in terms of heart rate at least, peaks at only 70-75% of their top speed (see Table 5). In addition, at these speeds, greatest cardiac flexibility was observed; that is, the horse's ability to rapidly decrease its HR following an intense physical effort. Here, rate of recovery of heart rate ('delta HR') was highest, perhaps indicating the ideal, sub-threshold training zones, respectively. We also noted marked variation between individual horses in terms of their HRpeak; values varied from 238 – 249 beats/min, similar to values (210 – 250 beats/min) reported by Poole and Erickson (2014), but slightly higher than reported in National Hunt racehorses (201 – 230 beats/min; (Allen et al., 2016a)).

Regardless, it is clear that training practices differ between countries. Large comparative studies on the latter are limited, perhaps due to the lack of consistency in reporting training speeds. Firth and Rogers analysed monthly training regimens in Australasian 2-year-olds and described average speeds of 8.9m/s at canter (total monthly distance of 63,200m) and ~14.6m/s at gallop (total monthly distance of 4800m) (Firth and Rogers, 2005). Similar measures were identified by Morrice-West et al. (2020). In the USA, studies report speeds of 11m/s at gallop (total monthly distance of 28,400m), 15–16m/s at 'breezing' (total monthly distance of 1000 m) and GPS recordings at >8 m/s (23,004m per month) (Pagan et al., 2017). In the UK, studies report lower total monthly training volume when compared to Australia: for example, 26,800 m/month slow-speed exercise (≤14 m/s) and 2800m galloping (>14 m/s) have been reported (Verheyen et al., 2009). Similarly, 2-year-olds in the UK completed 4200 m/week at ≤13.4 m/s and 380 m/week at >13.4 m/s. Our research complements these studies, also showing how Australian racehorses appear to be trained harder, as suggested by (Hodgson, 2014), compared to France. This could be explained by varying proportions of racehorse types (i.e., sprinters, milers or stayers) in each respective cohort. For example, ‘sprinters’ – horses better adapted for short race distances, would be expected to run at higher speeds, present higher stride frequency and a longer ground contact duration to allow more time for propulsion (Barrey et al., 2001). Such a categorisation of the horses in our cohorts was not available.

In an elite athlete, ‘fitness’ is usually measured as a consistent improvement in speed, power, economy of movement or recovery of heart rate after a standardised test. The athlete can maintain the same speed or power, but at a lower ‘cost’; for example, as measured by recovery of heart rate. In our study, the area-under-the-response-curve (AUC) for HR increased with exercise intensity (see Table 5), largely driven by the peak HR. Concomitantly, recovery of HR was dependent on the intensity of exercise, as reported previously (Couroucé et al., 2002, Evans, 2007a). However, no clear signal for improved ‘fitness’ with successive training sessions was observed, probably due to a lack of consecutive and standardised training sessions recorded for individual horses, with all other factors being equal (~ 4 per horse). Another explanation could lie in the fact that, for the recorded sessions, horses may have already been fit, which could explain the minimal difference. For many racehorses, the repeat training sessions of an equivalent load (and using the ‘Equimetre’) were all conducted in either the same or consecutive months; a length of time insufficient to detect a clear increase in ‘fitness’ in equine athletes. Fitness in the horse is defined as the ability to perform prolonged, continuous and is also referred to physical work capacity (McMiken, 1983). In human elite athletes, longitudinal follow-up methods require the summation of workload over a period of weeks to months. Clearly, for racehorses that were only sampled conveniently, then further data is needed to ascertain progression of ‘fitness’.

While peak HR cannot be considered a measure of fitness, as it doesn’t evolve with training, it is a useful cardiovascular indicator to establish training zones or individualise workload/intensity (e.g., % of peak HR) during exercise. As we report, racehorses at trot, canter and gallop were working at approximately 40%, 75% and 85-95% of HRpeak, respectively. Using wearable technology, individualised training zones for each racehorse could be established, allowing trainers to adjust training programs for each horse or for groups of similar horses. The principles of high-intensity interval sessions or sub-threshold training, or even periodisation of training could be applied using these established training zones. Such a system has been used previously in polo-ponies (Williams and Fiander, 2014). Our data demonstrated different HR responses within groups of horses that were trained together at the same speed (i.e., canter or gallop, see Figure 4a,b). This supposes the existence of tangible differences between horses that could be due to differing ‘fitness-level’ or athletic ability.

Grouping horses of similar athletic potential could allow for a more homogenous training approach. It would ensure that horses are exposed to a training load suited to their physical capabilities and potentially reduce any risk of injury or pathology. It could also help retrieve training sessions that do not provide a sufficient training stimulus.

Our data revealed a small signal indicating that the peak HR achieved during work of most intensities was lower in older (aged 5-6 years) relative to younger (aged 2-3 years) horses, particularly for the Australian cohort (see Figure 5a). Heart rate as measured at 15mins after the training session had ended, was also lower in older horses. This perhaps reflects either a reduced peak HR (and thus faster return to a lower value) or a less anxious//excitable, older horse (cf. two/three-year old). Similarly, previous work conducted by Couroucé et al. (2002) in Standardbreds has provided valuable insight on the effect of age on training. Muscular (i.e., blood lactate concentrations) and cardiovascular adaptations (i.e., corresponding heart rates) indicated higher levels of fitness in older horses, despite similar training stimuli. Similar findings have been previously reported in human athletes and other sport horses (Hinchcliff et al., 2013, Betros et al., 2002). Previous research conducted on Thoroughbred horses by Lightfoot et al. (2006) evidenced that the dimensions of the left ventricle increased with age and training. Thus, a higher volume of blood ejected per heartbeat could correlate with a lower peak HR during physical exertion. Our insight on the effect of age is limited, however, to only what we have been able to measure. It could be, that older horses are trained slightly differently, or are more relaxed in their surroundings than younger, relative novices. Since the effects were more obvious in Australia than France, and we know that the differences in training practices are reflected in our HR data, could suggest that the effect of age is also linked to differences in the training or handling of older horses. Other external factors could also affect young versus old horses differently such as temperature/humidity (Hargreaves et al., 1999) or rider and the tack (Byström et al., 2010).

Despite very little difference between male and female racehorses at given training intensities, there was a small, statistically significant, effect of training month (Figure 5e) but none of training session (Figure 5e) i.e., do racehorses gradually get faster, adjusted to each training session, throughout the year? To an extent, this study is likely underpowered to draw definitive conclusions on seasonality or accumulated training effects, given the variability in training between countries in different hemispheres with varying race seasons. Nevertheless, this question is of interest and could be investigated with greater fidelity with a larger dataset. We were, to an extent, limited to only the data available where an ‘Equimetre’ was used, and this was determined by the trainer. A prospective study on a sample of horses used for every training session throughout the year would offer more reliable data on genuine effects of study month and/or accumulated training sessions.

The study has several limitations, which should be acknowledged. First, there is a risk of selection bias due to the method of convenience sampling. However, when both datasets are combined from each country, then the sheer size of the study should minimise any slight effects of possible selection bias. Secondly, the study design was retrospective and descriptive. As a result, there are missing data for some horses along with other variables that have not been considered such as weight or sex of the rider. Nevertheless, using mixed-effect models to analyse the data with due incorporation of possible confounders and random effects, such as different racecourses, helps to reduce any bias and skew. Equally, whilst we have accounted for track surface in our analyses, there are potentially other variables associated with certain courses at the same racetrack that we may not have been able to account for, that may influence an individual racehorse’s response to training such as a track with a gradual incline or inadvertently soft sand or hard turf. Whilst in human performance, measurement of heart rate during, and recovery from, exercise has helped construct training zones and thus guide development of fitness, these parameters are less well established for equine athletes. From our data, whilst rate of recovery took longer for harder training intensities, it was less clear to see any improvement in rate of recovery of HR for a similar training session undertaken later in the training year. This, most probably, is because of insufficient numbers of equivalent training sessions extended over sufficient time for an equine athlete to display changes in ‘fitness’. Studying fewer horses in standardised conditions for every training session undertaken, rather than a convenience sample of many horses for fewer training sessions may help reveal these responses. The analysis of longitudinal effects of peak HR and HR recovery at a given speed in individual horses could potentially show improvement of fitness or signs of subclinical disease. Equally, any changes in stride length within individual horses over the course of time would also be of interest. It could provide trainers with early signs of lameness and a clearer understanding of every horse’s locomotory profile (i.e., milers, stayers, sprinters) to then choose the most appropriate race accordingly.

In conclusion, by using wearable technology, this study shows how simultaneous measurements of speed, cardiovascular (e.g., heart rate) and locomotory (stride length and frequency) responses may be accurately recorded in usual field conditions, revealing clear differences in training approach between countries. Further research is needed to explore and identify the physiological adaptations to training from one geographical setting to another. Additionally, such systems also have the potential to generate individualised data that could reliably inform trainers, owners and jockeys on racehorse response to training. Furthermore, at an individual level the data could likely be used to identify altered patterns of behaviour in sub-clinically injured horses by changes in stride length or frequency or those overly tired or over-trained by analysis of baseline heart rate. By using such a large dataset, we were able to show how relatively small effects nevertheless influence racehorse response to training, for example, with increasing age, peak heart rate appears to be relatively limited. Finally, track surface has marked effects on racehorse biomechanics. Technology can now help guide and influence racehorse training, likely bringing a multitude of benefits such as individualised training plans designed to optimise race preparation whilst minimising injury risk.

Chapter 3 Study 2: Does sex of the jockey influence racehorse physiology and performance

3.1 Abstract

The racing industry is supported by a predominance of female stablehands and work riders, but few become professional jockeys. Female jockeys have recently had notable race success. No study has assessed whether the sex of the rider may subtly influence racehorse physiology to affect performance. Here, using a validated exercise tracking system (the 'Equimetre'™) that records many physiological parameters simultaneously, this study characterised racehorse cardiovascular (heart rate, heart rate recovery) and biomechanical (stride length and frequency) parameters at various exercise intensities (slow canter to hard gallop) to address the question whether any parameter varied according to sex of the rider. A total of 530 Thoroughbreds, varying in age (2-7 years old) and sex (including geldings), from one racing yard in Australia, completed a total of 3,568 exercise sessions, monitored by a single trainer, on varying track surfaces (sand, turf, or fibre). Different work riders,103 in total (male, n= 66; female, n= 37) of which n= 43 were current or past registered professional jockeys, participated in the study. Data were analysed using analysis of variation (ANOVA) or mixed-effect models, as appropriate. Sex of the rider did not influence (P> 0.05) racehorse speed nor stride length at any training intensity. Racehorse heart rate and peak heart rate increased with training intensity (P<.001), with no difference according to sex of rider (P> 0.05). Racehorse heart rate recovery was influenced by sex of the rider, but only at the extremes of the reversed, usual training intensity on each surface (e.g., heart rate after galloping on sand was significantly lower with male riders, P= 0.03). Finally, analysis of 52,464 race results indicated a similar chance of a top-three placing for male and female jockeys. In conclusion, this study, using objectively obtained data, demonstrates for the first time no overt effect of the rider's sex on racehorse physiology in training and performance in racing. Such data could encourage greater female participation in racing and improve access of female jockeys to better quality mounts in racing events.

3.2 Introduction

In human elite sport, athletes are almost invariably segregated by sex. Male athletes tend to perform at a faster, higher, and stronger level due to a combination of various physical and morphological advantages (Bassareo and Crisafulli, 2020). Men usually have greater lean mass, less body fat and greater aerobic and cardiovascular dimensions such as heart size and cardiac output, suggesting a greater capacity for exercise (Durnin and Womersley, 1974). Interestingly, when male and female athletes were matched according to performance in a timed race, despite the males being taller, heavier, and with higher haemoglobin concentration the sexes did not differ in measures of aerobic performance such as VO_2max (ml·kg–1·min–1), heart rate (HR), respiratory exchange ratio, or the ventilatory equivalent of oxygen during submaximal running or at maximal exercise (Pate et al., 1985). Therefore, when obvious physical differences between males and females are taken into account, performance differences become minimal. Nevertheless, males and females likely differ in various functions unrelated to lean mass that suggest tailoring training programs, equipment or nutrition to optimise performance with these differences in mind would be beneficial (Kim et al., 2021, Felton et al., 2019, Smith et al., 2022). In any sport conducted at the highest level, the difference between winning or losing may purely be psychological. Here, men seemingly have an advantage with greater self-confidence (Woodman and Hardy, 2003), less pre-competitive anxiety (Perry and Williams, 1998) and an ability to focus purely on performance (Hanton et al., 2004) often being reported. Over the last few decades, representation of women in elite sport has markedly increased. Women were only allowed to officially compete in an Olympic marathon in 1972 (Boston, USA), whereas in Tokyo 2020, medal opportunities for male and female athletes were near parity (49% female representation rate). This represented a rise of 45% since Rio in 2016, and 38% since Sydney in 2000 (Houghton et al., 2017, International Olympic Committee, 2021). In various professional sports, female teams are increasingly being created, equality of prize money is being realised, and greater female participation rates are raising the popularity of women's sport (Claus, 2020, Oxley, 2021, Townes, 2019, Douglas, 2018).

In horse-racing, both male and female horses and male and female jockeys compete against each other in most races. An average racehorse weighs ~500-600kg, an average jockey, ~49-55 kg (e.g., see https://www.racing.com/jockeys). Yet, a few 100g extra, on the back of a racehorse, has been shown to influence race performance; thus, additional weights are often used in 'handicap' races, to potentially equalise any performance advantage (Oki et al., 1995, Oki et al., 1994, Buttram et al., 1988). In other equestrian sports where there is no attempt to control for perceived differences between sexes (both animal and human) such as show-jumping (McCombs and Sommers, 1983, Whitaker et al., 2012) or eventing (Whitaker, 2007), there is no evidence to suggest any influence of the riders' sex on performance. At a recreational level, in most equestrian sports, riders are predominantly female (Fox et al., 2008, Barclay, 1978, Barone and Rodgers, 1989). At an elite level, this ratio is often reversed (Dumbell et al., 2010). In horse racing, despite an increase in participation rates for female jockeys, the proportion of female/male jockeys riding at the elite level in racing nations such as England, France and the USA remains low (Binder et al., 2021) and see https://www.britishhorseracing.com/racing/participants/jockeys/). Physical strength, body shape and tradition were reported by Roberts & MacLean as perceived reasons of restricted opportunities for female jockeys, or the intimidating nature of the weighing room (Roberts and MacLean, 2012). In 2018, the French racing jurisdiction 'France Galop', implemented a 2kg weight allowance for female jockeys to encourage greater use of female jockeys (France Galop, 2017). Analysis of betting behaviour on races in the UK and Ireland (Brown and Yang, 2015), or USA (Binder and Grimes, 2021), was studied as an indirect proxy for public confidence in the ability of male or female jockeys to win races. In the UK and Ireland, a slight underestimation of the ability of female jockeys to win was found between the years 2003-2013 (i.e. female jockeys won +0.3% more races than estimated from the subjective assessment of the quality of the racehorse) (Brown and Yang, 2015). In the USA, the opposite was found for better quality 'stakes' races (-2.0% (Binder and Grimes, 2021). Any successful jockey must possess a combination of strength endurance, balance, fast reaction time and flexibility to be successful (Westerling, 1983, Maddox, 1976). Such attributes are equally shared by males and females who self-select to become successful jockeys, given equal opportunities to ride quality racehorses.

Successful jockeys are thought to readily form a partnership with each racehorse (Williams and Tabor, 2017). Competition, and the anxiety associated with it – as reflected in heart rate – usually alter in parallel (i.e., increase) in both horse and rider. In certain circumstances, for example when psychological aspects (i.e. 'pressure') are further imposed, such as performing in front of a crowd, then heart rate increases in the human, but not horse (von Lewinski et al., 2013)). It is well known that in human athletes during sporting events, cortisol production increases as a result of heightened anxiety or anticipation of the event, to the benefit of their performance (Crewther et al., 2011). Similarly, cortisol level in horses is higher during competition (Peeters et al., 2013), compared to training (Bohák et al., 2018), but no difference in equine plasma cortisol was found between race winners and losers (Tavanaeimanesh et al., 2022). Thus, a multitude of complex factors including anxiety, anticipation or other psychological factors could have an effect on an individual horse's race performance. Males and females per se approach competition differently (Gill, 1986), and there is no reason to believe this does not apply to jockeys. Yet, to date, there is a paucity of data on whether sex of the rider has any effect on aspects of racehorse physiology that are important for performance (e.g., the cardiovascular system) or on the actual performance itself in races. Using such data during the routine training of racehorses also mitigates any potential effect of race-day anxiety or other psychological factors.

Hence, the aim of the present study, the first of its kind to date, was to leverage a large database of racehorse training data collected routinely in a single racing stable in Australia using a validated fitness tracking device to investigate whether sex of the rider has an effect on aspects of racehorse speed (slow canter to hard gallop), cardiovascular function (e.g. recovery of heart rate) or locomotion (e.g. stride length) during race-speed training sessions. Furthermore, using publicly available databases of race outcomes (win, second, third place) from Australia and the UK the study also aimed to determine whether sex of the rider has an effect on racing performance. Our hypothesis was that sex of the rider has no effect on racehorse physiology in training or performance in racing.

3.3 Material and Methods

This retrospective, observational study used two large datasets: 1) a database of racehorse training sessions collected from a single racing yard (Ciaron Maher Racing) in Australia, where sex of the work-rider was known and 2) publicly-available datasets of race results in Australia and in the UK, with sex of the jockey recorded and downloaded from https://www.racing.com/jockeys/ and https://www.britishhorseracing.com/racing/participants/jockeys/

3.3.1 Racehorse physiological outcomes in training according to sex of the jockey

Ethical approval for this study was obtained from the University of Nottingham (School of Veterinary Medicine and Science) Research Ethics Committee (REC code: 3270 201029). The nature of this study involved no experimental protocols. All methods were carried out in accordance with relevant guidelines and regulations. The study is a retrospective, observational study of physiological data held in a database by an external company. The company work with racehorse trainers who collect data from individual horses that are owned by different individuals. The need for informed consent was waived by the Ethics Committee (School of Veterinary Medicine and Science) due to the retrospective nature of the study, and no personal information was collected on any individual beyond what the data capture device (‘Equimetre’) records or was inputted as part of routine data collection when exercising racehorses.

3.3.1.1 Horses

The study population represented a convenience sample and comprised 530 Thoroughbred racehorses of between 2 – 7 years of age and included males (colts/stallions; n= 100), females (fillies/mares; n=262) or geldings (n=168). Horses were tracked longitudinally as they trained on varying surfaces throughout the year. The racehorses were all regarded by the trainer as race fit; that is, actively in-training to sustain fitness levels and compete in races during the study period (March 2020 to September 2021).

3.3.1.2 Riders

There were 103 different work riders involved in this study. Participants were either regular work-riders who had never registered as a professional race jockey or were either current or past, professionally registered jockeys. Other information such as rider's age and weight was not available. The dataset comprised female work riders (n=37), of which n=8 were current or past registered professionals on https://www.racing.com/jockeys, n=29 female riders had never registered as a professional. The remainder were male work riders (n=66), of which n=35 were current or previous registered professionals. n=31 male riders had never registered as a professional.

3.3.1.3 Equipment

Horses wore their regular tack and were exercised by a randomly allocated work rider. Rider-horse allocations changed for each individual training session. The device was fitted prior to training by persons accustomed to the device. An electrode was fastened at the girth and the second secured under the saddle pad in the natural dip of the back, as previously described (ter Woort et al., 2021). The fitness tracker recorded physiological and locomotory parameters during designated periods of trot, canter and gallop. All trainers and local data analysts had previously integrated the Equimetre™ into their work regimes.

3.3.2 Training

The trainer directed each rider to work their respective horse according to given target timings for set distances, determined by a sound and light system fixed to the riders' helmet signalling to them the time taken to cover each furlong (200m). Each training session was evaluated based on the trainer's observation on the track, riders' feedback following exercise and the fitness tracker recordings ('Equimetre'™, Arioneo Ltd, France). Following exercise, all horses were systematically placed on a horse walker or walked in hand to recuperate until heart and respiratory rate had returned to a natural 'baseline'. The training locations were on racetracks or training centres with a choice of surface including sand, turf or fibre. These latter aspects were also recorded for each training session. Using the Equimetre, data were available on speed (i.e., time taken to cover 200m in seconds) recorded for each 200m segment (at 200, 400, 600, 800, 1000, 1200 and 1400m using GNSS (GPS+Glonass+Galileo) satellite data).

From these data, the Equimetre also calculated the fastest 200, 400, 600, 800 or 1000m segment. Using the ‘fastest 200m’ recorded, a data-driven categorisation of speed during the session from slow/medium/hard-canter to slow/medium/hard-gallop was adopted. Descriptive information on each training session was checked, and any sessions with missing information on the jockey was discarded.

3.3.3 Data collection

All data collection occurred between March 2020 to September 2021. A total of 3,568 training sessions were available with the rider recorded, with each racehorse completing 5 (2-10), median (first-third interquartile range [IQR]) training sessions. All 530 racehorses completed at least one training session, 134 racehorses completed 10 races, 22 racehorses completed 20 training sessions. Few racehorses completed ≥25 training sessions, therefore these were grouped. Month of training session was recorded for both years. From the exact date of training, the number of training sessions, and the interval between them, could also be recorded for each horse. The Equimetre recorded aspects of each horse’s cardiovascular responses to exercise (e.g., heart rate, HR) during trot, canter, gallop, peak heart rate (HRpeak) and HR during recovery (HR at 15 or 30 mins or at the end of the designated training session) and aspects of locomotion (stride length and stride frequency). From these live data that were instantly recorded by the device, further analyses were able to be conducted *post-hoc* that pertained to each training session such as the deltaHR (or rate of early recovery) ([HRpeak – HR at 15min recovery]/15), HR area under the curve (or overall recovery) (HRauc; ([HRpeak +HR at 15min]/2)+([HR at 15min+HR at 30min]/2)+ ([HR at 30min+HR at end of session]/2)). All areas under the curve (AUC) were calculated according to the trapezoid rule in Graphpad Prism (Graphpad Prism 9, Graphpad Software, La Jolla, USA). Environmental temperature and precipitation were recorded as potential covariates in any analyses.

3.3.4 Racehorse race outcomes according to sex of the jockey

3.3.4.1 Race results

For Australia, data for the 2021 racing season in Victoria state, involving all race meetings, were extracted online from https://www.racing.com/jockeys/. Aspects of the dataset such as venue, distance, track and class were not taken into consideration. Comparative data in the United Kingdom during the 2021 racing season, exclusively for flat race meetings, were provided by The British Horseracing Authority https://www.britishhorseracing.com/racing/participants/jockeys/. Both datasets included: Australia, n=169 registered jockeys (male, n=114, female, n=55); UK, n=436 registered jockeys (male, n=307, female, n=129). Overall, the combined dataset included a total of 52,464 race starts with all jockeys registered completing at least n=1 professional race. Recorded data included wins and win percentage (number of wins per total number of starts expressed as a percentage) for individual jockeys and, for Australia only, achieving a podium place (1^{st}, 2^{nd} or 3^{rd}).

3.3.5 Statistical analysis

3.3.5.1 Training data

Any descriptive data (e.g., continuous variables) that were normally distributed (e.g., speed, stride length, stride frequency) are presented as mean (± 1 standard deviation [SD]). Similar data that were not normally distributed or categorical are presented as median (1^{st} - 3^{rd} interquartile range) or as percentage (of total number) for categorical variables. Data distribution was checked either by standard tests (e.g., Shapiro-Wilk test) or checking of residuals post analysis. If necessary, data were log-transformed ($\log_{10}$) to normalise the distribution of the data prior to analysis. For some analyses, where assumptions for analysis of variance could not be met due to missing data (e.g., occasional missed speed or HR recording), then linear mixed models (restricted maximum likelihood; REML) was used, so that any missing data were assumed to be randomly distributed amongst treatment groups. Individual racehorses were included as random effects in the model to account for the reduced within-animal variation. Any available factors that were not part of the design but may influence outcome were included as co-variates (e.g., interval between training session in days, training month, temperature, precipitation). Different training centre/location was also added as further random effects when they had tracks of differing surfaces at the same location. Since few training sessions were conducted on fibre (all-weather), for further analyses of horse-level variation in cardiovascular or locomotory parameters then only sand and turf were considered, and these were analysed separately.

3.3.5.2 Race data

The percentage of race wins (i.e number of races won divided by total number of races, expressed as a percentage) as a proportion of total races entered was analysed by logistic regression with a logarithm-link function, and sex of the rider as the only fixed effect. Data for both countries were combined to increase sample size, but country was included as a fixed effect for potential secondary outcomes. With the overall win percentage estimated at 10% of total races started, in order to observe a 1% difference between male and female jockeys, with 90% power and 5% significance level would require a total sample size of n= 9781. All data were analysed using Genstat v21 (VSNi Ltd, Rothamsted, Harpenden, UK). Statistical significance was accepted at $P<0.05$.

