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An investigation of training and racing workloads in Thoroughbred racehorses in Australia and their relationship to performance and bone fatigue

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An investigation of training and racing workloads in Thoroughbred racehorses in Australia and their relationship to performance and bone fatigue

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ABSTRACT

Bone and joint injuries in Thoroughbred racehorses typically originate in areas of intense loading and are attributable to fatigue damage accumulated under repetitive cyclical loading. This thesis will focus on an epidemiological understanding of the bone fatigue process as it relates to Thoroughbred training and racing.

Factors investigated include workload, stride parameters, speed and distance worked. Specifically, this included an investigation of racehorse management, training and rest compared to previously published risk factors and how they relate to performance, stride characteristics of galloping horses during racing and how varying strides and race factors influence the estimated accumulation of bone damage over race starts. It was hypothesised that (i) there would be a large variation between trainers in the training and rest practices; (ii) greater workloads in training would not be associated with superior race performance; (iii) speed would be correlated with stride parameters, increasing proportionally more with stride duration than the number of strides (and therefore stride length) at higher speeds; (iv) stride parameters would differ by horse-and race-level factors; and (v) a higher percentage of bone fatigue life would be used for longer distance races, firmer track surfaces and higher classed races. These hypotheses were investigated by conducting a semi-structured in-person interview of 66 registered Thoroughbred trainers in Victoria, Australia; by analysing GPS and accelerometer data including speed and stride data from 25,245 Thoroughbred race starts in Tasmania, Australia; and by generating a mathematical model of bone fatigue accumulation using information from the stride parameter data.

Australian Thoroughbred training programs include high volumes of galloping with more than half exceeding previously reported risk levels for fracture. Older age and longer intended race distances were associated with higher galloping workloads, and there was a large degree of

variation between trainers in workloads, rest practices and surfaces used in training. Trainers who utilised the lowest and highest galloping workloads (at speeds of >13.3 or 13.3-14.3 m/s) as horses prepared for racing had fewer wins and places. There was substantial inter-horse variation in stride parameters, with speed predicting half or less of this variation. Male sex, greater race distance, better finishing position, and firmer track surfaces were associated with fewer strides per 200 m and longer stride durations. Females, older age, longer race distances, firmer track surfaces, and greater weights carried for high-classed races were associated with greater percentage fatigue life accumulated over each race start.

There was a wide variety of strategies implemented by trainers in preparing and maintaining horses for racing and managing them between racing campaigns, yet this variation did not translate to how well horses performed. Variation was identified for stride parameters of horses galloping in races under different conditions, but further variation existed based on innate qualities of the individual horse, therefore future studies assessing risk for individual horses would benefit from the inclusion of stride characteristics. The future goal is to establish appropriate racehorse training and racing programs which allow for appropriate bone adaptation to withstand load whilst avoiding fatigue failure.

DECLARATION

This is to certify that:

i. *the thesis comprises only my original work towards the PhD except where indicated in the Preface,*

ii. *due acknowledgment has been made in the text to all other materials used and,*

iii. *the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices*

Dr Ashleigh Morrice-West

BSc, DVM

26th of June, 2020

PREFACE

This thesis is based on my original research conducted at the University of Melbourne during my PhD candidature. No third-party editorial assistance was used in the preparation of this thesis. All results chapters of this thesis (Chapters 2-6) are either published articles, submitted for peer-review or intended for submission and were conducted in collaboration with others as follows.

All training data was collected via in-person interviews that I conducted and is presented in Chapters 2, 3 and 6. Adelene Wong was responsible for extracting performance data from the Australian racing repositories which I then used for analysis in Chapter 6. Stride data used in Chapters 4 and 5 was provided by TasRacing and Australian official race results were provided by Racing Victoria Ltd.

Chapter 2 was published in the *Equine Veterinary Journal* in 2020. The article was accepted for publication on the 25th of July 2019:

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Author	**Proportion**	**Contribution**
Ashleigh Morrice-West	70%	Study conceptualisation and design; data collection and methodology; data analysis and interpretation; draft and review of manuscript
Peta Hitchens	10%	Study design; methodology; data interpretation; review of manuscript
Elizabeth Walmsley	5%	Study design; review of manuscript
Mark Stevenson	5%	Methodology; review of manuscript
Chris Whitton	10%	Study conceptualisation and design; data interpretation; review of manuscript

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Author	**Proportion**	**Contribution**
Ashleigh Morrice-West	75%	Study conceptualisation and design; data collection and methodology; data analysis and interpretation; draft and review of manuscript
Peta Hitchens	10%	Study design; methodology; data interpretation; review of manuscript
Elizabeth Walmsley	5%	Study design; review of manuscript
Chris Whitton	10%	Study conceptualisation and design; data interpretation; review of manuscript

Chapter 4 was accepted for publication by the *Equine Veterinary Journal* on the 15th of October 2020 and was subsequently available online in a pre-print version.

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Author	**Proportion**	**Contribution**
Ashleigh Morrice-West	65%	Study conceptualisation and design; methodology; data analysis and interpretation; draft and review of manuscript
Peta Hitchens	10%	Study design; methodology; data interpretation; review of manuscript
Elizabeth Walmsley	5%	Study design; review of manuscript
Mark Stevenson	5%	Methodology; review of manuscript
Adelene Wong	5%	Sourcing funding; review of manuscript
Chris Whitton	10%	Study conceptualisation and design; data interpretation; review of manuscript

Chapters 5 and 6 have not yet been submitted for publication. The author contributions for the intended publications are as follows:

Chapter 5:

Author	Proportion	Contribution
Ashleigh Morrice-West	65%	Study conceptualisation and design; methodology; data analysis and interpretation; draft and review of manuscript
Peta Hitchens	10%	Study design; methodology; data interpretation; review of manuscript
Elizabeth Walmsley	5%	Study design; review of manuscript
Chris Whitton	20%	Study conceptualisation and design; data interpretation; review of manuscript

Chapter 6:

Author	Proportion	Contribution
Ashleigh Morrice-West	65%	Study conceptualisation and design; data collection and methodology; data analysis and interpretation; draft and review of manuscript
Peta Hitchens	10%	Study design; methodology; data analysis and interpretation; review of manuscript
Elizabeth Walmsley	5%	Study design; review of manuscript
Adelene Wong	5%	Data collection; review of manuscript
Chris Whitton	15%	Study conceptualisation and design; data interpretation; review of manuscript

Conference abstract presentations

The findings of Chapter 2 were presented at the International Conference of Equine Physiology:

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The findings of Chapter 4 were also presented at the International Conference of Equine Physiology:

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I would also like to thank David Hawke for his technical advice and assistance on the StrideMaster system.

Dedication

I would like to dedicate this thesis as follows.

To my grandfather, who would introduce me to anyone who would listen as his granddaughter that was going to become a doctor. First with a veterinary degree and now a PhD, I know this would have made him proud.

To my parents, who provided me with never-ending encouragement and every possible opportunity in life and education; my achievements are yours as well.

And finally, to my husband Joel, who has supported me through some of life's biggest obstacles and then several years undertaking this PhD, having you by my side has been life's greatest blessing.

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LIST OF ABBREVIATIONS

%FL	Percentage of fatigue life
AIC	Akaike's information criterion
AUD	Australian dollar
BIC	Bayesian information criterion
BM	Benchmark race
CMI	Catastrophic musculoskeletal injury
DMD	Dorsal metacarpal disease
GLONASS	Global Navigation Satellite System
GPS	Global positioning system
GRF	Ground Reaction Force
HCP	Handicap race
ICC	Intraclass correlation coefficient
IRR	Incident Rate Ratio
MC(MT)III	Third metacarpus/metatarsus
MSI	Musculoskeletal injury
N	Number of loading cycles
Nc	Number of horses per trainer assigned to four levels of maintenance training intensities
N_f	Number of cycles to failure
N_p	Number of horses per trainer assigned to a designated type of program
POD	Palmar/plantar osteochondral disease
RVL	Racing Victoria Ltd.
S	Stress; magnitude of load per unit area
SCB	Subchondral bone
Spf	Seconds per furlong
σ	Joint load (MPa)

CHAPTER 1. GENERAL INTRODUCTION AND OBJECTIVES

1.1 AUSTRALIAN THOROUGHBRED RACING INDUSTRY

The Thoroughbred racing industry contributes substantially to the Australian economy, with a wagering turnover of 20,944 million AUD and 809 million AUD total returns to investors and share-holders in the 2018/2019 race season (prize money, incentive schemes etc) [1]. There were 2,643 race meetings in Australia in the 2018/2019 race season consisting of 35,196 horses participating in 19,369 races, of which 19,276 were flat races [1]. For the state of Victoria, the Thoroughbred Racing Industry provided employment for 109,472 individuals, with 2,068 million AUD in direct spending by industry participants for wagering and non-wagering activities including Thoroughbred production and preparation as well as non-race-day activities (2017/2018 racing season)[2].

1.2 INTRODUCTION TO THOROUGHBRED RACEHORSE INJURIES

Trackside injuries worldwide have put the racing industry under intense scrutiny. Wastage, primarily as a result of musculoskeletal breakdown, has been an important issue of debate [3-5]. Lameness has been reported to be the most common reason for failure to train and reduced racing performance, reported to affect 52% of the racehorse population [4,6]. A range of musculoskeletal injuries (MSI) occur during racing and training, although the literature tends to focus on those sustained during races or officially timed trials, where data is more readily available [7-22].

The majority of equine MSI are nonfatal but often require veterinary intervention and time out of work [23]. Incidence of non-catastrophic MSI have been reported as 1.12 to 7.3 injuries per 1,000 starts in North America, and 4.79 injures per 1,000 days at risk in Australia [16,23,24]. Non-catastrophic bone injuries under consideration are predominately stress fractures and

subchondral bone injuries. For example, palmar/plantar osteochondral disease (POD) is a specific manifestation of repetitive fatigue of subchondral bone and subsequent disruption to overlying cartilage, affecting the distal condyles of the third metacarpal and, or metatarsal bone(s) (MC(MT)III) estimated to affect up to 70% of Thoroughbred racehorses [25].

A smaller proportion of events are catastrophic musculoskeletal injuries (CMI), which will be defined here as MSI which results in the death or euthanasia of a racehorse within 24 hours of the injury occurring, the majority of which are fractures [26]. In pooled meta-analysis, CMI for Australia and New Zealand has a reported incidence of 0.43 per 1,000 starts for flat races, although the most recent data available for inclusion for Australia were from 2006 [27]. This incidence rate was not statistically different from the UK (0.80 per 1,000 starts; P=0.09) or Hong Kong (0.60 per 1,000 starts; P=0.61), but was significantly lower compared to North American studies (United States 1.62 per 1,000 starts; Canada 1.17 per 1,000 starts; p≤0.01) [27]. Although of low prevalence in Australia, fatal injuries are clearly a welfare concern. Frequently, fractures originate from the condylar region of the third metacarpal or metatarsal bones and/or proximal sesamoid bones or the carpus [23]. Humeral and pelvic catastrophic fractures are also frequently reported as training injuries [28]. The majority of catastrophic and non-catastrophic bone injuries in racing horses are a result of a fatigue pathogenesis (bone degradation due to cyclical loading), which will be discussed in detail in section 1.4, below.

1.3 PHYSIOLOGIC RESPONSES OF BONE TO LOADING

1.3.1 Adaptation

During each stride the bones of the limb are loaded, the magnitude of which is a function of the weight of the horse and rider pair, duration of the limb stance phase and speed travelled, as well

as the properties of the contacting surface [29-32]. Bone responds to changes in loading stimulus by strengthening to keep local stresses and strains within a set range [33-35]. This process of adaptation involves a net increase or decrease in bone volume or change in architecture, termed modelling [33-35]. Bone adaptation results in increased cortical thickness in long bones and compressive strength of trabecular bone, with greater capacity to incur cycles of loading prior to a fracture event [36-38]. Modelling occurs in Thoroughbred racehorses in training, and has been demonstrated in young horses, after canter is introduced (~8.9 m/s) during the first nine weeks of training [33,39,40]. Subchondral bone (SCB) density has been shown to be equivalent in horses undergoing 18 weeks and 18 months of controlled treadmill exercise and, both groups accumulated greater density bone than control horses, consistent with early adaptation followed by a plateau [41,42].

1.3.2 **Bone repair**

When the bone structure is damaged, injured bone is removed and later replaced in a process termed remodelling. Remodelling results in a temporarily weakened state due to bone resorption, and this may occur in localised regions [43,44]. Replacement of injured bone follows resorption. Importantly, intense exercise has been shown to inhibit remodelling responses, leaving bone potentially vulnerable to fatigue injuries with the continued accumulation of damage under loading cycles [45,46]. The rapid phase of bone resorption is thought to take approximately two weeks, with a slower phase of replacement bone formation over a period of two to four months based on limited canine and equine data [47-49]. The primary method of strengthening bone during intense training when remodelling processes are paused is with the addition of more bone to reduce local stressors, but for SCB spatial limitations make this process finite. Rates of bone turnover increase when horses are in rest phases of their training campaigns, since the decrease in exercise intensity alleviates load experienced by the bone and allows repair processes to resume [46].

1.4 PATHOLOGIC RESPONSES OF BONE TO LOADING- BONE FATIGUE

Bone injuries can be the result of a single load exceeding the bone's ultimate stress level, however the majority of injuries sustained by racehorses appear to be the result of repetitive loads [50,51]. Bone fatigue is the degradation of the components of bone, in overall integrity as well as at the molecular level (microdamage and microcracks) due to cyclic loading [50]. Repeated loading of bone leads to microdamage; the breakdown of the structural elements of bone, particularly mineral and collagen components, altering its material properties [38,50,52,53]. Microscopically, this process is observed as microcracks which may coalesce into larger cracks, and eventually complete failure or fractures [44,52,54-58]. Fatigue injuries in horses in race training occur at specific predilection sites, and appear spontaneous; greater than 75% of intra-race breakdowns were shown to occur without any external precipitating factor [15,59]. Microdamage and pre-existing pathology is often observed at the site of fracture [28,51,58-61]. The lateral condylar region of the third metacarpus is a prime example of this, with one study reporting contralateral limb metacarpophalangeal pathology in 73% of cases [59].

The fatigue life of a material refers to the number of cycles at a defined magnitude of load that can be exerted on that material before failure [46,50,62]. Various in- and ex-*vivo* models predominately in laboratory animals, but also more recently in horses, have shown that repetitive loading of bone can result in damage at much lower forces compared to those that cause damage in a single event [38,52,54,56]. The number of loading cycles to failure (N) decreases exponentially as the magnitude of load per unit area (stress, S) increases, and is described by the S-N curve (Figure 1.1) [50,56]. As the magnitude of stress bone is subjected to increases (i.e. higher speed exercise), there are fewer cycles required to induce injury. Low intensity exercise, which is expected to produce forces of low magnitude, should comparatively be well tolerated;

i.e. slower speed exercise creates less structural injury and is therefore associated with a longer fatigue life.

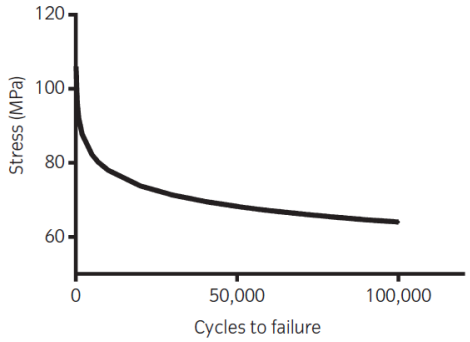

Figure 1.1. *S-N curve, showing the inverse exponential relationship of stress and failure, whereby as the load on bone increases, the number of cycles to failure decreases exponentially. Adapted from Martig et al 2014*

1.4.1 Equine *in vitro* studies

Few *in vitro* studies have been conducted on equine bone specimens to evaluate the fatigue process. Nunamaker *et al.* [63] provided evidence that whilst the incidence of dorsal metacarpal disease (DMD) is high in Thoroughbreds and uncommon in Standardbreds, there was no innate difference in (MCIII) bone's ability to withstand cyclic bending forces between the two racing breeds. The authors suggested this observation was due to higher speed exercise in Thoroughbreds in training compared to Standardbreds, inducing higher strains. The effects of loading on mechanical properties has been demonstrated to vary between cortical and SCB. Martin *et al.* [64] showed that there was no reduction in yield strength or elastic modulus of cortical bone after 100,000 cycles of load at similar strains to those measured in galloping horses. Martig *et al.* [56] more recently used compressive loading to show that SCB failed after only 4,000 cycles of compression *in vitro* at loads likely to be generated at galloping speeds. This finding of

failure at substantially fewer cycles compared to previous estimates is particularly important given that SCB is where the majority of injuries originate *in vivo* [50].

1.4.2 **Equine *in vivo* studies**

Initial work by Nunamaker *et al.* [65] estimated the number of gait cycles undertaken in training of six horses, calculating the point of failure (in this study defined as the onset of DMD) as up to 53,299 cycles. When considering fracture as the point of failure, Verheyen *et al.* [66] calculated distances for monthly workloads above which horses were at increased likelihood of failure. These distances equated to 7,700 bone loading cycles at a canter and 880 loading cycles at a gallop (using an estimation of stride lengths at 12m/s and 15m/s respectively) accumulated over a one-month period.

1.5 **THOROUGHBRED TRAINING WORKLOADS**

Estimates of *in vivo* workloads are difficult to make without having a clear understanding of the variation in training programs that racehorses undertake. Some "typical" training protocols have been described anecdotally, but it is unknown whether all trainers adopt a similar regimen or if this varies with geographic region, intended race distance or other factors [67-70]. Important aspects of a training program that may influence the overall load the skeleton is subject to include a number of factors, the fundamentals of which are speed at which exercise is undertaken, the distance at various speeds and the frequency of exercise sessions.

1.5.1 **Methods of quantifying workloads**

Speed can be measured via stopwatch recordings, treadmill programs and hoof mounted accelerometers (in research settings) [48,71,72]. More recently Global Positioning Systems (GPS)

have been employed, including devices designed for human athletes (of which there is a lack of published information on their validity or extent of use for equine locomotion) and equine-specialised systems [e.g. StrideMASTER ™ (Thoroughbred Ratings Pty Ltd, Romsey, Victoria, Australia), E-Trakka© (Equitronics Pty Ltd, Perth, Western Australia)] [73-75]. There are a limited number of studies utilising GPS data in various equine disciplines, and those that have been conducted typically have small sample sizes [76-79]. Few, however, have assessed the accuracy of such recordings. Trainer stop-watch times have in one study shown good agreement with GPS recorded mean speeds, but failed to identify the peak speeds recorded via GPS [80]. Others have also identified wide variation in the ability for riders to judge speed at which a horse is travelling, with the influence of individual rider on speed suggested to be influenced by experience, skill and style of riding [71]. Furthermore, rider perception of velocity may be impaired when multiple horses are exercising at once as well as being influenced by track type and condition [71,77]. Manual records workouts performed as increasing speeds of subjective gaits (i.e. gaits of subjectively estimated or intended number of seconds per track section; canter, 1/4-pace, 1/2-pace and gallop) were also inaccurate when compared with measured data [71]. There was significant overlap in the ranges of speeds actually exercised for the varying subjective gait categories intended [71]. The stage of a training preparation has also been shown to influence the accuracy of speed estimation, where speed was perceived to be lower than actual speed in the latter part of the training preparation [71]. These variations highlight the need for an objective system to measure horse velocity for the assessment of training workload.

In other studies, measurement of stride characteristics have been used to categorise training intensity. The number of (stride) cycles has been suggested to serve as an accurate reference for musculoskeletal adaptive responses [70,77]. The number of stride cycles incurred has typically being estimated using distance travelled according to an average speed and stride length. This may be reasonable since stride length and frequency are reported to be linearly correlated with

speed [72]. There are a number of devices available for the implementation of such recordings. Whilst hoof-mounted accelerometers evaluating over ground stride parameters have been used in research settings, this method is less practical for trainer implemented recording [72]. StrideMASTER ™ is an equine-specific product mounted behind the saddle on the saddle cloth. This system has been implemented in Tasmania, Australia as a method of quantifying race-day data, with specific recording of data relating to position in race as well as velocity, stride duration and the number of strides per 200 m sectional [75].