3.4 Results

3.4.1 Descriptive data of the cohort; number, type and intensity of training session by sex of work-rider

Female riders completed a higher proportion of the total number of training sessions in this cohort (n=1868 of 3568, 52.4%). The number of training sessions ridden by female riders was 19 (4 – 76) versus 9 (3 – 23) for male riders. The average distance horses were exercised was not different according to sex of the rider, female, 1981 (1701 – 2155); male, 1861 (1564 – 2160) metres, median (IQR). As the speed of the session increased from slow canter to hard gallop, the proportion of male riders increased (Figure 6a). Data for training sessions using an Equimetre were available from March 2020 to September 2021. Sessions were conducted on all three surfaces (fibre, turf and sand) throughout the year and gradually increased in frequency, reaching a maximum number of sessions (>400) in July-August 2021 (Figure 6b). Similarly, the number of training sessions stratified by training intensity (i.e., soft canter to hard gallop) followed the pattern of total training sessions over the course of both years with no marked variation in any particular month (Figure 6c). However, when considering the track surface chosen for specific training intensities then it was clear that the majority of canters and gallops were conducted on sand and turf, respectively (Figure 6d). For each track surface, variation in training intensity existed but, for example, only n=3 (of 1381, 0.2%) hard gallops were conducted on sand, and only n=28 (of 2165, 1.2%) soft canters were conducted on turf.

Figure 6 Classification of the number, type and intensity of training sessions

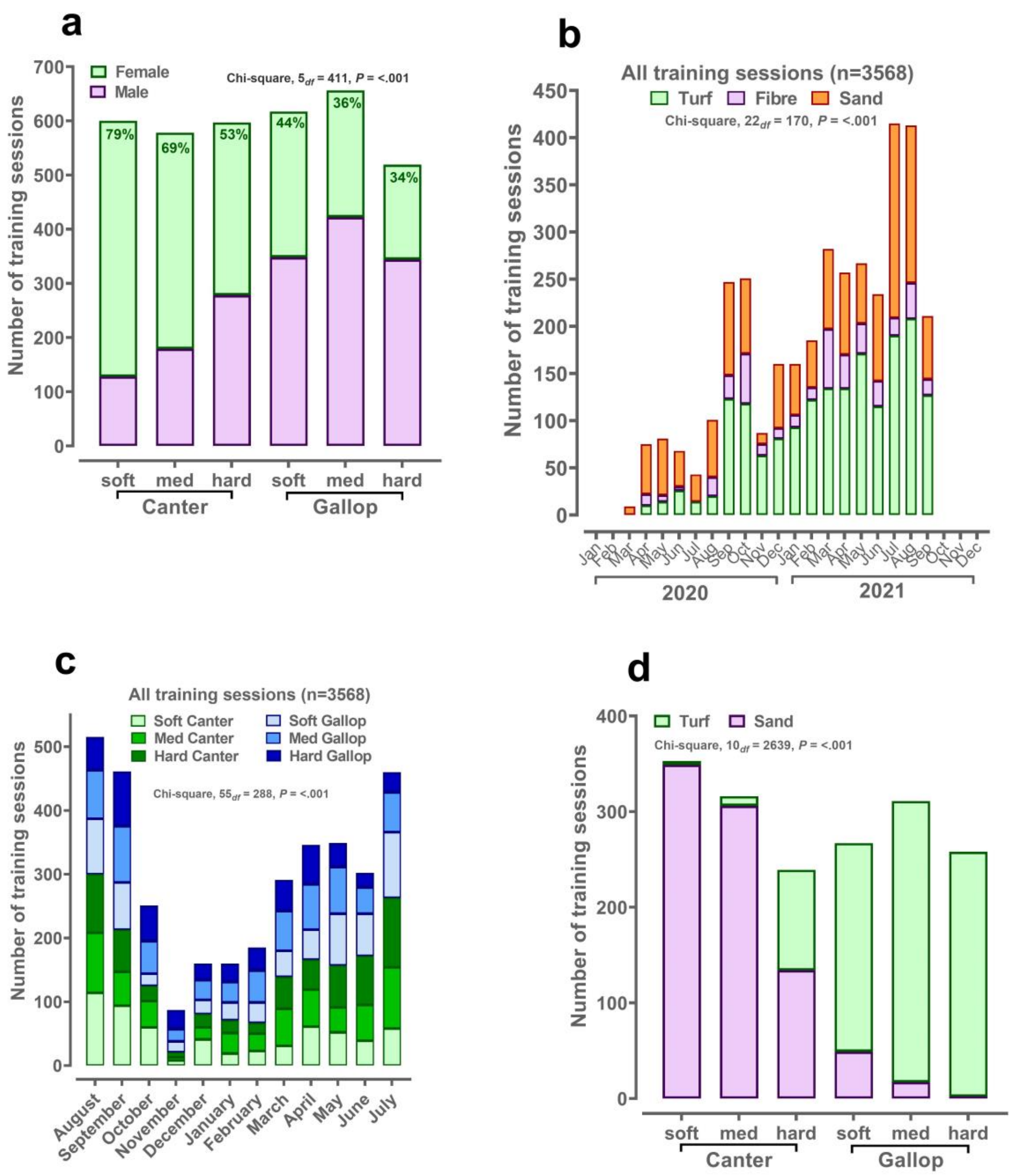


Figure. **a,b,c,d:** Data are numbers of training sessions stratified by training intensity, month of the year or track surface. A total of 3568 training sessions were included in this dataset from a single trainer in Australia. Data were available throughout the year. Training intensity (soft/med/hard canter; soft/med/hard gallop) was derived from calculating sextiles of the fastest furlong (200m interval) for the overall dataset. Statistics were generated by analysing proportions (percentage of group total) by chi-square (Genstat v20, VSNi, Rothampsted, UK).

3.4.2 Racehorse speed, stride length and effect of training on differing surfaces by sex of work-rider

Racehorses increase speed by partially increasing stride frequency (by ~ 19% and 20% for horses ridden by female and male riders, respectively) but with a far greater increment in stride length, which increases by ~56% and 57%, respectively; Table 6). The increment in speed with training intensity is not linear; that is, near maximal speeds are achieved at ‘soft gallop’ with only small increases thereafter (Table 6). The mean time taken for any 200m segment (i.e., each furlong) gradually decreases, the further the training distance, with no effect of rider sex on either turf or sand (Figure 7a,b). Stride length also increased with training intensity in a curvilinear fashion on both training surfaces, with no effect of sex of the rider (Table 6, Figure 7c,d). When training sessions were grouped according to the first 10 conducted versus the next 11-20+, and age of horse was adjusted for, and all heart rates recorded for each horse were analysed in a repeat-measures analysis from trot through canter to peak HR then a small, but statistically significant signal for lower HR during canter and soft-medium gallop on turf (Figure 7e) and sand (Figure 7f) was observed.

Table 6 Descriptive data for the complete cohort of racehorses training at a single racing yard in Australia

Parameter	Rider Sex	Soft Canter	Med Canter	Hard Canter	Soft Gallop	Med Gallop	Hard Gallop	*P*-value *sex*
Best 200m (secs)	Male	20.9 ± 2.2	15.9 ± 1.2	12.9 ± 0.5	11.8 ± 0.2	11.3 ±	10.8 ± 0.2	0.16
	Female	21.1 ± 2.2	16.3 ± 1.2	13.1 ± 0.6	11.8 ± 0.2	11.3 ±	10.8 ± 0.2	
Best 600m (secs)	Male	65.8 ± 9.5	49.7 ± 3.9	41.0 ± 2.0	37.4 ± 1.1	35.6 ±	34.2 ± 0.9	0.07
	Female	66.5 ± 8.3	51.0 ± 4.4	41.4 ± 2.8	37.6 ± 1.1	35.9 ±	34.5 ± 1.0	
Max speed (kph)	Male	35.5 ± 3.5	46.1 ± 3.4	56.1 ± 2.6	61.0 ± 1.0	63.7 ±	66.5 ± 1.4	0.20
	Female	35.1 ± 3.4	45.0 ± 3.4	55.7 ± 2.6	61.0 ± 1.1	63.6 ±	66.5 ± 1.4	
Peak heart rate (bpm)	Male	196 ± 24	216 ± 20	218 ± 15	218 ± 18	218 ±	218 ± 17	0.29
	Female	195 ± 24	210 ± 22	218 ± 16	217 ± 17	216 ±	215 ± 13	
Heart rate at 15min (bpm)	Male	61 ± 11	72 ± 15	83 ± 15	93 ± 18	95 ± 19	101 ± 18	0.89
	Female	61 ± 11	67 ± 14	85 ± 17	94 ± 18	97 ± 16	102 ± 16	
HR recovery auc (units)	Male	165 ± 23	188 ± 29	203 ± 33	217 ± 38	216 ±	218 ± 47	0.02
	Female	168 ± 23	184 ± 28	212 ± 30	223 ± 38	226 ±	229 ± 41	
Stride frequency (strides per sec)	Male	2.05 ±	2.17 ± 0.09	2.28 ± 0.09	2.35 ± 0.08	2.39 ±	2.44 ± 0.09	0.73
	Female	2.04 ±	2.17 ± 0.10	2.29 ± 0.09	2.35 ± 0.07	2.40 ±	2.45 ± 0.08	
Stride length (meters)	Male	4.87 ±	5.92 ± 0.36	6.87 ±	7.27 ± 0.25	7.47 ±	7.62 ± 0.30	0.07
	Female	4.83 ±	5.78 ± 0.38	6.77 ±	7.24 ± 0.23	7.43 ±	7.61 ± 0.28	

Values are Mean ± 1SD for continuous data recorded by ‘Equimetre’ (n=530 different racehorses, n=3568 different training sessions). Data were available throughout the year. Training intensity (soft/med/hard canter; soft/med/hard gallop) was derived from calculating sextiles of the fastest furlong (200m interval) for the overall dataset. Data were analysed by linear mixed models (REML) for the main effect of jockey sex, training type and their pre-specified interaction. Due to multiple training sessions for each racehorse and each rider, their individual IDs were included in the statistical model as nested, random effects. All data analyses were conducted using Genstat v20 (VSNi, UK).

Figure 7 Speed, stride and influence of multiple training sessions on different track surfaces by sex of work rider

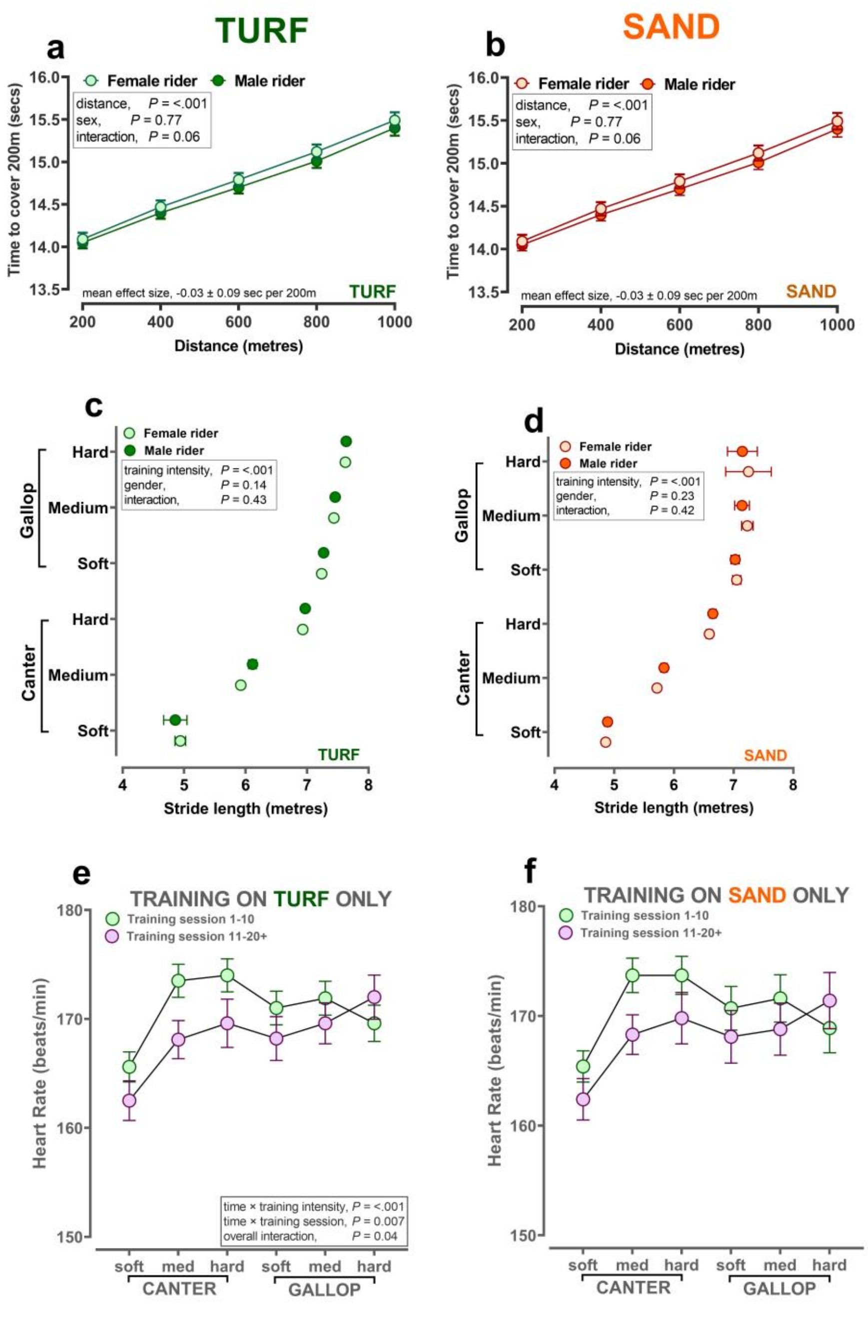


Figure. **a,d:** Values are predicted mean ± S.E.M. for continuous data recorded by 'Equimetre' in a cohort of racehorses in Australia (n=130 different racehorses, n=1,754 different training sessions). Data were available throughout the year. Training intensity (soft/med/hard canter; soft/med/hard gallop) was derived from calculating sextiles of the fastest furlong (200m interval) for the overall dataset. The statistical model generated predicted means (± S.E.M.) with the pre-specified interaction, training intensity × rider sex (or training session, **e,f**) fitted last after inclusion of rider registration status and track surface as fixed effects, HorseID and rider name as random effects, since both horses and riders completed multiple sessions. All data analyses were conducted using Genstat v20 (VSNi, UK) and graphs produced using Graphpad Prism v9.0 (La Jolla, USA).

3.4.3 Racehorse cardiovascular responses to incremental training intensity by sex of work-rider

During warm-up, heart rate (HR) for the racehorses in first recorded trot, according to sex of the rider, was: male, 131 ± 1.1 vs. female, 127 ± 1.1 beats/min, $P = 0.02$. During first canter, HR of the horses increased as expected, eliminating any difference by sex of the rider: male, 168 ± 1.4 vs. female, 166 ± 1.4 beats/min, $P = 0.38$ (Figure 8a,b). Incorporating heart rate peak, which was not significantly different according to sex of the rider (Figure 8c), with recovery of racehorse heart rate (predominantly over the first 15min after the training session), through 30mins after then end of the session (i.e. the walk back to stables;) allows for the overall area-under-the-response-curve (AUC) to be calculated for the session or for overall recovery (Figure 8d). Over the period of greatest rate of recovery (i.e., to 15mins), the delta HR ([peakHR minus HR at 15mins]/15) showed differences based on the sex of the rider on turf, but not sand (Figure 8e,f). That is, for the relatively slower training sessions conducted on turf then horses appeared to recover faster with a male rider. Delta heart rate is primarily driven by the peak heart rate achieved, which itself is influenced by the training intensity. Therefore, this analysis, and the potential signal for an effect of sex of the rider was further drawn out in AUC analyses at 15min recovery (more influenced by peak HR) and from 15 to 30min recovery (less influenced by peak HR).

Figure 8 Racehorse heart rate on different track surfaces by sex of work rider

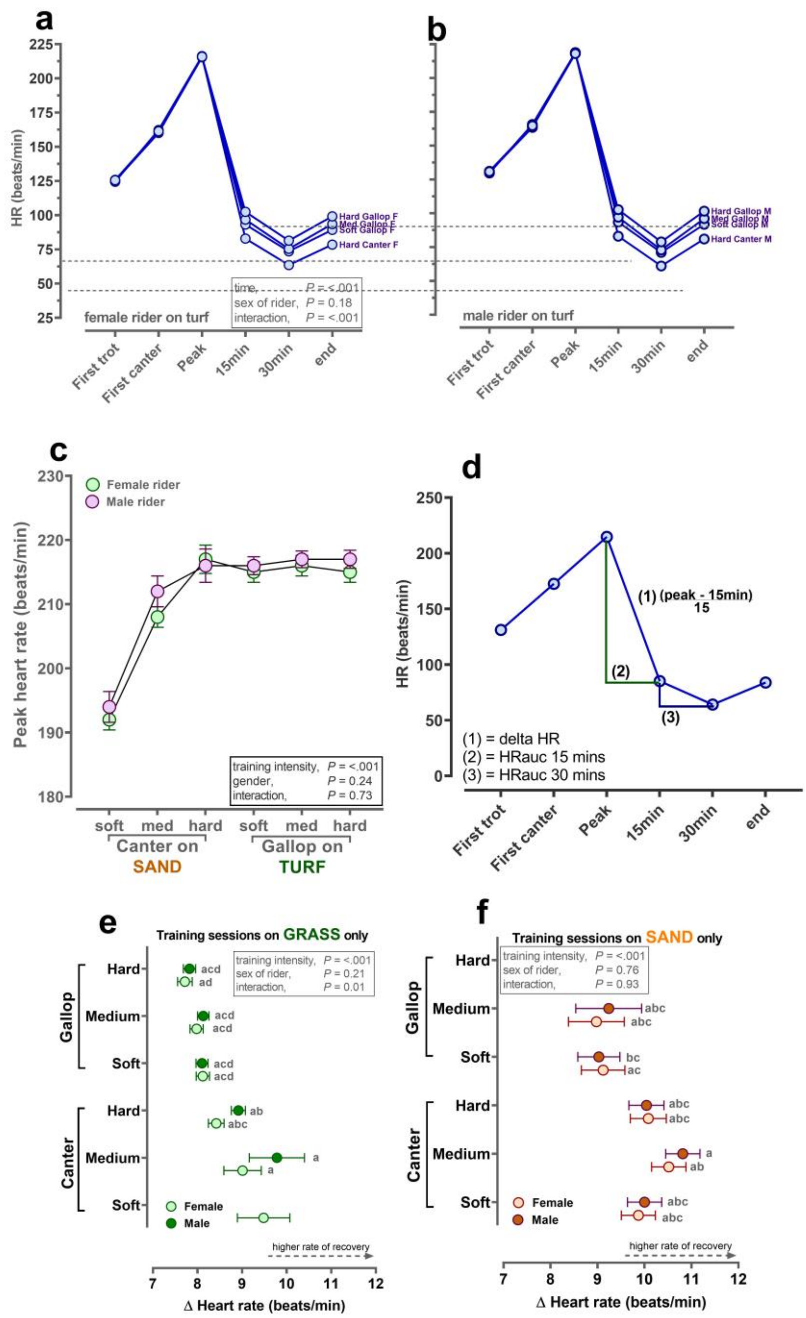


Figure. **a,b,c,e,f:** Values are predicted mean ± S.E.M. for continuous data recorded by 'Equimetre' in a cohort of racehorses in Australia (n=130 different racehorses, n=1,754 different training sessions). Data were available throughout the year. Training intensity (soft/med/hard canter; soft/med/hard gallop) was derived from calculating sextiles of the fastest furlong (200m interval) for the overall dataset. The statistical model generated predicted means (± S.E.M.) with the pre-specified interaction, training intensity × rider sex fitted last after inclusion of rider registration status and track surface as fixed effects. HorseID and rider name were included as random effects, since both horses and riders completed multiple sessions. d) describes calculation of delta HR and HR area-under-the-response-curve. All data analyses were conducted using Genstat v20 (VSNi, UK) and graphs produced using Graphpad Prism v9.0 (La Jolla, USA).

3.4.4 Racehorse recovery of heart rate after incremental training intensity by sex of work-rider

Overall racehorse recovery of heart rate, with larger numbers indicating a greater area and thus more beats/min, was influenced by the sex of the rider but *only* at certain training intensities on specific track surfaces (Figure 9a-d). That is, on turf where the majority of fast gallops are conducted, then racehorses appeared to recover more slowly at 15 and 30min (larger AUC for HR) with a male rider, but this observation was only at soft-medium canters i.e. at the paces rarely, but not unusually (n=119 canters on turf) conducted on that surface (Figure 9a,c). In contrast, the opposite was observed on sand; racehorses recovered more quickly with male riders, but only after medium-hard gallops (n=68 gallops on sand; Figure 9b,d). Accumulation of training sessions had little effect on the rate of recovery of heart rate (Figure 9e,f). In summary, sex of the rider being male only influenced recovery of racehorse heart rate when horses were exercised at the training intensity rarely conducted on that particular surface e.g., during steady cantering on turf, where most gallops occur and during hard gallops on sand, where the majority of canters were conducted.

Figure 9 Recovery of racehorse heart rate on different track surfaces by sex of work rider

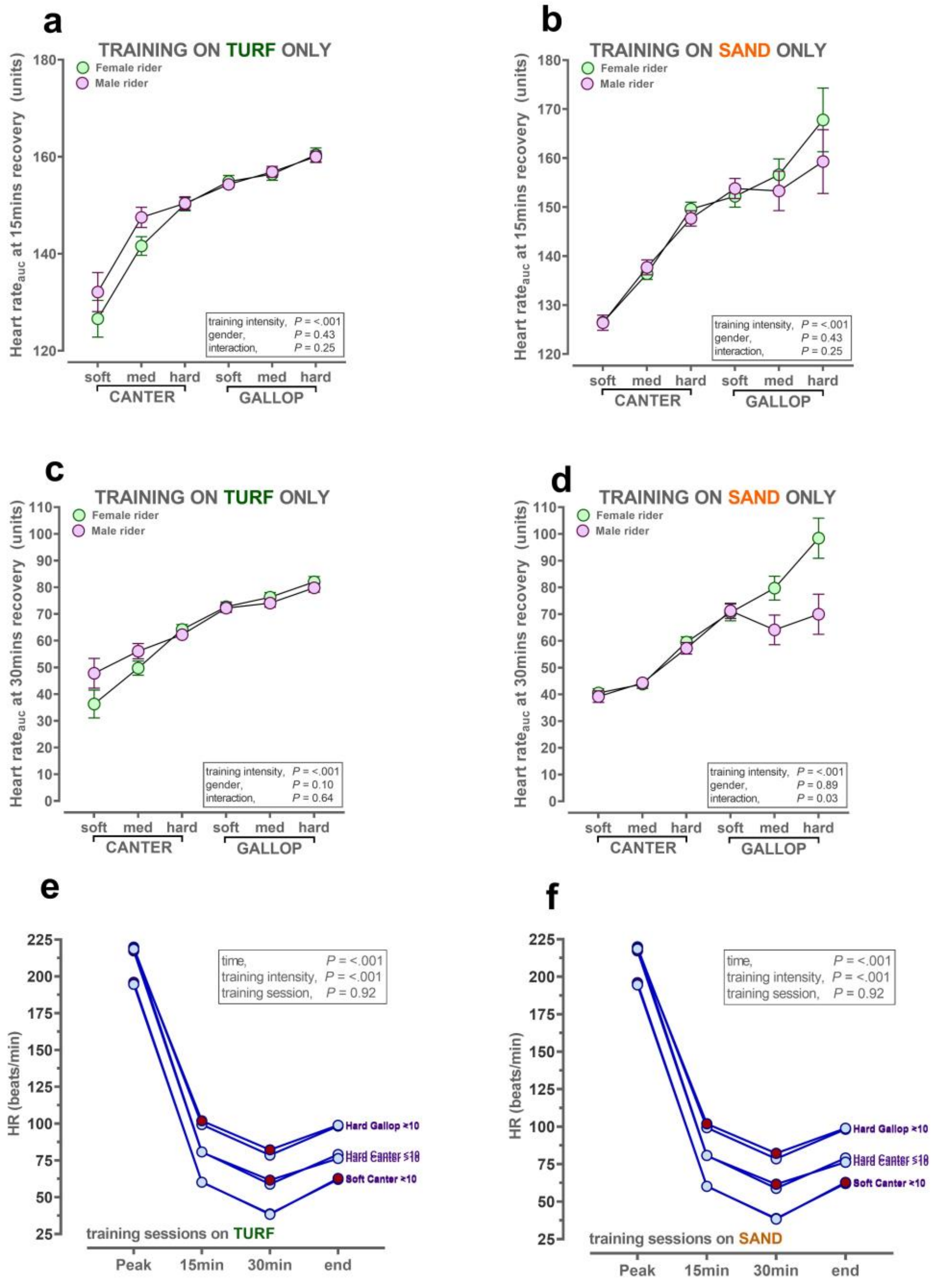


Figure. **a,b,c,d:** Values are predicted mean ± S.E.M. for continuous data recorded by 'Equimetre' in a cohort of racehorses in Australia (n=130 different racehorses, n=1,754 different training sessions). Data were available throughout the year. Training intensity (soft/med/hard canter; soft/med/hard gallop) was derived from calculating sextiles of the fastest furlong (200m interval) for the overall dataset. The statistical model generated predicted means (± S.E.M.) with the pre-specified interaction, training intensity × rider sex fitted last after inclusion of rider registration status and track surface as fixed effects. HorseID and rider name were included as random effects, since both horses and riders completed multiple sessions. HR area-under-the-response-curve (AUC) calculated as described in methods. All data analyses were conducted using Genstat v20 (VSNi, UK) and graphs produced using Graphpad Prism v9.0 (La Jolla, USA).