1.5.2 **Thoroughbred training programs**

A training program generally consists of a preliminary pre-training phase followed by a formal training regimen. Pre-training has been described as lasting for a minimum of four weeks (although there are country variations with periods greater than three months described in England) [81], in order to foster appropriate education, aerobic capacity and limb strength [70,81]. This phase targets endurance at under 20 seconds per furlong (spf) (moderate canter, approximately 10 m/s), with incremental increases every two to three weeks [67]. A typical regimen was described by Evans [67] as four to five weeks at a trot or canter for three to five km a day, then faster exercise of under 20 spf. Bayly [68] proposed a required base level for training consisting of slow work accumulating 400 km or more over a period of at least 70 days.

The formal training phase also varies geographically, but an early phase has been described that begins with 70-80% maximal speed (16 to 14 spf; 12.6-14.4 m/s), followed by the development of speed, acceleration and anaerobic fitness capacity, in the fast phase through near maximal velocity training, in preparation for racing [67]. This may consist of 600-1600 m at 16 to 14 spf, then gallops of 200 to 600 m at 95-100% maximal speed [81]. A New Zealand study of seven fillies under one trainer proposed that a “typical” program in Australasia entailed four weeks slow cantering, four weeks fast cantering, then adding in twice weekly fast gallops [82]. An Australian

routine has been described as alternating slow and fast mornings, consisting of approximately 5,500 m at four to seven m/s and a 1,000 m warm up with 1,000-2,000 m at 12-16 m/s, respectively [67]. However, this publication is from 1994 and whether programs had altered in recent years was unclear in the literature. These ranges of speeds and distance are clearly broad, particularly the distances travelled at fast speeds, making it difficult to accurately assess the implication this may have on the development of injury.

The limited literature on Thoroughbred training has focussed on the development of cardiovascular fitness with less of an emphasis on skeletal conditioning. Most reported training regimens involve increasing speeds of exercise to the finish line of the training track, but interval training has also been suggested for more high-intensity work which, whilst not necessarily affecting race speed, enabled horses to compete more frequently [68]. Interval training has been reported to result in greater cardiovascular capacity based on greater VO_2max (the speed at maximal oxygen consumption) compared to continuous incremental training, whilst requiring less galloping strides [83]. Another study compared different numbers of high-intensity sprint sessions over a six-week conditioning period and found no effect of those training regimens on the onset of blood lactate accumulation during standardised exercise testing on a treadmill [84]. A detailed interval training program was proposed where Thoroughbreds in preparation for racing over 1,000 to 1,400 m were worked every four days, with specific criteria for when a horse was fit enough to move up to the next target over distances of 600 to 800 m in one to four heats, based on heart rate, achieving set targets for speed etc. [68]. The use of interval-based training regimes has not yet been reported in Australia.

1.6 THE EFFECTS OF SPECIFIC TRAINING AND RACING FACTORS ON THE RISK OF BONE INJURY

There has been a wide spectrum of racing and training factors associated with the probability of an injury occurring. These include track surfaces, speed and distance raced and trained, rest periods, individual trainer and age at start of training and racing. Other factors including frequency of racing and training and use of alternatives to overground exercise in training also have the potential to influence injury risk. In addition to race-level factors, an individual horse's level of risk may be complicated by trainer influence, previous injuries and veterinary interventions or management practices, and rest periods [18,19,85-87]. Different studies have shown contradictory effects of trainer on musculoskeletal injury rates, and in keeping with many retrospective analyses, these studies are often limited by information bias (i.e. misclassification, affected by issues such as self-reporting and recall bias), making interpretation of data challenging [88]. A study looking at the effect of distance and speed on fracture risk found no significant effect of trainer [66], whilst others highlighted trainer as important, particularly for the risk of stress fractures during training [87,89]. Variations in training intensity between horses and between trainers have been reported, but data on large populations is unknown [90,91].

The majority of studies to date have used retrospective data to examine associations between training practices and injury [24,87,92-95]. Much of the conclusions on the influences of track, speed and distance have been drawn from race-related data [7-22]. A smaller subset of the research on training has collected data prospectively, however, most studies infer distances galloped in training based on officially timed trials rather than true training data [66,82,85-87,91,96-98]. Due to the broad scope of this topic the remainder of this discussion will focus on flat racing and will include the most consistent or influential variables only.

1.6.1 **Speed and distance**

Speed of racing and exercise sessions has been implicated as an important risk factor for musculoskeletal breakdown [22,66,86,89,99]. This has been demonstrated both through race-day investigations where greater distances of higher speed events are associated with higher rates of catastrophic breakdown, and on a smaller scale in training environments where increased speed of training gallops are associated with increased injury risk [15,21,66,89,100-102]. As the speed of activity increases the torque and force applied to the joint surfaces of the limbs increases [30]. Based on the strain to fatigue life relationship described earlier, it follows, that increased force would lead to increased microdamage if applied over multiple loads. In humans, a reduction in sprint speed resulted in a significant reduction in bone strain and reduced risk of stress fracture [103]. Thoroughbred injury rates were reported to decrease when track design was altered by the addition of a home stretch incline which reduced sprint speed [100].

Speed and distance are not mutually exclusive, therefore distances travelled with relation to velocity need to be considered rather than cumulative distance travelled in isolation. High-speed training's proportionate nature to injuries has been described as a function of distance [99]. Using officially timed trials and races, greater cumulative distance of high-speed exercise and average daily distance, greater racing intensity over a horse's career and longer race distances has been associated with greater risk of CMI [9,21,22,27,104]. Mathematical models have shown that a 20% reduction in the frequency of high-speed training sessions over six furlongs predicted a 9% reduction in annual incidence of metacarpal condylar fracture [85], and a daily distance of as little as 0.6 compared to 0.5 furlongs resulted in a 1.8 times higher risk for catastrophic fracture [20]. Conversely, lower distances of high-speed work has been reported to increase the risk of bone injuries [19,27]. These seemingly conflicting results may be explained by the inclusion of horses that had undertaken lower levels of high-speed work leading to poor skeletal adaptation, or, that

the presence of pathology may have limited horses' capacity to undertake such exercise, as speculated in other studies [18,27,104,105].

There is scant data relating to the influence of lower velocity work on cumulating fatigue and few analyses have assessed trot parameters [21,82]. Verheyen *et al.* [66] showed that higher accumulated canter distances increased the risk of fractures, with greater than 44 km in the preceding 30 days determined to be high risk (in combination with gallop distances of 6 km). Another study found that galloping at 15-16 m/s significantly reduced the prevalence of dorsal metacarpal disease whilst slower galloping at 11 m/s increased the risk, and there was no association with distances trotted [91].

1.6.2 **Stride parameters**

Stride parameters include stride length and its inverse stride count, and stride duration (seconds per stride) and its inverse, stride frequency (number of strides per second). There is a paucity of literature on these parameters, especially at high-speed, and much of the data is from treadmill studies which may not compare well with overground training and race activities [72,106,107].

In equine locomotion studies the most frequently reported parameters are stride length and either duration or frequency [108-111]. Stride length is reported to act independently of stride timing variables, i.e. horses can alter one without necessarily altering the other [112,113]. Linear relationships have been described between speed and stride length, as well as speed and stride frequency [72,107-109]. However, there is disagreement over which parameter horses use to increase velocity at high speeds; stride frequency may be limited by a minimum inspiration time and / or individual horses may have a maximal intrinsic stride length, beyond which the only mechanism that can increase speed is an increase in stride frequency [72,107-109,112]. Stride

length in lame horses may have an important effect on reducing velocity [109]. Whilst certain studies have suggested that training does not improve inherent speed parameters, it has been shown that training can have a positive effect on a horse's ability to increase stride frequency [77,106]. This has been further supported by a recent study using GPS and motion sensors to evaluate a population of racehorses where 2-year-olds had an initial reduction in duration of stride with training followed by a flattening off, and 3-year-olds did not change their stride duration over time except following a rest period [114].

Stride characteristics have been reported to vary according to age and sex for horses galloping under non-racing conditions and with training [106,107,114]. Lameness has also been reported to affect the intra-horse variability in length of stride [115]. Identifying changes in horses' strides over time through a training preparation and racing campaign may therefore be useful for the early identification of bone fatigue damage before the onset of an overt injury.

1.6.3 **Frequency and variation of work**

There is a lack of published literature on the frequency or variation of workloads of racehorses. The most common scenario for Australasian training programs appears to be five to six days of work per week, two of which include fast work days [70]. An Australian prospective cohort study demonstrated that as the proportion of days of high-speed work increased in the fast phase of training, the risk of injury increased [101]. However, it cannot be determined if this is a true effect of number of fast days, as the cumulative distance of galloping would be necessarily increased if the percentage of fast days was greater. The percentage of fast days varies according to the stage of preparation, horse, injury history, trainer etc. Work programs are progressive and therefore the stage in the preparation is relevant when considering propensity for fracture. For example, Vallance *et al.* [105] described the risk of catastrophic (scapular) fracture being higher in horses early in their training preparation and with greater time periods between workouts through

official records. It has been suggested that as the percentage days of work under 15 spf (13.4 m/s) increase in the fast phase preparation the risk of MSI increases [86]. However, many prospective studies of exercise regimens compare horses in active training to horses undertaking no exercise, therefore the effect of varying levels of exercise cannot be determined [34,40,82,116]. Horses spending greater periods of time in active training have also been reported to have higher rates of certain fracture events, which may be in part because exercise at high-speed accumulates greater amount of bone damage and simultaneously inhibits bone repair [46,117].

1.6.4 **Training interruptions and rest periods**

Resting horses during and between their racing and training campaigns allows for enhancement of the reparative processes of bone and thus should minimise the risk of future failure. However rest periods also result in de-adaptation of bone to high-speed galloping and increased risk of fracture is associated with a return to high speed work. The optimal frequency or duration of rest within or between racing preparations has not been determined.

Rest periods from training are associated with increased bone remodelling rates, and resting horses have been shown to have a greater density of resorption canals throughout the skeleton [46,118,119]. Horses in rest periods have also been shown to have lower microcrack density in subchondral bone compared to horses in active training, and mathematical modelling of fracture in humans points to remodelling as the most important intrinsic preventative process for stress fractures [119,120].

Horses which are briefly rested without sufficient time for bone deposition following resorption, particularly when they are immediately returned to a heavy workload, may be at increased risk of injury [47,118]. Likewise, prolonged periods of rest may be associated with increased risk of

injury due to de-adaptation, as has been demonstrated in a study of pelvic and humeral fracture risk [121]. Recent mathematical modelling of subchondral bone behaviour in racehorses showed that in an under-loaded state (as in the case of a rest period), there is a rapid rate of reduction in bone volume in the first three to six weeks [122]. The time required to reach homeostasis was longer for horses starting resting at higher bone volumes with less bone specific surface available for remodelling, suggesting that horses under intensive training and racing schedules may require longer rest periods for appropriate bone turnover [122]. Bone volume fraction after the introduction of loading rapidly increases in the first month, followed by a plateau period, with loading equivalent to galloping speeds requiring approximately 14 weeks to achieve a homeostatic state [122].

The details of rest periods including duration, timing and how prior or subsequent training influence these factors are unknown for Australian racehorses and require detailed investigation.

1.6.5 **Track surface**

Track surfaces (turf, dirt, sand and various synthetic tracks) are reported to influence the propensity for limb injury and the type of injuries which occur [100,123,124]. Sand and dirt surfaces have a reportedly higher risk compared to turf [8,18,31,123,125-127]. Others have not found a difference in risk of injury between dirt and turf surfaces [19,128,129]. However, when dirt surfaces were stratified by condition, muddy/sloppy tracks ("off-dirt") has been reported to be higher risk compared to turf which may explain the inconsistency [12,130]. There have also been conflicting reports on the impact of synthetic surfaces on rates of injury, which may be due to the variations between different types of synthetic material composition and differing manufacturers, and their respective ability to withstand variations in climatic conditions [131]. In pooled meta-analysis however there was no difference between turf and synthetic tracks for the risk of CMI [27]. Certain studies have reported a higher incidence of stress fractures after

changing from dirt to synthetic tracks [123], and one study found synthetic surfaces were associated with higher percentage of cases with bilateral or right limb lesions compared to dirt [124]. For catastrophic fracture at certain locations (namely distal limb/lower limb, third metacarpal lateral condyle, biaxial proximal sesamoid), synthetics have also been reported to be higher risk compared to turf [28,132-135].

A significant degree of the effect of track surface relates to the track firmness, as indicated by the properties of the material itself as well as the moisture levels [123]. Firmer track surfaces are associated with decreased racing times and increased fracture incidence rates [9,10,27,127,132,136-138]. Other track surface properties that may be important for injury risk include the degree of impact absorption of the surface, the stability achieved by the hoof and distal limb on impact, and the degree to which the hoof slides on the surface during the stance phase of the gait [32,125]. Regardless of which surface type is being used, however, maintenance protocols including frequent harrowing are vital, as hoof impact forces over previous hoof prints are higher than on freshly harrowed surfaces [31,125]. Recent research has focused on testing the effects of depth, surface type and frequency of harrowing in laboratory settings and through complex computational modelling systems to analyse the effects of hoof impact under the given parameters [139-142]. Maintenance protocols of track surfaces are no doubt important but there is still a relatively large degree of uncertainty regarding the extent of risk created by different surface types.

1.7 ASSOCIATIONS BETWEEN WORKLOAD AND PERFORMANCE

There are limited studies assessing the association between workload and performance in Thoroughbred racing. Horses with their first start as a 2-year old were reported to be associated with longer career lengths and higher success rates [143]. The authors of that study speculated

that this may provide evidence of the importance of early exercise on the development and adaptive maturation of the equine skeleton. Individual trainer has been shown to be associated with performance outcomes, but the relationship is complicated by a large degree of the variation in performance outcomes due to individual horse effects [144]. Having started in a race in the preceding month and greater distances of sub-maximal speed exercise have been reported to be associated with better performance in various racing disciplines [79,144,145]. Galloping distances in training and racing have been described by quadratic relationships with performance measures, where moderate distances were associated with a greater rate of wins and whether a horse earnt any prize money [144]. Interestingly the nature of this association mimics the overall trend of the effects of training distances on risk of fracture [66]. A 'healthy horse effect,' however, has been described whereby horses with less underlying injury undertake a higher workload [66]. It is therefore inherently difficult to differentiate the effect of a reduced workload on performance from lower workloads that are a result of an underlying condition.

In order to make recommendations to trainers on ways to minimise bone fatigue injuries, it is critical that the impact that such recommendations will have on success rates is concurrently examined.

1.8 SUMMARY

The principles of bone fatigue have been demonstrated through *in vitro* studies, but how measured workouts *in vivo* relate to bone's fatigue life has not been determined. There is still a lack of understanding of the workloads Thoroughbred racehorses undertake and how much variation in workload exists between trainers and types of horses (age, intended race distance etc.). More information relating to the quantity of fast work undertaken in the lead up to and after

achieving race fitness is required. The proportion of rest periods to active training periods and the factors directly influencing this also requires further investigation.

It is clear that aspects of daily training regimens have the potential to influence rates and types of injuries that occur among Thoroughbred racehorses, but the extent to which this is the case and specific details of the influencing factors warrants further investigation. The key to successful reduction of injuries will therefore be to determine which aspects of the training program increase risk of injury, and then find ways to manipulate workouts such that performance is maintained while fatigue related injuries are reduced.

1.9 RESEARCH AIMS AND OBJECTIVES

1.9.1 General aim

The primary aim of this thesis was to investigate the extent of variation in the training and racing practices of Australian Thoroughbred racehorses, and, whether these practices influence overall performance and the degree of accumulated bone damage.

1.9.2 Specific objectives

The specific aims, and questions to be answered, of the research were:

AIM 1: To determine the typical workloads, exercise methods, track surfaces used and rest practices for Australian Thoroughbred racehorses in training.

- How much variation exists within different horses and between trainers?
- How do training programs compare to other countries and previously reported risk data?
- Do training factors correlate with trainer's race performance results?

AIM 2: To determine the interaction between speed and stride characteristics during races, and their variation across a population of Thoroughbred racehorses.

- How well does speed predict stride characteristics in races?
- How do race and horse level factors influence stride characteristics?

AIM 3: By modelling bone fatigue accumulation in racing, improve our understanding of how MSI in Thoroughbreds develop, and identify which data are the most important for predicting injury onset.

1.10 THESIS OUTLINE

Despite the potential influence of training and racing factors on an individual horses' propensity for injury or racing career success, there is limited data detailing the workload Australian Thoroughbred racehorses undertake and how much variation in workload exists between trainers, or how much variation in strides exists between different horses whilst galloping and under different environmental conditions. This thesis aims to explore these relationships by comparing;

- Racehorse management, training and rest practices (including surfaces used for exercise) between trainers and compared to previously published risk factors;
- The variation between trainers in surface use in training and racing and how this relates to known and postulated risky conditions;
- The stride characteristics during racing and how this varies between horses;
- How varying strides and race factors influence the estimated proportion of fatigue life consumed over race starts, and;
- How training and resting practices compare to trainer performance results.

1.11 POSTSCRIPT

This chapter detailed the primary reasons why workload in training and galloping stride characteristics are considered; to improve our understanding and prediction of injury and performance, and to monitor training under an Australian racing environment. The following Chapters 2-5 present a series of studies undertaken to investigate these factors, firstly training practices for a cohort of Victorian trainers, and then through the use of race-day GPS data to assess strides and estimated rates of fatigue life used in racing in a cohort of racehorses in Tasmania. Chapter 6 will then explore the effect of management practices on outcomes of racing success.

1.12 REFERENCES

[1] Racing Australia Ltd Racing Season 2018/2019 Fact Book, Racing Australia Limited, Flemington, Victoria.

[2] IER PTY. LTD. (2018) Size and Scope of the Victorian Racing Industry.

[3] Rogers, C.W., Bolwell, C.F., Tanner, J.C. and van Weeren, P.R. (2012) Early exercise in the horse. *J Vet Behav* **7**, 375-379.

[4] Jeffcott, L.B., Rossdale, P. D., Freestone, J., Frank, C. J., Towers-Clark, P. F. (1982) An assessment of wastage in Thoroughbred racing from conception to 4 years of age. *Equine Vet J* **14**, 185-198.

[5] Stover, S. (2003) The epidemiology of Thoroughbred Racehorse Injuries. *Clinical Techniques in Equine Practice* **2**, 312-211.

[6] Dyson, P.K., Jackson, B. F., Pfeiffer, D. U., Price, J. S. (2008) Days lost from training by two- and three-year-old Thoroughbred horses: A survey of seven UK training yards. *Equine Vet J* **40**, 650-657.

[7] Peloso, J.G., Mundy, G.D. and Cohen, N.D. (1994) Prevalence of, and factors associated with, musculoskeletal racing injuries if Thoroughbreds. *J Am Vet Med Assoc* **204**, 620-626.

[8] Cruz, A.M., Poljak, Z., Filejski, C., Lowerison, M. L., Goldie, K., Martin, S. W., Hurtig, M. B. (2007) Epidemiologic characteristics of catastrophic musculoskeletal injuries in Thoroughbred racehorses. *Am J Vet Res* **68**, 1370-1375.

[9] Boden, L.A., Anderson, G.A., Charles, J.A., Morgan, K.L., Morton, J.M., Parkin, T.D.H., Clarke, A.F. and Slocombe, R.F. (2007) Risk factors for Thoroughbred racehorse fatality in flat starts in Victoria, Australia (1989-2004). *Equine Vet J* **39**, 430-437.

[10] Bailey, C.J., Reid, S. W. J., Hodgson, D. R., Bourke, J. M., Rose, R. J. (1998) Flat, hurdle and steeple racing risk factors for musculoskeletal injury. *Equine Vet J* **30**, 498-503.

[11] Henley, W.E., Rogers, K. and Harkins, L. (2006) A comparison of survival models for assessing risk of racehorse fatality. *Prev Vet Med* **74**, 3-20.

[12] Mohammed, H., Hill, T, Lowe, J (1991) Risk factors associated with injuries in Thoroughbred horses. *Equine Vet J* **23**, 445-448.

[13] Bailey, C.J., Reid, S. W. J., Hodgson, D. R., Suann, C. J., Rose, R. J. (1997) Risk factors associated with musculoskeletal injuries in Australian Thoroughbred racehorses. *Prev Vet Med* **32**, 47-55.

[14] Schweizer, C., Ramseyer, A., Gerber, V., Christen, G., Burger, D., Wohlfender, F. D. (2015) Retrospective evaluation of all recorded horse race starts in Switzerland during a four year period focusing on discipline-specific risk factors for clinical events. *Equine Vet J*.