3.4.5 Race results

There were far more registered male professional jockeys than female in both UK and Australia. Overall, male jockeys had a small, but significantly greater win percentage compared to female jockeys (female, 9.9 ± 0.5%; male, 11.0 ± 0.2%: F-prob, 0.03). However, the effect was influenced by country; in Australia the effect size was significant (female, 7.9 ± 0.8 vs. male, 10.4 ± 0.4%) but in the UK it was not (female, 10.7 ± 0.7 vs. male, 11.3 ± 0.2%). In Australia, there was no difference between male and female jockeys achieving a top three 'podium' position (female, 25 (10 – 35) %; males, 27 (18 – 35) %, Mann-Whitney U test, P=0.20).

3.5 Discussion

No study has directly, and objectively, compared whether female *versus* male jockeys influence any aspect of racehorse physiology (e.g., heart rate) or performance (e.g., speed, stride length). This study, the first of its kind to date, sought to ascertain whether sex of the rider has a measurable difference (positive or negative) on racehorse performance physiology such as speed (e.g., during race-pace training sessions), cardiovascular function (e.g., maximum heart rate, heart rate recovery) or locomotion (e.g., stride length) during training. In addition, we asked whether sex of the jockey has a significant effect on a successful race outcome i.e., either by winning or achieving a top-three placing. There was no overt effect of the sex of the rider on any aspect of racehorse speed or stride length, at race-speed training intensities. However, when the converse training intensity was conducted on the opposite, usual training surface (e.g., a slow canter on turf or a fast gallop on sand, both of which were unusual) then small, but significant physiological effects – reduced or greater rates of recovery of racehorse heart rate, respectively – were observed. Female jockeys had very similar racing success compared to male jockeys. Hence, we suggest that sex of the jockey has few direct effects on racehorse physiology or performance.

In this study, there was a clear difference in the proportion of training sessions completed by male or female work-riders. Despite a lower number of female (n=37) compared to male riders (n=64), female riders completed a higher number of training sessions (52.4%) than male riders (47.6%). This contrasts with a previous study, and our current data, where in actual races, there are fewer female riders getting proportionately fewer race rides (Ray and Grimes, 1993). Thus, despite female riders completing many more work-rides in training, fewer appear to progress to become professionals, securing race-rides. This observation questions equal racing opportunities between female and male jockeys. Indeed, in training rides, as the intensity of the training session increases, far more male riders are used, with female work-riders completing most slower, canter sessions. This variation may be explained by an unconscious bias made by trainers; the assumption that male riders with greater strength are more suited to higher work intensities. However, our data show that there is no evidence to support this contention; for all training intensities as directed by the trainer, there was no difference in the fastest 200m between racehorses ridden by a male or female work-rider (across 3,568 training sessions).

The faster training sessions may be preferentially ridden by registered professional jockeys of which many more are men. In our dataset, a far greater proportion of ‘gallop’ sessions were conducted by past or current race registered male professional jockeys (male, 31.8% vs. female, 4.5%). This could, separately to the study, reflect an effect of rider’s experience on racehorse performance: trainers choosing to use riders with greater race experience to recapitulate a race environment in training. In Australia, the majority of high-intensity workouts (i.e., gallops) were conducted on turf, while canters were completed on sand. This is consistent with the findings of Morrice-West et al. (2018), who surveyed Australian trainers on the use of track surfaces for training. Sand or synthetic ‘all-weather’ surfaces were commonly used for slow workouts, while gallop work was conducted on turf. It is likely, therefore, that racehorses anticipate certain training intensities according to the track surface. Supporting this contention, in our study, heart rate at trot prior to galloping on grass was 124 ± 26 beats/min (mean ± S.D.) versus 114 ± 26 beats/min prior to a gallop on sand, where most canters occur. Racehorses no doubt anticipate the type of training session they are about to conduct. Additionally, the greater number of training sessions in 2021, may be explained by a possible increase in the number of Equimetre trackers at hand.

To increase speed from canter to gallop, horses increase frequency of their stride, to an extent, but speed predominantly increases due to an extended stride length, as reported here and previously by others (Ratzlaff et al., 1985). Near maximal speeds (55-60kph) were attained at a training intensity of ‘soft-gallop’ and only minimally increased thereafter. We acknowledge that speed can be affected by the track condition (i.e. a harder turf or relatively softer sand (Maeda et al., 2012)), which was not measured in this study, but the size of our dataset would limit these relatively small effects. Here, the mean time taken for a horse to cover a furlong (200m), regardless of distance of the training session, did not differ according to the sex of the work rider. As expected, the longer the training session (for example, from 1500m to 3000m), then the average time taken to cover each furlong gradually increased (see Figure 6a,b), suggesting a gradual slowing. Interestingly, riding style can influence racehorse speed; a crouched posture reduces aerodynamic drag and can improve racing times by up to 5-7%

(Pfau et al., 2009). Whilst this was not measured in the current study, we assume that male and female work-riders, wearing body protectors, do not adopt significantly different riding postures in training.

Stride length increased with training intensity but was not affected by the work rider's sex. Information on the riders' weights was not obtained for the study. Nevertheless, we appreciate that an increment in the rider's weight has the potential to reduce the stride length of horses and alter performance (Gunnarsson et al., 2017). The rider's experience, registered race professional *versus* non-registered race professional was accounted for and no marked effect on speed or stride was highlighted. These findings run counter to those of (Kapaun et al., 1998), who found that horses ridden by professional riders had the highest trotting speed and the longest stride length compared to horses mounted by a hobby-rider. The effect of accumulated training sessions on heart rates of horses on both turf and sand, revealed greater fitness levels (i.e., lower heart rate for the same intensity) in horses having completed 11 - 20+ workouts. Age of the horse was included as a confounder, which couldn't have influenced our results for this observation. Indeed, heart rates during submaximal exercise provide a means of monitoring the adaptation of the cardiovascular system to chronic exercise, commonly referred as the 'fitness" status of an athlete. Foreman drew similar conclusions in Thoroughbreds undergoing exercise testing at different intensities; heart rate was lower following a conventional training program (Foreman, 1984).

Racehorse training and racing requires the cooperative effort of two distinctive individuals: horses and humans. Indeed, in any equestrian discipline including racing, positive interaction between horse and rider is paramount to cope with the emotional and physical challenges of the demands of training and the stress of competing. A few studies have described how equine cardiovascular responses interact with the rider; in one, fear or distress signals of the rider were not faithfully transmitted to the horse, as reflected in disparate heart rate responses (Merkies et al., 2014). However, optimally 'matched' horse-rider combinations translated into reduced HR responses of horses to novel stimuli (Munsters et al., 2012). Here, there was no effect of sex of the rider on racehorse heart rate, nor the peak of heart rate, during training at differing exercise intensities. That is, when male and female work-riders are instructed to exercise the racehorses at tempo (canters) or race-pace (gallops) then both do just that – there was no measurable difference, according to sex of the rider – on racehorse speed or on racehorse cardiovascular response. However, it has been shown that rider 'emotion/nerves' can be faithfully transmitted to the horse. For example, when exposed to a novel stimulus (Christensen et al., 2006) or mounted for the first time by a novel rider (Schmidt et al., 2010), horses respond with an increase in heart rate. When the rider, but not horse, knows in advance that a novel stimulus/object that is known to cause the horse to startle is about to be encountered, the increment in rider heart rate, in anticipation, is matched by an increment in the horses heart rate (Keeling et al., 2009). Such acute fight-or-flight responses, most likely mediated by catecholamines and the stress hormone, cortisol, may facilitate improved training responses via energy mobilisation (Reynaert et al., 1976) and/or activated behavioural responses (Korte, 2001).

Whilst in this study we found few effects of sex of the rider on the racehorse, we did note a significant effect on recovery of heart rate (see Figure 5), but only at each extreme of exercise intensity when conducted on the track surface that was opposite to that usually used for that exercise intensity; that is, for example, only after medium-hard gallops on sand, heart rate was lower when ridden by a male jockey, whereas after slow canters on grass, heart rate was significantly higher when ridden by a male jockey. Most gallops are done on grass and slow canters on sand. We interpret this response as indicating that male work-riders, more so than female, may anticipate the 'expected' training-intensity on a given surface and their higher or lower heart rate may be being transmitted through to the horse. Without simultaneous measurement of work-rider heart rate, we cannot confirm this point but it is intriguing and has been noted in other circumstances (Saad and Vongas, 2009). Further prospective data collection is warranted to confirm this observation. The extent to which male work-riders 'push' the horses more (i.e., reaching the horses peak HR sooner) on turf, despite instructions to exercise horses at low speed is unknown, but there was no difference in average speed between rider sex at differing training intensities on each surface. It is also possible that for faster sessions on sand (it is unlikely to have happened for slow canters on turf) that changes in work rider for the main galloping session may have provoked changes in the horses' heart rate. Nevertheless, this is only likely to have occurred for faster gallop sessions on sand, where we observed relatively faster recovery of heart rate with male riders aboard. The observations on AUC may be limited by the lack of data on the resting heart rate of the horses. However, this observation was only observed during recovery, where the final recorded heart rate was close to, if not below, usual resting heart rate of racehorses.

In addition to the training data, the study also used publicly available race data to investigate whether male or female jockeys have greater competitive success. While small effects were observed in Australia for win percentage (~1% favouring male jockeys), but not for a placing in the top three of each race, no difference was observed in the UK. Hence, based on our analysis, we conclude that the sex of the rider does not significantly influence racehorse performance in competitive races. The ~1% difference is likely attributable to factors not recorded in our dataset, such as male riders getting more rides on better horses with a higher rating and therefore more likely to win in the first place. We were not able to get the starting odds for all the races to adjust for the 'quality' of the races. A previous study suggested that women win 0.3% more races than the British and Irish racing markets predict (Brown and Yang, 2015), suggesting that, as far as betting behaviour goes, there may be a slight underestimation of the ability of female jockeys to win races.

The study has a few limitations which should be acknowledged. First, there is a risk of selection bias due to the method of convenience sampling. However, the large sample size should minimise such an effect. Secondly, the study design is retrospective and descriptive. As a result, there are missing data for some riders and horses, along with other variables that have not been considered such as riders anxiety levels, heart rate responses and weight. Active management of the latter, particularly for professional jockeys could have influenced rider performance, although this is unlikely during routine training sessions as recorded in our study. Significant effects of rapid weight loss (i.e. 2% dehydration), have been noted to reduce performance, for example a 5% reduction of leg strength and 14% reduction in chest strength, with no effect on cognition (Wilson et al., 2014b). Our datasets do not record whether or not any work-rider was to any extent, injured or was carrying any unreported injury, which could impact performance. We have no reason to suspect a substantial bias between males/females with or without injuries in our dataset, despite studies outlining that riders do not necessarily rest or fully recuperate when injured (Rueda et al., 2010). Nevertheless, using mixed-effect models to analyse the data with due incorporation of any possible hitherto unforeseen confounders should mean that any missing data or confounding factors are distributed at random, minimising any inherent bias in our data.

The number of training sessions available for each individual rider was not balanced; many riders had only participated in <5 training sessions, while some had participated in >100. However, we were not as interested in individual rider effects and incorporating jockeyID in REML models, allows for such unbalanced datasets. When grouped by our main outcome, sex of the jockey, then the proportions of sessions were approximately even overall. Future studies could also include the horse's body weight (if recorded routinely), plasma lactate and cortisol in the racehorses and aspects of the rider's physical status (e.g., heart rate) which could provide novel insight into the unique interactions between different riders and different horses. Further research could expand on performance profiling in both male and female riders across different racing nations and types of racing (e.g., National Hunt or jump-racing).

To conclude, by leveraging a relatively small, but well-controlled dataset, we were able to demonstrate for the first time no overt effect of the rider's sex on racehorse physiology in training and performance in racing. Using measurements from objective fitness tracking systems, no marked sex differentials between work riders were observed on racehorse cardiovascular physiology, locomotory profiles and speed in race-speed training sessions. Furthermore, no marked effect of sex of the rider was noted on hard outcomes such as race performance; the chance of achieving a top three position during >52,000 competitive races. Therefore, this study provides objective evidence that female jockeys are as effective as male jockeys on racehorse physiology and performance. The data should encourage greater female participation in racing and improve access of female jockeys to higher quality racehorses competing in more prestigious races.

Chapter 4 Study 3: Locomotory profiles in Thoroughbreds: peak stride length and frequency in training and association with race outcomes

4.1 Abstract

Racehorses competing in short (i.e., 'sprinters'), middle- or longer-distance (i.e., 'stayers') flat races are assumed to have natural variation in locomotion; sprinters having an innately shorter stride than stayers. No study has objectively tested this theory. Here, racehorses (n= 421) were categorised as sprinters, milers or stayers based on known race distance (n= 3269 races). Stride parameters (peak length and frequency) of those racehorses were collected from prior race-pace training sessions on turf (n= 2689; 'jumpout', n= 1013), using a locomotion monitoring device. Pedigree information for all 421 racehorses was extracted to three-generations. In training, sprinters had a shorter stride of higher frequency and covered consecutive furlongs faster than stayers ($P < 0.001$). Relatively short or longer stride did not predict race success, but stayers had greater race success than sprinters ($P < 0.001$). Peak stride length and frequency were moderately heritable ($h^2 = 0.15$ and 0.20, respectively). In conclusion, differences in stride were apparent between sprinters and stayers (e.g., shorter stride in sprinters) during routine training, even after accounting for their pedigree. Objective data on stride characteristics could supplement other less objectively obtained parameters to benefit trainers in the appropriate selection of races for each individual racehorse.

4.2 Introduction

In flat racing, Thoroughbreds compete in various types of races usually categorised as short (<1500m), middle (1600–2500m) or long (>2500m) distance. Racehorses are usually considered to be naturally predisposed to one type of race distance, due to various physiological and morphological characteristics such as size, musculature (Tozaki et al., 2011), and stride (Hellander et al., 1983). Genetics is also important (Hill et al., 2010), although the precise contribution of genetics versus environmental variables which classify successful sprinters or stayers are relatively undefined. Nevertheless, subjective information is often used by many buyers and trainers of racehorses to assign them to become predominantly short or longer-distance performers. Even so, many racehorses initially race at shorter-distance, but subsequently perform better at longer-distances (i.e., 'sprinter-miler' or miler-stayer'). It is a common assumption and practice that racehorses are trained similarly, regardless of their labelling as a 'sprinter' or 'stayer'. In human sport, the training regimes of 100 m sprinters will contrast markedly to marathoners; short anaerobic bursts of speed requiring high muscular energy versus high aerobic capacity, efficient fuel utilisation and fatigue resistance (Kusy and Zielinski, 2015, Thompson, 2017). If trainers could complement their own assessment of a racehorses' best distance (i.e., subjective experience or their 'eye') with objectively obtained training data that classified the racehorses on locomotory characteristics that distinguished a sprinter from a stayer, then more specific training sessions could be implemented to increase the chances of better performance earlier in the racehorses' careers: horses would race at their appropriate distances and wastage could be reduced. Monitoring speed and stride length over time allows trainers to identify or anticipate musculoskeletal injuries early on during racehorse training (Wong et al., 2022).

Early determination of any type of racehorse involves complex decisions and multiple parameters. For example, shorter distance races (i.e., those at a distance of < 7 furlongs or ~1400m) require explosive speed and rapid, short strides to quickly reach maximum speed. Such a racehorse is often of shorter stature and greater muscularity, much like human sprinters. In contrast, racehorses that excel over longer-distance (>12 furlongs or ~2500m) require stamina, often associated with leanness and longer strides. Because such disparity in phenotype can underpin sports performance, genetic testing has grown in popularity across the racing industry (Hill et al., 2010, Tozaki et al., 2011). Variation in single-nucleotide polymorphisms of the myostatin gene (MSTN), which controls muscle development, has shown that nearly all sprinters are homozygous ('C/C') at the MSTN locus, while heterozygous ('C/T') horses tend to favour middle-distance races (7–12 furlongs; 1400 m–2400 m). Racehorses homozygous ('T/T') appear better suited to longer distance races (>10 furlongs, 2000 m), according to previously obtained race performance (Hill et al., 2010, Binns et al., 2010, Tozaki et al., 2010).

It is axiomatic that in order to win any competition based on speed, the fastest individual will get to the finish line first. Racehorses increase speed firstly by increasing stride frequency (SF) up to a pace consistent with gallop (45+ kph) and then by increasing stride length (SL; 45–65+ kph) (Clayton, 2016, Schrurs et al., 2022b). Therefore, in sprint races of shorter distance, the racehorse that is able to rapidly increase, or maintain a higher stride frequency, is more likely to achieve a higher speed and good performance. Over longer distances, longer stride becomes more important, alongside endurance capacity (Deuel and Park, 1990). For decades, breeders and trainers have attempted to relate the physiological characteristics of racehorses during their training to their race-day performance (Saastamoinen and Barrey, 2000). Objective measurements of locomotory parameters have only recently become available for racehorse trainers, allowing them to potentially ascertain whether a young racehorse has a greater aptitude for sprinting or longer-distance races (Schrurs et al., 2022b). However, to date, no study has related race performance over multiple seasons with information on locomotory profile in training–do racehorses that have only raced in sprint races demonstrate an innately shorter stride early on in training? With the advent of smart devices that record multiple parameters in the equine athlete, the possibility for such an early insight into locomotory differences between sprinters, milers or stayers is now possible. A better understanding of individual horse stride characteristics could help racehorse professionals select suitable race distances, while also taking into account their own experience at placing racehorses in suitable meetings alongside other historical aspects of how racehorse conformation and pedigree information can influence such decisions. No study has specifically evaluated stride patterns in different types of racehorses (stratified by performance in short, middle or longer distance races) and retrospectively assessed locomotory profile in training in the same racehorses, considering their pedigree information, to account for the influence of genetics on racing outcomes.

Hence, in the present study, an observational study was conducted, using a fitness tracking device to study peak stride (length and frequency) in racing Thoroughbreds categorised according to the type of turf race they have participated in (sprint, mile or staying' race; based on distance) and their subsequent racing result (win/podium/top5). Using this classification of racehorses according to their race distance, we have retrospectively classified the training data of the same horses galloping at race-speed on turf to observe whether any differences in locomotory parameters were apparent in training sessions prior to and during subsequent races. We were further able to determine whether any training parameters within each category of racehorse could predict race performance. The primary hypothesis of the study is that racehorses categorised according to race distance (sprinter/miler/stayers) may be distinguished in training by having relatively short, medium or long stride, respectively when analysed at race speed (soft-medium-hard gallop session or 'jumpout'). Secondary hypotheses are: 1) sprinters-milers-stayers with relatively short or long stride within each category are more successful in their respective races, and 2) that locomotory parameters have moderate-to-high heritability. Finally, since many racehorses compete in different types of races (e.g., sprint, mile and/or staying race) we analysed the extent to which locomotory profiles (e.g., peak stride frequency, length) in training evolved over time within individual horses throughout the race season.

4.3 Material and Methods

4.3.1 Databases

This retrospective, observational study used three large datasets, all including the same cohort of racehorses: (1) racehorse training sessions: collected by means of a fitness tracker (the 'Equimetre'™) from a single racing yard (Ciaron Maher Racing) in Victoria, Australia (2) racehorse pedigree information: publicly available and downloaded from https: //www.pedigreequery.com (accessed 4 August 2022) (3) race results: available upon subscription in Australia, with race data recorded and downloaded from http://www.racing.com (accessed 7 July 2022).

4.3.2 Designation of racehorses according to race distance

A total of n= 421 racehorses participating in a total of n = 3269 races were included in this study. Races were categorised according to class of race. In Australia, Group and Listed races are those established by the Australian Racing Board to reflect the highest standard of racing for races run in Australia. Group 1 are the highest-class races, followed by Group 2, Group 3 and Listed races. In this study, the highest-class races (n= 347, 10.6% of total) comprised; Group 1 (n= 65 of 3269 races; 1.9 %), Group 2 (n= 55 races, 1.6%), Group 3 (n= 97 races, 2.9%) and Listed (n= 130 races, 3.9%), whereas all other races were classed as Uncategorised (n= 2922 races; 89.7%). Race distance was known from http://www.racing.com (accessed on 28 October 2022) and was classified for this particular study as a 'sprint' race< 1600m, 'mile race' 1601-2500m or 'staying race' > 2501m. All races were conducted on turf between 20 March 2020 to 13 May 2022. Five types of racehorse were created: (1) pure sprinter–exclusively racing over sprint distance only (n= 265 horses, 1563 races); (2) sprinter-miler, competing predominantly in sprint but also some mile races (n= 81 horses, 775 races); (3) miler, pure mile races only (n= 22 horses, 167 races); (4) sprinter-miler-stayer, competing in all types of race (n= 37 horses, 327 races) and (5) stayer-miler, purely or predominantly racing at stayer distance with some mile races (n= 16 horses, 131 races). Racehorses were aged between 2–10 years of age at the time of racing and included males (colts/stallions; n= 33 average age, 2.93 ± 0.42 years), females (fillies/mares; n= 197, 3.88 ± 0.90 years), geldings (n= 174, 4.67 ± 1.42 years) or of unknown/unrecorded sex (n= 17, 3.76 ± 0.69 years). All race data were extracted online from http://www.racing.com, accessed on 28 October 2022. Other aspects of the dataset such as venue, track condition, carried weight, handicap, rating and prize money were recorded.

4.3.3 Training data

Horses wore their regular tack and were exercised by a randomly allocated work rider, who varied according to individual training sessions. A tracking device (‘Equimetre™’, Arioneo, Ltd. Paris, France) was fitted to the girth prior to training by persons accustomed to using the device, as previously described (ter Woort et al., 2021). The device recorded locomotory parameters (peak stride length and frequency) alongside speed (by GNSS) and cardiovascular parameters (peak HR), as previously described in detail (Schrurs et al., 2022b). The trainer determined the nature of each individual training session, directing the work-rider as appropriate. The Equimetre was not systematically placed on each horse for every individual training session, rather for specific sessions. From the GNSS (GPS + Glonass + Galileo) satellite data, speed (i.e., time taken to cover 200m in seconds) recorded for each 200 m segment (at 200, 400, 600, 800, 1000, 1200 and 1400m) was recorded. The fastest 200 m was then used to designate the session as soft, medium or hard gallop. All training sessions at gallop were conducted on turf. In addition, a separate dataset of ‘jumpout’ training sessions were available for analysis with similar logged data. These sessions aim to replicate race-day barrier trials and conditions. Horses of similar ability are grouped to ‘race’ simultaneously from starting gates for the duration of the training session. All jumpout sessions were also conducted on turf. All training data were collected between 7 April 2020 to 19 April 2022 and comprised a total of 2689 training sessions, with 12 (8–19) median (first-third interquartile range [IQR] per racehorse. From the exact date of training, together with the exact race date, the number of days prior to each race plus the interval in days between races could also be recorded for each horse. Final datasets were checked for artifacts and corrected accordingly in MS Excel. Environmental temperature and precipitation were recorded as potential covariates in any analyses. Using the hard outcome of race performance in races of known distance to classify five categories of racehorse from sprinter to stayer, then the same categorisation was applied retrospectively to all 421 racehorses during their gallop training sessions that occurred prior to, and during the two race seasons as recorded here (2020 to 2022).