[15] Parkin, T.D.H., Clegg, P.D., French, N.P., Proudman, C.J., Riggs, C.M., Singer, E.R., Webbon, P.M., Morgan, K.L., (2006) Analysis of horse race videos to identify intra-race risk factors for fatal distal limb fracture. *Prev Vet Med* **74**, 44-55.

[16] Hernandez, J., Hawkins, DL, Scollay, MC (2001) Race start characteristics and risk of musculoskeletal injury in Thoroughbred racehorses. *J Am Vet Med Assoc* **218**, 83-86.

[17] Hernandez, J.A., Scollay, M.C., Hawkins, D.L., Corda, J.A.., Krueger, T.M (2005) Evaluation of horseshoe characteristics and high-speed exercise histroy as possible risk factors for catastrophic musculoskeletal injury in Thoroughbred racehorses. *Am J Vet Res* **66**, 1314-1320.

[18] Parkin, T., Clegg , P., French , N., Proudman , C., Riggs, C., Singer, E., Webbon, P. and Morgan, K. (2004) Horse-level risk factors for fatal distal limb fracture in racing Thoroughbreds in the UK. *Equine Vet J* **36**, 513-519.

[19] Cohen, N.C., Berry, S.M., Pelso, J.G., Mundy, G.D. and Howard, I.C. (2000) Association of high-speed exercise with racing injury in Thoroughbreds. *J Am Vet Med Assoc* **216**, 1273-1278.

[20] Estberg, L., Stover, S.M., Gardner, I.A., Rake, C.M., Johnson, B. and Ardans, A. (1996) High-speed exercise history and catastrophic racing fracture in Thoroughbreds. *Am J Vet Res* **57**, 1549-1555.

[21] Estberg, L., Gardner, I.A., Stover, S.M., Johnson, B.J., Case, J.T. and Ardans, A. (1995) Cumulative racing-speed exercise distance cluster as a risk factor for fatal musculoskeletal injury in Thoroughbred racehorses in California. *Prev Vet Med* **24**, 253-263.

[22] Estberg, L., Gardner, I.A, Stover, S.M et al (1998) A case-crosover study of intensive racing and training schedules and risk of catastrophic musculoskeletal injury and lay-up in Californian Thoroughbred racehorses. *Prev Vet Med* **33**, 159-170.

[23] Hill, W. (2003) Survey of Injuries in Thoroughbreds at the New York Racing Association Tracks. *Clinical Techniques in Equine Practice* **2**, 323-328.

[24] Cogger, N., Evans, D.L., Hodgson, D.R., Reid, S.W. and Perkins, N. (2008) Incidence rate of musculoskeletal injuries and determinants of time to recovery in young Australian Thoroughbred racehorses. *Aust Vet J* **86**, 473-480.

[25] Pinchbeck, G.L., Clegg, P.D., Boyde, A., Barr, E.D. and Riggs, C.M. (2013) Horse-, training- and race-level risk factors for palmar/plantar osteochondral disease in the racing Thoroughbred. *Equine Vet J* **45**, 582-586.

[26] Boden, L.A., Anderson, G.A., Charles, J.A., Morgan, K.L., Morton, J.M., Parkin, T.D.H., Slocombe, F.R. and Clarke, A.F. (2006) Risk of fatality and causes of death of Thoroughbred horses associated with racing in Victoria, Australia; 1989-2004. *Equine Vet J* **2006**, 4.

[27] Hitchens, P., Morrice-West, A.V., Stevenson, M. and Whitton, R.C. (2018) Meta-analysis of risk factors for racehorse catastrophic musculoskeletal injury in flat racing. *Vet J* **245**.

[28] Parkin, T.D., Clegg, P.D., French, N.P., Proudman, C.J., Riggs, C.M., Singer, E.R., Webbon, P.M. and Morgan, K.L. (2006) Catastrophic fracture of the lateral condyle of the third metacarpus/metatarsus in UK racehorses - fracture descriptions and pre-existing pathology. *Vet J* **171**, 157-165.

[29] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2014) Evaluation of a subject-specific finite-element model of the equine metacarpophalangeal joint under physiological load. *J Biomech* **47**, 65-73.

[30] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2010) Relationship between muscle forces, joint loading and utilization of elastic strain energy in equine locomotion. *J Exp Biol* **213**, 3998-4009.

[31] Setterbo, J.J., Yamaguchi, A., Hubbard, M., Upadhyaya, S.K. and Stover, S.M. (2011) Effects of equine racetrack surface type, depth, boundary area, and harrowing on dynamic surface properties measured using a track-testing device in a laboratory setting. *Sports Eng.* **14**, 119-137.

[32] Setterbo, J.J., Garcia, T.C., Campbell, I.P., Reese, J.L., Morgan, J.M., Kim, S.Y., Hubbard, M., Stover, S.M., (2009) Hoof accelerations and ground reaction forces of Thoroughbred racehorses measured on dirt, synthetic, and turf track surfaces. *Am J Vet Res* **70**, 1220-1229.

[33] Firth, E.C., Rogers, C.W., Doube, M. and Jopson, N.B. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 6. Bone parameters in the third metacarpal and third metatarsal bones. *New Zeal Vet J* **53**, 101-112.

[34] Firth, E.C. and Rogers, C.W. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 7. Bone and articular cartilage response in the carpus. *N Z Vet J* **53**, 113-122.

[35] Riggs, C. and Boyde, A. (1999) Effect of exercise on bone density in distal regions of the equine third metacarpal bone in 2-year-old Thoroughbreds. *Equine Vet J* **31**, 555-560.

[36] Warden, S.J., Hurst, J.A., Sanders, M.S., Turner, C.H., Burr, D.B. and Li, J. (2005) Bone adptation to a mechanical loading program significantly increases skeletal fatigue resistance. *J Bone Miner Metab* **20**, 809-816.

[37] Fatihhi, S., Rabiatul, A., Harun, M., Kadir, M.R.A., Kamarul, T. and Syahrom, A. (2016) Effect of torsional loading on compressive fatigue behaviour of trabecular bone. *J Mech Behav Biomed Mater* **54**, 21-32.

[38] Carter, D.R., Hayes, W.C. (1977) Compact bone fatigue damage—I. Residual strength and stiffness. *J Biomech* **10**, 325-337.

[39] Whitton, R.C., Trope, G.D., Ghasem-Zadeh, A., Anderson, G.A., Parkin, T.D., Mackie, E.J. and Seeman, E. (2010) Third metacarpal condylar fatigue fractures in equine athletes occur within previously modelled subchondral bone. *Bone* **47**, 826-831.

[40] Boyde, A. and Firth, E.C. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 8. Quantitative back-scattered electron scanning electron microscopy and confocal fluorescence microscopy of the epiphysis of the third metacarpal bone. *New Zeal Vet J* **53**, 123-132.

[41] Firth, E., Delahunt, J., Wichtel, J., Birch, H. and Goodship, A. (1999) Galloping exercise induces regional changes in bone density within the third and radial carpal bones of Thoroughbred horses. *Equine Vet J* **31**, 111-115.

[42] Firth, E., Goodship, A., Delahunt, J. and Smith, T. (1999) Osteoinductive response in the dorsal aspect of the carpus of young thoroughbreds in training occurs within months. *Equine Vet J* **31**, 552-554.

[43] Bentolila, V., Boyce, T.M., Fyhrie, D.P., Drumb, R., Skerry, T.M. and Schaffler, M.B (1998) Intracortical Remodeling in Adult Rat Long Bones After Fatigue Loading. *Bone* **23**, 275-281.

[44] Herman, B.C., Cardoso, L., Majeska, R.J., Jepsen, K.J. and Schaffler, M.B. (2010) Activation of bone remodeling after fatigue: differential response to linear microcracks and diffuse damage. *Bone* **47**, 766-772.

[45] Whitton, R.C., Mirams, M., Mackie, E.J., Anderson, G.A. and Seeman, E., (2013) Exercise-induced inhibition of remodelling is focally offset with fatigue fracture in racehorses. *Osteoporosis Int* **24**, 2043-2048.

[46] Holmes, J.M., Mirams, M., Mackie, E.J. and Whitton, R.C. (2014) Thoroughbred horses in race training have lower levels of subchondral bone remodelling in highly loaded regions of the distal metacarpus compared to horses resting from training. *Vet J* **202**, 443-447.

[47] Riggs, C.M. (2002) Fractures - A Preventable Hazard of Racing Thoroughbreds? *Vet J* **163**, 19-29.

[48] McCarthy, R.N. and Jeffcott, L.B. (1992) Effects of treadmill exercise on cortical bone in the third metacarpus of young horses. *Res Vet Sci* **52**, 28-37.

[49] Burr, D., Schaffler, M., Yang, K., Wu, D., Lukoschek, M., Kandzari, D., Sivaneri, N., Blaha, J. and Radin, E. (1989) The effects of altered strain environments on bone tissue kinetics. *Bone* **10**, 215-221.

[50] Martig, S., Chen, W., Lee, P.V. and Whitton, R.C. (2014) Bone fatigue and its implications for injuries in racehorses. *Equine Vet J* **46**, 408-415.

[51] Muir, P., Peterson, A.L., Sample, S.J., Scollay, M.C., Markel, M.D. and Kalscheur, V.L. (2008) Exercise-induced metacarpophalangeal joint adaptation in the Thoroughbred racehorse. *J Anat* **213**, 706-717.

[52] Danova, N.A., Colopy, S.A., Radtke, C.L., Kalscheur, V.L., Markel, M.D., Vanderby, R., McCabe, R.P., Escarcega, A.J. and Muir, P. (2003) Degradation of bone structural properties by accumulation and coalescence of microcracks. *Bone* **33**, 197-205.

[53] Cui, W. (2002) A state-of-the-art review on fatigue life prediction methods for metal structures. *J Mar Sci Technol* **7**, 43-56.

[54] Muir, P., Sample, S.J., Barrett, J.G., McCarthy, J., Vanderby, R., Jr., Markel, M.D., Prokuski, L.J. and Kalscheur, V.L. (2007) Effect of fatigue loading and associated matrix microdamage on bone blood flow and interstitial fluid flow. *Bone* **40**, 948-956.

[55] Colopy, S.A., Benz-Dean, J., Barrett, J.G., Sample, S.J., Lu, Y., Danova, N.A., Kalscheur, V.L., Vanderby, R., Jr., Markel, M.D. and Muir, P. (2004) Response of the osteocyte syncytium adjacent to and distant from linear microcracks during adaptation to cyclic fatigue loading. *Bone* **35**, 881-891.

[56] Martig, S., Lee, P.V., Anderson, G.A. and Whitton, R.C. (2013) Compressive fatigue life of subchondral bone of the metacarpal condyle in thoroughbred racehorses. *Bone* **57**, 392-398.

[57] Radtke, C., Danova, NA, Scollay, MC Santschi, E.M., Markel, M.D., Gómez, T.D.C. and Muir, P. (2003) Macroscopic changes in the distal ends of the third metacarpal and metatarsal bones of Thoroughbred racehorses with condylar fractures. *Am J Vet Res* **64**, 1110-1116.

[58] Stepnik, M.W., Radtke, C.L., Scollay, M.C., Oshel, P.E., Albrecht, R.M., Santschi, E.M., Markel, M.D. and Muir, P. (2004) Scanning Electron Microscopic Examination of Third Metacarpal/Third Metatarsal Bone Failure Surfaces in Thoroughbred Racehorses with Condylar Fracture. *Vet Surg* **33**, 2-10.

[59] Muir, P., McCarthy, J., Radtke, C.L., Markel, M.D., Santschi, E.M., Scollay, M.C. and Kalscheur, V.L. (2006) Role of endochondral ossification of articular cartilage and functional adaptation of the subchondral plate in the development of fatigue microcracking of joints. *Bone* **38**, 342-249.

[60] Riggs, C., Whitehouse, GH, Boyde, A (1999) Pathology of the distal condyles of the third metacarpal and third metatarsal bones of the horse. *Equine Vet J* **31**, 140-148.

[61] Norrdin, R.W., Stover, S.M. (2006) Subchondral bone failure in overload arthrosis: A scanning electron microscopic study in horses. *J Musculoskelet Neuronal Interact* **6**, 251-257.

[62] Salkind, M. (1972) Fatigue of composites. In: *Composite Materials: Testing and Design (Second Conference)*, ASTM International. pp 333-364.

[63] Nunamaker, D., Butterweck, D. and Black, J. (1991) In vitro comparison of Thoroughbred and Standardbred racehorses with regard to local fatigue failure of the third metacarpal bone. *Am J Vet Res* **52**, 97-100.

[64] Martin, R., Gibson, V., Stover, S., Gibeling, J. and Griffin, L. (1997) Residual strength of equine bone is not reduced by intense fatigue loading: mplications for stress fracture. *J Biomech* **30**, 109-114.

[65] Nunamaker, D.M., Butterweck, D.M. and Provost, M.T. (1990) Fatigue Fractures in Thoroughbred Racehorses- Relationships with Age, Peak Bone Strain, and Training. *J Orthop Res* **8**, 604-611.

[66] Verheyen, K., Price, J., Lanyon, L. and Wood, J. (2006) Exercise distance and speed affect the risk of fracture in racehorses. *Bone* **39**, 1322-1330.

[67] Evans, D.L. (1994) Training Thoroughbred Racehorses. In: *The athletic horse: principles and practice of equine sports medicine* Ed: D.R. Hodgson, Saunders, Philidelphia, PA, USA.

[68] Bayly, W.M. (1985) Training Programs. *Vet Clin N Am-Equine* **1**, 597-610.

[69] Foreman, J.H., Bayly, W.M., Grant, B.D. and Gollnick, P.D. (1990) Standardized exercise test and daily heart rate responses of Thoroughbreds undergoing conventional race training and detraining. *Am J Vet Res* **51**.

[70] Rogers, C.W., Rivero, J.L.L., van Breda, E., Lindner, A. and Sloet van Oldruitenborgh-Oosterbaan, M.M. (2007) Describing workload and scientific information on conditioning horses. *Equine and Comparative Exercise Physiology* **4**, 1.

[71] Rogers, C.W. and Firth, E.C. (2004) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 2. Measurement error and effect of training stage on the relationship between objective and subjective criteria of training workload. *New Zeal Vet J* **52**, 272-279.

[72] Witte, T.H., Hirst, C.V. and Wilson, A.M. (2006) Effect of speed on stride parameters in racehorses at gallop in field conditions. *J Exp Biol* **209**, 4389-4397.

[73] Witte, T.H. and Wilson, A.M. (2004) Accuracy of non-differential GPS for the determination of speed over ground. *J Biomech* **37**, 1891-1898.

[74] Pollock, P.J., Reardon, R.J.M., Parkin, T.D.H., Johnston, M.S., Tate, J. and Love, S. (2009) Dynamic respiratory endoscopy in 67 Thoroughbred racehorses training under normal ridden exercise conditions. *Equine Vet J* **41**, 354-360.

[75] Tasmania Racing (2012) StrideMASTER Fact Sheet.

[76] Bazzano, M., Giudice, E., Rizzo, M., Congiu, F., Zumbo, A., Arfuso, F., Di Pietro, S., Bruschetta, D. and Piccione, G. (2016) Application of a combined global positioning and heart rate monitoring system in jumper horses during an official competition - A preliminary study. *Acta Vet Hung* **64**, 189-200.

[77] Fonseca, R.G., Kenny, D.A., Hill, E.W. and Katz, L.M. (2010) The association of various speed indices to training responses in Thoroughbred flat racehorses measured with a global positioning and heart rate monitoring system. *Equine Vet J Suppl **42***, 51-57.

[78] Vermeulen, A., Evans, DL (2006) Measurements of fitness in Thoroughbred racehorses using field studies of heart rate and velocity with a global positioning system. *Equine Vet J* **38**, 113-117.

[79] Berkman, C., Teixeira, L.G., Pereira, M.C., Sampaio, R.d.C.d.L., Bernardi, N.S., Lacerda Neto, J.C.d., Queiroz Neto, A.d. and Ferraz, G.d.C. (2015) Distance exercised during submaximal training on race winnings for Thoroughbred racehorses. *Ciência Rural* **45**, 1268-1273.

[80] Kingston, J., Soppet, GM, Rogers, CW, Firth, EC (2006) Use of a global positioning and heart rate monitoring system to assess training load in agroup of thoroughbred racehorses. *Equine Vet J 7* **38**, 106-109.

[81] Evans, D.L. (1994) Training regimes: Overview. In: *The athletic horse: principles and practice of equine sports medicine* Ed: D.R. Hodgson, Saunders, Philidelphia, PA, USA.

[82] Firth, E.C., Rogers, C.W., Perkins, N.R., Anderson, B.H. and Grace, N.D. (2004) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 1. Study design, and clinical, nutritional, radiological and histological observations. *New Zeal Vet J* **52**, 261-271.

[83] Bronsart, L.L., Sides, R.H. and Bayly, W.M. (2009) A comparative study of interval and continuous incremental training in Thoroughbreds. *Comp Exerc Physiol* **6**, 49-57.

[84] Lindner, A., Signorini, R., Brero, L., Arn, E., Mazzini, R. and Enriquez, A. (2012) Effect of conditioning horses once, twice, or thrice a week with high-intensity intermittent exercise on V4. *J Equine Vet Sci* **32**, 153-157.

[85] Hill, A.E., Carpenter, T.E., Gardner, I.A. and Stover, S.M. (2003) Evaluation of a stochastic Markov-chain model for the development of forelimb injuries inThoroughbred racehorses. *Am J Vet Res* **64**.

[86] Cogger, N., Perkins, N., Hodgson, D.R., Reid, S.W. and Evans, D.L. (2006) Risk factors for musculoskeletal injuries in 2-year-old Thoroughbred racehorses. *Prev Vet Med* **74**, 36-43.

[87] Verheyen, K.L., Wood, JL (2004) Descriptive epidemiology of fractures occuring in British Thoroughbred Racehorses in training. *Equine Vet J* **36**, 167-173.

[88] Althubaiti, A. (2016) Information bias in health research: definition, pitfalls, and adjustment methods. *J Multidiscip Healthc* **9**, 211.

[89] Verheyen, K.L., Newton, J.R., Price, J.S. and Wood, J.L. (2006) A case-control study of factors associated with pelvic and tibial stress fractures in Thoroughbred racehorses in training in the UK. *Prev Vet Med* **74**, 21-35.

[90] Lam, K.K., Parkin, T.D., Riggs, C.M. and Morgan, K.L. (2007) Evaluation of detailed training data to identify risk factors for retirement because of tendon injuries in Thoroughbred racehorses. *Am J Vet Res* **68**, 1188-1157.

[91] Boston, R.C. and Nunamaker, D.M. (2000) Gait and speed as exercise components of risk factors associated with onset of fatigue injury of the third metacarpal bone in 2-year-old Thoroughbred racehorses. *Am J Vet Res* **61**, 602-608.

[92] Ramzan, P., Palmer, L (2011) Musculoskeletal injuries in Thoroughbred racehorses: A study of three large training yards in Newmarket, UK (2005-2007). *Vet J* **187**, 325-329.

[93] Dyson, P.K., Jackson, B.F., Pfeiffer, D.U. and Price, J.S. (2008) Days lost from training by two- and three-year-old Thoroughbred horses: A survey of seven UK training yards. *Equine Vet J* **40**, 650-657.

[94] Ely, E.R., Avella, C.S., Price, J.S., Smith, R.K.W., Wood, J.L.N. and Verheyen, K.L.P. (2009) Descriptive epidemiology of fracture, tendon and suspensory ligament injuries in National Hunt racehorses in training. *Equine Vet J* **41**, 372-378.

[95] Perkins, N.R., Reid, S.W. and Morris, R.S. (2005) Risk factors for musculoskeletal injuries of the lower limbs in Thoroughbred racehorses in New Zealand. *N Z Vet J* **53**, 171-183.

[96] Bolwell, C.F., Russell, L.J. and Rogers, C.W. (2010) A cross-sectional survey of training practices of 2-year-old racehorses in the North Island of New Zealand. *Comp Exerc Physiol* **7**, 37-42.

[97] Perkins, N.R., Reid, S.J., Morris, R.S. (2004) Profiling the New Zealand Racing Industry. 1. Training, racing and general health patterns. *N Z Vet J* **53**, 59-68.

[98] Bolwell, C.F., Rogers, C.W., French, N.P. and Firth, E.C. (2013) The effect of interruptions during training on the time to the first trial and race start in Thoroughbred racehorses. *Prev Vet Med* **108**, 188-198.

[99] Parkin, T. (2008) Epidemiology of Racetrack Injuries in Racehorses. *Vet Clin Equine* **24**, 1-19.

[100] Oikawa, M., Ueda, Y., Inada, S. (1994) Effect of restructuring of a racetrack on the occurance of racinginjuries in Thoroughbred Horses. *J Equine Vet Sci* **14**, 262-268.

[101] Cogger, N., Perkins, N., Hodgson, D.R., Reid, S.W.J. and Evans, D.L. (2006) Risk factors for musculoskeletal injuries in 2-year-old Thoroughbred racehorses. *Prev Vet Med* **74**, 36-43.

[102] Verheyen, K., Henley, W., Price, J. and Wood, J. (2005) Training-related factors associated with dorsometacarpal disease in young Thoroughbred racehorses in the UK. *Equine Vet J* **37**, 442-448.

[103] Edwards, W.B., Taylor, D., Rudolphi, T.J., Gillette, J.C. and Derrick, T.R. (2010) Effects of running speed on a probabilistic stress fracture model. *Clin Biomech (Bristol, Avon)* **25**, 372-377.

[104] Hitchens, P.L., Hill, A.E. and Stover, S.M. (2018) Relationship between historical lameness, medication usage, surgery, and exercise with catastrophic musculoskeletal injury in racehorses. *Front Vet Sci* **5**, 217.

[105] Vallance, S.A., Entwistle, R.C., Hitchens, P.L., Gardner, I.A. and Stover, S.M. (2013) Case-control study of high-speed exercise history of Thoroughbred and Quarter Horse racehorses that died related to a complete scapular fracture. *Equine Vet J* **45**, 284-292.

[106] Ferrari, M., Pfau, T., Wilson, A.M. and Weller, R. (2009) The effect of training on stride parameters in a cohort of National Hunt racing Thoroughbreds: A preliminary study. *Equine Vet J* **41**, 493-497.

[107] Seder, J.A. and Vickery, C.E. (2003) Temporal and Kinematic Gait Variables of Thoroughbred Racehorses At or Near Racing Speeds. *J Equine Vet Sci* **23**, S82-S112.

[108] Heglund, N.C., Taylor, C.R. and McMahon, T.A. (1974) Scaling stride frequency and gait to animal size: Mice to horses. *Science* **186**, 1112-1113.

[109] Ratzlaff, M., Shindell, R. and White, K. (1985) The interrelationships of stride lengths and stride times to velocites of galloping horses. *J Equine Vet Sci* **5**, 279-283.

[110] Deuel, N. and Lawrence, L. (1986) Gallop velocity and limb contact variables of quarter horses. *J Equine Vet Sci* **6**, 143-147.

[111] Rooney, J. (1984) Preliminary observations on stride length and frequencey in relation to velocity of horses. *J Equine Vet Sci* **4**, 33-34.

[112] Deuel, N. and Lawrence, L. (1986) Gallop velocity and limb contact variables of quater horses. *J Equine Vet Sci* **6**, 143-147.

[113] Rooney, J.R., Thompson, K. N, Shapiro, R. (1991) A contribution to the study of velocity, stride length, and frequency in the horse. *Equine Veterinary Science* **11**, 1991.

[114] Parkes, R.S., Weller, R., Pfau, T. and Witte, T.H. (2019) The effect of training on stride duration in a cohort of two-year-old and three-year-old Thoroughbred racehorses. *Animals* **9**, 466.

[115] Peham, C., Licka, T., Girtler, D. and Scheidl, M. (2001) The influence of lameness on equine stride length consistency. *Vet J* **162**, 153-157.

[116] Firth, E.C. and Rogers, C.W. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. Conclusions. *N Z Vet J* **53**, 377-383.

[117] Anthenhill, L., Stover, SM, Gardner, IA et al (2007) Risk factors for proximal sesamoid bone fractures associated with exercise history and horseshoe characteristics in Thoroughbred racehorses. *Am J Vet Res* **68**, 760-771.

[118] Sun, T. (2016) *Fracture incidence rates and the association of rest with bone remodelling in Thoroughbred racehorses at the Hong Kong Jockey Club*, The University of Queensland.

[119] Whitton, R., Ayodele, B., Hitchens, P. and Mackie, E. (2018) Subchondral bone microdamage accumulation in distal metacarpus of Thoroughbred racehorses. *Equine Vet J* **50**, 766-773.

[120] Taylor, D., Casolari, E. and Bignardi, C. (2004) Predicting stress fractures using a probabilistic model of damage, repair and adaptation. *J Orthop Res* **22**, 487-494.

[121] Carrier, T.K., Estberg, L., Stover, S.M., Gardner, I.A., Johnson, B.J., Read, D.H. and Ardans, A.A. (1998) Association between long periods without high-speed workouts and risk of complete humeral or pelvic fracture in thoroughbred racehorses: 54 cases (1991-1994). *J Am Vet Med Assoc* **212**, 1582-1587.

[122] Hitchens, P., Pivonka, P., Malekipour, F. and Whitton, R.C. (2018) Mathematical modelling of bone adaptation of the metacarpal subchondral bone in racehorses. *Biomech Model Mechan*.

[123] MacKinnon, M.C., Bonder, D., Boston, R.C. and Ross, M.W. (2015) Analysis of stress fractures associated with lameness in Thoroughbred flat racehorses training on different track surfaces undergoing nuclear scintigraphic examination. *Equine Vet J* **47**, 296-301.

[124] Dimock, A.N., Hoffman, K.D., Puchalski, S.M. and Stover, S.M. (2013) Humeral stress remodelling locations differ in Thoroughbred racehorses training and racing on dirt compared to synthetic racetrack surfaces. *Equine Vet J* **45**, 176-181.

[125] Setterbo, J.J., Fyhrie, P.B., Hubbard, M., Upadhyaya, S.K. and Stover, S.M. (2013) Dynamic properties of a dirt and a synthetic equine racetrack surface measured by a track-testing device. *Equine Vet J* **45**, 25-30.

[126] Georgopoulos, S.P. and Parkin, T.D.H. (2017) Risk factors for equine fractures in Thoroughbred flat racing in North America. *Prev Vet Med*, 99.

[127] Oikawa, M. and Kusunose, R. (2005) Fractures sustained by racehorses in Japan during flat racing with special reference to track condition and racing time. *Vet J* **170**, 369-374.

[128] Cohen, N.D., Mundy, G.D., Peloso, J.G., Carey, V.J. and Amend, N.K. (1999) Results of physical inspection before races and race-related characteristics and their association with musckuloskeletal injuries in Thoroughbreds during races. *J Am Vet Med Assoc* **215**, 654-661.

[129] Estberg, L., Stover, S.M., Gardner, I., Johnson, B.J., Jack, R.A., Case, J., Ardans, A., Read, D.H., Anderson, M.L. and Barr, B.C. (1998) Relationship between race start characteristics and risk of catastrophic injury in thoroughbreds: 78 cases (1992). *J Am Vet Med Assoc* **212**, 544-549.

[130] Georgopoulos, S. and Parkin, T. (2016) Risk factors associated with fatal injuries in Thoroughbred racehorses competing in flat racing in the United States and Canada. *J Am Vet Med Assoc* **249**, 931-939.

[131] Bridge, J.W., Peterson, M.L. and McIlwraith, C.W. (2015) The Effect of Temperature on the Tangent Modulus of Granular Composite Sport Surfaces. *Experimental Techniques* **39**, 30-37.

[132] Williams, R.B., Harkins, L.S., Hammond, C.J. and Wood, J.L.N. (2001) Racehorse injuries, clinical problems and fatalities recorded on British racecourses from flat racing and National Hunt racing during 1996, 1997 and 1998. *Equine Vet J* **33**, 478-486.

[133] Kristoffersen, M., Parkin, T. and Singer, E. (2010) Catastrophic biaxial proximal sesamoid bone fractures in UK Thoroughbred races (1999–2004): Horse characteristics and racing history. *Equine Vet J* **42**, 420-424.

[134] Reardon, R.J., Boden, L., Stirk, A.J. and Parkin, T.D. (2014) Accuracy of distal limb fracture diagnosis at British racecourses 1999-2005. *Vet Rec* **174**, 477.

[135] Parkin, T., French, N., Riggs, C., Morgan, K., Clegg, P., Proudman, C., Singer, E. and Webbon, P. (2004) Risk of fatal distal limb fractures among thoroughbreds involved in the five tpes of racing in the United Kingdom. *Vet Rec* **154**, 493-497.

[136] Maeda, Y., Tomioka, M., Hanada, M. and Oikawa, M.-A. (2012) Influence of Track Surface Condition on Racing Times of Thoroughbred Racehorses in Flat Races. *J Equine Vet Sci* **32**, 689-695.

[137] Bolwell, C., Rogers, C., Gee, E. and McIlwraith, W. (2017) Epidemiology of musculoskeletal injury during racing on New Zealand racetracks 2005–2011. *Animals* **7**, 62.

[138] Rosanowski, S., Chang, Y., Stirk, A. and Verheyen, K. (2017) Descriptive epidemiology of veterinary events in flat racing Thoroughbreds in Great Britain (2000 to 2013). *Equine Vet J* **49**, 275-281.

[139] Symons, J.E., Hawkins, D.A., Fyhrie, D.P., Upadhyaya, S.K. and Stover, S.M. (2016) Hitting the ground running: Evaluating an integrated racehorse limb and race surface computational model. *J Biomech* **49**, 1711-1717.

[140] Symons, J., Hawkins, D., Fyhrie, D., Upadhyaya, S. and Stover, S. (2016) Modelling the Interaction Between Racehorse Limb and Race Surface. *Procedia Engineering* **147**, 175-180.

[141] Symons, J.E., Fyhrie, D.P., Hawkins, D.A., Upadhyaya, S.K. and Stover, S.M (2015) Modeling equine race surface vertical mechanical behaviors in a musuloskeletal modeling environment. *J Biomech* **48**, 566-572.

[142] Swanstrom, M.D., Zarucco, L., Hubbard, M., Stover, S.M. and Hawkins, D.A. (2005) Musculoskeletal modeling and dynamic simulation of the Thoroughbred equine forelimb during stance phase pf the gallop. *J Biomech Eng* **127**, 318-328.

[143] Tanner, J.C., Rogers, C.W. and Firth, E.C. (2013) The association of 2-year-old training milestones with career length and racing success in a sample of Thoroughbred horses in New Zealand. *Equine Vet J* **45**, 20-24.

[144] Verheyen, K.L., Price, J.S. and Wood, J.L. (2009) Exercise during training is associated with racing performance in Thoroughbreds. *Vet J* **181**, 43-47.

[145] Ely, E.R., Price, J.S., Smith, R.K., Wood, J.L. and Verheyen, K.L. (2010) The effect of exercise regimens on racing performance in National Hunt racehorses. *Equine Vet J Suppl*, 624-629.

CHAPTER 2. TRAINING PRACTICES, SPEED AND DISTANCES UNDERTAKEN BY THOROUGHBRED RACEHORSES IN VICTORIA, AUSTRALIA

2.1 PREFACE TO CHAPTER 2

Through Chapter 1 I have established that there is a lack of published literature detailing how Australian racehorses are managed, and that the relevance of international practices to the Australian Thoroughbred Racing Industry has not been determined. Chapter 2 therefore set out to detail the variation in training regimens implemented by a cohort of Thoroughbred trainers in Victoria, Australia. I collected the data presented in this chapter by surveying in person 66 Thoroughbred trainers across the state of Victoria.

A version of this chapter has been previously published in the *Equine Veterinary Journal* (2020; 52(2), 273-280).

Supplementary material is presented in Appendix A.

2.2 ABSTRACT

Background: Musculoskeletal injuries (MSI) in racehorses are commonly due to bone fatigue, a function of the number of cycles (strides) and the magnitude of load applied to the limb. These parameters can be estimated using speed and distance, with greater than 6,000 m/month at a gallop (>14 m/s), in combination with canter distances greater than 44,000 m/month, reported to increase fracture risk. Despite their importance there are limited data on the distances and speeds horses are exposed to during training.

Objectives: Estimate training volume at different speeds undertaken by Australian Thoroughbred racehorses.

Study Design: Cross-sectional study of registered trainers in Victoria, Australia (*n*=66).

Methods: Survey questions were designed to assess the full training workload from initial pre-training to training performed to achieve and maintain race fitness, as well as information on rest periods. Descriptive analyses were stratified by trainer- and horse-level factors, with assessment of variance within and between groups. Cluster analyses were used to identify similar workload intensity groups.

Results: Horse-level factors (age, targeted race distance) were associated with workload (younger<older, sprinters<stayers). Trainer categorisation did not influence workload, but there was significant variation in volume of total gallop exercise between trainers [median gallop distance 8,000 m/month (IQR 6,400-12,000)]. Cluster analyses identified four workload programs (medians): low-intensity (4,800 m/month), medium-volume (8,000 m/month), medium-volume with a higher proportion of high-speed workouts (12,800 m/month) and high-volume programs (19,200 m/month), with 23%, 50%, 17% and 9% of trainers predominately training racehorses under each of the respective programs. Horses three-years and older were rested twice yearly for 6.3 (95%CI 5.7, 6.8) weeks, with more experienced trainers resting horses for shorter periods (P=0.03).

Main limitations: Possible selection bias, subjective reporting of workloads by trainers.

Conclusions: Australian Thoroughbred training programs include high volumes of galloping with more than half exceeding previously reported risk levels for MSI.

2.3 INTRODUCTION

Musculoskeletal injuries (MSI) in Thoroughbred racehorses are a common cause of lost training days, early retirement, and death [1]. The majority are attributable to bone fatigue; the degradation of bone mechanical properties due to repetitive loading [2]. Fatigue is a function of the magnitude of applied load and number of load cycles [3]. An important determinant of the magnitude of load applied to equine limbs is the speed of the gait and the number of cycles is a function of distance travelled [4]. Verheyen *et al.* [5] showed an interaction between canter and galloping distances and found 7,700 bone loading cycles at a canter (up to 14 m/s) in conjunction with 880 loading cycles of galloping (over 14 m/s) per month increased the risk of fracture. However, because bone can adapt to its loading environment, both the total volume of high-speed training and the rate at which the training load is accumulated are important. In human sports medicine, the recent focus for injury prevention has been the balance between acute and chronic workload where a high acute-to-chronic workload ratio, indicative of a rapid increase in workload, is associated with injury [6].

To understand the loading environment of the equine skeleton, quantification of the speeds and distances undertaken by horses in training is required. If variation in training volumes exist, exploration of associated success and injury rates is warranted. Rest periods without training similarly have the potential to influence bone's ability to remodel and repair following intensive training schedules [7]. Identifying current practices is necessary to allow future investigations to determine the most appropriate regimen(s) for reducing injury.

With this background, our objectives were to determine: (1) the volume and variation of training workloads at different speeds; (2) the duration, frequency and variation of rest periods for healthy Thoroughbred racehorses; and (3) to assess for differences across levels of trainer

licencing. We hypothesised that there is large variation between trainers in the training volumes and rest periods used for horses under their care.

2.4 MATERIALS AND METHODS

2.4.1 Study participants

This was a cross-sectional study of registered Thoroughbred trainers in Victoria, Australia. The source population comprised all Thoroughbred trainers registered with *Racing Victoria Ltd* (RVL) in 2016-2017 (*n*=889).[a] Victorian trainers are categorised by the type of training licence held: Class A (*n*=86), General (*n*=418) or Restricted (*n*=385) corresponding to most to least experienced (Supplementary Material S1).

Separate *a priori* sample size calculations were performed based on the binary and continuous data collected for two sister studies investigating racehorse management practices. Binary (yes/no) outcome calculations required a higher number of trainers (n=65; based on activity prevalence of 50% with a power of 0.80, a Type I error probability of 0.05 and an absolute error of 20%), the results of which are presented elsewhere [8]. For the present study, calculations were conducted to determine the number of trainers to sample to reject the null hypothesis that monthly gallop distances across the three trainer groups were equal with a probability (power) of 0.80 and a Type I error probability of 0.05. Our *a priori* estimate of the distance galloped per month was derived from the 'typical Australasian' monthly gallop distance described by Firth et al. (2004) of 4,800 m. We then consulted industry experts (*n*=2) to determine the minimum and maximum plausible monthly gallop distances, given the paucity of published literature in this area. Estimates of the minimum and maximum monthly gallop distances were 1,600 metres and 6,400 metres, respectively. Assuming the distribution of monthly gallop distance followed a normal distribution our estimate of the standard deviation of monthly gallop distance was (6,400

- 1,600) ÷ 6 = 800 metres. We assumed that the monthly gallop distance varied across trainer class with mean monthly gallop distances for Class A, General and Restricted trainers to be 5280 m, 4800 m and 4300 m, respectively. Based on these assumptions, a total of 45 trainers (15 for each trainer group) were required to meet the objectives of the present study.

Interviews were conducted between November 2016 and August 2017. Training tracks were classified as metropolitan, provincial or country according to their distance from urban areas.[b] An article explaining the project to Victorian trainers was published in "Inside Racing" an official RVL Thoroughbred racing industry publication and in addition, trainers listed in the official registry[a] were contacted via telephone to set up an in-person interview. We made a cross-tabulation of trainers by licence level and training track. The first round of participant selection was through veterinarian and industry personnel recommendations based on likely willingness to participate, with representation of a cross-section of training methodologies and reasonably sized operations. We then consulted our cross-tabulation and weighted the remainder of the trainers to be sampled by the underrepresented trainer licence level-training track combinations. A random number generator was used to pick the remaining trainers to be contacted from the official trainer registry. Multiple trainers at all major training centres in Victoria were selected (i.e. all metropolitan and provincial training tracks) as well as trainers from regional areas. All trainers who agreed to participate were interviewed. Where a face-to-face interview was not possible, the survey was conducted via telephone (n=2). Interviews were arranged within one month of the date of agreeing to participate. All interviews were conducted by the first author (AMW).

2.4.2 **Survey**

Trainer responses were recorded in a custom designed form (Supplementary Material S2).[c] Trainers were asked to provide details about stable management, pre-training arrangements,

training regimens and typical rest periods. Trainers were specifically asked about intended workout and rest practices for healthy horses in the absence of injury or other training limiting factors. Pre-training was classified as the period of initial training for young horses to walk, trot and canter under saddle with control and reasonable fitness, and for initial fitness for older horses following a rest period.

Speed categories: Slow-speed workouts typically consisted of trot and cantering at <10 m/s, but also include trail rides, lunging, walkers, treadmills and/or swimming. Speed categories for fast workouts were based on trainers' descriptions (Supplementary Table S3) in seconds per furlong (s/f). A slow gallop ('even time') or 15 s/f, equates to 13.33 m/s. Speeds of fast gallop increase from that point, with trainers generally describing speeds of 14½, 14, 13½, 13, 12½, 12, 11½, or 11 s/f (13.3-18.2 m/s).

2.4.3 **Data analyses**

Data analyses were conducted using Stata 15.0.[d] Keyword searches were manually performed for questions on training program design and rest period rationale that were answered in free-text format (Supplementary Material S1). Count data (the number of trainers undertaking a particular practice) are presented as the number of trainers out of the total (n=66 unless otherwise specified). Continuous variables were assessed for normality using frequency histograms and the Shapiro-Wilk test. Data were reported as mean, standard deviation (SD) and 95% confidence-intervals except when they were non-normally distributed (median, interquartile ranges (IQR) and minimum-maximum). Descriptive statistics for each outcome variable were stratified by horse-level (age, targeted race distance) and trainer-level characteristics (trainer licence category, size of training yard, region).