4.3.4 Pedigree data

For each individual racehorse, an online search was first conducted on the Thoroughbred. Pedigree Database http://www.pedigreequery.com, accessed on 28 October 2022 to obtain a three-generation pedigree for all 421 individual racehorses The resulting pedigree dataset consisted of n= 2690 horses from 629 sires (259 of which were founders), and 1628 dams (693 founders). Where racehorses were either not present or multiple racehorses with the same name existed, then data were cross-checked using a further database (Equineline.com). The data for each individual racehorse was then manually reverified on http://www.racing.com/horses/, accessed on 28 October 2022 for trainer, horse age, sex and racing profile. As a further check, using a random number generator in MS Excel (between 001–421), ten further racehorses were cross-checked for accuracy. The final three generation pedigree was used to estimate heritability.

4.3.5 Statistical analysis

Any normally distributed descriptive data (e.g., peak stride length, stride frequency) are presented as mean (±1 standard deviation [SD]). Similar data that were not normally distributed or categorical are presented as median (1st–3rd interquartile range) or as percentage (of total number) for categorical variables. Data distribution was checked either by standard tests (e.g., Shapiro–Wilk test) or checking of residuals post analysis. If necessary, data was log-transformed (log10) to normalise the distribution of the data prior to analysis. For some analyses, where assumptions for analysis of variance (ANOVA) could not be met due to occasional missing data (e.g., artefacts removed or no data present), linear mixed models (restricted maximum likelihood; REML) were used with the main effect of interest fitted as a fixed effect and HorseID or racecourse fitted as random effects. This statistical model assumes that occasional missing data are distributed at random amongst fixed effects. Other potentially confounding factors that were not part of the design but may influence outcome, as assessed by univariate analysis ($P < 0.10$) were included as co-variates (e.g., interval between race days, temperature, precipitation). Estimates of heritability were generated using a sparse inverse relationship matrix ('ainv') generated for all 421 racehorses and their three-generation pedigree. Combining the pedigree file with phenotypic outcomes such as stride length in an animal model (i.e., using REML) allowed us to obtain variance parameters and narrow sense heritability estimates (additive genetic variance; Genstat v21, VSNi, Rothamsted, Harpenden, UK). Approximate standardised error (SE) for h^2 was obtained using the delta method, which uses a Taylor's expansion to get the variance of a function of a parameter (Var(f(x)) = Var(x) × (f'(x))2). Estimates were obtained after adjusting for age and including the type of racehorse (e.g., sprinter versus stayer) as fixed effects. Significant variation in the proportion of wins/placing according to the type of racehorse ('sprinter versus stayer') was analysed by logistic regression fitting win, top3 or top5 as individual binomial outcomes (yes/no) and type of horse as a fixed effect adjusted for any significant confounding variables (age of horse, track condition, race class). All data were analysed using Genstat v22 (VSNi Ltd., Rothamsted, Harpenden, UK). Statistical significance was accepted at $P < 0.05$.

4.4 Results

4.4.1 Racing data and performance

Within each category, racehorses participated in a similar number of races: (pure sprinter, 4 [1–8] races); sprinter-miler, 7 [1–14] races; miler, 6 [1–11] races; sprinter-miler-stayer, 8 [1–12] races; stayer, 7 [2–12] races, median [1st–3rd IQR]. Sprinters were significantly younger than milers, who were younger than stayers at the time of racing: (pure sprinter, 3.6 ± 0.9 years; sprinter-miler, 4.6 ± 1.2 years; miler, 4.8 ± 1.3 years; sprinter-miler-stayer, 4.9 ± 1.0 years; stayer, 6.6 ± 1.3 years mean ± 1 SD). Average prize money won according to the class of the race was significantly different between race classes, (Group 1, $93,898 ± 85,880; Group 2, $38,955 ± 42,618; Group 3, $28,573 ± 29,159; Listed, $27,012 ± 33,646; Uncategorised, $9847 ± 12,938). For n = 35 of 3268 races the final position was unknown. Overall, 508 races were won by 255 different racehorses, 331 different racehorses achieved a top three placing in a total of 2175 races and 375 of 421 racehorses were placed top five in a total of 1668 races. The remainder were unplaced. Racehorses therefore either won or were placed top three or top five in 15.5, 36.4 or 51.0% of races, which varied significantly according to the type of horse (Table 7). ‘Stayers’ were less common, competed in fewer races but were more successful than sprinters (Table 7). Race distance (meters) was not different ($P > 0.05$) between different class of race (Group 1, 1712 ± 664; Group 2, 1624 ± 427; Group 3, 1564 ± 501; Listed, 1762 ± 653; Uncategorised, 1566 ± 571m).

Table 7 Race performance stratified by type of horse

	All races (n = 3269)	Sprinter races (n = 1671)	Sprinter-Miler races (n = 874)	Miler races (n = 167)	Sprint-Mile-Stay races (n = 408)	Stayer races (n = 149)	*P-value
Wins (%)	508 (15.5)	234 (14.0)	134 (15.3)	27 (16.2)	74 (18.1)	39 (26.2)	<.001
Top3 (%)	1190 (36.4)	593 (35.5)	299 (34.2)	60 (35.9)	166 (40.7)	72 (48.3)	<.001
Top5 (%)	1668 (51.0)	823 (49.3)	422 (48.3)	89 (53.3)	239 (58.6)	95 (63.8)	<.001

Values are number meeting criteria for each row (proportion [%] of total races in each column). Data as per Racing.com racing records in Victoria, Australia (n=421 different racehorses, n=3269 different races). *Significant variation in the proportion of wins/placing according to the type of racehorse was analysed by logistic regression fitting win, top3 (i.e ranking among the top three finishers) or top5 (i.e ranking among the top five finishers) as a binomial outcome (yes/no) and type of horse as a fixed effect adjusted for any significant confounding variables (age of horse, track condition, race class).

4.4.2 Training data and locomotory performance

All sessions were effectively ‘race-pace’, as illustrated in Table 8, with horses covering a furlong (200 m) in 10–12 s, achieving speeds of up to 67 kph, with peak stride frequencies and length increasing with speed and indicative of race-pace efforts, as previously described. However, when categorised according to the type of racehorse, then significant differences were apparent; sprinters per se had significantly shorter peak stride length and higher frequency than stayers, with a gradual change between intermediary categories (Table 9). The expected increments in peak stride length and frequency with harder training sessions were observed across all categories of racehorse (Table 9).

Table 8 Descriptive characteristics of the training dataset

Training type…	Soft Gallop (n= 635)	Medium Gallop (n= 579)	Hard Gallop (n= 585)	P-value
Best 0-200m (secs)	11.6 ± 0.1	11.3 ± 0.1	10.8 ± 0.4	<.001
Max speed (kph)	62.5 ± 0.9	64.2 ± 0.8	66.8 ± 1.4	<.001
Peak stride frequency (stride/sec)	2.37 ± 0.08	2.40 ± 0.00	2.45 ± 0.08	<.001
Peak stride length (meters)	7.35 ± 0.24	7.48 ± 0.24	7.63 ± 0.27	<.001

Values are Mean ± 1SD for continuous data recorded by 'Equimetre' in Australia (n=421 different racehorses, n=1799 different training sessions). Data were available throughout the year. Training intensity (soft/med/hard gallop) was calculated from the cohort based upon the fastest furlong (200m interval) for each session and slower intensities (slow/med/hard canter) were excluded. Such data was restricted to training sessions conducted on turf track surfaces. Data were analysed by one-way ANOVA, blocking for the individual horse to account for multiple training sessions conducted by the same horse.

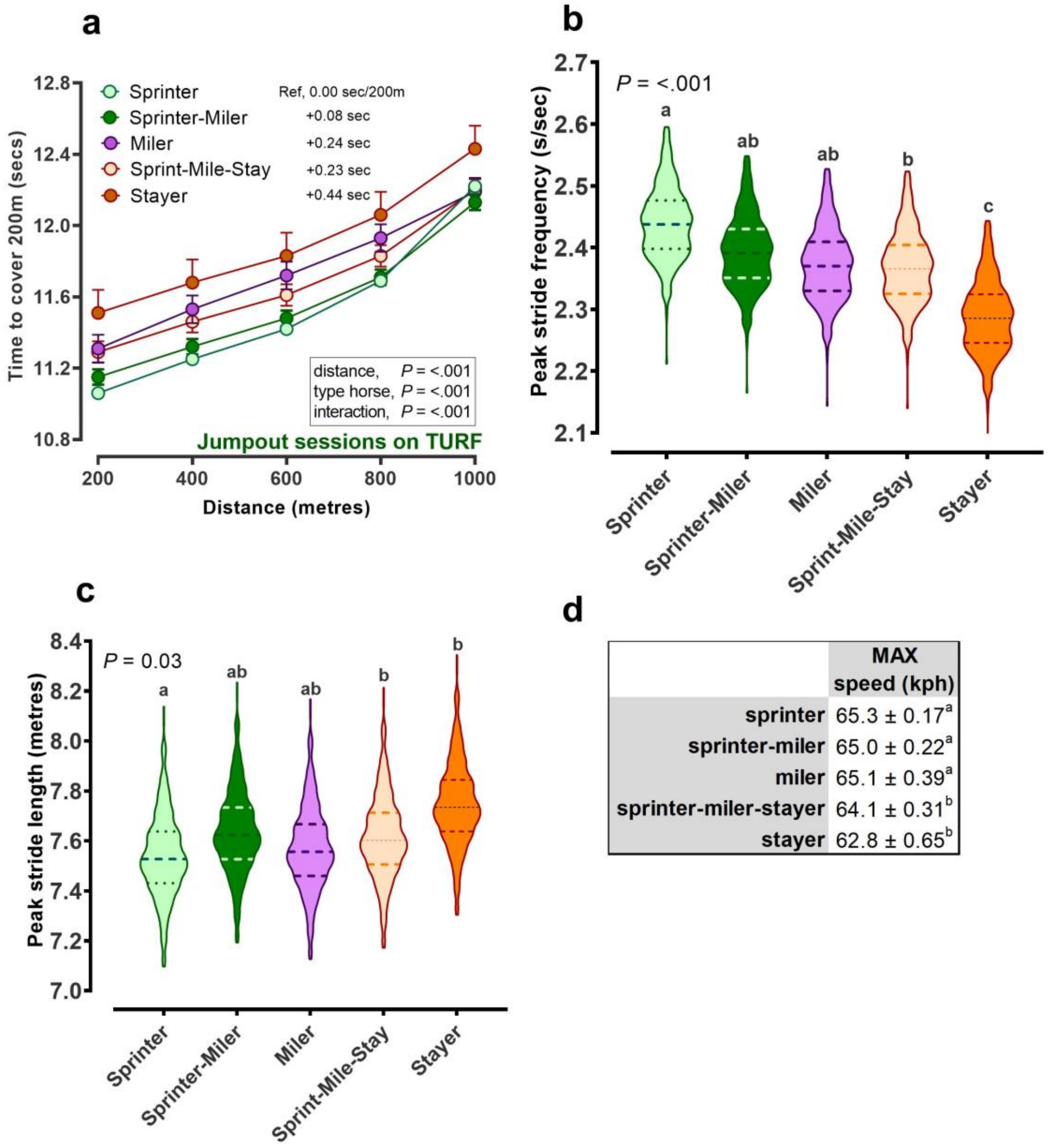
Table 9 Peak stride frequency and length in race-speed training efforts categorised by type of racehorse

type horse…	Sprinter	Sprinter-Miler	Miler	Sprint-Mile-Stay	Stayer	*P-value
Training distance	4924 ± 1146[a]	4987 ± 1232[ab]	4993 ± 1192[ab]	5167 ± 1240[b]	5333 ± 1148[ab]	**0.018**
'Work' distance	1802 ± 380[a]	1912 ± 479[b]	1968 ± 479[b]	2124 ± 565[c]	2292 ± 650[c]	**<.001**
Peak stride frequency (strides per sec)						
Soft Gallop	2.39 ± 0.07[a]	2.36 ± 0.07[b]	2.38 ± 0.08[bc]	2.35 ± 0.08 [bc]	2.28 ± 0.06 [c]	**Type horse, <.001**
Medium Gallop	2.41 ± 0.07	2.39 ± 0.07	2.38 ± 0.08	2.37 ± 0.06	2.29 ± 0.08	**Train intensity, <.001**
Hard Gallop	2.46 ± 0.08*	2.43 ± 0.08*	2.46 ± 0.05*	2.41 ± 0.06*	2.34 ± 0.05*	**Interaction, 0.03**
Peak stride length (meters)						
Soft Gallop	7.31 ± 0.23[a]	7.41 ± 0.23[ab]	7.37 ± 0.21[b]	7.41 ± 0.24[bc]	7.60 ± 0.20[c]	**Type horse, <.001**
Medium Gallop	7.44 ± 0.24	7.50 ± 0.22	7.52 ± 0.30	7.56 ± 0.22	7.77 ± 0.24	**Train intensity, <.001**
Hard Gallop	7.61 ± 0.28*	7.67 ± 0.27*	7.54 ± 0.20*	7.67 ± 0.24*	7.88 ± 0.08*	**Interaction, 0.07**

Values are Mean ± 1SD for continuous data recorded by 'Equimetre' in Australia (n=421 different racehorses, n=1799 different training sessions). Horse profile (sprinter, miler, stayer) was determined based on race distance and subcategories (pure sprinter/miler, sprinter-miler, sprinter-miler-stayer) were formed according to the nature/proportion of the races for every individual horse (see Methods). Data were available throughout the period before (not more than three months) and during racing. Data were analysed by restricted maximal likelihood (REML) for the main effect of type of racehorse, the individual racehorse as a random effect and after adjusting for significant covariates (age and weight of the horse). [abc]Values within a row with differing superscripts are significantly different at P<0.05, with Bonferroni correction for multiple testing. *Significant effect of training intensity (hard versus soft gallop)

In further data, for 378 of the 421 horses where speed and locomotory information were available for pre-race ‘jumpout’ training sessions (n= 1013); that is, starting from a standing start in stalls, then the best time to cover any 200m (furlong) from the first to the fifth furlong at 1000 m, then speed gradually became slower for all categories of horse, as expected, but was always significantly faster for retrospectively designated sprinters versus stayers (Figure 10a). In addition, peak stride frequency was higher (Figure 10b), stride length was shorter (Figure 10c) and peak recorded speed was higher (Figure 10d) in sprinters versus stayers. During the course of two racing seasons, we described whether locomotory parameters changed within individual racehorses of each category (sprinters to stayers; Figure 11). Whilst significant variability with individual training session from the first to tenth (relatively few horses completed ≥10, data censured at n= 10 training sessions) existed for peak stride length (Figure 11a) and peak speed (a slight increment; Figure 11c), the effect sizes were relatively small and not consistent, suggesting little evolution of locomotory parameters (i.e., no effect for peak stride frequency, Figure 11b,d).

Figure 10 Training data during jumpout for different categories of racehorse



d

	MAX speed (kph)
sprinter	65.3 ± 0.17[a]
sprinter-miler	65.0 ± 0.22[a]
miler	65.1 ± 0.39[a]
sprinter-miler-stayer	64.1 ± 0.31[b]
stayer	62.8 ± 0.65[b]

Figure. **a:** data are estimated marginal means ± SEM for consecutive 200m segments **b:** data are for all horses' peak stride frequency or **c:** peak stride length during jumpout training sessions, **d:** mean ± 1SD speed, according to category of racehorse. All data obtained from an 'Equimetre' used at a single racing yard in Victoria, Australia (n=378 different racehorses, n=1013 different 'jumpout' training sessions). Category of racehorse applied retrospectively to training data after competing in races of known distance. Data analysed for the main effect of type of racehorse by Restricted Maximal Likelihood (REML), with individual racehorse included as a random effect, and after adjusting for significant covariates (age and weight of the horse). Differing superscripts are significantly different at P<0.05.

Figure 11 Evolution of locomotory parameters throughout the training season

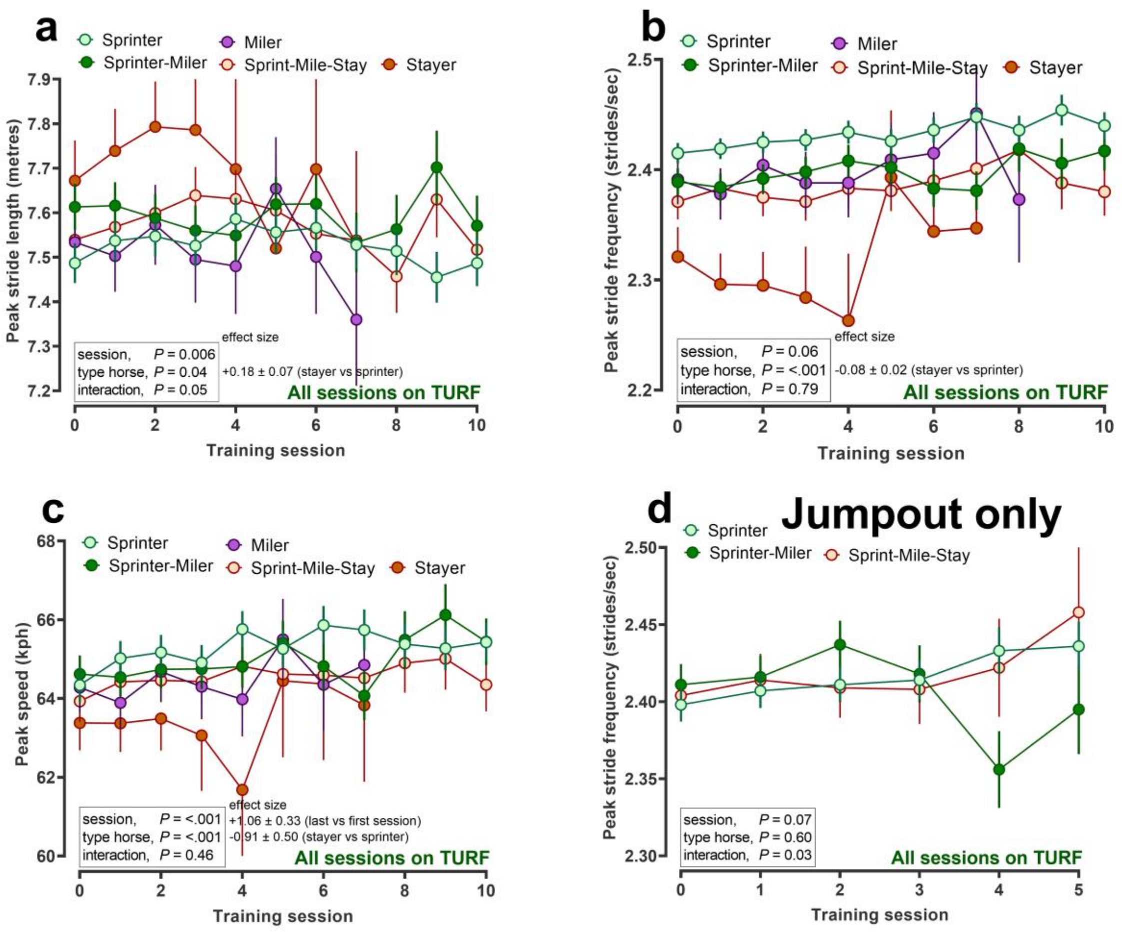


Figure. Racehorses were categorised based on competing in races of known distance, as described in Methods. **a-d:** data are estimated marginal means ± SEM for consecutive training sessions (x-axis) over the course of two racing seasons. Means were adjusted for age of racehorse and interval between training sessions. Individual racehorse, year/training month were included as random effects. Data were obtained using an appropriately fitted 'Equimetre' device from a single racing yard in Victoria, Australia. Change in locomotory parameter with number of training sessions ('session') for each category of racehorse ('type horse') and their pre-specified interaction were fitted as the main effects.

4.4.3 Training data, type of racehorse and predicting race outcome

Combining locomotory data during training for each individual racehorse with their race outcomes (win or top three 'podium') suggested that colts were more likely to win than geldings, with the chance of winning a group race declining as the class of race increased (Figure 12a). There was a small effect for racehorses with longer peak stride length (i.e., stayers) to have an increased chance of winning and finishing in the top 3, regardless of race class and racehorse type (Figure 12b).

Figure 12 Predicting race wins or podium places on training data

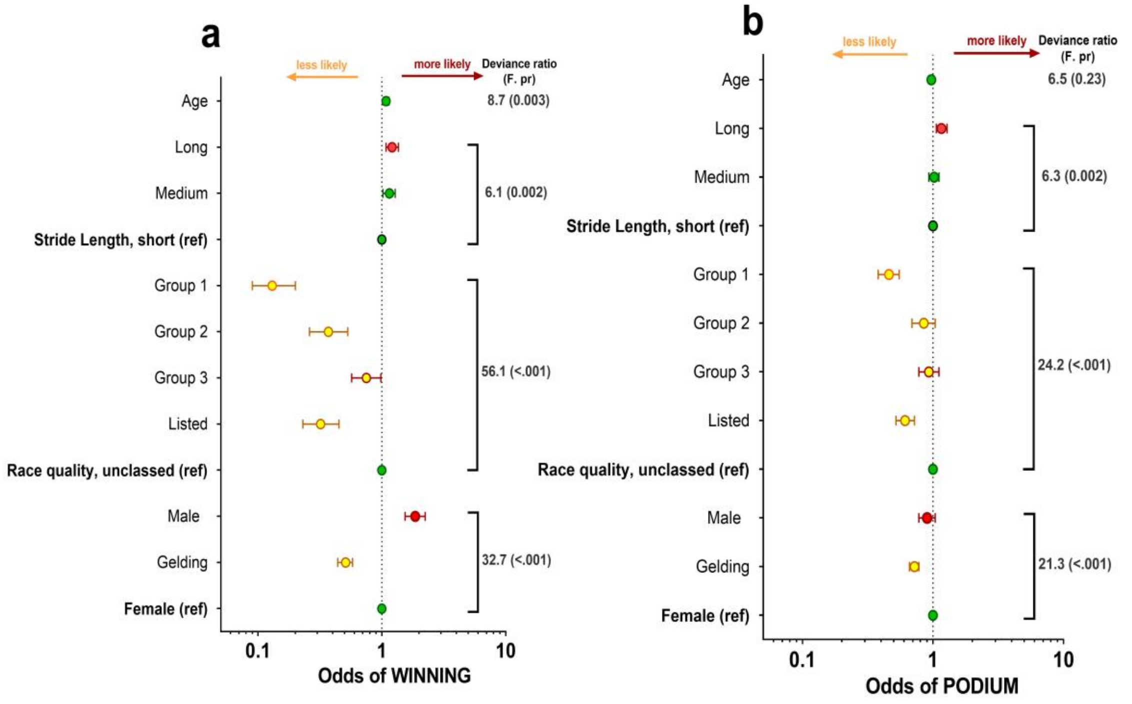


Figure. Data are odds ratios ± 95% CI for **a:** winning a race or **b:** achieving a top three placing. Odds ratios were obtained by integrating known race outcome data from Racing.com (Victoria, Australia; n=421 different racehorses, n=3269 different races) with training data (only gallop on turf) for the same horses before and during two race seasons (n=1799 different training sessions). Data were analysed with race outcome (e.g., win or top three) as the variable of interest, fitting sex of horse (female as referent category), race quality (unclassed as referent category), stride length (short as referent category) and age as a continuous variable. Since the same horse completed multiple training sessions and multiple races then HorseID was fitted as a random effect using Generalised Linear Mixed Models (GLMM). Statistics for main effects are indicated on the right on the graph with associated Wald statistic. Statistical significance was accepted at P<0.05.

4.4.4 Heritability of stride parameters and peak heart rate

After accounting for pedigree, which incorporates all traits with high genetic potential that were not recorded in our dataset (e.g., height, musculature etc…) then the difference in stride parameters recorded during training, according to the type of racehorse, was maintained (e.g., sprinters having shorter stride with higher frequency than stayers; Table 10).The estimates of narrow-sense heritability were significant (as determined by change in the log2 deviance ratio when pedigree information was included or not) and the values of h^2 were low to moderate (Table 10). The heritability of peak heart rate was however not significantly different across racehorse categories (Table 10).

Table 10 Heritability (h^2) of locomotory and peak heart rate during race-speed training efforts categorised by type of racehorse

parameter…	Sprinter	Sprinter-Miler	Miler	Sprint-Mile-Stay	Stayer	Heritability	*P-value
Peak stride frequency (s/sec)	2.43 ± 0.01^{a}	2.39 ± 0.01^{b}	2.38 ± 0.01^{b}	2.37 ± 0.01^{b}	2.31 ± 0.02^{c}	0.20 ± 0.15	**<.001**
Peak stride length (meters)	7.45 ± 0.02^{a}	7.54 ± 0.03^{ab}	7.49 ± 0.05^{ab}	7.53 ± 0.04^{b}	7.62 ± 0.06^{ab}	0.15 ± 0.14	**0.003**
Peak heart rate (beats/min)	217 ± 0.6^{a}	216 ± 0.8^{a}	214 ± 1.6^{a}	215 ± 1.2^{a}	215 ± 1.8^{a}	0.19 ± 0.15	0.08

Values are Mean ± 1SE for continuous data recorded by 'Equimetre' in Australia (n=421 different racehorses with three-generation pedigree). Horse profile (sprinter, miler, stayer) was determined based on race distance and subcategories (pure sprinter/miler, sprinter-miler, sprinter-miler-stayer) were formed according to the nature/proportion of the races for every individual horse (see Methods). Data are averaged values for each horse from all available gallop sessions (n= 1699). Data were analysed and heritability estimated by REML analysis of an Animal Model. SE for Heritability (h^2) was calculated using the delta method which uses a Taylor's expansion to get the variance of a function of a parameter (Var(f(x)) = Var(x)*(f'(x))^2). Type of racehorse was fitted as the fixed effect. Values within a row with differing superscripts are significantly different at P<0.05, with Bonferroni correction for multiple testing. *Overall P-value for comparison between groups of main effect.