In most situations trainers preferred to provide their response to a given question (e.g. 'For what period of time do you rest your horses in work?') as a range rather than as a single numeric value. Where trainers provided their response as a range, we calculated an expected mean and expected standard deviation for the variable, assuming the variable was consistent with a normal distribution. For each horse within each stable we took a random draw from this specified distribution, providing a credible estimate of the variable for each individual horse. A trainer mean was then calculated using the vector of individual horse random draws. We reasoned that this approach was necessary (in preference to simply taking the mid-point of the range of reported values) because it allowed for inherent variability in the stable-level mean where the number of horses per stable was small. Training-yard makeup of horse-ages was obtained using RVL's horse and trainer profiles on 7/8/2017.[a] Reported pre-trial workloads were divided into 2-year-old and mature horse programs (3-years and above). Race-fit programs were categorised according to age, targeted race distance and horses considered superior performers by the trainer. Seven broad types of galloping programs for race-fit horses are commonly used in the Australian racing industry; 2-year-old (Type 1); 3- to 5-year-old (Type 2); horses 6-years and older (Type 3); sprint race <1,300 m (Type 4); middle-distance 1,301-2,100 m (Type 5); staying race >2,100 m (Type 6), and elite horse (Type 7). With a study population of 66 trainers and the six types of programs for mature race-fit horses (excluding 2-year-olds), 379 trainer-program combinations were present, compared with a theoretical maximum of 66 × 6 = 396 trainer-program combinations.

Differences between groups were assessed by linear regression or Kruskal-Wallis equality-of-populations rank test according to data distribution. Variance within groups (and therefore variation between individual trainers) was assessed using Brown and Forsythe's F statistic (median).

To assess grouping of trainer programs across the study population, cluster analysis was performed using k-means or medians [9]. Three separate analyses were performed according to age and stage of preparation [(1) pre-trial 2-year-old programs; (2) pre-trial 3-year-old and above programs; and (3) maintenance (race-fit) programs of mature horses]. For our cluster analyses, where the trainer did not report undertaking exercise in a given speed category, we recorded this as zero metres. Variables relating to workloads were chosen for input into the cluster analysis through forwards and backwards selection to identify significant determinants of the cluster structure. Dendrograms (see example Supplementary Item S4) were used to identify clusters of training groups. A series of dendrogram analyses were carried out where the number of candidate clusters was serially increased, with the most appropriate number of training group clusters assessed visually [10,11].

Each of the six mature horse race-fit programs in use for each of the n=66 trainers were tabulated. A series of univariable multilevel, ordered logistic regression models were developed where the outcome of interest was the training group cluster (a four-level categorical variable) and, for each model, the explanatory variable was one of the trainer- or program-level factors listed in Supplementary Table S8. In each model a zero-mean, Gaussian distributed random intercept term was included to account for lack of independence in the data arising from race-fit program types clustered within individual trainers. All assessed explanatory variables satisfied the proportional odds assumption, except for whether or not a trainer had 2-year-olds in work [12]. The contribution of the unobserved trainer-level effects to the total unaccounted-for variation in the data (the intraclass correlation coefficient, ICC) was calculated as $\sigma_T^2 \div (\sigma_T^2 + \pi^2/3)$ where σ_T^2 represents the estimated variance of the trainer-level random effect term [13].

To allow us to make general statements about the most common mature race-fit horse training regimens (cluster) used by each trainer, the number of horses in each program type by trainer

(N_p) was estimated by multiplying the reported proportions of stable make-up (horse program types; *n*=6) by the number of horses in each age group obtained from the official repository. A trainer's estimated number of horses assigned to each of the four clusters (N_c) was calculated by summing the N_p for each cluster group. The cluster group with the highest number of assigned horses (N_c) was then determined to be the most common workload group for that trainer.

2.5 RESULTS

2.5.1 Study group

Sixty-six trainers with 1,720 horses in training at the time of interview, were surveyed. Participating trainers were recruited predominately based on veterinary or industry personnel recommendation (*n*=15 and 36, respectively), with the remaining 15 trainers selected at random from the registry. Participants included 19 Class A, 24 General, and 23 Restricted trainers (of the population of 86, 418 and 385 trainers, respectively) that used 19 metropolitan, 36 provincial and 11 country training tracks. Trainers had a median of 18 horses in training at the time of survey [IQR 4-35; range 0-190 (trainers could have zero horses in work at the week of interviewing e.g. single horses on a rest break, but still have a starter for the season to maintain their licence)], compared to the average number of individual starters (8,752 horses) by each trainer in Victoria of 10. This included a median of three 2-year-olds (IQR 1-10), 13 3- to 5-year-olds (IQR 3-21), and 15 horses 6-years of age or above (IQR 4-24).

2.5.2 Pre-training programs

Fifty-six percent (37/66) of trainers performed their own pre-training. A further 16 (24%) pre-trained the majority (at least 90%) of horses in their care, whereas 13 trainers (20%) predominately used external pre-trainers. Time in pre-training for 2-year-olds ranged from two to eight weeks (mean 4.5; 95%CI 4.1, 4.9), generally not achieving speeds above canter (<10 m/s).

For horses older than 2-years, 60% of trainers reported immediate re-entry to the training stable following a rest period, 24% reported an interim two to four-week preparation phase, and 16% reported greater than four-week preparatory phase during which horses typically exercised up to canter (<10 m/s).

2.5.3 **Slow workouts**

Horses performed slow-workouts a median of six days/week (range 4-7 days/week for 2-year-olds, 5-7 days/week for mature horses). Fourteen (21%) trainers included one day of swimming and/or exercise on mechanical walkers rather than slow-workouts under saddle.

Ten trainers provided details on the slow-workout distances and generally did not differentiate distances of trot versus canter. For 2-year-olds, the median distance of slow-workouts per month was 60,000 m (IQR 57,200-74,400) and 73,200 m (IQR 62,400-90,750) for mature horses. Older horses (16/66; 24% of trainers), colts (4/66; 6%), horses described to be 'heavy' or 'overweight' by the trainer (8/66; 12%), and stayers (14/66; 21%) were reported to undertake greater distances than younger, lighter horses, fillies and sprinters. There were insufficient numbers of responses to stratify slow work distances by trainer category. For pace work (11.1-12.5 m/s) median reported distances per month were 1,600 m (IQR 1,200-3,200; *n*=4) for 2-year-olds, mature horses 5,200 m (IQR 2,400-8,640; *n*=17) and older horses 4,400 m (IQR 3,200-9600; *n*=10).

2.5.4 **Fast workouts**

Trainers provided 24 distinct reasons as rationale for the distance and speed of each training session. Age and race distance were commonly reported by trainers as important in training program design (32% and 24% of trainers, respectively), therefore the results are stratified by

these factors. Other common factors result in individual tailoring to the horse which included performance in previous workouts (24/66; 36%), recovery from workouts (19/66; 29%) and demeanour (15/66; 23%), followed by previous injuries (13/66; 20%), weight (11/66; 17%), appetite (8/66; 12%), level of fitness (8/66; 12%), and upcoming races (7/66; 11%). Twenty-five trainers (38%) reported specifically tailored programs, ten (15%) standardised and 25 standardised with horse specific minor adjustments (38%). Seventeen trainers (26%) reported that they started all horses with a standardised program (of which 11 also reported individual adjustments by horse).

Two-year-olds fast galloped a mean of 1.7 times per week (95%CI 1.5, 1.8). Eight trainers (12%) never galloped 2-year-olds. Horses older than 2-years of age were galloped a mean of twice per week (95%CI 1.8, 2.2).

Ten trainers (15%) did not allow 2-year olds to participate in trials. Of the 85% of trainers who trialled 2-year-olds (56/66), 33% reported they would not subsequently race those horses as 2-year-olds. For trainers who reported participating in trials and/or racing of 2-year-olds, 88% of their horses were expected to trial and 50% to race.

Progressive program to trial fitness: 2-year-old horses that trialled took a mean of 10.5 (95%CI 9.7, 11.2) weeks to reach trialling stage from paddock fitness, including a mean of 4.6 (95%CI 4.1, 5.0) weeks of an initial slow-workout phase (either at the training stable or with a pre-trainer). Horses 3-years and older took a mean of 9.5 (95%CI 9.0, 9.9) weeks to trial, including a mean of 4.0 weeks (95%CI 3.7, 4.3) of an initial slow-workout period. The slow phase generally commenced with speeds up to 11.8-13.2 m/s, followed by introduction of slow gallops at 13.3-14.3 m/s with gradual increases in speed and distance in preparation for trialling. Gallop

programs typically included early stages of 13.3-14.3 m/s, with a mid-stage introducing 'improving speed gallops' at 14.4-15.4 and/or 15.5-16.7 m/s, followed by a late stage adding in gallops of 15.5-16.7 and/or ≥16.8 m/s as horses became fit enough to trial. From the end of the initial slow-workout stage to trial, 2-year-olds accumulated a mean of 6,500 m (95%CI 5,500, 7,500) of gallop workouts, or 1,200 m per week over a mean of 5.7 weeks (SD.1.9). By increasing categories of speed this equated to a mean of 4,300 m (95%CI 3,500, 5,000) at 13.3-14.3 m/s, 2,100 m (95%CI 1,600, 2,500) at 15.5-16.7 m/s and 200 m (95%CI 100, 300) at ≥16.8 m/s.

For preparation of 2-year-olds for trialling, there were three clusters of programs (in addition to the subset of trainers who avoided fast workouts and/or trialling, Supplementary Table S6, and program glossary Supplementary Table S5): (1) 'high-volume over extended time' had the highest cumulative gallop distance (≥13.3 m/s) over the longest preparatory period (*n*=7); (2) 'moderate programs' had an intermediate duration of fast training and trial preparation, with a moderate overall gallop distance cumulating over the program (*n*=23); and (3) 'fast and light' trainers had the shortest duration in fast training and shortest preparation before trialling with the lowest cumulative gallop distances ≥13.3 m/s (*n*=26); Figure 2.1.

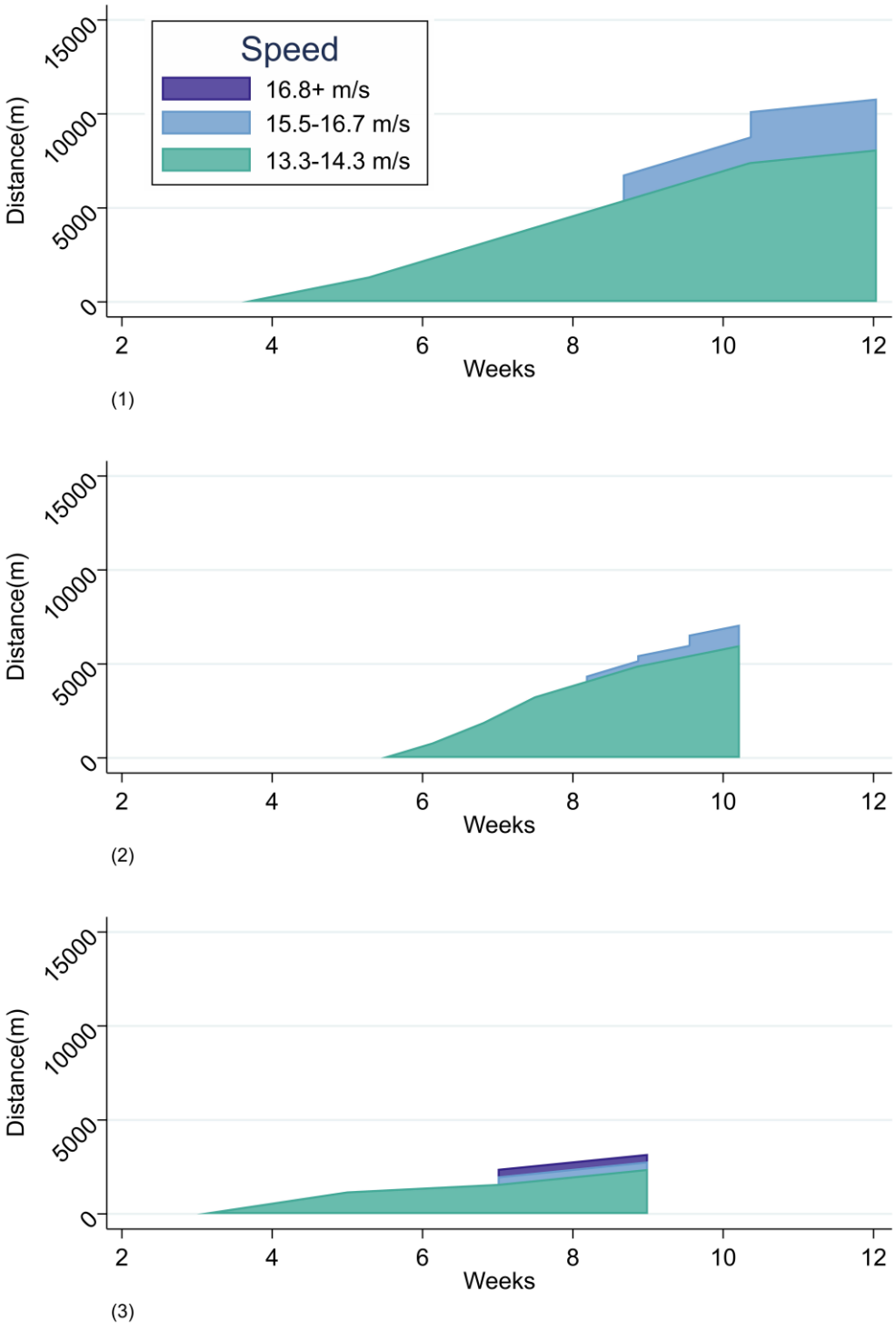

Figure 2.1. *Example of programs of progressing gallop workloads of 2-year old Thoroughbred racehorses as they approach trialling in Victoria, Australia. Each plot represents an example of an individual trainer's program in each of the three clusters of workload volume and intensity, where time at zero weeks indicates entry into work following a paddock (or equivalent) rest period. Groups of workload intensity represent: (1) High volume workload over extended time-period; (2) Moderate program and; (3) Fast and light workload.*

Cumulative program distances prior to trialling were higher for horses 3-years and over compared with 2-year-olds in each speed category, and for combined speeds ≥13.3 m/s (approximately 40% greater total gallop distance, p≤0.05) (Supplementary Tables S6 and S7), excluding 14.4-15.4 m/s, for which there were too few reported values in the 2-year-old group. Horses 3-years of age and older galloped a mean of 9,700 m (95%CI 8,400, 11,000) during the fast training phase approaching trialling (5.9 weeks), averaging 1,800 m per week over the program. This equated to a mean of 6,300 m (95%CI 5,200, 7,400) at 13.3-14.2 m/s, 100 m (95%CI 0, 100) at 14.4-15.4 m/s, 3,100 m (95%CI 2,600, 3,600) at 15.5-16.7 m/s and 300 m (95%CI 0, 500) at ≥16.8 m/s (with only a small number of trainers reporting training horses at speeds at 14.4-15.4 m/s (n=4) and ≥16.8 m/s (n=7) when describing their progressive workloads). Programs for horses aged 3-years and older were similarly clustered into three types of progressive program workloads; high-volume with slower speed galloping, moderate, and fast and light (Supplementary Table S7). There was less program variation in total time to trial and time in fast training compared to 2-year-olds.

Race-fitness workloads: Reported racing frequency was a mean of 2.3 weeks between starts (95%CI 2.1, 2.4). Total monthly galloping distances (≥13.3 m/s) for a fit racehorse was a median of 8,000 m (IQR 6400-12000) and varied according to trainer and horse level factors (Table 2.1). General trainers had greater variance in training distance for all gallop speeds (P=0.03). At 13.3-14.3 m/s, provincial trainers reported lower monthly distances than metropolitan or country trainers (χ^2 9.8; 2 *df*; P<0.01). Metropolitan trainers had higher monthly distances for speeds of 14.4 to 16.7 m/s (P<0.01) but provincial trainers had the highest distance of race speed gallops (≥16.8 m/s, P<0.01).

Two-year-olds were trained over shorter distances compared to mature horses over all speeds (Table 2.1; P<0.01). Within each age category there was a large spread of distances worked

($P<0.01$). Differences in distance travelled between sprinters, middle distance horses and stayers were greatest for slow-speed gallops (13.3-14.3 m/s; $P<0.001$). For fast galloping (>14.3 m/s) there was no difference between these groups of horses. The spread of distances within sprinters, middle distance and stayers was also different (Brown & Forsythe's F statistic $P<0.01$), with greater variations in training distances between trainers as race distance increased across all speed categories except race speed gallops (≥16.8 m/s).

Table 2.1. *Monthly gallop distances by speed for horses of ages 3-years old and above at race-level fitness, according to trainer and horse factors from n=66 trainers in Victoria, Australia*

		Median (IQR) distance galloped per month (m) at incremental gallop speeds (m/s)				
		13.3-14.3m/s	14.4-15.4m/s	15.5-16.7m/s	≥16.8m/s	Combined speeds[1] (≥13.3m/s)
Total Cohort		4000(2400-6400)	1600(1600-3200)	2400(1600-3200)	2400(1600-4000)	8000(6400-12000)
Trainer Factors	n					
Licence category						
Class A	19	4,800(2,400-6,400)	4,000(3,200-4,800)	2,400(1,600-3,200)	2,400(1,600-4,800)	8,000(6,400-11,200)
General	24	4,800(1,600-7,200)	2,400(800-10,000)	3,200(1,600-4,800)	1,600(1,600-4,800)	9,600(6,400-12,800)
Restricted	23	4,000(2,400-4,800)	1,600(1,600-1,600)	2,400(1,600-3,200)	2,400(1,760-2,800)	8,000(6,400-11,200)
Between group p-value[2]		0.72	0.01	0.82	0.51	0.14
Within group p-value[3]		0.01	<0.001	<0.001	0.03	<0.001
Region						
Metropolitan	19	4,800(3,200-7,200)	4,800(3,200-10,000)	3,200(1,600-4,000)	1,600(1600-3,200)	8,000(6,400-12,000)
Provincial	36	3,200(2000-5,600)	1,600(1,600-2,000)	2,400(1,600-3,200)	2,400(1,600-4,800)	8,000(6,400-12,000)
Country	11	4,800(3,200-6,400)	1,600(1,600-1,600)	2,400(1,200-4,800)	800(800-800)	8,000(6,400-9,600)
Between group p-value		0.01	0.001	0.02	0.05	0.19
Within group p-value		0.53	<0.001	<0.001	0.01	<0.001
Number of horses in work						
1-5	18	4,000(2,400-6,400)	1,600(1,600-1,600)	2,400(1,600-3,200)	2,400(1,120-2,400)	8,000(6,400-12,000)
6-20	18	4,800(2,400-7,200)	2,400(800-2,400)	3,200(1,600-4,800)	4,800(3,200-4,800)	8,000(4,800-11,200)
21-30	11	3,200(1,600-4,800)	10,000(10,000-10,000)	3,200(1,600-3,200)	1,600(1,200-1,600)	8,000(4,800-10,800)
31-50	11	4,800(3,200-6,400)	4,000(3,200-4,800)	2,400(1,600-3,200)	1,600(1,600-2,800)	8,000(6,400-9,600)
51+	8	4,800(1,600-6,400)		3,200(1,600-4,800)	1,600(1,600-4,800)	9,600(6,400-12,000)
Between group p-value		0.10	0.001	0.06	0.03	<0.001
Within group p-value		0.90	<0.001	<0.001	0.01	<0.001
Horse Factors						
Age (Years)						
2		3,200(1,600-4000)		1,600(1,600-3,200)	1,600(1,120-2,400)	6,400(4,800-8,000)
3-5		4,800(2,400-7200)	1,600(1,600-3,200)	2,400(1,600-3,600)	2,400(1,600-4,800)	9,600(6,400-12,800)
6+		4,800(3,200-6400)	1,600(1,200-5,800)	3,200(1,600-4,800)	2,400(1,600-4,800)	9,600(6,400-11,200)

Between group p-value	<0.001	0.57	0.001	0.023	<0.001
Within group p-value	<0.001	<0.001	<0.001	0.39	<0.001
Desired race distance					
Sprinter	3,200(1,600-4,800)	2,000(1,600-2,400)	2,400(1,600-3,200)	2,400(1,600-3,200)	8,000(6,400-9,600)
Middle Distance	4,800(3,200-7,200)	1,600(1,600-2,400)	3,200(1,600-4,000)	2,800(1,600-4,800)	9,600(8,000-12,800)
Stayer	7,600(3,600-9,600)	3,200(2,400-4,000)	3,200(1,600-4,800)	3,600(1,600-4,800)	12,800(9,600-16,000)
Between group p-value	<0.001	0.24	0.19	0.49	<0.001
Within group p-value	<0.001	<0.001	<0.001	0.61	<0.001

[1] Combined speed column was derived from all raw data inclusive of Speed Categories 1-4, i.e. all gallop workouts at speeds of 13.3m/s and above (therefore not a simple summation across columns.)

[2] Differences between groups were assessed by Kruskal-Wallis equality-of-populations rank test, with corresponding p-values reported here (KW).

[3] Variance within groups was assessed via Brown & Forsythe's F statistic (median) with corresponding p-values reported here (BF).

Cluster analyses performed across 379 mature race-fit programs identified four distinct workloads (Table 2.2), with frequency of galloping increasing for each cluster: (1) low-volume programs (*n*=90; 24%); (2) medium-volume programs (*n*=173; 46%); (3) medium-volume programs with greater high-speed workouts (*n*=76; 20%); and (4) high-volume programs (*n*=50; 11%). Fifty trainers (76%) had at least one program in cluster (1), 37 trainers (56%) in cluster (2), 31 (47%) in cluster (3) and 18 (27%) in cluster (4). The number and proportions of programs for each type of horse assigned to the four cluster group levels are presented in Supplementary Table S8. Three- to 5-year-old horses tended to be within the low- and medium-volume cluster. Older horses were most commonly in the medium-volume, with programs also in the low and medium with greater high-speed exercise intensity clusters, but rarely the high volume (5%). The high-volume cluster contained the highest number of stayer programs, though programs for stayers were evenly distributed across all except the low-volume group. Sprinters tended to be within the first two clusters (low- or medium-volume) and middle-distance horse programs across all four, but predominantly in the two medium-intensity groups. Clustering for volume of training for elite horses were distributed similarly to basic maintenance-programs, however there were limited numbers of trainers with elite horses.

The proportion of unaccounted-for variation in the data attributable to the trainer was 69% (95%CI 57, 78). Trainer factors were not associated with workload clustering (Supplementary Table S8). The proportion of programs within clusters increased from low to high-volume as targeted race distance increased (P<0.001).

The main clusters [(1)-(4), low-volume through to high-volume] in which each trainers' programs predominately fell, weighted by the distribution of horse types in each training stable, were 15 (23%), 32 (50%), 11 (17%) and six (10%), respectively. An additional two trainers had an even distribution across a combination of two to three clusters.

Table 2.2. *Cluster analysis generated groups of gallop training programs of mature Thoroughbred racehorses (≥3-year-old) at race-level fitness from n=66 trainers in Victoria, Australia.*

Program Group[1]	Program Description	Time between starts [weeks; mean(SD.)]	Frequency of fast work [gallops per week; weeks; mean(SD.)]	Distance per month [m; median (IQR)], by speed of galloping (m/s)				
				13.3-14.3m/s	14.4-15.4m/s	15.5-16.7m/s	≥16.8m/s	Combined speeds (≥13.3m/s)
1	Low-Volume programs	2.15(0.42)	1.43(0.52)	1,600(0-2,400)	1,600(1,200-1,600)[2]	2,400(1,600-4,000)	1,600(1,600-3,200)[2]	4,800(3,600-5,600)
2	Medium-Volume programs	2.39(0.64)	1.98(0.34)	4,800(3,200-4,800)	1,100(1,100-1,100)[2]	3,200(3,200-4,800)	2,400(1,600-4,800)[2]	8,000(8,000-9,600)
3	Medium-Volume programs with greatest high-speed workouts	2.23(0.6)	2.11(0.44)	8,000(6,400-9,600)	2400(1,600-10,000)[2]	4,800(2,400-6,000)	4,800(3,200-5,400)[2]	12,800(11,200-14,400)
4	High-Volume programs	1.97(0.39)	2.8(0.37)	12,000(11,200-14,200)	2,400(2,400-2,400)[2]	4,800(3,200-7,200)	2,400(1,600-4,800)[2]	19,200(16,800-19,200)

[1] Workload intensity groups were generated via k-medians according to frequency of galloping and racing, type of racing participated in and cumulative monthly gallop distances.

[2] For speed categories of 14.4-15.4 and ≥16.8m/s, median gallop distances were zero [0(0-0)]. This was due to the low number of trainers reporting typically training at these speeds (therefore calculated as zero reported metres). To better demonstrate the range of data, the median and inter-quartile ranges were therefore recalculated with zero excluded for 14.4-15.4m/s & ≥16.8m/s to be displayed here. Cluster analyses were conducted according to raw data unadjusted data.

2.5.5 **Rest periods**

The rationale for rest periods was typically made for an individual horse rather than a set regimen. Of the 66 trainers, the most common reasons for resting were a change in horse demeanour (36; 55%), reduced racing or training (22; 33%) performance, poor appetite (17; 26%), seasonal horse preferences for track surface hardness (14; 21%), preparation for future campaigns (13; 20%), physical fatigue (9; 14%), for growth and skeletal development (9; 14%), lack of appropriate races (6; 9%) or loss of condition (5; 8%). As trainer licensing-level decreased, rest periods lengthened for mature horses (P=0.03) and 2-year-olds (P=0.06; Table 2.3). Two-year-old rest periods were longest for country trainers compared to provincial and to metropolitan trainers (P=0.02).

Table 2.3. *Rest periods frequency and duration in Thoroughbred Racehorses in training in Victoria, Australia, by horse age and trainer factors from n=66 trainers [mean(SD.)].*

		2-year-olds		Mature Horses (3-years and above)	
	Number of contributing trainers (%)	Frequency of rest-periods (rests/year)	Length of rest-period (weeks)	Frequency of rest-periods (rests/year)	Length of rest-period (weeks)
Total Cohort		2.1(0.9)	6.6(2.5)	1.9(0.7)	6.3(2.4)
Licence category					
Class A	19(28.8%)	2.2(0.7)	5.5(1.4)	2.1(0.5)	5.5(1.6)
General	24(36.4%)	1.8(0.9)	6.7(2.3)	1.7(0.8)	6.0(2.3)
Restricted	23(34.9%)	2.2(1.0)	7.4(3.1)	1.7(0.8)	7.3(2.6)
p-value		0.3	0.06	0.33	0.03
Region					
Metropolitan	19(28.8%)	2.3(1.1)	6.1(1.8)	2.1(0.6)	5.9(2.1)
Provincial	36(54.6%)	2.2(0.7)	5.5(1.4)	2.1(0.5)	5.5(1.6)
Country	11(16.7%)	2.0(0.9)	8.6(3.3)	1.9(0.9)	6.8(2.5)
p-value		0.51	0.02	0.36	0.56
Number of horses in work					
1-5	18(27.3%)	2.1(0.8)	7.3(2.9)	1.9(0.7)	7.4(2.7)
6-20	18(27.3%)	1.6(0 .9)	6.9(2.6)	1.5(0.7)	6.7(2.6)
21-30	11(16.7%)	2.2(0 .9)	6.3(2.44)	2.2(0.8)	5.2(2.0)
31-50	11(16.7%)	2.3(0.5)	5.8(2.4)	2.1(0.5)	5.4(1.5)
51+	8(12.1%)	2.7(1.1)	6.1(0.9)	2.1(0.5)	6.2(1.5)
p-value		0.06	0.56	0.04	0.09

2.6 DISCUSSION

Thoroughbred trainers surveyed for this study reported large volumes of monthly galloping exercise in the horses under their care with 2-year-olds undergoing less total gallop distance than older horses, and sprinters less than stayers. We identified four levels of training intensity; horses in the highest volume group undertook four times the gallop distance of those in the lowest volume group. Trainers of higher licence levels rested horses for shorter periods of time, and country trainers, for longer periods.

Trainers reported high monthly training distances at all speeds. Comparison with international findings is difficult due to the lack of consistency in reporting of training speeds. Firth *et al.* [14] described a typical Australasian 2-year-old monthly regimen of 63,200 m canter (8.9m/s) and 4,800 m at 'gallop' (~14.6 m/s), a similar distance of canter but lower gallop distance than trainers reported in this study. United States of America (USA) studies reported 19,300 m 'jogging' (5 m/s), 28,400 m 'galloping' (11 m/s), and 1,000 m 'breezing' (15-16 m/s) per month, and based on GPS recordings 2,130 m per session (23,004 m per month) at >8 m/s [15,16]. Although not directly comparable, Australian trainers report substantially greater monthly distances at all speeds. Studies in the United Kingdom (UK) report 26,800 m/month slow-speed exercise (≤14 m/s) and 2,800 m galloping (>14 m/s) [5], each of which are considerably lower than reported by Australian trainers. Similarly, 2-year-olds in the UK are reported to undertake 4,200 m/week at ≤13.4m/s and 380 m/week at >13.4 m/s [17], less than Australian 2-year-olds.

The rate of introduction of speeds above 13.3 m/s has been proposed as a risk factor for MSI [18]. There is, however, limited data on training programs transitioning horses from rest to race-level fitness. A twelve-week period has been detailed, from beginning training to first trial for 2-year-old horses in New Zealand (NZ) of three stages; slow canter (weeks one to four), faster-canter (9

m/s in weeks five to eight), and then the introduction of biweekly galloping from week nine [13]. We report a slightly shorter time to trial (10 weeks, including four weeks of initial slow phase). Also in this survey Australian 2-year-olds undertook some fast workouts in the lead up to trial, compared to NZ where there was minimal or no galloping exercise of 13.3 m/s and above [19]. UK regimens are reportedly longer compared to those described here, with slow-speed training phases of three months or more, particularly for 2-year-old's in training [20]. Conventional timeframes for a nine week program in the USA includes the introduction of fast breezing (15-15.8 m/s) from the seventh week [20].

We observed significant variation in prescribed workload between trainers. Comparison with other studies is difficult because wide ranges in workload will be reported when examining a population of horses where individual animals can influence the extremes and horses are not stratified by type. For example UK horses showed a range of zero to 82,400 m and zero to 17,700 m per month of canter and gallop, respectively [5]. In our study, the unaccounted-for trainer-level variation in the intercept only model (that did not include explanatory variables) was 69% of the total variation. However, when the designated horse program (targeted race distance) was included as a fixed effect, the proportion of unexplained variation increased to 82%. This is likely because the variation in distance exercised within a designated horse program increased as the intended race distance increased, as shown in Table 2.1.

We found that trainers rest horses on average twice yearly for short time periods. A previous Australian study also found that 2-year-olds spend longer resting than older horses [21]. NZ trainers report resting horses less frequently (once a year) but for longer (median 8.7 weeks) [22]. Rest period frequency and duration depend on trainer and horse factors, but also on climate, racing seasons and availability of spelling facilities. For example, the Hong Kong racing season

includes a mandatory two-week break in July when there is typically the highest ambient temperatures and humidity, with otherwise year-round racing [23].

More than 10% of trainers avoided training gallops for 2-year-old horses. This is despite evidence of benefits in career longevity and a protective effect of galloping on fracture risk [5,24]. It has been demonstrated that high-speed workouts, over short distances in a training environment, stimulates appropriate adaptation of bone for future racing [15]. Our findings are consistent with those from NZ where only 50% of 2-year-olds were in active training and 20% intended to race at that age [22]. Of trainers participating in 2-year-old trials that we surveyed, all exposed their horses to some fast gallop workouts in the lead up to trialling.

Categories of trainer were not associated with cluster grouping suggesting that there are factors other than region, size of stable or trainer licence that influence individual trainers' decisions on appropriate regimens. This is supported by findings of an Australasian study of 2-year-old musculoskeletal injuries where differences in distances between trainers were present after all other factors under investigation in the study were accounted for [18]. The only exception was a trend for country trainers' programs to belong to the lowest three volume groups rather than the high-volume group. We did not identify any change in training practices between different trainer licence types. We speculate that this lack of convergence with increasing trainer experience or in the higher profile metropolitan training centres over time indicate that training volumes may have limited effect on success, warranting further investigation. Others have found both low- and high-volumes of training are associated with poorer performance in individual horses [25].

Investigations of associations between training volumes and MSI indicate a complex relationship with both low- and high-volumes of high-speed training associated with increased MSI risk [5,26-

28]. This is consistent with a bone fatigue model of injury in that an optimum amount of high-speed exercise is required for appropriate adaptation of the skeleton to racing without exceeding the fatigue life of the bone [2]. Many injuries develop gradually and it is challenging to differentiate between forced reductions in workload due to injury and planned training levels. By exploring how trainers intended to train their horses in the absence of restricting factors we avoided the confounding effect of injury. There are no data on the association of MSI with training volume under Australian conditions, however in horses trained in the UK exceeding 44,000 m at canter in combination with 6,000 m at gallop per month increases the risk of fractures [5]. Differences in speed definition make it difficult to compare the slower speed training however our second gallop speed category onwards (14.4 m/s) are similar to the reported UK gallop speeds (>14 m/s). Given the interaction between canter and gallop distances identified in that study, canter distance cannot be dismissed, but by combining the medians of these speed categories, at least 50% of Australian trainers have horses exceeding the galloping 6,000 m/month risk point. Despite the high volume of galloping we have identified, race-day fatal MSI rates in Australia are lower than North America, and not significantly different from the UK [1,29]. Focussing solely on total workload is simplistic as it is not the only training management factor that may influence injury. The rate of workload increase is also likely to be important, as found in human athletes [6]. In addition, the proportion of time resting from training will influence the bone repair process [6,7]. Reasons for lower catastrophic injury rates in Australia could include shorter duration of training periods, more rest periods, better adaptation to high workloads by commencement of galloping at a younger age or by the methods used to introduce horses to fast exercise over time.

Limitations of this study include a possible selection bias as trainers with a desire to understand the effects of their horses' workloads may have been more willing to participate. Further, we targeted larger stables in the first phase of sampling, and therefore our median number of horses

in training was higher than the state average (18 *vs* 10), and our proportionate number of Class A trainers was higher than the other classes. The study population was therefore likely to be more representative of more intensively managed horses compared to the general population. The study also assessed only trainers from a single state, and therefore how well the training practices reported here reflect the industry at a national level cannot be determined. Even though we explicitly asked about rest periods in the absence of injury or illness, we cannot be certain that horses were not unknowingly affected by subclinical or undiagnosed issues. Speeds that trainers report and the speeds actually achieved may differ, and manual records of gaits or approximated speed workouts are potentially inaccurate when compared with calculated recording data [30].

There were a multitude of reasons provided for tailoring workout plans and rest practices to the individual horses but it was our purpose to determine general practices by trainers rather than what each individual horse might achieve, to enable characterisation of training loads that are not clouded by the effects of injury or other limitations. Some trainers described responses in a range which may indicate that they are tailoring to individual horse needs and although we attempted to estimate a mean individual value there may be inaccuracy in our data as a result. Further validation is required through more advanced technological recording methods on individual horses and investigations into the effect of adjunctive exercise means requires further examination.

2.7 CONCLUSIONS

This study provides baseline information on training practices for Thoroughbreds in Victoria, Australia and showed a wide variation in the volume of workloads across all categories of trainer. There is a need for more detailed research to improve understanding of the interaction between workloads, performance and injury, and effective communication of findings to industry

stakeholders. Our findings demonstrate that there is considerable opportunity to modify training volumes with potential implications for the industry given the costs involved in training horses and the risks to riders and horses alike.

Declarations:

Ethics: Approval was obtained from the Faculty of Veterinary and Agricultural Sciences Human Ethics Committee at the University of Melbourne (reference 1647911.1). There was no use of animals.

Competing interests: The authors have no competing interests to declare.

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2.8 FOOTNOTES

a. Racing Victoria Limited 2017, www.racing.com
b. Racing Australia Limited 2017, www.racingaustralia.horse
c. SI. SurveyMonkey. San Mateo, California, USA.
d. StataCorp, 2017. Stata Statistical Software: Release 15. College Station, TX: StataCorp LLC

2.9 POSTSCRIPT

In this chapter the typical training practices of Victorian Thoroughbred racehorse trainers were established. Importantly, training methodologies were highly diverse with a large range of workloads prescribed by trainers in preparing horses for racing and for maintaining horses during race campaigns. This suggests that there is substantial scope for future recommendations on the modification of training intensity. The following chapter (Chapter 3) will detail the variation in surface use for slow and fast training regimens and adjunctive exercise modalities employed by this cohort of trainers. Then in Chapter 6, I investigate how the training practices identified in this chapter are related to the performance outcomes of the cohort of horses trained by survey participants.

2.10 REFERENCES

[1] Boden, L.A., Anderson, G.A., Charles, J.A., Morgan, K.L., Morton, J.M., Parkin, T.D.H., Slocombe, F.R. and Clarke, A.F. (2006) Risk of fatality and causes of death of Thoroughbred horses associated with racing in Victoria, Australia; 1989-2004. *Equine Vet J* **2006**, 4.

[2] Martig, S., Chen, W., Lee, P.V. and Whitton, R.C. (2014) Bone fatigue and its implications for injuries in racehorses. *Equine Vet J* **46**, 408-415.

[3] Martig, S., Lee, P.V., Anderson, G.A. and Whitton, R.C. (2013) Compressive fatigue life of subchondral bone of the metacarpal condyle in thoroughbred racehorses. *Bone* **57**, 392-398.

[4] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2014) Evaluation of a subject-specific finite-element model of the equine metacarpophalangeal joint under physiological load. *J Biomech* **47**, 65-73.

[5] Verheyen, K., Price, J., Lanyon, L. and Wood, J. (2006) Exercise distance and speed affect the risk of fracture in racehorses. *Bone* **39**, 1322-1330.

[6] Bourdon, P.C., Cardinale, M., Murray, A., Gastin, P., Kellmann, M., Varley, M.C., Gabbett, T.J., Coutts, A.J., Burgess, D.J., Gregson, W. and Cable, N.T. (2017) Monitoring Athlete Training Loads: Consensus Statement. *Int J Sport Physiol* **12**, S2161-S2170.

[7] Holmes, J.M., Mirams, M., Mackie, E.J. and Whitton, R.C. (2014) Thoroughbred horses in race training have lower levels of subchondral bone remodelling in highly loaded regions of the distal metacarpus compared to horses resting from training. *Vet J* **202**, 443-447.

[8] Morrice-West, A., Hitchens, P., Walmsley, E. and Whitton, R. (2018) Track surfaces used for ridden workouts and alternatives to ridden exercise for Thoroughbred horses in race training. *Animals* **8**, 221.

[9] Makles, A. (2012) Stata tip 110: How to get the optimal k-means cluster solution. *The Stata Journal* **12**, 347-351.

[10] Schonlau, M. (2002) The clustergram: A graph for visualizing hierarchical and nonhierarchical cluster analyses. *The Stata Journal* **2**, 391-402.

[11] Schonlau, M. (2004) Visualizing Hierarchical and Non-Hierarchical Cluster Analyses with Clustergrams. *Computational Statistics* **19**, 95-111.

[12] Wolfe, R. (1997) OMODEL: Stata modules to perform tests on ordered probit and ordered logit models, Statistical Software Components Boston College Department of Economics.

[13] Snijders, T. and Bosker, R. (1999) *Multilevel Analysis: An Introduction to Basic and Advanced Multilevel Modelling*, Sage, London.

[14] Firth, E.C., Rogers, C.W., Perkins, N.R., Anderson, B.H. and Grace, N.D. (2004) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 1. Study design, and clinical, nutritional, radiological and histological observations. *New Zeal Vet J* **52**, 261-271.

[15] Boston, R.C. and Nunamaker, D.M. (2000) Gait and speed as exercise components of risk factors associated with onset of fatigue injury of the third metacarpal bone in 2-year-old Thoroughbred racehorses. *Am J Vet Res* **61**, 602-608.

[16] Pagan, J.D., Mulvey, E., Oneill, K., Ireland, N. and Davies, M. (2017) Intensity and distance of exercise during training in advanced three-day event horses and thoroughbred racehorses assessed using KER ClockIt smartphone application. *J Equine Vet Sci* **52**, 67-68.

[17] Verheyen, K., Henley, W., Price, J. and Wood, J. (2005) Training-related factors associated with dorsometacarpal disease in young Thoroughbred racehorses in the UK. *Equine Vet J* **37**, 442-448.

[18] Cogger, N., Perkins, N., Hodgson, D.R., Reid, S.W. and Evans, D.L. (2006) Risk factors for musculoskeletal injuries in 2-year-old Thoroughbred racehorses. *Prev Vet Med* **74**, 36-43.

[19] Bolwell, C.F., Rogers, C.W., French, N.P. and Firth, E.C. (2013) The effect of interruptions during training on the time to the first trial and race start in Thoroughbred racehorses. *Prev Vet Med* **108**, 188-198.