4.5 Discussion

This study has directly, and objectively, outlined how differences in locomotory profile (short, medium, or long peak stride length/frequency) are already apparent in sprinter versus stayer racehorses, during race-speed training sessions. Indeed, during mock-races from a standing start, i.e., 'jumpout' sessions, sprinters also achieved higher speeds than stayers. Nevertheless, racehorses with relatively short or long stride within sprint or stayer categories, respectively did not predict race performance (i.e., winning or podium position). However, we are able to report for the first time that locomotory parameters of racehorses have moderate heritability. Therefore, the study provides evidence to support our primary hypothesis, that racehorses can be distinguished in training by having relatively short, medium, or long stride. Whilst locomotory parameters have moderate heritability, locomotory parameters in individual racehorses do not evolve significantly during the course of a race season. Hence, we suggest that differences in locomotory profiles are tangible for each type of racehorse (e.g., sprinter, miler, stayer), necessitating unique stride and speed aptitudes for the required distance. Race-day performance remains complex and may be influenced by a multitude of factors including sex of the horse, stride and to some extent pedigree as described in this study.

4.5.1 Racing data and performance

In Australia, horses race all year long with the season running from August to July, including a period of 'spell or detraining'. A spell or period of detraining refers to an extended period, usually 6 to 8 weeks, during which a racehorse is given a rest in the paddock. This break is dependent on the number of race starts completed during that year (Velie et al., 2013b). Thoroughbreds begin racing at the age of two and often progress from relatively shorter to longer distances (~ above 1600m) as their stamina and musculature develops, usually when they reach the age of three (Huggins, 2014). Previous research has shown that 2-year-old racehorses are more suited to shorter races than any other age group (Farries et al., 2018, Hill et al., 2010, Hill et al., 2012). Older racehorses, between 4 to 5 years of age, are therefore more likely to race over longer distances (i.e., 1600–3200 m) (Butler et al., 2017). These findings were consistent with the ages observed across the three racehorse profiles (sprinter, miler or stayer) in this study; younger horses tend to be sprinters, whilst milers and stayers were significantly older.

Racehorses being trained in Australia are predominantly sprinters. 39% of Group races in Australia are run over less than 1400m compared with 23% in both the UK and Ireland (Racing Australia, 2016, Horse Racing Ireland, 2017, British Horseracing Authority, 2017). This may be partially explained by the fact that, in some racing nations, a premium is allocated to horses participating in shorter distance races, as the prizemoney/ class of the races tends to be higher than other race distances. Sprinters largely characterised our dataset; we observed a much higher proportion of sprinters with both race and training data than stayers (according to a race distance classification established by (Rooney et al., 2018)). This is not surprising considering the strong selection for early speed which characterises the Australian racing industry. However, there has been a surge of global initiatives to boost and encourage the breeding of stayers to counteract this phenomenon (Webb-Carter, 2015). Evoking greater prestige and higher prize money, some examples of long-standing stayers' race include The Epsom Derby (UK; 2420m), Prix de L'Arc de Triomphe (France; 2400m), Breeders' Cup Classic (USA; 2000m) and the Melbourne Cup (Australia; 3200m).

The limited number of pure stayers in our dataset nevertheless presented the highest proportion of race wins, compared to other categories of racehorse. Stayers were significantly older, were possibly more mature and of better 'quality' and thus retained to race or were better placed in suitable races given greater knowledge about their optimal characteristics. Younger, less talented and successful horses may also have dropped out of the yard and thus dataset. To an extent, therefore, perhaps such longer distance races are comprised of more appropriately placed and better racehorses. Additionally, in longer distance races, there is more opportunity for jockeys or trainers to utilise racing tactics (Sobczynska, 2006). Interestingly, a racehorse's peak racing age was previously suggested to be 4.45 years (Gramm and Marksteiner, 2010), a two-year difference with the stayers in this study.

4.5.2 Training data and locomotory performance

Racehorse athletic careers generally only span a few years, during which racing opportunities can be limited (Velie et al., 2013b). Opting for a race distance that matches the individual horse's characteristics and racing ability could markedly contribute to increasing its chance of winning. Therefore, trainers subjectively determine individual racehorse locomotory profile (sprinter, miler or stayer) early on in their training in order to ideally target the most appropriate exercise program and maximise their racing performance. Yet, a racehorse's ability to gallop over five furlongs for a sprint race, as opposed to twenty for a stayer's race, will differ significantly in terms of locomotion strategy. As they approach peak speeds, individual horses will either naturally increase their peak stride length or frequency. Over shorter distances, the requirements for acceleration and speed are pivotal, but as the distance increases, then efficiency of stride and stamina become more important. Stride length, rather than frequency is the main determining parameter to achieve higher maximal speeds (Schrurs et al., 2022b).

During standard gallop training sessions, our results revealed clear locomotory differences: sprinters had shorter stride length of a higher frequency than stayers. It is conceivable that the effect of warm up, if different between sprinters and stayers (not to our knowledge) may have exerted some effect on these stride characteristics, as previously evidenced in showjumpers (Tranquille et al., 2017). Fatigue can also cause racehorses to lose a stable stride frequency (Johnston et al., 1999), triggering a decrease in stride length (Wickler et al., 2006). We were unable to account for such aspects in our study, but in-field biomarking of fatigue through spot-sampling of blood could reveal important differences that could be trained in.

In preparation for racing, racehorses are often exposed to 'jump-out' training sessions, which consist of grouping horses of similar age/level, to start from barrier stalls and to race against each other under timed conditions. This race-day simulation exercise is different to official race-day barrier trials (Racing Victoria, 2011), but, from the horses' perspective, is akin to a race. Unsurprisingly, speeds recorded during such sessions were among the highest recorded in our dataset yet were still significantly higher for sprinters compared to milers/stayers. Thus, in both regular training sessions and race-speed simulation sessions, sprinters and stayers could be clearly differentiated on stride characteristics. Nevertheless, we did not note any significant evolution of stride characteristics through incremental training sessions over the course of two race seasons (~10 training sessions per horse). Such differences are likely small for any individual horse, and it is likely that a very large dataset would be required to observe significant differences to validate the evolution of stride over a racehorse's career. Previous research has suggested that a typical racehorse improves its race time by approximately 10 (horse) lengths in sprints of <1 mile and up to 15 lengths for middle-longer distance races (≥1 mile) from the age of 2 to 4.5 years (Gramm and Marksteiner, 2010). Hypothetically speaking, a proportion of this improvement could be attributed to alterations in the speed or efficiency of locomotion, although this was not measured in that study.

4.5.3 Training data, type of racehorse and predicting race outcome.

Racehorse success on the track results from a complex combination of genetics (Gaffney and Cunningham, 1988), nutrition (Hintz, 1994) and training (Morrice-West et al., 2021). Such factors determine the expression of physical traits specific to the athletic demands of the sport. In Thoroughbreds, muscle strength, speed and endurance have been identified as traits that favour superior performance at various race distances (Kay and Vamplew, 2012). In this study, colts (i.e., younger male horses not gelded) had higher odds of winning than geldings. This aligns with previous research which identified some of the non-genetic factors that affect racehorse performance: sex, age, class of race, track condition, handicap weight and distance

(Hintz, 1980), and suggests that younger ‘entire’ male horses have the greatest chance of winning a race. Such an observation is also at odds with the fact that, in our dataset, the few stayers, who were older, had more race success. Perhaps the greater competition between horses in sprint races, the predominant race category in our dataset, is primarily won by colts as opposed to geldings. In stayer races, primarily competed in by older mares and geldings, and for obvious reasons very few entire males, then such differences are not apparent.

Thoroughbreds present unique musculoskeletal characteristics compared to other breeds. Notably, they have a large mass of skeletal muscle, low body-fat proportion and a greater percentage of fast twitch muscle fibres (Kearns et al., 2002). The composition of muscle fibre type, namely in the propulsive gluteal muscles, evolves with age and training, progressively improving stamina (Rivero, 2007). Previous work on racehorse wither height, has also revealed interesting insights. In mature horses, wither height was positively correlated with racing performance (Dolvik and Klemetsdal, 1999) and stride length (Galisteo et al., 1998). The relationship between conformation and stride variables in foals aged 6–8 months has also been studied: increased speed was attained by longer stride length in heavier foals and higher stride frequency in taller foals (Leach and Cymbaluk, 1986). The effect of training on performance has also been examined. (Rivero, 2007) outlined that training strategies targeting both strength and endurance concurrently impinge on performance when compared to training programmes aimed at optimising either one or the other (Rivero, 2007). This is explained by the fact that strength for acceleration is required for a sprint race. Strength is associated with an increased muscle mass, a shift from slow twitch to fast twitch muscle fibres and an increase in ATP utilisation. As a result, adaptations for sprinters would be disadvantageous for stayers as they rely on slow twitch muscle fibres and aerobic metabolism.

In Standardbreds and Thoroughbreds, after three years of training, changes in the trotting strides were observed: stride length, stride duration and swing phase increased (Drevemo et al., 1980). Training plays an important role in the development of the above parameters (Miró et al., 2009). Our findings highlighted a tendency of increased odds of winning and/or finishing in the top 3 in horses displaying a longer stride length. Similarly, in harness trotters, a test performed on the track showed that performing horses presented the highest maximal stride frequency and a long stride length (Barrey et al., 1995).

4.5.4 Heritability of stride parameters and peak heart rate

For the last three centuries, Thoroughbreds have been intensely bred for their elite athleticism, stamina and aptitude for speed. Racehorse pedigree information is registered in The General Studbook, 1791 (Weatherby, 1791) and can be traced back to their original ancestry. The Thoroughbred genetic pool is narrow and emerges from three foundation stallions (Arab, Barb and Turk) and approximately 30 foundation mares (United Kingdom) (Cunningham et al., 2001, Bower et al., 2011, Wallner et al., 2017). Since then, the continuity of the breed has become ever more controlled and refined. For example, English and Irish breeding industries focused on producing distinctive types of horses from precocious, fast, 2-year-old sprinters, 'classic' middle-distance runners or horses with enhanced stamina suitable for less popular 'classics' races such as the St Leger. Heritability of any given trait refers to the percentage of the parental trait that could effectively be transmitted to its offspring. Calculations on narrow-sense heritability estimates (h^2) for specific traits such as stride length aim to estimate the strength of genetic determinants for the particular characteristic (human height being highly heritable at 0.85), with the remainder being non-genetic, additive, environmental effects such as trainer, rider (Schrurs et al., 2022c), track, etc. In flat racing, heritability of performance has been estimated as relatively low with wide confidence intervals, e.g., h^2 between 0.15 to 0.55 (Langlois, 1980, Hintz, 1980). The heritability of locomotory characteristics (speed, stride length and frequency) has been estimated previously in French saddle horses and was considered to increase with pace (e.g., from walk [$h^2 = 0.23$], trot, canter through to gallop [$h^2 = 0.52$]) (Barrey et al., 2002). In this study of racing thoroughbreds, heritability of peak stride length and frequency was moderate ($h^2 = 0.15–0.20$), suggesting that 15–20% of the variation in locomotion in Thoroughbreds is due to the particular genes each racehorse inherited, with the remaining 80–85% of the variation due to environmental (non-genetic) factors. Since peak heart rate was consistently measured in our training data, we thought it interesting to also assess its heritability, despite previous papers indicating that between-individual variability is likely high (Couroucé et al., 2002, Betros et al., 2002, Schrurs et al., 2022b). Nevertheless, similar to locomotory characteristics heritability of peak HR was moderate ($h^2 = 0.19$).

Finally, it should be recognised that the study is a convenience sample of racehorses having used an 'Equimetre' intermittently, but in a repeatable fashion in training. The study is retrospective and observational. One test of our data would be to prospectively assign racehorses based on stride characteristics in training to being a sprinter or stayer and observe whether greater success in that category was achieved. Other factors that could influence stride but were not recorded consistently such as different warm-up protocols or accumulated fatigue were not taken into account. Since many racehorses compete in different types of races (e.g., sprinter or mile, mile or staying race) it would be interesting to analyse the extent to which locomotion (e.g., peak stride frequency, length) evolves over the course of a racehorse's career for different profiles (sprinter, miler, stayer).

In conclusion, this study demonstrates that locomotory differences exist (peak stride length, frequency) between various types of racehorses (sprinters, milers and stayers). Stride characteristics measured at the onset of training can predict aptitude to racing in a given category, regardless of the potential progress obtained with training. Peak stride length is a moderately heritable trait that can be bred for. Considering heritability of stride along with objective locomotory data and other aspects (i.e., preferred ground, going), may also help trainers choose early on what type of training (short, middle- or long-distance work outs) or which race to enter (distance, profile, going etc…). Such a hybrid approach using data alongside experience may contribute to improved welfare on the track and prolong racing careers.

Chapter 5 Study 4: Cardiovascular fitness and stride acceleration in race-pace workouts for the prediction of performance in Thoroughbreds

5.1 Abstract

In-training racehorse physiological data can be leveraged to further explore prediction of race-day performance. To date, no large retrospective, observational study has analysed whether in-training speed and heart rate recovery are reliable predictors of racehorse success. Speed (i.e. categorised as 'slow' to 'fast' according to the last 600m away from a virtual finish line) and heart rate recovery (from average during gallop to 1min after exercise) of flat racehorses (n= 485) of varying age, sex and locomotory profile (e.g. sprinter, miler, stayer) were collected from a single racing yard in Australia from prior race-pace training sessions conducted on turf ('fast gallop', n= 3418; 'jumpout', n= 1419), using a fitness tracking device. A posteriori racing information (n= 3810 races) for all 485 racehorses was extracted and combined to the timed-trial training sessions, with race performance analysed as a binomial outcome for 'win' (yes/no). Of all aspects tested, colts ($P < 0.001$), stayers ($P < 0.001$) and fast finish speed ($P < 0.008$) were predictive of race performance, as opposed to heart rate recovery ($P = 0.21$) and speed at the 600m mark ($P = 0.94$). In-training physiological data does not clearly predict when a racehorse may win a race but does distinguish those racehorses considered worthy of participating in black-type races. Any race-day performance is likely affected by a multitude of other factors not recorded in our dataset. In-training physiological data may help trainers identify and build a legacy of promising horses. Such data alongside experience may contribute to improved decision-making and a safer sport for all those involved in horseracing.

5.2 Introduction

The value of any racehorse depends upon its ability to win. Racing performance is complex as it involves multiple variables; horses compete over different distances (i.e 1,000 to 3,200m), at different ages (often starting at two years of age), on different surfaces (dirt, turf or synthetic) and track layouts (circular versus open) and in varying weather conditions (dry fast tracks versus wet, heavy tracks). To measure individual racehorse performance over a season, trainers closely keep a record of the number of wins, places and earnings to ultimately guide both their short and long term decision-making (Wylie and Newton, 2018).

Worldwide, generations of trainers continue to share a common objective: to strive towards superior performance and increase the career longevity of their horses. However, a trainer’s approach towards race-day preparation remains a subjective and singular practice. It may be founded on experience, data-driven technology, research or a combination of several factors. To date, a great disparity in training regimens is observed across the horseracing industry. In Australia, training patterns typically include a high proportion of gallop work at consistent timings (e.g. medium gallops at 15s/200m or 13.3–14.3 m/s), with a short sprint at peak speed towards the end of the exercise session (Morrice-West et al., 2020). Such workouts aim to ultimately engage horses in ‘barrier trials’ or ‘jumpouts’, practice races often supervised by racing stewards at an official racetrack.

The volume and type of workload that optimise performance in racehorses has recently been investigated. The study surveyed 66 racehorse trainers in Victoria and outlined that pre-trial total galloping (≤13.m/s) distances of between 7500m and 15,000m correlated with a higher win-rate, previous season wins and places per start (Morrice-West et al., 2021). Slower-speed (13.3–14.3 m/s) gallops between 5000m to 12,500m also correlated with a higher rate of career placings per start. Similar results were observed by Berkman et al. (2015). Interestingly, the timeframe (i.e. number of days prior to a race) during which combined training and race gallops occur can also predict a greater chance of winning or earning more prizemoney (Verheyen et al., 2009). Frequent periods of rest or ‘spells’ between racing seasons are often implemented by trainers. Such breaks in racehorse training directly associated with greater prizemoney per start acquired in the previous race season, as highlighted in the paper by (Morrice-West et al., 2021).

Horses that begin racing early in their career (i.e. at two years of age) are often better performers and have longer careers than those that begin at a later age (Tanner et al., 2011, Physick-Sheard, 1986, Saastamoinen and Nylander, 1996). Horses imported from overseas, may be accustomed to cooler and/or drier environments. Therefore, a period of environmental acclimation is essential to ensure sufficient physiological adaptation and exercise tolerance prior to the start of racing, especially in differing climates (Marlin et al., 1999). Early exercise induces the onset of cardiorespiratory and musculoskeletal changes to acquire the necessary fitness and cardio-respiratory maturity to maximise the chance of race success. Previous studies have attempted to correlate physiological parameters with race performance. For example, in racehorses, it has long been assumed that their large athletic hearts could be associated with success. This was subsequently shown by a study that demonstrated a positive correlation between British Horseracing Board Official rating or Timeform rating and heart size measured by echocardiography in 200 National Hunt horses (Young and Wood, 2001). Similarly, blood lactate concentration sampled after strenuous submaximal treadmill exercise also correlated with Timeform rating and/or subsequent race performance (Evans et al., 1993).

Wearable technologies have now facilitated the measurement of such parameters on the field to maximise athletic performance (Schrurs et al., 2022b). Systems combining telemetric heart rate (HR) and global positioning satellite (GPS) were leveraged in a small-size study (n=20 horses) that concluded that heart rate recovery (i.e. at one minute after work) following interval exercise could be used as a predictor of fitness or readiness to race and subsequent race position (i.e. finishing in top three i.e. on the 'podium') (Wilson and McGowan, 2019).

Values of stride length or frequency may also be used to predict performance. Top racehorses can maintain or peak at maximum speed over a specific distance, by increasing their stride frequency up to ~2.40 strides per second. The last 200 meters represent the most competitive section of any race. Strategy, agile peloton positioning, and bursts of speed are equally needed to reach the finish line and will distinguish a winner from its competitors. From a locomotory perspective, it is assumed that stride length would be longer in better performing horses. However, a study showed that in the latter part of a race, greater stride counts or shorter stride lengths were associated with better finishing positions (Morrice-West et al., 2021). Equally in human athletes, a positive correlation between stride length and performance was also found (Landers et al., 2011). Similar observations were drawn from a locomotory field-test conducted on Trotters, using an accelerometer device, maximum speed and stride length were positively correlated with the performance index (Barrey et al., 1995).

Large populations of highly trained running athletes, such as racehorses, could provide unique insights into the relationship between physiological variables and performance. However, to date, no study has related race performance over multiple seasons with combined information on stride acceleration and cardiovascular fitness in race-pace training sessions. A better understanding of speed and recovery benchmarks could help the decision-making of racehorse professionals for race-day readiness and the selection of appropriate races according to speed and recovery profile. No study has specifically evaluated the utility of measuring heart rate recovery over different types of speed training (i.e., stratified by 'slow-medium-fast' horses) and retrospectively assessed whether any index predicts performance (i.e., categorised by winning or being placed in a race versus not winning or finishing outside the first three) in the same racehorses, accounting for other potentially influential factors such as age or sex of the horse.

Hence, in the present study, a retrospective, observational study was conducted, using a fitness tracking device to study peak stride (length and frequency), speed (last 200 and 600m) and heart rate (peak and recovery) in racing Thoroughbreds categorised according to their subsequent racing result (win, podium or lose). Using speed to classify racehorses (slow-medium-fast), to observe whether any differences in recovery parameters were apparent in training sessions prior to races, we were further able to determine whether any training parameters within each category of racehorse could predict race performance.

The primary hypothesis of this study is that cardiovascular fitness (e.g., rate of recovery of heart rate) or stride acceleration (e.g., the average time in seconds over consecutive 200 meters from a standing start) during race-pace workouts (i.e., hard gallop or jumpout sessions only) predict performance (win or lose) race-day performance, taking into account other potential confounding factors such as age or sex. Secondary hypotheses are that relatively high daily temperature and/or humidity significantly blunt racehorse recovery of heart rate and confound prediction of race performance.

5.3 Material and Methods

5.3.1 Databases

This retrospective, observational study used two large datasets, pertaining to the same cohort of racehorses:

(1) **training** sessions: collected by means of a fitness tracker (the 'Equimetre'™) from a single racing yard (Ciaron Maher Racing) in Victoria, Australia.

(2) **race results** from the same cohort: available upon subscription in Australia, with race data recorded and downloaded from http://www.racing.com (accessed 16 January 2023).

5.3.2 Horses

Ethical approval for this study was obtained from the University of Nottingham (School of Veterinary Medicine and Science) Research Ethics Committee (REC code: 3270 201029).

The study population represented a convenience sample and included 485 Thoroughbred racehorses that were recruited from the same racing yard in Australia. The horses were aged between 2-10 years at the start of training. For n=10 horses, age was not recorded. The sex of the horse was coded as male (colts/stallions; n=108), female (fillies/mares; n=229), gelding (n=148). Sex of the horse was randomly checked online at http://www.racing.com (accessed on 3 April 2023). The trainers regarded all horses as race fit; that is, horses that were actively in training to sustain their fitness levels and competing in races during the study period.

5.3.3 Equipment

Horses wore their regular tack and were exercised by a randomly allocated work rider, to the discretion of the trainer, who varied according to individual training sessions. A tracking device (the ‘Equimetre™’, Arioneo, Ltd. Paris, France) was fitted to the girth prior to training by persons accustomed to using the device, as previously described (ter Woort et al., 2021). The device recorded locomotory parameters (peak stride length and frequency) alongside speed (by GNSS) and cardiovascular parameters (peak HR, HR at 15 minutes after exercise), as previously described in detail (Schrurs et al., 2022b, Schrurs et al., 2022a). Prior to the study, trainers had previously integrated such systems into their training regimes.

5.3.4 Training data

The trainer determined the nature of each individual training session, directing the work-rider as appropriate. The Equimetre was not systematically placed on each horse for every individual training session, rather for specific sessions. Each individual training session was evaluated based on the trainer’s observation on the track, riders’ feedback following exercise and the fitness tracker recordings (‘Equimetre’™, Arioneo Ltd, France). For this study, only race-pace sessions (i.e., hard gallop and jumpouts) were included.

From the GNSS (GPS + Glonass + Galileo) satellite data, speed (i.e., time taken to cover 200m in seconds) measured for each 200m segment (at 200, 400, 600, 800, 1000, 1200 and 1400m) was recorded. Speed during the third 200m section (i.e., at 600m into any effort) was then used to form quintiles of the fastest and relatively slowest sessions for any horse, deemed ‘Fast – top quintile’ or ‘Slow – bottom quintile’. Training sessions labelled as ‘jumpout’ sessions by trainers were also included for analysis. These sessions simulate race-day barrier trials and conditions and are held at various locations on specific days in Victoria, Australia. Jumpout sessions aim to simulate race-day conditions (i.e., racehorses departing from gates and running side by side), tracks and speeds and horses of similar ability (i.e., stage of physical preparation or ‘fitness’) and age are grouped to ‘race’ side by side from starting gates for the duration of the exercise bout. Horses may participate in these sessions to clear a vet check by an official steward or to prepare and gain experience. Jumpouts are usually considered by trainers as ‘benchmark sessions’ to evaluate and decide whether a racehorse is physically ready to enter a specific race or not. Both hard gallop and jumpout sessions were conducted on turf.