[20] Hodgson, D.R. and Rose, R.J. (1994) *The Athletic Horse: Principles and Practice of Equine Sports Medicine*, Saunders, Philidelphia, PA, USA.

[21] Bailey, C.J., Reid, S.W., Hodgson, D.R. and Rose, R.J. (1999) Impact of injuries and disease on a cohort of two- and three-year-old thoroughbreds in training. *Vet Rec* **145**, 487-493.

[22] Bolwell, C.F., Russell, L.J. and Rogers, C.W. (2010) A cross-sectional survey of training practices of 2-year-old racehorses in the North Island of New Zealand. *Comp Exerc Physiol* **7**, 37-42.

[23] Sun, T. (2016) *Fracture incidence rates and the association of rest with bone remodelling in Thoroughbred racehorses at the Hong Kong Jockey Club*, The University of Queensland.

[24] Tanner, J.C., Rogers, C.W. and Firth, E.C. (2013) The association of 2-year-old training milestones with career length and racing success in a sample of Thoroughbred horses in New Zealand. *Equine Vet J* **45**, 20-24.

[25] Verheyen, K.L., Price, J.S. and Wood, J.L. (2009) Exercise during training is associated with racing performance in Thoroughbreds. *Vet J* **181**, 43-47.

[26] Parkin, T., Clegg , P., French , N., Proudman , C., Riggs, C., Singer, E., Webbon, P. and Morgan, K. (2004) Horse-level risk factors for fatal distal limb fracture in racing Thoroughbreds in the UK. *Equine Vet J* **36**, 513-519.

[27] Estberg, L., Stover, S.M., Gardner, I.A., Rake, C.M., Johnson, B. and Ardans, A. (1996) High-speed exercise history and catastrophic racing fracture in Thoroughbreds. *Am J Vet Res* **57**, 1549-1555.

[28] Vallance, S.A., Entwistle, R.C., Hitchens, P.L., Gardner, I.A. and Stover, S.M. (2013) Case-control study of high-speed exercise history of Thoroughbred and Quarter Horse racehorses that died related to a complete scapular fracture. *Equine Vet J* **45**, 284-292.

[29] Hitchens, P., Morrice-West, A.V., Stevenson, M. and Whitton, R.C. (2018) Meta-analysis of risk factors for racehorse catastrophic musculoskeletal injury in flat racing. *Vet J* **245**.

[30] Rogers, C.W. and Firth, E.C. (2004) Musculoskeletal responses of 2-year-old Thoroughbhred horses to early training. 2. Measurement error and effect of training stage on the Relationship between objective and subjective criteria of training workload. *N Z Vet J* **52**, 272-279.

APPENDIX A. SUPPLEMENTARY INFORMATION TO CHAPTER 1

S1 SUPPLEMENTARY METHODS

Study population:

The study population comprised those registered trainers who agreed to take part in the study. The three trainer categories were chosen to ensure our sample represented a broad range of trainers with different levels of experience and performance ratings, and with varying numbers of horses in training.

Victorian trainer licencing:

Class A trainers have the most experience being required to have held an unrestricted training licence for at least five years. They are required to have a minimum of 25 starters or five winners per racing season. General Trainers are experienced professional trainers who have held a restricted trainer licence for a minimum of six years, or have previously have held a General licence for one year or were a registered Assistant Trainer within five years. They are required to have a minimum of five starters or one winner per racing season. Restricted Trainer Licence holders are comparatively less experienced, but typically have experience either as a registered jockey, assistant trainer/foreperson, non–Thoroughbred racehorse experience or previously held a Thoroughbred training licence for a defined time period. They are required to have a minimum of one starter per year and are limited to five horses for external (beyond immediate family) owners.

Approach to missing data:

A breakdown of horse ages in training under each trainer was obtained using *Racing Victoria Ltd*'s online published horse and trainer profiles (www.racing.com). These counts were converted to proportions to approximate the number of horses in each age group in the stable at the time of survey. Where trainers had no (current) horses in training, calculations were made based on having just one horse in training. If values were missing (e.g. because horse numbers were not

reported, or answers to questions were unclear), we imputed these with the study population mean (varying from zero to four responses).

Where the distribution of types of mature horses (e.g. targeted race distance) was not specified, equal proportions of horse types were assumed for whole-stable level workload comparisons.

Free-text responses:

Rationale for training and rest period decisions answered in free text was manually searched, counting the number of times each response was given. Multiple reasons in each section could be answered, therefore the number of trainers that listed each reason during the interview were counted (a word/phrase could be counted a maximum of 66 times for each search). Words of identical/similar meaning were counted as one variable based on manual assessment (e.g. bloods and haematology; bleeders, exercise induced pulmonary haemorrhage and its acronym EIPH; wind problems and respiratory concerns etc.).

For designing training regimes answers searched for included:

age
appetite
breeding history
conformation
exercise induced pulmonary haemorrhage
growth/bone development
haematological profiles
history of exertional rhabomyoloysis
history of injury
hormonal factors/ gender
length of pre-training
level of education
level of fitness
previous workout performance
race distance
race or trial history
recovery from fast work
respiratory concerns
rest periods
size
time in work
treadmill aptitude
upcoming races
weight

For rest period practices, searches included:

after a set time
demeanour/attitude
financial
future campaigns
growth/bone development
haematological profiles
lack of appropriate races
physical fatigue
poor recovery
reduced racing performance
reduced training performance
reward for successful performance
trainer convenience
weight or condition loss

length of time in work wet vs dry track preference horses

S2 SURVEY PROFORMA

An Investigation of the Training Practices Undertaken by Victorian Thoroughbred Racehorses

1. Trainer Categories

Survey Details

Date of survey:

Time:

Administrator:

1. Contact Information

Name

Company

Suburb

Email Address

Phone Number

2. Trainer Category

- ○ A
- ○ General
- ○ Restricted

3. Region

- ○ Metropolitan
- ○ Country

4. Main training track(s)

An Investigation of the Training Practices Undertaken by Victorian Thoroughbred Racehorses

2. General Stable Management

1. How many horses do you have in work this week?

2. What is the average cost to clients for horses in work per month?

Training Fees	
Veterinary Fees	
Farrier Fees	
Transport Fees	
Approximate total	

3. How many track riders do you have working your horses this week?

4. What is their skill/experience levels?

Approximate number years riding track work	
Age ranges	
Certificates	
Other training	

5. What type of races are you generally targeting? (Class, distance, flat/jumps etc.)

An Investigation of the Training Practices Undertaken by Victorian Thoroughbred Racehorses

3. Pre-Training

1. Are you directly involved in the pre-training stage, do you use a specific pre-trainer to pre-train all of your horses or do clients organise their own pre-training prior to seeing you?

2. How many weeks are 2-year-olds in pre-training for before they come to you?

Note: This could be in ranges if easier- e.g. 0-3, 4-6, 7-9, 10+

3. What is the fastest pace 2-year-olds have generally trained at in pre-training?

- ◯ Canter
- ◯ Fast Gallop
- ◯ Slow Gallop
- ◯ Race Speed Gallop

Comments:

4. How many <u>additional</u> weeks of training would a 2-year-old undergo in you stables prior to their first start or official trial?

Note: This could be in ranges if easier- eg. 0-3, 4-6, 7-9, 10+

5. For horses returning to training after a spell, do they repeat a preparatory stage before re-entering your stables?

- ◯ No, Straight back into Training
- ◯ Yes, 2-4 Weeks
- ◯ Yes, <2 weeks
- ◯ Yes, >4 Weeks

Comments:

6. What is the fastest pace experienced race horses (3+) have trained at in the last preparation period?

- ◯ Canter
- ◯ Fast Gallop
- ◯ Slow Gallop
- ◯ Race Speed Gallop

7. How many additional weeks of training would an experienced horse undergo in your stables prior to their first start or official trial?

Note: This could be in ranges if easier- eg.. 0-3, 4-6, 7-9, 10+

8. Do you have any other comments about pre-training phase you would like to add?

An Investigation of the Training Practices Undertaken by Victorian Thoroughbred Racehorses

4. Training Practices

Training surfaces

1. What surfaces do you train on for slow work? Tick all that apply and detail the percentage of work on each surface

Synthetic -polymeric binder	
Synthetic- wax coated	
Dirt	
Turf	
Sand	
Other	

2. What surfaces do you train on for fast work? Tick all that apply and detail the percentage of work on each surface

Synthetic -polymeric binder (eg. Poly-Ride)	
Synthetic- wax coated (eg. Visco-Ride)	
Dirt	
Turf	
Sand	
Other	

3. Do your horses race on any surface you do not regularly train them on? (Yes / No)

If Yes, please describe

4. Do you use workout methods other than over ground exercise? If so what proportion of work is performed through alternative methods?

- ☐ Walker
- ☐ Swimming
- ☐ Beach exercise- hard sand
- ☐ Treadmills
- ☐ Incline galloping
- ☐ Beach exercise- soft sand

Or Other?

What proportion of work is performed through these alternative methods?

Designing your training programs

1. Do you use a standardised training protocol or do you tailor the program to the horse?

- ○ Standardised
- ○ Specialised
- ○ Comments:

2. If they are specialised what sort of things do you consider when designing the program?

- [ ] Age
- [ ] Performance in previous workouts
- [ ] Race/trial History
- [ ] Time in lay-up
- [ ] Previous Injuries
- [ ] Weight

Other (please specify)

3. If they are standardised do you have the same general program regardless of age?

- ( ) Yes (just answer one age group program)
- ( ) No (go through each age group)

4. What would a typical training program look like for:

A). 2-Year-Olds:

Type and frequency of slow work undertaken

Type

Number Days

Number of fast days per week

Typical speeds on fast days (seconds to the furlong)

- ( ) 18+
- ( ) 17-16
- ( ) 15
- ( ) 14
- ( ) 13
- ( ) 12
- ( ) 11
- ( ) under 11's

General fast work program:

Note: Many differences in nomenclature, please answer whatever suits your usual routine!
As a guide:
Slow Canter 400m/min = 6.7 m/s
Medium Canter 500m/min= 8.3m/s
Fast Canter 600-650m/min= 10.8m/s (this is about "1/2 pace", 19s/200m, (10.5m/s), "3/4 pace" is 16 or 17ms/200m, about 12 m/s)
Slow Gallop 800m/min =13.3 m/s ("evens"/even-time 15s/200m)
Fast Gallop 900m/min= 15m/s
Racing gallop

Minimum and maximum distances galloped of fast days (metres)

Minimum

Maximum

B). 3-Year-Olds +

Type and frequency of slow work undertaken

Type

Number Days

Number of fast days per week

Typical speeds on fast days (seconds to the furlong)

- ◯ 18+
- ◯ 17-16
- ◯ 15
- ◯ 14
- ◯ 13
- ◯ 12
- ◯ 11
- ◯ under 11's

General fast work program:

Minimum and maximum distances galloped on fast days (metres)

Minimum

Maximum

C) Older horses >4yo's - are there any major changes to the way you train older horses

5. Are there major changes to the distance and speed undertaken by horses of different race distances? (Yes / No), Please describe any changes for each category:

Sprint races
(1000-1300m)

Middle distance
(Mile & Intermediate Races, 1301-2100m)

Long distance/Stayers
(Long & extended, 2101m+)

6. How many weeks do you normally keep a horse without any problems in full work from time of first start?

2 year old

3 year old

4 year old +

7. How long between starts do you generally give a fit (race ready) horse? (weeks)

Recording your training programs

1. Do you record workout speed and distance?

- yes
- no
- sometimes

2. If you record workouts, do you use manual or digital recordings?

- ◯ manual
- ◯ digital

3. If you record workouts, what method do you use for these recordings?

- ◯ guestimated
- ◯ stop watch recorded
- ◯ GPS software recording devices

4. If you use GPS devices, what products do you use?

- ☐ E-Trakka
- ☐ Garmin watches

Other (please specify)

5. If you use stopwatch measurement over specified distances, what percentage of workout quantified?

- ◯ <10%
- ◯ 10-50%
- ◯ 50%+ of high speed work
- ◯ All high speed work

6. If you use GPS recording devices, do you track all your horses or only specific ones?

- ◯ all
- ◯ specific horses
- ◯ If specific, what proportion of horses would you use GPS recording devices on?

7. If selective, what do you base the decision to use recording devices on for the selected horses?

- ☐ Elite horses
- ☐ Horses struggling with the workouts in some way

Other (please specify)

8. If you use GPS recorded devices, what proportion of the workout of those horses are recorded?

- ◯ <10%
- ◯ 10-50%
- ◯ 50-95%
- ◯ 95-100%

9. How do you use the workout records?

- [ ] Monitoring of the horses ability
- [ ] Monitoring of the horses fitness level
- [ ] Monitoring of the horses general workload
- [ ] To help decide which races to target
- [ ] Other (please specify)

10. Do you have any other comments about your training practices?

An Investigation of the Training Practices Undertaken by Victorian Thoroughbred Racehorses

5. Lay Ups

1. In the absence of injury or sickness what are you criteria for sending a horse for a spell?

- [ ] reduced training performance
- [ ] reduced racing performance
- [ ] lack of appropriate races
- [ ] all horses spelled after a set period of time
- [ ] Other (please specify)

2. Approximately how often are your horses turned out for voluntary spells? (rest period, not injured)

3. When needing to refresh horses following a preparation do you:

- ○ a) completely rest them or
- ○ b) utilise periods of lower levels of training
- ○ Comments:

4. What length of time is your average spell period in weeks for each of the following age groups:

2-year olds:

- ◯ 0-1 weeks
- ◯ 2-3 weeks
- ◯ 4-6 weeks
- ◯ 6-8 weeks
- ◯ 8-12 weeks
- ◯ >12 weeks

3-year olds:

- ◯ 0-1 weeks
- ◯ 2-3 weeks
- ◯ 4-6 weeks
- ◯ 6-8 weeks
- ◯ 8-12 weeks
- ◯ >12 weeks

4-year olds:

- ◯ 0-1 weeks
- ◯ 2-3 weeks
- ◯ 4-6 weeks
- ◯ 6-8 weeks
- ◯ 8-12 weeks
- ◯ >12 weeks

4+ year olds:

- ◯ 0-1 weeks
- ◯ 2-3 weeks
- ◯ 4-6 weeks
- ◯ 6-8 weeks
- ◯ 8-12 weeks
- ◯ >12 weeks

5. Do you have any other comments about spelling horses?

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6. Further investigation

1. Would you allow us to access and utilise your recorded training data?

Please note- the information you provide will be recorded confidentially, without reference to your personal details or details of your stable. All data stores will be password protected and accessible only by researchers directly involved in the study, and all material presented will not reference where the information was obtained from.

- ◯ Yes
- ◯ No
- ◯ N/A

2. Would you be interested in using E-Trakka equipment to monitor your horses workload?

- ◯ Yes
- ◯ No

3. Would you allow us to use training data you provide for further studies by the Equine Limb Injury Research Group at the University of Melbourne ?

- ◯ Yes
- ◯ No

4. Would you be happy for us to contact you with any further questions?

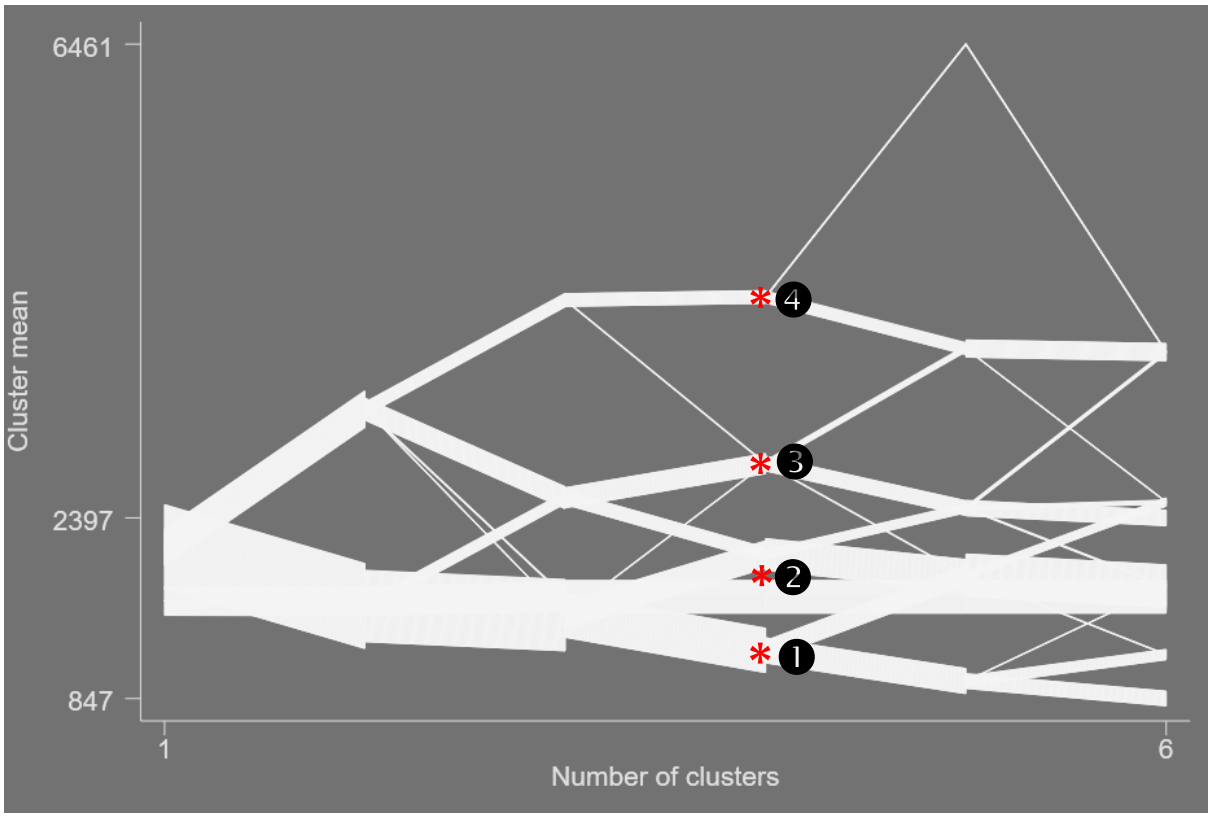
- ◯ Yes
- ◯ No

S3 AUSTRALIAN THOROUGHBRED SPEED TERMINOLOGY

Supplementary Table S3. Categories of increasing galloping speeds during fast work exercise, according to terminology used in Australian Thoroughbred racehorse training. Showing conversion from seconds per furlong (s/f) reported speeds into metres per second (m/s).

Gallop Speed Category	Speed Range (m/s)	Australian equivalents (s/f)	Australian terminology
1	13.3-14.3	15s/14s	"Even time"
2	14.4-15.4	13/13.5	13's- Fast gallop/ improving gallop
3	15.5-16.7	12/12.5	12's- Fast gallop
4	≥16.8	<12	Sub 12's- Fast gallop/ race speed gallop

S4 CLUSTER GROUP DIAGRAM



Supplementary Figure S4. Clustergram (non-hierarchical dendrogram) to select number of groups of maintenance (race-fit) workloads for training programs reported by 66 Thoroughbred trainers in Victoria, Australia using k-median clustering in Stata V.15.1. Cluster groups were generated according to the frequency of fast track-work and racing, intended race distance and cumulative monthly gallop distances at four categories of galloping speeds. Thicker lines represent larger numbers of training programs assigned to each particular cluster. The number of clusters selected was four (shown in red asterixis in the figure) and therefore four levels of training intensity. Clusters one to four (low volume, medium volume, medium volume with high-speed galloping and high volume) contained n=90, n=173, n=76 and n=50 observations respectively.