All training data were collected between 18 January 2021 to 14 January 2023 and comprised a total of 4837 training sessions (hard gallop n= 3418 sessions; jumpout n= 1419 sessions). Horses would train all year-round throughout the racing season, before entering a period of ‘spell’, usually one month but up to the trainer’s discretion, during which horses are turned out in the paddock to rest and recover. The spell period for each individual horse represents an important reference point for the trainers, as it enables them to keep a record of the number of days in full training. Such information is used by trainers to establish whether an individual horse is ready to enter a jumpout session or race. Overall, an average of 6 (1 – 38) training sessions median (first-third interquartile range [IQR]) were recorded per racehorse. Race pace efforts were categorised sequentially from 1 to 25, with only n=14 horses completing 25+ training sessions. Therefore, these sessions were grouped into a 25+ category. The mean interval between training sessions using an Equimetre was 29 ± 49 days (mean ± S.D.). Any horses completing only a single training session were removed from the dataset. From the exact date of training, together with the exact race date, the number of days prior to each race plus the interval in days between races was calculated and included in the dataset for each individual horse.

During trot, canter, and gallop, the Equimetre recorded aspects of each horse’s cardiovascular responses to exercise (e.g., heart rate, HR), peak heart rate (HRpeak) and HR during recovery (HR at 1-5 and 15mins after exercise), aspects of locomotion (speed, stride length and stride frequency) and distance. From these live data that were instantly recorded by the device, further analyses were able to be conducted *post-hoc* that pertained to each training session such as the deltaHR (rate of recovery; HR gallop – HR at 1-5 min recovery). Based on GPS coordinates of the device, then a virtual finish line at 1000 metres was generated for each race-pace session. Consequently, with timings recorded at each 200m segment (i.e., one furlong), then quintiles of first and third 200m speed (slow; slow-medium; medium; medium-fast; fast) were manually formed, to categorise horses accordingly. Environmental temperature and humidity were recorded by the device prior to the start of each individual training session, with data obtained from the nearest weather station. Final datasets were checked for artifacts and corrected accordingly in MS Excel.

5.3.5 Racing data

The same cohort of racehorses (n=485) participated in a total of 3810 races. In this study, when race class was recorded, then it was described as either a Group or Listed race. Group 1 (n= 93 of 3810 races; 2.44 %), Group 2 (n= 73 races, 1.92 %), Group 3 (n= 143 races, 3.75 %) and Listed (n= 182 races, 4.77 %), whereas all other races were manually labelled as

Uncategorised (n= 3289 races; 86.3%). Race distance was known from http://www.racing.com (accessed on 16 January 2023) and was classified as a 'Sprint' race < 1600m (n= 2246 races, 77%), 'Miler race' 1601-2500m (n= 521 races, 18%) or 'Stayer's race' > 2501m (n= 138 races, 5%), as previously classified (Schrurs et al., 2022a). From the finish position, where available (n=54 had no finish position recorded) the proportion win (n=608 occurrences) or lose (n= 3148 occurrences) could be calculated plus whether the horse finished in the top three, 'podium' (n= 1369) versus 'non-podium' (n= 2387). Races conducted on a synthetic track were excluded from the study. Races occurred between 19 January 2021 and 17 January 2023. Other aspects of the dataset such as venue, track condition, carried weight, handicap, rating and prize money were recorded.

5.3.6 Statistical analysis

Analysis of training data: Any normally distributed descriptive data (e.g., peak stride length, stride frequency) are presented as mean (±1 standard deviation [SD]). Data distribution was checked either by standard tests (e.g., Shapiro–Wilk test) or checking of residuals post analysis. If necessary, data was log-transformed (log10) to normalise the distribution of the data prior to analysis. For some analyses, where assumptions for analysis of variance (ANOVA) could not be met due to occasional missing data (e.g., artefacts removed or no data present), linear mixed models (restricted maximum likelihood; REML) were used with the main effect of interest fitted as a fixed effect and HorseID fitted as a random effect. For analyses of sequential speed or stride in the same horse over repeated 200m segments, then repeated-measures ANOVA or REML with time fitted as a fixed effect was used. To account for multiple training sessions in the same horse then training session was coded (1 – 25) by date and analyses were blocked by HorseID.

Analysis of racing data: For any aspect of performance in training (e.g., speed or heart rate recovery) then the two datasets were combined according to individual horse including all instances of gallop training with each race result. To account for multiple training sessions in the same horse then training session was coded (1 – 25) by date and analyses were blocked by HorseID. Any training data were excluded if the date was ≥ 60 days (i.e., two months) before any race. To determine if training data predicted race outcomes, then race performance was categorised as a binomial outcome with win (yes/no) or podium (yes/no) fitted as the outcome. Model fit and significant variables included as fixed effects were assessed using backwards stepwise regression, that is, they were included if on univariable analysis each was significant at ≤0.10 as analysed by logistic regression. Using this method, age, sex of horse, track condition, race-class were all included in any outcome. The training variable of interest (e.g., HRR or speed at 600m) was always fitted last in any model. All data were analysed using Genstat v23 (VSNi Ltd., Rothamsted, Harpenden, UK). Statistical significance was accepted at $P < 0.05$.

5.4 Results

5.4.1 Descriptive characteristics of the racehorse training dataset

Prior to any specific training session, horses would warm up at trot and canter pace over a distance of 1308 ± 617m and 583 ± 410m, respectively. Hard gallop and jumpout sessions were ‘race-pace’ and corresponded to previously reported benchmark data (e.g. ‘hard’ gallop reference points in previous publications; (Schrurs et al., 2022b, Schrurs et al., 2022a). Horses were galloping on turf tracks at an average of ~60km/h, covering 200m (i.e. one furlong) in ~11 seconds (e.g. time last metres), at maximum heart rate ~200-210 bpm, and with stride lengths and frequency as observed during previously reported race efforts (Schrurs et al., 2022b). The main work distance was less in jumpout versus gallop sessions (Table 11). Regardless of the distance covered, racehorse heart rate recovery following exercise was similar in both exercise groups ~120 bpm without accounting for varying track condition and inclination (Table 11).

Table 11 Descriptive characteristics of the racehorse training dataset

Training type	Hard gallop	Jumpout
Main work distance (meters)	2027 ± 390	1500 ± 254
Max speed (kph)	62.7 ± 3.0	64.3 ± 2.3
Best 200m (secs)	11.6 ± 0.6	11.3 ± 0.4
Best 600m (secs)	36.6 ± 1.9	34.9 ± 1.6
Time last 600-400m (secs)	13.1 ± 0.8	12.0 ±1.1
Time last 400-200m (secs)	12.1 ± 0.8	11.9 ± 1.4
Time last 200-0m (secs)	11.8 ± 0.9	12.2 ± 1.8
Peak stride frequency (strides/sec)	2.39 ± 0.09	2.42 ± 0.09
Peak stride length (meters)	7.35 ± 0.32	7.46 ± 0.29
Peak heart rate exercise (bpm)	212 ± 19	211 ± 17
Heart rate after effort (bpm)	120 ± 16	121 ± 15

Values are mean ± standard deviation for continuous data recorded by 'Equimetre' (n=485 different racehorses). A total of n=4837 different training sessions were recorded and analysed to only include n=3418 gallop and n=1419 jumpout sessions for standardisation purposes. All exercise sessions occurred on turf tracks with varying ground conditions. Data were available throughout the year. Training intensity was dictated by the trainer and included only race-pace gallops and jumpout sessions (i.e., race simulation workout starting from gates). Time last meters was calculated from a virtual finish line based on GPS coordinates and refers to the average time in seconds over consecutive 200 meters (i.e., one furlong). All data are described and not statistically analysed.

5.4.2 Racehorse heart rate and recovery during training

Heart rate measures analysed across the entire racehorse population increased with pace from trot to hard gallop as expected and peaked at ~210bpm. The greatest heart rate recovery (i.e. slope of HR once peakHR is attained) occurred within the first minute after exercise (Figure 13) with no systematic and repeated difference occurring with age category (from 2-10 years of age; Figure 13, unlabeled to aid clarity). Thereafter, HR linearly decreased to 5 minutes before declining further at a consistent rate to ~100bpm at 15 minutes post exercise.

Figure 13 Racehorse heart rate and recovery during hard gallop training according to age

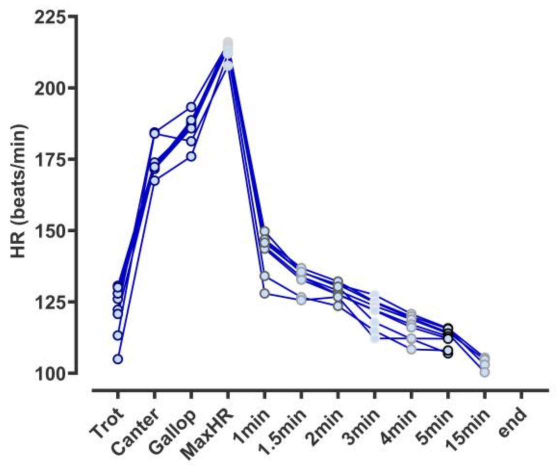


Figure. Individual data points are heart rate at varying paces during and after hard gallop training (shown on the x-axis). Values were recorded by a fitted 'Equimetre' on each racehorse. Data are predicted means (standard error of the mean, too small to be seen) for each racehorse (adjusted for multiple sessions by the same racehorse). Age and sex of horse was included in the statistical model, but neither significantly interacted with time. HorseID and track condition were included as random effects in the model. Data analysed by Genstat v23.

Some differences in HR were observed between exercise groups (gallop *versus* jumpout) as the pace increased from trot to canter, before similar values were obtained at both gallop (~180bpm) and jumpout (~210bpm; Figure 14). As a proof of principle that HRR is greater after a harder effort then, recovery over the first 3 minutes after exercise was slower after jumpout than after gallop (recovery to ~160 versus ~140bpm, respectively; Figure 14). Thereafter, from 4,5 to -15 minutes after exercise, then any difference in HRR were less marked. At 30 minutes post exercise values remained above baseline but had stabilised.

Figure 14 Racehorse heart rate and recovery during training according to exercise group

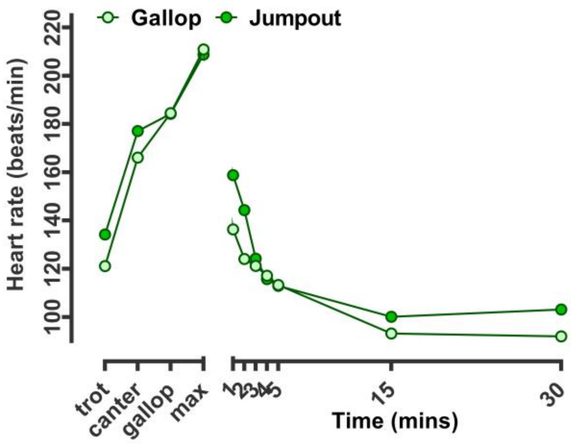


Figure. Data are predicted mean (± standard error of the mean) of heart rate for all racehorses in training recorded at gallop or jumpout. Predicted means were calculated from continuous heart rate data recorded for each horse at every minute following exercise, with training type (i.e hard gallop versus workout) as the fixed effect in a repeated measures design. HorseID and track condition were included as random effects in the model.

Examining heart rate recovery in more detail, and excluding HRpeak as values were higher per se, but not different between training intensities than as recorded at gallop, then HRR was non-linear. From the average value recorded during gallop to recovery at 1 minute, the greatest decline in HR was observed, together with the largest mean difference between training intensities (Figure 15). This was categorised as the 'early phase' of recovery (HRgallop – HR1min), during which most of the recovery in HR occurred (e.g., ~23bpm between gallop and jumpout sessions). Subsequently, the 'mid-phase' of recovery occurred to 3 minutes (HRgallop – HR3min) when differences between training intensities were no longer evident (e.g., ~21bpm difference at 2 minutes). The 'late phase' of recovery was designated as 3-15 minutes post exercise, when recovery was gradual and slow. At this stage no differences overall were noted between training intensities.

Figure 15 Racehorse heart rate recovery phases during training according to exercise group

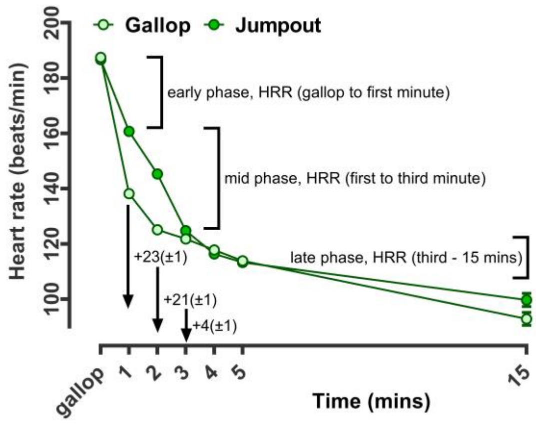


Figure. Data are predicted mean (± standard error of the mean) of heart rate for all racehorses in training recorded at gallop or jumpout. Predicted means were calculated from continuous heart rate data recorded for each horse at every minute following exercise, with training type (i.e hard gallop versus workout) as the fixed effect in a repeated measures design. HorseID and track condition were included as random effects in the model. Early, mid, and late phase HRR were as designated to allow for categorical assignment and potential for such categories to be able to 'predict' race success in a logistic regression model.

In Australia, the horses are trained year-round except for their monthly rest period and environmental temperature and humidity can vary considerably. Here, we note that average temperature but not humidity varied throughout the year from a few sessions at minus 1-3°C up to ≥28°C (noting that all training efforts are conducted early in the morning; Figure 16). Therefore, with such a large dataset we were able to interrogate whether recovery indices were affected by environmental conditions. Temperature was divided into quantiles to form 5 groups from relatively 'Hot' (≥°18C; 934 sessions at this temperature) to relatively 'Cold' (≤5°C; 954 sessions). In addition, we restricted the dataset to only gallop – having the greater number of training sessions evenly spread through the year. In addition, such a categorisation would allow easier clarification of the effect of temperature and/or humidity on HRR after intense training efforts in racehorses. When accounting for racehorse age, sex , days-in-training and number of training sessions completed, then horses recovered better during hotter temperatures: from 2 – 5 minutes after exercise HRR was greater by ~4 ± 2 bpm hot compared to cold conditions (e.g. at 2 minutes, 124 in hot versus 128bpm in cold) (Figure 17a).

A similar approach was taken to explore the effect of humidity on racehorse recovery during race-pace efforts. Humidity was divided into quantiles to form 5 groups to compare the first (high-humidity, ≥95%; ‘wet’) versus the last quantile (low-humidity, ≤67%; ‘dry’). No significant difference in HRR was found regardless of training intensity (Figure 17b).

Figure 16 Evolution of temperature and humidity according to training month throughout the study period

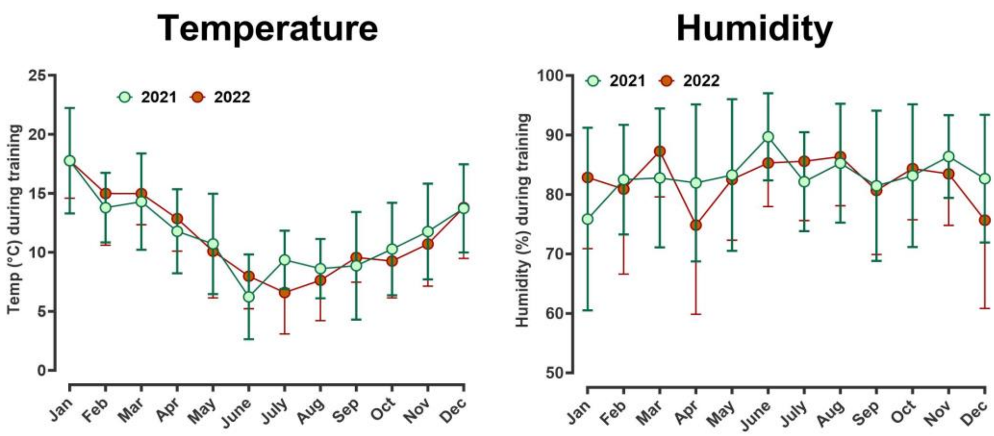


Figure. Temperature and Humidity. Data are mean ± standard deviation as transmitted from the nearest weather station in Victoria, Australia and recorded by the ‘Equimetre’ according to training month for the years 2021-2022. In Melbourne, Australia designated ‘Winter’ months with less racing are June, July, August while ‘Summer’ months are December, January, and February.

Figure 17 Racehorse heart rate recovery according to environmental conditions during a hard gallop workout

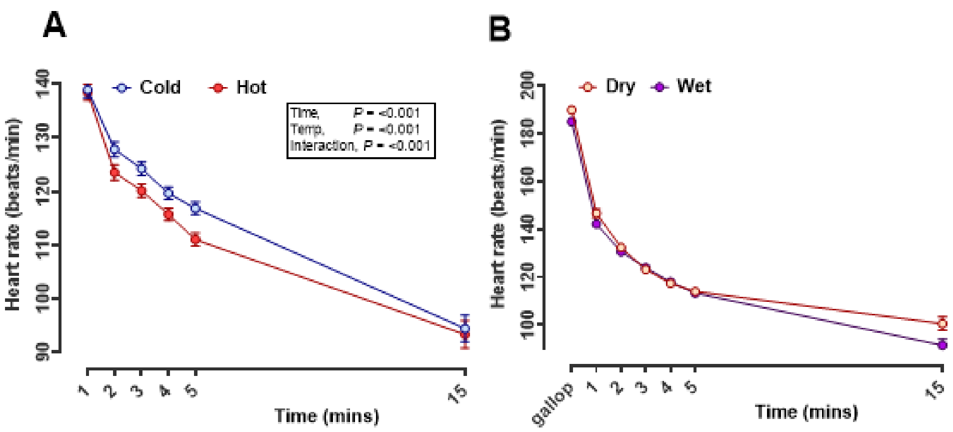


Figure. **A**: Temperature, **B**: Humidity. Data are predicted mean ± standard error of the mean as recorded by ‘Equimetre’ in Australia for the entire population of racehorses at every minute following exercise. Extremes of temperature (i.e., first versus fifth quintile of temperature, ‘cold versus hot’) or humidity (i.e., first versus fifth quintile of humidity, ‘dry versus wet’) are plotted against heart rate recovery. Each horse had multiple training sessions and thus was included as a random effect in the model. Age, sex, number of training sessions and days in training were included as potential confounding factors and means plotted after adjusting for these effects.

5.4.3 Racehorse speed during training

Racehorse speed categories were established to compare locomotory parameters amongst groups. Five groups were created according to quintiles of speed (i.e., time taken to complete 200m between 400-600m into a 'timed-trial'). At this point, stride length, but not frequency, was significantly different between racehorse speed categories (from relatively slow to relatively fast) during the 1000m distance trial, with 0m being the virtual finish line (Table 12). Overall, for stride length, a 0.17m difference existed between slow and fast horses. Stride frequency was similar across speed profiles at ~2.37 stride/sec. At this point in the timed-trial, significant differences in gallop speed were observed between slow (i.e., ~38.2 km/h) and fast horses (~41.6km/h).

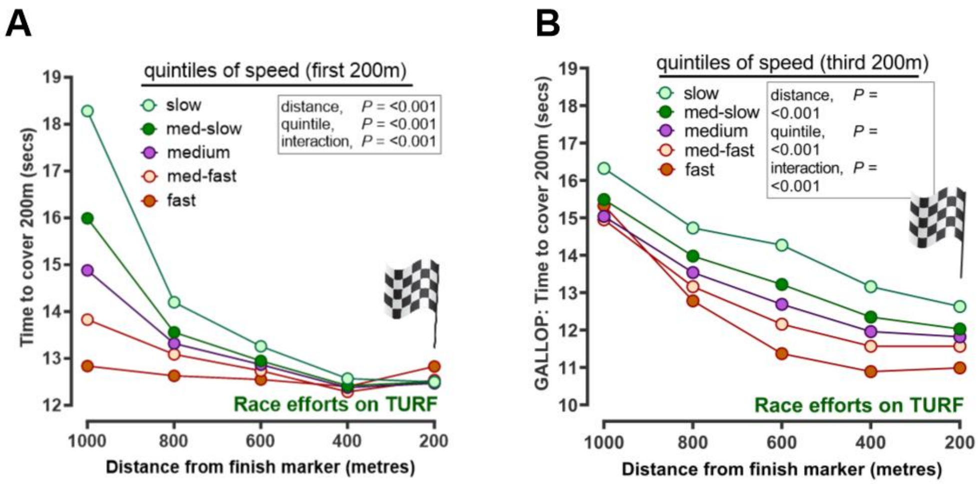
Table 12 Stride length and frequency at 600m stratified by quintiles of speed

	Slow Speed category	Med-Slow Speed category	Medium Speed category	Med-Fast Speed category	Fast Speed category	*P-value
Stride length (m)	7.25 ± 0.02 ^{a}	7.30 ± 0.02 ^{b}	7.38 ± 0.02 ^{c}	7.34 ± 0.02 ^{bc}	7.42 ± 0.02 ^{d}	<.001
Stride frequency (stride/sec)	2.37 ± 0.01	2.37 ± 0.01	2.38 ± 0.01	2.37 ± 0.01	2.37 ± 0.01	0.16
Gallop speed (km/h)	38.2 ± 4.87 ^{a}	39.2 ± 4.41 ^{b}	39.5 ± 4.41 ^{b}	40.5 ± 4.12 ^{c}	41.6 ± 4.07 ^{d}	<.001

Values are Mean ±1 SD for continuous data recorded by the Equimetre in Australia (n=485 different racehorses, n=1419 different gallop sessions). The speed category (slow, medium-slow, fast, medium-fast, fast) was determined based on quintiles of the time taken to cover a furlong at 400 – 600m for every individual horse, with a virtual finish line at 1000metres distance. Data were available throughout the year. Data were analysed by restricted maximal likelihood (REML) for the main effect of speed category, the individual racehorse as a random effect and after adjusting for significant covariates (track condition and training session). ^{abcd}Values within a row with differing superscripts are significantly different at P<0.05, with Bonferroni correction for multiple testing.

The time taken to cover successive furlongs from 1000 meters away from and to a virtual finish line at 0m (i.e. five successive 200m segments) was then compared according to a speed classification of racehorses (slow to fast) taken at the first 200m (Figure 18a) or third 200m (i.e. 600m; Figure 18b). The differences between fast and slow sessions (and thus racehorses) were significantly more marked at the first 200m (i.e 1000 meters away from the virtual finish line), with 'slow' horses taking longer to cover a furlong (i.e ~18.5 seconds) than faster horses (i.e ~12.8 seconds). Thus, for speed-in-training to potentially predict whether a given racehorse was more likely to win or come top-three in a race, then the classification of speed at 600m was used as being more reflective of that training effort. After 600meters, the time taken to cover a furlong was comparable between groups up to reaching the virtual finish line.

Figure 18 Racehorse time to cover various 200m segments up to a virtual finish line during a gallop workout



(A)

Figure. **A:** Speed categorised according to the first 200m. **B:** Speed categorised according to third 200m. Data are predicted mean ± standard error of the mean as recorded by 'Equimetre' in Australia for the entire population of racehorses over successive 200m distance marks up to a 1000m virtual finish line. Predicted means were calculated from time taken to cover 200m recorded for each horse at every furlong (i.e 200m), with quintiles of speed (slow-fast) as the fixed effect in a repeated measures design. Number of training sessions and track condition were included as random effects.

5.4.4 Racehorse recovery and speed for the prediction of race-day performance

Race participation categories were established to retrospectively compare heart rate recovery parameters amongst groups during a hard gallop workout. Two groups were manually created according to racehorse previous participation/or not in a Group race ('yes' or 'no'; EVER group raced or not). Overall, a consistent but small effect was observed over the 5 first minutes following exercise: horses that had previously participated in a Group race recovered faster than those that hadn't. The greatest differences between groups were observed in the first 1-2 minutes, where a difference of 5.5 and 6.7bpm were recorded respectively (Figure 19). Both groups showed similar measures of heart rate up to the 15-minute recovery mark.

Figure 19 Racehorse heart rate and recovery during a hard gallop workout according to participation in a group race

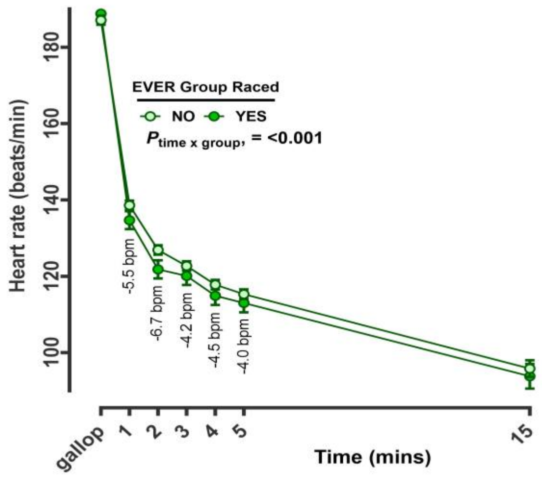


Figure. Data are predicted mean (± standard error of the mean) of heart rate for all racehorses in training recorded at gallop. Predicted means were calculated from continuous heart rate data recorded for each horse at every minute following exercise, with group race participation (i.e yes versus no) as the fixed effect in a repeated measures design. Age, sex, number of races, days in training and track condition were included as co-variates in the model.

The same categorisation was used to retrospectively compare racehorse speed amongst groups during a hard gallop workout over 1000m. Overall, some slight differences were observed between groups. Racehorses that had previously participated in Group races appeared to be faster, on average, than those racehorses that had never participated in a Group race. The greatest differences were observed at the start of the exercise, at 1000m away from the virtual finish line, with those that had Group raced completing the first 200m in ~14.8 seconds compared to ~15.5 seconds for racehorses that were to have never participated in a group race (Figure 20). Towards the end of the exercise, at the 200m mark, both groups reached similar values of speed ~12 seconds to cover the last furlong.

Figure 20 Racehorse speed during a hard gallop workout according to participation in a group race

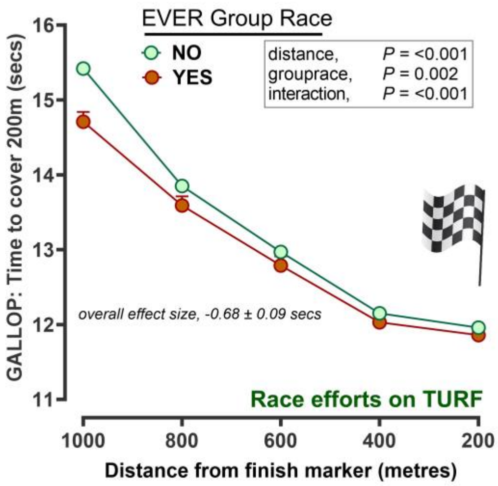


Figure. Predicted means were calculated from time taken to cover 200m recorded for each horse at every furlong (i.e 200m), with participation in a group race (yes versus no) as the fixed effect in a repeated measures design. Age, sex, number of races, track condition was included as co-variates in the model.

Locomotory and cardiovascular data recorded during training (i.e speed, stride, heart rate and recovery) for each individual racehorse were then combined with their race outcomes (i.e win or lose) to explore whether any aspect significantly predicted the chance of horses winning, regardless of the race class (i.e Group, Listed or Unrecorded). Much like the previous published paper (Schrurs et al., 2022a), results outlined that colts were more likely to win compared to mares and geldings, with 'filly' as reference point. Stayers presented an increased chance of winning as opposed to the other horse profiles (i.e milers), with sprinters as the referent category.

Racehorse timed-trial training sessions were restricted to a maximum of two months (i.e ≤ 60 days) before racing, to analyse whether any aspect of it could predict their likelihood of winning. Interestingly, the finish speed (i.e., the average speed over the last 600m), from the point of horses covering the third furlong to the fifth furlong (800-1000m) showed a small signal. Indeed, relatively fast horses during this training timed trial appeared to have a greater chance of winning. If horses showed a fast heart rate recovery in the early phase (i.e their average HR during gallop compared to their HRR at 1min, suggesting they are fitter) then it suggested that the horse had a greater chance of winning. In contrast, speed at 600m was not predictive (Figure 21).

Figure 21 Predicting race wins on training data

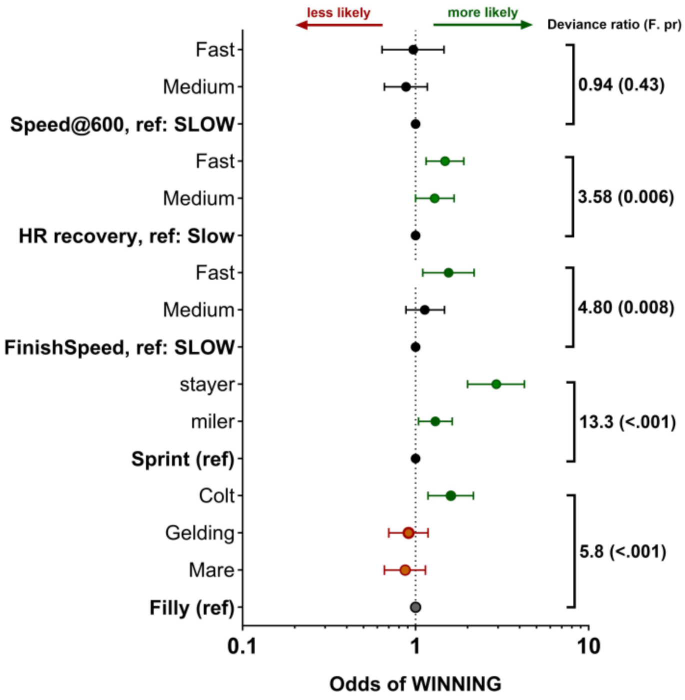


Figure. Data are odds ratios ± 95% CI for predicting winning a race from training data. Odds ratios were obtained by integrating known race outcome data from Racing.com (Victoria, Australia; n=485 different racehorses, n= 3810 different races) with training data (only fast gallop and jumpout on turf) for the same horses before and during two race seasons (n=3418 different training sessions). Data were analysed with race outcome (e.g., win) as the variable of interest, fitting sex of horse (filly as referent category), racehorse profile (sprinter as referent category), finish speed (slow as referent category), heart rate recovery (slow as referent category) and speed at 600m mark (slow as referent category) as other factors of interest. Statistics for main effects are indicated on the right on the graph with associated Wald statistic. Statistical significance was accepted at P<0.05.

Some horses presented multiple instances of racing with tendencies of winning or losing more races compared to other horses. When accounting for such variability in individual horse racing success, then colts and stayers were still more likely to win races, but aspects of training data, with the exception of finishing speed, was much less significant. The change in HRR showed no predictive effect for winning races (Figure 22).

Figure 22 Predicting the percentage chance of race wins on training data

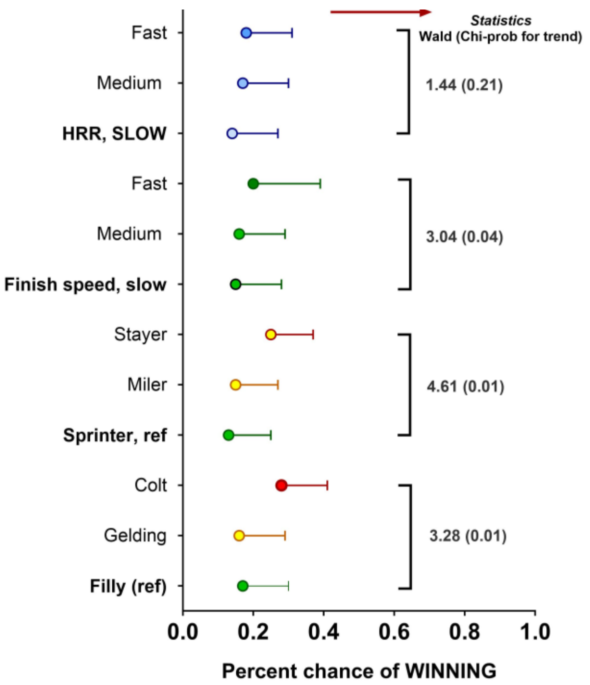


Figure. Data are predicted mean log odds (as a percentage) ± SEM for winning a race from training data. Data obtained by integrating known race outcome data from Racing.com (Victoria, Australia; n=485 different racehorses, n= 3810 different races) with training data (only fast gallop and jumpout on turf) for the same horses before and during two race seasons (n=3418 different training sessions). Data were analysed with race outcome (e.g., win) as the variable of interest, fitting sex of horse (filly as referent category), racehorse profile (sprinter as referent category), finish speed (slow as referent category), heart rate recovery (slow as referent category) and speed at 600m mark (slow as referent category) as other factors of interest. Since the same horse completed multiple training sessions and multiple races then HorseID was fitted as a random effect using Generalised Linear Mixed Models (G_zLMM). Statistics for main effects are indicated on the right on the graph with associated Wald statistic. Statistical significance was accepted at P<0.05.

5.5 Discussion

This study has directly, and objectively, analysed in-training racehorse speed and heart rate recovery for the prediction of race-day performance (categorised as winning versus not winning). The speed of heart rate recovery to one minute after a high-speed training session did predict race performance, but the effect was markedly reduced when the variation between different horses was accounted for. In addition, horses recovered better in relatively hot, but not relatively dry, weather conditions. Similarly, racehorses that were categorised as being relatively 'fast' from 600 to 1000m, that is consistently fast over the last 600m of the timed trial in training also appeared to have a greater chance of winning a race. Such an effect diminished, but nevertheless remained, when variability by horse was accounted for. This study provides evidence to support our primary hypothesis; training data can be used to predict which racehorses will a) go on to participate in a group race and b) be relatively more successful. Nevertheless, the absolute difference in practice is small (~4-6 beats/min; ~1-1.5sec/furlong) such that monitoring may not be of practicable use. Hence, we suggest that aptitude for superior performance is variable for each individual racehorse, relying on unique physiological factors. Furthermore, race-day performance prediction can equally be influenced by intrinsic aspects such as the sex and age of the horse and possibly other extrinsic factors (e.g., running strategy).

5.5.1 Descriptive characteristics of the racehorse training dataset

As racehorses initiate their training, milestones are commonly established by trainers to plan their progression towards racing (Tanner et al., 2011). The first milestone typically involves the registration of a horse with a specific trainer. A trainer is required to officially inform his relevant racing authority or governing body (such as Racing Victoria) that a horse has initiated training in his stable. The second milestone consists of entering a horse in an official trial or 'jumpout'. In Australia, it is mandatory for any horse to run in a qualifying trial before being entered in a race. The number of completed jumpouts of any individual horse prior to a race varies from one trainer to another. Some trainers only opt for one jumpout and consequently consider the first race as a 'fitness test'. In the present study, jumpouts occurred approximately 10 days before a race. Racing is perceived as the ultimate training milestone.

With the advancement of field technologies such as portable fitness trackers, the ability to evaluate racehorse speed, stride and heart rate in an environment similar to official race meetings has become increasingly feasible and reproducible (ter Woort et al., 2021, Schrurs et al., 2022b, Schrurs et al., 2022a). When routinely observing horses exercise live on the track, it is still common practice for trainers to manually time the fastest workouts by means of a stopwatch. Usually, they will measure the time taken in seconds for a given horse to cover a furlong (sec/f). In Australia, speeds of fast gallop were surveyed among 66 trainers established in Victoria. Results outlined timings of 11-14 sec/f and speeds of 47.9–65.5 km/h during high intensity workouts (Morrice-West et al., 2020). These values were consistent with those reported in the present study and are comparable to what has been recorded during race-day performance (Takahashi, 2015). Although the race distance was greater (i.e. long distance or 'staying' races), stride lengths and frequency were similar to those identified by Takahashi et al. (2021), that is, 7.42m and 2.34 strides/sec respectively. Maximum heart rate did not further increase with training intensity, as previously observed by us and others (Ferrari et al., 2009) and was similar in both types of race-pace efforts (jumpout versus hard gallop).

5.5.2 Racehorse heart rate and recovery during training

As horses progress in their training program, so does their cardiovascular fitness. Cardiovascular fitness refers to the ability of an individual to rapidly recover or drop its HR from peak to baseline after an intense effort. Heart rate measures are known to vary from one horse to another as they rely on unique aerobic capacity influenced by breed, age or training (Couroucé-Malblanc and Hodgson, 2014). At sub- and maximal exercise intensities, HR is a reliable indicator of fitness and performance in Thoroughbreds (Gramkow and Evans, 2006, Evans, 2007a). In flat racehorses running at top speeds, heart rates peak at ~200bpm (Krzywanek et al., 1970). Such observations were reaffirmed in the present and past work, as presented in this thesis.

To date, there is still little research that addressed the use of HRR to measure equine fitness (Evans et al., 1993), as opposed to what has been published in the human literature (Daanen et al., 2012, Rabbani et al., 2020). Racehorse HRR is directly proportionate to the intensity of work (Schrurs et al., 2022b) and was reflected in our findings: horses that conducted jumpouts took longer to recover compared to those that had completed hard gallop sessions. The nature of jumpout sessions undeniably places more stress on the cardiovascular system of the horses and as a result a prolonged recovery is to be expected. It is also conceivable that factors such as excitement, pulling excessively or not putting in a hard run could have contributed to a longer HRR during jumpouts, considering the nature of the exercise. However we acknowledge that older horses were possibly more familiar to the jumpout routine and environment, thus less affected by the excitement of interval exercise than the younger horses (Hodgson, 2014). Overall, the greatest heart rate recovery occurred during the first minute after exercise. Interestingly, the post 1 min HRR measure is a common indicator used in human performance and is applied in many athletic sports (Daanen et al., 2012, Blomqvist and Saltin, 1983, Hagberg et al., 1980). The post 1 min HRR parameter was integrated in recent work that analysed HRR for the prediction of performance in a cohort of 20 National Hunt racehorses (Wilson and McGowan, 2019).

It is widely assumed that aspects of environmental heat and humidity may influence cardiorespiratory responses to exercise and recovery in horses. Since the World Equestrian Games in Stockholm (1990) and the Olympic Games in Barcelona (1992), heat stress in horses has received significant media attention along with a surge in studies investigating how to preserve equestrian competitions in challenging environmental conditions (Jeffcott and Kohn, 1999, Marlin et al., 1996, Marlin et al., 1995, Kohn et al., 1995, McCutcheon et al., 1995, Lindinger et al., 1995). One example of study evaluated a small cohort of 5 Thoroughbreds exercised on a treadmill exposed to varying environmental conditions (Geor et al., 1995). Geor et al. (1995) found that heart rate during and after exercise was significantly higher in a hot and humid controlled setting compared to other conditions. Although the study was performed in a laboratory environment, this contradicts our findings as we noted the opposite: improved recovery in hotter conditions with an absence of humidity effect. The explanation may lie in the fact that the majority of the cohort participating in our study were Australian-bred horses, not imported from overseas and therefore more ‘acclimated’ to the vagaries of the environment in Melbourne. Work by Munsters et al. (2024) evidenced that training for 14 days in a heated indoor arena contributed to the reduction of thermal strain on elite sport horses, facilitating competing in hot weather. The study also highlighted that high-level horses can acclimate to heat while remaining in training, a crucial factor for their participation in events such as the Olympics. Another explanation may lie in the trainer’s subconscious or active decision to not gallop horses as hard during hotter months. In colder winter months, horses may not be as fit as they are coming into the Spring racing time of the year. This associates with the assumption that more horses could’ve been in work in the warmer months of the year, because of the increased race opportunities at that time of the year. Lastly, this observation could be explained by a vast majority of lower class of horses racing in winter, as opposed to better horses that would be racing in spring and thus warmer weather.

5.5.3 Racehorse speed during training

Whether a human sprinter, a marathoner, or a racehorse, speed is the driving force behind athletic performance. Speed, acceleration rate and the ability to hold maximum speed over a certain distance are highly sought after performance characteristics. All play a part in building efficient racehorse locomotion acquired through the implementation of suitable training programs (Bloomfield et al., 2007, Witte et al., 2006). Speed is the combination of stride frequency and length (Schrurs et al., 2022b, Clayton, 2016). Horses are known to reach peak speeds, first by increasing their stride frequency up to the pace of gallop then by increased stride length (Schrurs et al., 2022a). Our results converged to this principle, as stride length was significantly different between racehorse speed categories. The unrealised heterogeneity of racehorse profiles (e.g. sprinters versus stayers) in this study should however be acknowledged, as horses are expected to each present unique locomotion (Schrurs et al., 2022a). The differences observed at the first 200m between fast and slow racehorses may indeed highlight the diversity in racehorse locomotory profiles or, to a further extent, equally represent diverging types of workouts. The variability in the first 200m could also be explained by the fact that trainers instruct the riders differently towards building up speed of their horses. For example, a horse doing a middle- or long-distance workout will not be going as fast into the first 200 or last 400m compared to a ‘sprinter’. Depending on the workout, they may only start to increase speeds ≥200m into the workout (i.e., 800m away from the finish line). It is therefore assumed that the classification of speed at 600m was more pertinent to compare groups up to the virtual finish line.

The effect of track condition on speed recordings was accounted for, as firmer ground are known to contribute towards faster racing speeds on turf surfaces (Maeda et al., 2012). We were not able to account for several aspects which may have influenced to some extent racehorse response to training and speeds. The first example is training strategy. Equally, the amount of weight carried (variation between jockeys) and influence of the jockey (skill, intentionally or unintentionally holding the horse back) were data that was not available to us but that have previously altered running times and thus race performance (Oki et al., 1995).

5.5.4 Racehorse heart rate recovery and speed for the prediction of race-day performance

The Australian racing industry is relatively homogeneous, facilitating the extraction of annual racing data for the purpose of large observational studies such as the present study. Few previously published studies have involved hundreds of racehorses and thousands of races to explore any association between physiology in-training (speed and HRR) with racing outcomes.

To explore the correlation of physiological and horse-related measures with performance outcomes, two measures were employed in the statistical tests: percentage chance and odds ratio. Percentage chance, also known as probability, represents the likelihood of an event occurring as a percentage, calculated by dividing the number of favourable outcomes by the total number of possible outcomes. On the other hand, odds ratio compares the likelihood of an event occurring to the likelihood of it not occurring, expressed as a ratio of two odds. The odds of an event occurring are determined by dividing the probability of the event by the probability of it not occurring. While percentage chance provides a direct measure of likelihood as a percentage, odds ratio offers a comparison between the chances of the event happening versus not happening.

A first approach consisted of comparing HRR and speed between groups of horses categorised according to previous participation in a group race or not. Results showed that the horses that had participated in a Group race recovered better and ran faster than the horses with no subsequent Group race exposure. This suggests that these physiological data could potentially 'predict' race performance. However, to an extent, the observation could be partially influenced by the age of the horse, despite us statistically controlling for this factor. The nature of the Australian racing programme is such that substantial incentives are given to race young horses (2- and 3-year-olds). The large offer of races makes it easier for young Thoroughbreds to qualify in Group races. This so-called 'black type racing' (Group races for 2–3-year-olds) is of a volatile nature and results from the high breeding turnover. Such races remain very attractive and accessible, as the inclusion criteria may at times only include winning one race to qualify for such 2-year-old Group races.
Thus, a second approach was to integrate all racehorse characteristics including physiological data alluded to above (speed, heart rate recovery) and inherent data on the horse itself (age, sex, days in training) to identify which aspects predicted the chance of winning. Overall, stayers had a greater chance of winning relative to other categories of racehorse (sprinters and milers), as previously published (Schrurs et al., 2022a). This is not surprising considering that stayers were older, thus possibly more mature, of better 'quality' and experienced at races or were better placed in more suitable races by the trainer. Colts were also more likely to win, as opposed to fillies, mares, or geldings. More (1999) drew similar conclusions: performing horses were more likely to be male, have started as a 2-year-old and acquired more starts in the preceding 12 months (More, 1999).

Clearly, having greater ability to go faster, 'speed', is known to favour superior racehorse performance (Kay and Vamplew, 2012). In this study, after accounting for individual racehorse variability, then finish speed more so than HRR, showed a small effect towards the prediction of race wins percentage. This aligns with a treadmill study that conducted exercise testing in flat racehorses, where results evidenced lactate as opposed to post exercise HR associated more positively correlated with Timeform ratings (Evans et al., 1993). Other, more recent, literature contrasts with this finding, showing that HRR at 1min following interval exercise in

National Hunt racehorses on the field was a tangible predictor of subsequent race position, such as finishing in the top three (i.e. podium) (Wilson and McGowan, 2019).

Aspects of genetics (Gaffney and Cunningham, 1988) and nutrition (Hintz, 1994) also contribute to racehorse success on the track, but were not addressed in this study. Furthermore, the influence of the trainer has also been reported to significantly associate with racing performance (Ely et al., 2010). We could not account for the trainer's entry strategy for each individual horse. For example, placing a less performant or injured horse in a lower class of race to increase its chances of winning and as a result, prolong its racing career. Relying on official racing databases may not fully adjust for health or injury status of the horses. Additionally, the racing dataset did not provide information on the number of horses participating in the race which could have skewed the data. Another limitation could have related to the success criteria established for race performance, which could equally influence the results – for example, certain aspects of training were predictive of race performance when classified as 'win' or not, but not when classified as 'podium' or not. Finally, it should be noted that the study is a convenience sample of racehorses having used an 'Equimetre' intermittently, but in a repeatable fashion in training. The study is retrospective and observational. One test of our data would be to conduct the same study using a larger database to confirm or contradict the minimal effect sizes across the different speed and winning races. Alternatively, another one could involve establishing benchmarks of speed and heart rate data according to racehorse age in previously identified winning horses.

In conclusion, this study demonstrates that in-training racehorse physiological data can be used to identify which horses are more likely to win or not. Of all aspects tested, there was a slight indication for the finish speed to be predictive of race performance. It can therefore be deducted that winning a race is about a multitude of aspects. Considering speed and recovery data along with other aspects (i.e., genetics, preferred ground and distance, psychological state of the horse, training programs, the jockey-horse partnership), may help trainers identify and build a legacy of promising horses. Such a hybrid approach using data alongside experience may contribute to better selection of horses in suitable races and improve overall health and welfare on the track.

Chapter 6 Overall Discussion

6.1 Project overview

The aim of this thesis was to explore the application of data science to further understand racehorse physiology and performance, in the context of both training and racing across large populations of racing Thoroughbreds. Objectively monitoring racehorses' response to exercise 'live' on the track along with the assessment of race-day readiness requires validated technologies (ter Woort et al., 2021). Such tools are purposely designed to instantly record and collect multiple parameters relating to fitness (e.g., heart rate and heart rate recovery), locomotion (speed, stride length/frequency), location (GPS, distance) and other external measures (temperature/humidity, ground condition etc). However, while such fitness trackers are gradually being commercialised, and a number of isolated studies have investigated their use in various contexts (Fraipont et al., 2012, Hodgson, 2014, Kingston et al., 2006, Williams et al., 2019), no study had involved hundreds of individuals to describe racehorse physiology in training, factors that may affect their performance and correlations between training and racing. This thesis was therefore developed to take a comprehensive approach to racehorse physiology and performance.

The primary research questions for each separate study of this project were:

(1) what physiological patterns (i.e., cardiovascular and locomotory parameters) are observed in large racehorse cohorts during training and are these similar between racehorses in different countries (Australia and France). The study also described what other aspects (e.g., track surface, horse age and sex) may influence cardiovascular and locomotory patterns.

(2) having objective physiological data being recorded for every training session alongside knowledge of which jockey was used for each training session allowed us to ask what effect the sex of the jockey may have on racehorse physiology (cardiovascular and biomechanical parameters) and/or performance (win percentage and chance of a top-three placing in both UK and Australia).

(3) whether stride length (short, medium, or long) recorded during training sessions conducted at race speed (soft-medium-hard gallop or 'jumpout') characterises racehorses prior to them performing in categorised registered races as a sprinter, miler, or stayer. Also, to what extent is stride length heritable?

(4) what aspects of cardiovascular fitness (e.g., rate of recovery of heart rate) or stride acceleration (e.g., average time over consecutive 200m from a standing start) recorded during 'jumpout' and standard gallop sessions can predict the likelihood of race success defined as winning or losing a race.

This project primarily focused on training and racing in Australia, despite lots of data being initially available in other countries such as the United Kingdom, France, and the United Arab Emirates. The data in Australia was systematically collected and better collated, enabling more controlled sampling and analysis with greater interpretive value, as it utilised data from a convenience sample (i.e., a single racing yard located in Victoria state). However, in some instances throughout the thesis then additional data was also used, so as to integrate training and racing databases from other racing nations such as France and the United Kingdom, for comparative purposes.

In the equine exercise physiology literature, no studies exist that describe racehorse heart rate, stride, and speed measures in large datasets (i.e., hundreds of individuals). Hence the first study was developed to report physiological patterns (i.e., cardiovascular and locomotory parameters) in large racehorse populations during training and compare them between countries (i.e., Australia and France). The study also outlined what other aspects (e.g., track surface, horse age and sex) may influence such patterns. The effect of increased training speed from slow canter to hard gallop were analysed for racehorse heart rate, heart rate recovery and stride length/frequency, while considering aspects of varying track surface, horse age and sex. Racehorses increased speed predominantly by an increment in stride length, then frequency, as also demonstrated in a study by Ratzlaff et al (1985). In both countries, speed was lower on sand, stride values (stride length and frequency) were reduced as previously reported (Rogers and Firth, 2004), but horses appeared to recover better when compared to turf. This observation could be justified by the intended use of each track surface for a particular training intensity. Indeed, in Australia, sand or synthetic surfaces are commonly integrated for slow workouts (such as slow canters) while turf tracks are leveraged for fast workouts (Morrice-West et al., 2018). In both France and Australia, considering the geographical proximity between some training yards and the sea, then sand beaches may also serve as suitable and softer training surfaces for both trotter and flat racehorses. Such training sessions may build cardiovascular fitness on the softer surface, like sand, or mimic race-day demands on soft turf. Nevertheless, surface undoubtedly influences speed, stride length and frequency as shown here and previously by others (Burn and Usmar, 2005, Crevier-Denoix et al., 2010, Symons et al., 2014, Maeda et al., 2012). For these reasons, appropriate grounds are carefully selected by trainers for each individual horse to also minimise the risk of track-related injuries (MacKinnon et al., 2015, Crevier-Denoix et al., 2010, Peterson et al., 2021, Symons et al., 2014). Peak heart rate and recovery increased with training intensity, with some differences observed between countries. We assumed this may be due to differences in training strategies between countries, as outlined in previous work conducted in Australasia, USA and the UK (Firth and Rogers, 2005, Morrice-West et al., 2020, Pagan et al., 2017, Verheyen et al., 2006b, Hodgson, 2014). Older horses recording lower heart rate at 15mins after training, which may be explained by the effect of age and/or improved fitness (Ohmura and Jones, 2017, Poole and Erickson, 2014, Yamanobe et al., 1993). No effect of sex of the horse was reported on speed. This is surprising considering significant heart rate differences have previously been highlighted between male and female horses (Mukai et al., 2003). With large datasets such as the one in the present study, accurate technologies have the potential to comprehensively measure physiological data on racehorses in training, revealing clear differences in training strategies between countries. The higher heart rate measures (e.g., a consistent ~20bpm difference between peak HR compared to France) over shorter intervals of work distance (1200m versus 1700m in France) suggest that in Australia trainers implement interval training as opposed to more 'conventional' training in France. Altogether, it can be affirmed that all original hypotheses, aims, and objectives were addressed.

As described in Chapter 2, track surface, horse age and a given country's approach to training all provided factors that appeared to significantly influence racehorse cardiovascular and locomotory measures in training. With this in mind and given the recent success of female jockeys around the world together with the high proportion of professional (female) jockeys racing in Australia, it was therefore of interest to objectively study whether male or female jockeys had any influence over racehorse physiology and performance in training and, using other datasets, in performance on the racecourse. Therefore, in Chapter 3 the effect of the sex of the jockey was investigated on the same physiological data as previously used, but with the addition of known sex of the jockey used for each and every training session in Australia. This second study characterised racehorse cardiovascular (heart rate, heart rate recovery) and biomechanical (stride length and frequency) parameters at various exercise intensities (slow canter to hard gallop) to address the question whether any parameter altered according to sex of the rider and experience (professional versus non-professional) and/or race-day performance (win percentage and chance of a top-three placing in both UK and Australia).
Sex of the rider did not influence any aspect of racehorse speed, stride length, heart rate and peak heart rate at any training intensity. This is interesting considering other aspects have shown to influence speed or stride such as riding style (Pfau et al., 2009), weight (Gunnarsson et al., 2017) and rider's experience (Kapaun et al., 1998). However, racehorse heart rate recovery was influenced by sex of the rider when looking at the extremes of the reversed usual

training intensity, that is: heart rate after galloping on sand was significantly lower with male riders. This observation draws attention to the nature of the horse-rider partnership dimension. Studies have explored the interactions between the cardiovascular responses of rider and horse in the context of fear/distress (Merkies et al., 2014), novel stimuli (Munsters et al., 2012) or rider (Schmidt et al., 2010). Keeling et al (2009), in their investigation on human and horse interactions, concluded that rider anticipation to a novel stimulation or object caused an increase in heart rate which equally matched an increment in horse's heart rate. Concomitant with our findings, this introduces the idea that male riders in our study may have anticipated, more than their female counterparts, the expected training intensity on a set surface which translated in a high/low heart rate that was transmitted through to the horse, probably subconsciously. Simultaneous heart rate measurement of horse and rider in such a context could address this question, as has been conducted in humans (Saad and Vongas, 2009). Another supposition, although unable to be answered here due to the data available to us, could lie in any possible change of work rider for riding on certain surfaces (i.e., changing from female to male when faster sessions on turf are to be conducted). However, to our knowledge this was not a common practice in the yard from which we drew our data. Finally, analysis of race results in Australia and the UK indicated a similar chance of a top-three placing and win percentage for male and female jockeys. However, we could not account for quality of the mounts and races. To date, no similar research has been produced on the topic. For this study, it can be concluded that all original hypotheses, aims, and objectives were met.

As all available factors that could possibly influence racehorse locomotion were explored in Study 1 and 2, we were then interested in further uncovering any differences in locomotory profiles. Similar to human athletes, Thoroughbreds compete at various race distances (e.g., short 'sprinter', <1600m; middle 'miler' and longer distance 'stayer', >2500m) and are assumed to be naturally pre-disposed to a specific distance according to either their locomotion (sprinters having an innately shorter stride compared to stayers) or their pedigree (sprinters versus stayers). However, no study had specifically explored this. Therefore, our research question asked whether stride length (short, medium, or long) recorded during training sessions conducted at race speed (soft-medium-hard gallop or 'jumpout') characterised racehorses prior to them performing in categorised registered races as a sprinter, miler, or stayer. We also investigated the heritability of stride length and assessed whether differences in stride length persisted between racehorses destined to race as sprinters or stayers when considering their three-generation pedigree.
Our study found that, in training, sprinters had a shorter stride of higher frequency and covered consecutive furlongs faster than stayers. However, we were unable to account for the effect of warm up (Tranquille et al., 2017) and fatigue (Johnston et al., 1999), aspects that have

previously been reported to influence stride characteristics. Relatively short or longer stride did not predict race success in sprint versus staying races, respectively. This is surprising as muscle strength, speed and endurance are previously identified traits that contribute to superior performance in Thoroughbreds at various race distances (Kay and Vamplew, 2012). Racehorse performance prediction remains complex as it results from a combination of genetics (Gaffney and Cunningham, 1988), nutrition (Hintz, 1994) and training (Morrice-West et al., 2021). Overall, in our results, stayers had greater race success than sprinters, to an extent perhaps because older, more experienced, and better-quality horses were naturally retained by the trainer. Research has demonstrated that longer races allowed jockeys and trainers to better leverage racing tactics (Sobczynska, 2006). Taking pedigree information into account, then peak stride length and frequency were only moderately heritable, as others have shown recently (Barrey et al., 1995).

After deepening our understanding of locomotory profiles and the heritability of stride, it was of interest to comprehensively explore the prediction of race-day performance leveraging race-pace training data. To this purpose, the question posed aimed to discern what aspects of cardiovascular fitness (e.g., rate of recovery of heart rate) or stride acceleration (e.g., average time over consecutive 200m from a standing start) recorded during ‘jumpout’ and standard gallop sessions could predict the likelihood of race success defined as winning or coming in the top three of a race, versus losing or being outside the top-three.
Thus, race-pace in-training speed (categorised as ‘slow’ to ‘fast’ according to the last 600m away from a virtual finish line) and heart rate recovery (from average during gallop to 1min after exercise) conducted on turf were analysed in racehorses of varying age, sex and locomotory profile (e.g., sprinter, miler, stayer) to identify whether such physiological data were reliable predictors of racehorse success. A posteriori racing information was extracted and combined to the timed-trial training sessions, with race performance analysed based on success outcome as ‘win’ (yes/no). Of all aspects tested, colts, stayers and fast finish speed were predictive of race performance and aligned with previously published work (More, 1999, Schrurs et al., 2022a, Kay and Vamplew, 2012). Opposingly, heart rate recovery and speed at the 600m mark did not show signals of performance prediction. The available literature on post exercise HR for performance prediction is somewhat contradictory as it includes either positive or negative corelations (Wilson and McGowan, 2019, Evans et al., 1993). It would have been interesting to account for the influence of the trainer, as it has been evoked to significantly associate with racing performance (Ely et al., 2010). In the context of this study, it is believed that all original hypotheses, goals, and objectives were individually addressed and realised.

6.2 Limitations of using data analytics to assess racehorse physiology and performance

All four studies constituting this thesis shared common limitations, primarily attributable to their retrospective study design. The data were systematically and consistently, with some minor exceptions, the same recurrent convenience sample provided by the fitness tracker company (Arioneo Ltd, France), albeit independent datasets, with different horses and dates of training and/or racing. The primary dataset was made available thanks to the buy-in of a major Australian horseracing yard, identified and acknowledged as Ciaron Maher Racing (https://www.ciaronmaher.com.au). It is therefore assumed that there may have been a risk for selection bias when manually cleaning the database prior to analyses. Extending the analyses to multiple training yards, possibly with different training methods would increase the likelihood of the results being more generally applicable.

Because each individual study, thus chapter, presented a retrospective and observational study design, several aspects and parameters could not be accounted for. For example, in the first piece of research focusing on descriptive characteristics of racehorse physiology in training, then further information on track surface (incline, composition, penetrometer information) would have allowed for more thorough analyses. However, as the technicalities of the fitness tracker device continued to be refined, then new information was automatically integrated by the company in the extracts of data to complement the existing parameters. Moreover, the nature of in-field sampling, as opposed to a more laboratory environment such as a treadmill, did not allow for any level of experimental control, as what would be with prospective sampling.

Although the sample size was significant (hundreds of individual racehorses, thousands of training sessions) compared to what is currently found in the literature, larger sample sizes may have allowed for more subtle effects to be identified. This is especially important when the primary outcome is binomial, such as race wins (see Chapter 4), where the effects revealed were relatively small. However, at the time of writing, we could only make use of what was available. Equally, it is acknowledged that the Equimetre device was not repeatedly used for every training session on each horse, but rather only as and when asked to do so by the trainer (e.g., as a baseline or testing session to assess ‘fitness’). Only a limited number of devices (up to 20 systems) were at disposition of the trainer and were randomly allocated to individual horses for routine checks or to address concerns. Without funding and a prospective design, for this study, we were not able to dictate when and on whom the Equimetre device should be used in order to test hypotheses. Thus, retrospective studies can also suffer from a degree of inherent bias.

To some extent, we could not account for horses being already ‘fit’ when evaluating various aspects of physiological responses to exercise. Additionally, speed categorisation, regardless of taking a data-driven approach, was to some extent dependent on the trainers chosen instructions.

6.3 Future work

This project highlighted the benefit of integrating objective and comprehensive tools in large-scale studies to further understand racehorse physiology and performance, in-field. In comparison to treadmills, wearable technologies now allow for real-time monitoring of racehorse performance in their natural environment, with little to no interference with their usual work routine. However, certain challenges persist for with field sampling, such as blood or lactate measurement, due to their vivid demeanour of racehorses. Therefore, such measurements may still be better suited for treadmill conditions. As such, numerous future studies could build on the findings from the current project.

For example, similar descriptive studies could compare other leading racing nations amongst each other (e.g., Japan, USA, Ireland, South Africa). Such work could explore and identify unique racehorse physiological adaptations and training approaches, to which the findings from Chapter 2 of this project are applicable and highlight any notable regional or environmental differences. It could also investigate the extent to which horses are adapted to extreme environmental fluctuations. Chapter 2 outlined the potential of longitudinal monitoring over time to investigate the evolution of fitness of an equine athlete. This could be performed by involving fewer horses in standardised conditions, perhaps on a treadmill for every training session undertaken, focusing on parameters of peak HR and HR recovery at a given speed. The implications could assist trainers in evaluating an individual racehorse’s improvement of fitness. Additionally, individualised data could also contribute to establishing training zones using % of peak HR to understand racehorse response to workload/intensity. It could help detect those overly tired or over-trained by analysis of baseline heart rate. Furthermore, the data could also be leveraged to identify altered patterns of behaviour in sub-clinically injured horses by deviations/changes in their usual stride metrics (length or frequency).

Investigating the effect of the sex of the rider on racehorse physiology and performance shed a light on other future work that could be conducted. For example, it would be interesting to draw on the analysis of Chapter 3 to delve into comprehensive performance profile analyses of racehorses. This could be done by examining horse body weight, plasma lactate, and cortisol levels along with other physiological parameters like muscle mass, oxygen consumption, and metabolic rates. The ultimate aim of such work would be to analyse how these factors collectively impact racehorse performance. Alternatively, the horse-rider interactions were only superficially discussed and explored in Chapter 3. Therefore, future work could also investigate the dynamic relationship between riders and their horses during races. For example, by collecting data on rider characteristics (e.g heart rate and body composition) to understand how these factors influence the horse's performance. Implications could translate to whether certain rider-horse pairings result in better racing outcomes and if rider physical condition/fitness plays a role. Lastly, performance profiling research could be addressed in future studies to include male and female riders. By comparing any relevant physiological responses, riding techniques, and performance outcomes to evaluate potential sex-related differences in racing performance and rider-horse interactions.

The findings of the third study relating to locomotory profiles in racehorses could lead to directions such as prospective racehorse performance assignment. Racehorses could prospectively be assigned to either sprinter or stayer categories based on their stride characteristics during training. The aim would then be to monitor and analyse their subsequent race performances to determine whether greater success can be achieved in their assigned distance category. Another avenue to explore lies in the impact of unrecorded factors such as warm-up protocols and accumulated fatigue, on racehorse stride characteristics and overall performance. Such findings could help trainers develop standardised protocols for warm-up routines and fatigue management to see how they affect racehorse stride and race results.

Lastly, the final study of this thesis highlighted another interesting future direction. Researchers could conduct the same study using a larger database to confirm or contradict the minimal effect sizes across the different speed and winning races. Another one could involve establishing benchmarks of speed and heart rate data according to racehorse age in previously identified winners.

In essence, the integration of objective fitness trackers shapes a promising new era for improved racehorse health and welfare on the track. With ‘live’ data on the track, such innovative devices offer real-time monitoring capabilities allowing trainers and veterinarians to gather precise data on various aspects of equine physiology and performance. By tracking parameters such as heart rate, ECG and stride, fitness trackers provide invaluable feedback that can inform more targeted training regimens and identify early signs of stress, injury or fatigue.

6.4 Conclusions

The findings of this project outline how tracking technologies facilitate a comprehensive approach to monitoring racehorse physiology and performance. Fitness trackers represent an additional, yet very valuable resource available to racehorse trainers. Recorded measurements may be evaluated at a fine scale, focusing on a particular horse in its routine work environment, or at a larger scale as conducted in this work, across major racing yards and countries. While horseracing remains a sport of tradition (Ely et al., 2010), objective tools have gradually paved their way into a new racing era, to positively impact the health, welfare and safety of its participants (i.e. horses and jockeys) on the track.

Our work highlighted that track surface influenced racehorse speed, stride and heart rate recovery (i.e lower values on sand compared to turf). Older horses presented lower heart rate values. Overall, there were marked differences in training strategies between countries, with Australia conducting shorter intervals of distance at faster speeds, compared to France, where a more conventional training approach was adopted.
The sex of jockey did not appear to influence speed, stride length nor heart rate. Both male and female jockeys presented a similar chance for top 3 ranking and win percentage.
When comparing locomotory racehorse profiles, then sprinters presented a shorter stride but of increased frequency, being on average faster than stayers. Short and long stride did not predict racing success. With all aspects considered, then stayers had greater chances of success, with peak stride length/frequency being moderately heritable.
Lastly, analysis of cardiovascular fitness and stride acceleration in race-pace workouts for the prediction of performance outlined that aspects such as colts, stayers and fast finish speed were predictive as opposed to heart rate recovery and speed at the 600m distance mark.

The integration of such fitness trackers is presumed to stay on the rise amongst racehorse trainers, as global efforts led by researchers and racing jurisdictions continue to strive towards reduced racehorse wastage and injury (Verheyen and Wood, 2004, Parkin, 2008, Maeda et al., 2016, Hitchens et al., 2019).

Studies leveraging fitness trackers to further understand the effects of the environment (e.g., track surface and condition, temperature/humidity, rider), genetics (e.g., heritability of certain traits), exercise (e.g., speed and fitness, locomotory profile, winning prediction) on racehorse physiology and performance can serve as foundations to explore future directions and applications. Some examples of future work could include data-driven betting and new regulatory implications. In summary, the insights gained from this research on racehorse physiology and performance could have far-reaching effects on the horse racing industry, encompassing performance improvement, injury prevention, ethical considerations, and technological advancements. These findings could equally have broader applications in sports science and animal welfare.

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Chapter 8 Published Papers

Comparative Exercise Physiology, 2022; 18 (3): 185-199

Wageningen Academic Publishers

Cardiovascular and locomotory parameters during training in Thoroughbred racehorses: a multi-national study

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Received: 9 September 2021 / Accepted: 10 February 2022

RESEARCH ARTICLE

Abstract

Studies assessing concurrent speed, cardiovascular physiology and biomechanical parameters in racehorses during training have been rarely reported, mostly due to a lack of available comprehensive technology. Here, using a validated device (the 'Equimetre™') that records all parameters simultaneously, we report the effect of increased training speed and thus intensity, from slow canter to hard gallop, on racehorse heart rate, heart rate recovery and on biomechanical parameters, such as stride length and frequency. We also demonstrate the effects of varying track surface, horse age and sex. Cohorts comprised a total of 509 Thoroughbred racehorses in-training in either Australia or France, completing a total of 1,124 and 6,016 training sessions, respectively. Horses varied by age (2-9 years old) and sex (including geldings) and were trained by either a single trainer (Australia) or two trainers (France); both using multiple training centres that varied by track surface (sand, turf or fibre). Data were analysed using Analysis of Variation (ANOVA) or linear mixed-effect models as appropriate. Racehorses increased speed predominantly by an increment in stride length, then frequency, both of which varied according to track surface (shorter stride on sand; $P<0.001$). Cardiovascular parameters (peak, and recovery of, heart rate) increased with training intensity, but not linearly ($P_{trend}<0.001$). Older horses recorded lower heart rate at 15 mins after training ($P=0.002$), often due to lower achieved peak heart rate at most training intensities ($P<0.001$ for the cohort in Australia). In conclusion, this immersive field study demonstrates the value of technology for recording physiological and biomechanical parameters of racehorses-in-training. The data could inform trainers, jockeys and owners on aspects of individual racehorse health, welfare and suitability for certain races.

Keywords: horse, exercise, racetrack surface, heart rate, locomotion

1. Introduction

Thoroughbred racehorses have evolved, comparatively, as elite athletes. By any measure, they have superior speed, oxidative threshold and exhibit greater circulatory responses to exercise such as release of red cells from the splenic reservoir, when compared to man (Allen *et al.*, 2016b). Racehorses are trained consistently from two years of age to race and ideally win against other racehorses at ages two, three or older. Despite much progress in the understanding of equine sports performance, training practices remain predominantly grounded in tradition, experience, observation and the rider's feedback (Ely *et al.*, 2010) rather than evidence-based principles of performance (Williams, 2013). In contrast, development of human elite performance toward readiness for competition has been influenced and informed by objective feedback from a variety of training aids, such as monitoring of heart rate (HR) or of recovery (HRR), or power output (particularly for cycling) for decades. Indeed, relatively recently, incorporation of variations in training intensity (e.g. high-intensity intervals during a training session) and variations in training patterns over time (e.g. periodisation of training over the racing season) have been introduced

ISSN 1755-2540 print, ISSN 1755-2559 online, DOI 10.3920/CEP210037

PLOS ONE

RESEARCH ARTICLE

Does sex of the jockey influence racehorse physiology and performance

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Abstract

The racing industry is supported by a predominance of female stablehands and work riders, but few become professional jockeys. Female jockeys have recently had notable race success. No study has assessed whether the sex of the rider may subtly influence racehorse physiology to affect performance. Here, using a validated exercise tracking system (the 'Equimetre'™) that records many physiological parameters simultaneously, this study characterised racehorse cardiovascular (heart rate, heart rate recovery) and biomechanical (stride length and frequency) parameters at various exercise intensities (slow canter to hard gallop) to address the question whether any parameter varied according to sex of the rider. A total of 530 Thoroughbreds, varying in age (2–7 years old) and sex (including geldings), from one racing yard in Australia, completed a total of 3,568 exercise sessions, monitored by a single trainer, on varying track surfaces (sand, turf, or fibre). Different work riders,103 in total (male, n = 66; female, n = 37) of which n = 43 were current or past registered professional jockeys, participated in the study. Data were analysed using analysis of variation (ANOVA) or mixed-effect models, as appropriate. Sex of the rider did not influence ($P >$ 0.05) racehorse speed nor stride length at any training intensity. Racehorse heart rate and peak heart rate increased with training intensity ($P < .001$), with no difference according to sex of rider ($P > 0.05$). Racehorse heart rate recovery was influenced by sex of the rider, but only at the extremes of the reversed, usual training intensity on each surface (e.g. heart rate after galloping on sand was significantly lower with male riders, $P = 0.03$). Finally, analysis of 52,464 race results indicated a similar chance of a top-three placing for male and female jockeys. In conclusion, this study, using objectively obtained data, demonstrates for the first time no overt effect of the rider's sex on racehorse physiology in training and performance in racing. Such data could encourage greater female participation in racing and improve access of female jockeys to better quality mounts in racing events.

OPEN ACCESS

Citation: Schrurs C, Dubois G, Van Erck-Westergren E, Gardner DS (2022) Does sex of the jockey influence racehorse physiology and performance. PLoS ONE 17(8): e0273310. https://doi.org/10.1371/journal.pone.0273310

Editor: Yaodong Gu, Ningbo University, CHINA

Received: April 7, 2022

Accepted: August 7, 2022

Published: August 31, 2022

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pone.0273310

Data Availability Statement: All anonymized data used in this manuscript are available from Arioneo, Ltd at https://vet.arioneo.com/en/bdd-publication/ (racehorse training data with sex of jockey listed) and all data used to calculate the win percentage of male or female jockeys are available at The

Introduction

In human elite sport, athletes are almost invariably segregated by sex. Male athletes tend to perform at a faster, higher, and stronger level due to a combination of various physical and

animals MDPI

Article

Locomotory Profiles in Thoroughbreds: Peak Stride Length and Frequency in Training and Association with Race Outcomes

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Simple Summary: Racehorses compete in short ('sprinters'); medium ('milers') or long distance ('stayers') races. Sprinters are thought to naturally have a shorter stride than stayers; but no study has objectively tested this theory. Here, using known race distance to categorize racehorses into one of the three aforementioned categories together with a stride tracking device that objectively measures locomotion; this study demonstrates that peak stride length in racehorses is a heritable trait that is different in sprinters versus stayers prior to them even racing at that distance. In training, sprinters took shorter strides of higher frequency and were faster to cover furlongs in race-speed training sessions from a standing start than stayers. These stride data were recorded during training sessions before the horses raced and thus categorised as 'sprinters' or 'stayers'. Stride length during training did not predict later racing success. This study provides the first objective insight into locomotory differences between sprinters and stayers. Such information when coupled with the trainer's experience/eye could help them choose the most suitable race for each individual horse; to benefit both its health and safety on the track.

Abstract: Racehorses competing in short (i.e., 'sprinters'), middle- or longer-distance (i.e., 'stayers') flat races are assumed to have natural variation in locomotion; sprinters having an innately shorter stride than stayers. No study has objectively tested this theory. Here, racehorses (n = 421) were categorised as sprinters, milers or stayers based on known race distance (n = 3269 races). Stride parameters (peak length and frequency) of those racehorses were collected from prior race-pace training sessions on turf (n = 2689; 'jumpout', n = 1013), using a locomotion monitoring device. Pedigree information for all 421 racehorses was extracted to three-generations. In training, sprinters had a shorter stride of higher frequency and covered consecutive furlongs faster than stayers ($p < 0.001$). Relatively short or longer stride did not predict race success, but stayers had greater race success than sprinters ($p < 0.001$). Peak stride length and frequency were moderately heritable (h^2 = 0.15 and 0.20, respectively). In conclusion, differences in stride were apparent between sprinters and stayers (e.g., shorter stride in sprinters) during routine training, even after accounting for their pedigree. Objective data on stride characteristics could supplement other less objectively obtained parameters to benefit trainers in the appropriate selection of races for each individual racehorse.

Keywords: horse; exercise; stride; performance; heritability

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Citation: Schrurs, C.; Blott, S.; Dubois, G.; Van Erck-Westergren, E.; Gardner, D.S. Locomotory Profiles in Thoroughbreds: Peak Stride Length and Frequency in Training and Association with Race Outcomes. *Animals* **2022**, *12*, 3269. https://doi.org/10.3390/ani12233269

Academic Editors: Hilary Clayton and Lindsay St. George

Received: 29 October 2022
Accepted: 21 November 2022
Published: 24 November 2022

1. Introduction

In flat racing, Thoroughbreds compete in various types of races usually categorised as short (<1500 m), middle (1600–2500 m) or long (>2500 m) distance. Racehorses are usually considered to be naturally predisposed to one type of race distance, due to various physiological and morphological characteristics such as size, musculature [1], and