S5 TRAINING PROGRAM GLOSSARY

Supplementary Table S5. *Training program intensity glossary from cluster analysis of gallop work programs of Thoroughbred racehorses in Victoria, Australia.*

2-year-old progressive programs	Detailed description
(1) High volume over extended time period	Take a longer period to trial with a greater duration of time in fast workouts, resulting in in the highest cumulative gallop distance (≥13.3m/s).
(2) Moderate workload	Moderate time undertaking fast workout training and time to trial, with a moderate overall gallop distance cumulating over the program. This group's weekly slow speed gallops were similar to group (1), and race speed gallops (≥16.8m/s) similar to group (3).
(3) Fast and light	Shortest time undertaking fast workout training and total time to trial, with the lowest cumulative distances across all speed categories.
3-year-old and above progressive programs	
(1) High volume with slower speed gallops	Highest amount of slow speed galloping (13.3-14.3 m/s) and fast gallops (≥15.5m/s) resulting in in the highest cumulative gallop distance pre-trialling.
(2) Moderate program	Moderate time undertaking fast workout training and time to trial, with a moderate overall gallop distance cumulating over the program. This groups weekly and cumulative program slow and total (≥13.3m/s) speed gallop distance was between group (1) and group (3), but with higher distances above 15.5m/s.
(3) Fast and light	Shortest time undertaking fast workout training and total time to trial, with the lowest cumulative distances across all speed categories (≥13.3 m/s).
3-year-old and above race fitness monthly workloads	
(1) Low volume programs	Lowest total distance per month including lower slow galloping (13.3-14.3 m/s) and lower fast galloping (≥15.5 m/s).
(2) Medium volume programs	Moderate total distance, with more slow speed gallops (13.3-14.3 m/s) compared to the low volume group and marginally more high-speed work.
(3) Medium volume programs with greatest high-speed work	Second highest total gallop distance, with moderate slow speed gallops (13.3-14.3 m/s) and the highest race-speed gallops (≥16.8 m/s).
(4) High volume programs	Highest total gallop distance per month, with high values across all gallop speeds (≥13.3 m/s).

S6 PROGRESSIVE PROGRAMS TO TRIAL (2-YEAR-OLDS)

Supplementary Table S6. *Summary of Progressive programs for 2-year old thoroughbred racehorses as they approach a trialling stage by categories of increasing speed (m/s) of workloads, including time in work until trialling, cumulative distances and average weekly distance accumulated by clustered groups of trainers in Victoria, Australia.*

		Length of time [weeks; mean (SD.)]			Distance (m) at each speed category [mean (SD.)]*				
Program group	Number of trainers	To Trial	In fast training		Speed Category-1 (13.3-14.3 m/s)	Speed Category-2 (14.4-15.4 m/s)	Speed Category-3 (15.5 - 16.7 m/s)	Speed Category-4 (≥16.8 m/s)	Combined speeds[1] (≥ 13.3 m/s)
(1)	7	12.9 (3.2)	9.1 (2.9)	Cumulative program[2]	9,500 (3,000)	.	5,000 (1,700)	200 (600)	14, 700 (2,600)
				Average weekly[3]	1,100 (300)	.	600 (300)	20 (60)	1,700 (300)
(2)	23	10.1 (1.7)	5.7 (1.5)	Cumulative program	5,300(1,000)	.	2,200 (1,100)	200 (600)	7,700 (1,000)
				Average weekly	1,000 (300)	.	400 (200)	40 (130)	1,400 (400)
(3)	26	9.7 (1.7)	5.0 (1.8)	Cumulative program	2,400 (1,200)	.	1,400 (1,100)	200 (300)	4,000 (1,300)
				Average weekly	600 (400)	.	300 (200)	40 (100)	1,000 (400)

[1] Combined speeds column was derived from all raw data inclusive of Speed Categories 1-4, i.e. all gallop workouts at speeds of 13.3 m/s and above

[2] Cumulative program distance is the distance accumulated over the total number of weeks in fast training (Column four)

[3] Average weekly distances do not indicate timelines but rather the workload averaged across the period of fast training (column four). See Figure 2.1 for representation of staged progression of gallop work speeds.

S7 PROGRESSIVE PROGRAMS TO TRIAL (MATURE AGE)

Supplementary Table S7. *Summary of progressive programs 3-year olds and older as they approach a trialling stage by categories of increasing speed (m/s) of workloads, including time in training until trialling, cumulative distances and average weekly distance accumulated by clustered groups of trainers in Victoria, Australia.*

		Length of time [weeks; mean (SD.)]			Distance (m) at each speed category [mean(SD.)]*				
Program group	Number of trainers	To Trial	In fast work		Speed Category-1 (13.3-14.3 m/s)	Speed Category-2 (14.4-15.4 m/s)	Speed Category-3 (15.5 - 16.7 m/s)	Speed Category-4 (≥16.8 m/s)	Combined speeds[1] (≥ 13.3 m/s)
(1)	8	10.5 (1.3)	6.9 (1.4)	Cumulative program[2]	15,000 (3,400)	200 (500)	3,700 (2,700)	1,000 (2,300)	19,800 (3,000)
				Average weekly[3]	2,300 (700)	20 (60)	500 (400)	100 (300)	3,000 (700)
(2)	26	9.8 (1.2)	6.1 (1.3)	Cumulative program	7,600 (1,800)		3,800 (1,800)	300 (900)	11,700 (2,500)
				Average weekly	1,300 (300)		700 (300)	100 (200)	2,000 (500)
(3)	31	9.0 (1.7)	4.7 (2.0)	Cumulative program	3,000 (1,600)	100 (400)	2,300 (1,700)	40 (300)	5,400(1,900)
				Average weekly	800 (500)	20 (60)	500 (300)	10 (80)	1,300(500)

[1] Combined speeds column was derived from all raw data inclusive of Speed Categories 1-4, i.e. all gallop workouts at speeds of 13.3 m/s and above.

[2] Cumulative program distance is the distance accumulated over the total number of weeks in fast training (Column four)

[3] Average weekly distances do not indicate timelines but rather the workload averaged across the period of fast training (column four).

S8 ORDERED LOGISTIC REGRESSION OF TRAINER AND DESIGNATED HORSE-PROGRAM FACTORS TO CLUSTERED TRAINING INTENSITY

Supplementary Table S8. Univariable random-effect *Ordered Logistic Regression models generated from race-fit mature horse (3-year-old and above) gallop program volumes, by monthly cumulative workload groupings of programs from low volume to high volume of Thoroughbred horses for n=66 trainers in Victoria, Australia. Cluster groupings were generated according to frequency of galloping and racing, type of racing participated in and cumulative monthly gallop distances.*

			Number of programs (%) by cluster grouping										
			Cluster 1		*Cluster 2*		*Cluster 3*		*Cluster 4*				
	Number of contributing trainers (%)	Number of Programs	Low Volume programs		Medium Volume programs		Medium Volume programs with greatest high-speed workouts		High Volume programs		OR (95% CI)	p-value	Intraclass correlation coefficient (95%CI)
Total	66	379[1]	90	23.8%	173	45.7%	76	20.1%	40	10.6%			0.69(0.57-0.78) [2]
Trainer factors													
Licence category													
Class A	19 (28.8%)	107	29	27.1%	47	43.9%	21	19.6%	10	9.4%	1.00		0.69(0.57-0.78)
General	24 (36.4%)	139	36	25.9%	53	38.1%	30	21.6%	20	14.4%	1.28(0.50-3.30)	0.61	
Restricted	23 (34.9%)	133	25	18.8%	73	54.9%	25	18.8%	10	7.5%	1.13(0.50-2.54)	0.77	
Region													
Metropolitan	19 (28.8%)	103	14	13.6%	45	43.7%	31	30.1%	13	12.6%	1.00		0.68(0.56-0.77)
Provincial	36 (54.6%)	210	59	28.10%	92	43.8%	33	15.7%	26	12.4%	0.51 (0.23-1.14)	0.11	
Country	11 (16.7%)	66	17	25.8%	36	54.6%	12	18.2%	1	1.5%	0.41(0.17-1.03)	0.06	
Number of horses in work													
1-5	18 (27.3%)	103	19	18.5%	54	52.4%	19	18.5%	11	10.7%	1.00		0.68(0.57-0.78)
6-20	18 (27.3%)	102	33	32.4%	41	40.2%	17	16.7%	11	10.8%	0.68(0.23-2.00)	0.49	
21-30	11 (16.7%)	61	19	31.2%	23	37.7%	16	26.2%	3	4.9%	0.77(0.21-2.51)	0.62	
31-50	11 (16.7%)	66	11	16.7%	38	57.9%	6	9.1%	11	16.7%	1.03(0.37-2.85)	0.95	
51+	8 (12.12%)	47	8	17.0%	17	36.2%	18	38.3%	4	8.5%	1.48(0.58-3.79)	0.41	
Trainer has 2-year olds in training[3]													

No	8 (12.1%)	45	20	44.4%	14	31.1%	5	11.1%	6	13.3%	1.00		0.68(0.57-0.78)
Yes	58 (87.9%)	334	70	21.0%	159	47.6%	71	21.3%	34	10.2%	2.18(0.42-11.49)	0.36	
Region													
Western Metro	10 (15.2%)	52	8	15.4%	24	46.2%	11	21.2%	9	17.3%	1.00		0.68(0.56-0.77)
Eastern Metro	9 (13.6%)	51	6	11.8%	21	41.2%	20	39.2%	4	7.8%	0.13(0.37-3.44)	0.82	
Greater Western	9 (13.6%)	54	15	27. 8%	28	51.9%	10	18.5%	1	1.9%	0.43(0.12-1.53)	0.19	
Greater Northern	11 (16.7%)	72	18	27.3%	24	36.4%	13	19.7%	11	16.7%	0.72(0.17-3.02)	0.66	
Greater South-Eastern	26 (39.4%)	150	43	28.7%	70	46.7%	22	14.7%	15	10.0%	0.49(0.17-1.47)	0.20	
Designated horse program													
Desired race distance													
Sprinter		64	24	37.5%	33	51.56%	4	6.3%	3	4.7%	1.00		0.82(0.70-0.90)
Middle Distance		64	13	20.3%	27	42.19%	18	28.1%	6	9.38	2.91(1.94-4.35)	<0.001	
Stayer		64	7	10.9%	18	28.13%	21	32.8%	18	28.1%	8.15(4.39-15.14)	<0.001	
Elite horse													
No		62	16	25.8%	32	51.61%	8	12.9%	6	9.7%	1.00		0.68(0.57-0.78)
Yes		61	14	23.0%	32	52.46%	11	18.0%	4	6.6%	1.10(0.91-1.24)	0.30	
Horse age													
< 6 years		62	16	25.8%	32	51.61%	8	12.9%	6	9.7%	1.00		0.86(0.70-0.94)
≥ 6 years		64	16	25.0%	31	48.44%	14	21.9%	3	4.7%	1.07(0.77-1.51)	0.67	

[1] With a study population of 66 trainers and six types of programs for mature race-fit horses (excluding 2-year-olds), there was a potential total of 396 combinations. As not all trainers trained all types of horses the total was reduced from a "possible" 396 in the analysis down to 379.

[2] The Intraclass Correlation Coefficient (ICC) for the random-effects regression model at the trainer level (no predictor variable) was 0.69 (95% CI 0.57-0.78).

[3] Likelihood ratio of proportionality test results were significant, therefore odds ratios and associated p-values cannot be accurately interpreted here due to low numbers in certain groups

CHAPTER 3. TRACK SURFACES USED FOR RIDDEN WORKOUTS AND ALTERNATIVES TO RIDDEN EXERCISE FOR THOROUGHBRED HORSES IN RACE TRAINING

3.1 PREFACE TO CHAPTER 3

Chapter 3 was conducted using data collected from in-person trainer surveys of Thoroughbred trainers in Victoria, Australia, as per Chapter 2. Chapter 2 focused predominately on training workloads. Here I detail the type of track surfaces the survey participants used for their racehorses in conducting the training regimens described. I will then compare how the surfaces used in training compare with race-day surface use, and the potential implications of this comparison. This chapter also reports alternative exercise methods employed to supplement or replace track-based workouts.

A version of this chapter has been published in *Animals* (2018; 8(12), 221).

3.2 SIMPLE SUMMARY

Musculoskeletal injury rates for Thoroughbred racehorses in training and racing differ between racing jurisdictions. The aetiology of these injuries is multifactorial, but one potentially important and modifiable risk factor is the track surface on which horses train. However, the extent to which different track surfaces are used by trainers has not been clearly established. Similarly, the extent of use of alternatives to ridden exercise between different jurisdictions is unknown. Trainers in Victoria, Australia use a combination of turf, sand, synthetic and dirt training track surfaces. Sand or synthetic surfaces were most commonly used for slow workouts and turf or synthetic tracks for fast workouts. A high proportion of trainers raced horses on surfaces that were not regularly used for training and 89% of trainers used alternative exercise methods in addition to overground ridden workouts. Determining types of surfaces and alternatives to ridden exercise used during training, and to what extent they are used, is the first step in understanding their association with the risk of injury. The future aim is mitigating injury risk by recommending safer track surfaces.

3.3 ABSTRACT

Little is known about the types of surfaces used during training of Thoroughbred racehorses or methods of exercise used in addition to ridden track-work. Our aims were to (1) describe the types of surfaces used in the training of Thoroughbred racehorses and to (2) identify alternative approaches used to exercise horses in addition to, or in place of, ridden overground track-work. Information regarding surface and alternative exercise methods was collected as part of an in-person survey of training practices of 66 registered Thoroughbred trainers in Victoria, Australia. Sand and synthetic surfaces were used by 97% (n=64) and 35% (n=23) of trainers, respectively, for slow-workouts. Galloping on turf training tracks was used in training regimens by 82% (n=54) and synthetic by 58% of trainers (n=38). Of those trainers utilising turf tracks, only 34% of gallop training was completed on turf despite turf being the predominant racing surface. Almost 90% of trainers used alternatives to ridden exercise. There is substantial variation in training surface used and alternative types of exercise undertaken by Victorian trainers. Future research should

focus on how such practices relate to injury risk, particularly as it relates to the importance of musculoskeletal adaptation to specific race-day surfaces.

Keywords: Thoroughbred; racehorse; equine; training; exercise; surface; track

3.4 INTRODUCTION

The track surface on which horses train and race, and methods of fitness training that reduce galloping on a track are two potentially modifiable risk factors for injury in Thoroughbred racehorses [1-6]. Despite more fractures occurring in horses when training compared to those on race-days, likely attributable to greater time spent training than racing and therefore greater time at risk, investigations of track surface as a risk factor for musculoskeletal injury (MSI) have predominantly been confined to the surface on which the horse was racing on the day of injury [1-3,7-9]. Track surface type and condition is consistently a risk factor for race-day MSI, but there is also evidence that training track surface is associated with fracture risk and site of fracture, with high-speed exercise on sand and dirt tracks at higher risk of catastrophic injury compared to turf. [4,10-15].

In Australia, racing is predominantly conducted on turf tracks, although in recent years racing on synthetic surfaces has been introduced. In Victoria in the 2016/17 racing season (1 August 2016 to 31 July 2017), 91.6% (38,150/41,668) of flat race starts were conducted on turf tracks, with the remaining conducted on synthetic surfaces [16]. Generally training tracks in Victoria are turf (grass), sand, synthetic or dirt. Synthetic track surfaces are made up of varying proportions of sand, synthetic fibres and wax or polymeric binder over a hard porous base. Sand tracks are pure sand over a non-porous base so that they can be kept moist to maintain some binding of the sand particles. Victorian synthetic surfaces are predominately Polytrack (Martin Collins Enterprises Ltd, Australia) and Pro-Ride (Pro Ride Racing Australia Pty Ltd, 2010, VIC, Australia). Dirt tracks are a combination of clay and sand on a hard base. The proportion of different types of surfaces utilised in racehorse training in Australia is unknown, therefore the extent to which horses' bones are prepared for racing by training on specific surfaces is yet to be established.

A variety of exercise approaches have been proposed as alternatives to ridden track work on a flat surface. Treadmills provide a consistent firm surface without rider weight and are unaffected

by climatic conditions with complete control over the speed of the workout [5,17]. Swim training has been suggested to reduce the frequency of limb injuries due to the absence of weight bearing forces [6]. Hill work and incline treadmills reduce the speed of the workout; speed being a factor associated with higher injury risk [18,19].

Despite the potential importance of training surface on injury risk, there are few studies detailing the types of surfaces used during overground racehorse training, or that investigate the impact of alternative exercise methods. The aims of this study were, therefore, to describe the variation in training practices of Thoroughbred trainers in Victoria, Australia as they relate to (1) surface use in slow and fast workouts; and (2) exercise alternatives to overground ridden workouts. Determining types of surfaces and alternatives for ridden exercise used during training, and to what extent they are used, is the first step in understanding their association with the risk of injury.

3.5 METHODS

This study was conducted as a component of a semi-structured survey of training regimens of 66 registered Victorian Thoroughbred trainers as described in Chapter 2 [20]. Briefly, the total population of 889 registered trainers were eligible to participate in the study. Participating trainers were a convenience sample according to industry personnel and veterinarian recommendations, followed by random selection from the registry to enlist approximately equal numbers of the three licensing levels according to experience and number of horses, and across the three regional classifications (Metropolitan, Provincial, Country) at all major training centres in Victoria, Australia. All trainers who agreed to participate were interviewed.

Trainers were asked about the typical surfaces utilised by their horses for slow workouts and gallop exercise, the proportion of monthly slow workouts and fast workouts on each surface used,

and how these surfaces related to the types of surfaces raced on (i.e. not used in routine training but some exposure prior to racing, no use of the surface prior to racing, or used routinely in training). Trainers were also asked whether or not they utilised alternative training methods in addition to ridden track-work and the details of their use.

Data analyses were conducted using Stata/SE version 15.0 (StataCorp. 2017. Stata Statistical Software: Release 15. College Station, TX: StataCorp LP). Data was examined for normality via Shapiro-Wilk tests and histograms. Normally distributed data were reported as mean and standard-deviations and median (interquartile range, IQR) for non-normally distributed data. Count data were reported as counts and percentages.

Ethics approval was obtained by the University of Melbourne Faculty of Veterinary and Agricultural Sciences' Human Ethics committee (Reference 1647911.1).

3.6 RESULTS

Surveyed trainers included 19 Class A, 24 General, and 23 Restricted trainers primarily based at 19 Metropolitan, 36 Provincial and 11 Country training tracks. There was wide variation in surfaces on which horses were trained and the proportion of training spent on each surface for both slow workouts (Table 1) and fast workouts (Table 2). Trainers frequently used more than one type of surface and the selection of surface was generally based on the anticipated maximal speed of the workout. Most trainers used sand or synthetic surfaces for slow workouts, with fewer using dirt or turf tracks. Most trainers used turf or synthetic tracks for galloping horses though many utilised both surfaces. Sand was the next most commonly used surface for galloping, whereas dirt tracks were rarely used for galloping horses. Thirty-four trainers provided rationale for their surface use decisions based on the tracks available to them. The most common response was; limited access or availability of turf tracks (n=16), followed by synthetic surfaces being in

better condition in wet weather (n=7) and sand tracks providing less concussion (n=7), with another two trainers reporting synthetic surfaces as too compacted. Two trainers described basing the decision on which track was best maintained and two described dirt tracks being the most natural surface. One trainer reported that smaller tracks were more appropriate choices for 2-year-olds entering work.

Table 3.1. *Number and percentage of Thoroughbred trainers (n=66) using each surface type for slow workouts, and the mean percentage of workouts spent on each surface used in Victoria, Australia.*

			Percentage of work by surface type		
Slow work surface	Number of trainers	Percentage of trainers (%)	Mean	SD.	Range
Synthetic	23	34.9	35.4	27.6	5, 100
Sand	64	97.0	83.4	25.3	10, 100
Dirt	9	13.6	37.3	32.7	1, 90
Turf	3	4.6	15.3	21.4	1,40

Table 3.2. *Number and percentage of Thoroughbred trainers (n=66) using each surface type for fast workouts, and the mean percentage of workouts spent on each surface used in Victoria, Australia.*

			Percentage of work by surface type		
Fast work surface	Number of trainers	Percentage of trainers (%)	Mean	SD.	Range
Synthetic	38	57.6	68.4	27.9	10, 100
Sand	22	33.3	71.3	30.1	5, 100
Dirt	5	7.6	83.0	17.2	60, 100
Turf	54	81.8	34.2	33.7	1, 100

The most utilised racing surface in Victoria is turf. Among trainers that utilised turf tracks in training (n=54), only 28% (n=15) undertook half or more of their gallop exercise on this surface. For all race-day surfaces (turf and synthetic), 36% (n=24) of trainers only raced horses on surfaces those horses were regularly exposed to in training (i.e. at least weekly). Thirty four percent (n=23) of trainers raced horses on surfaces those horses had previously raced or trained on but were not surfaces used routinely for training (i.e. use of the specific surface only for the occasional gallop in or prior to trialling or racing). The scenario was reported to occur when certain training facilities restricted access to gallop on turf tracks, allowing only those horses that were nominated in specific upcoming races that week. Twenty-nine percent (n=19) of trainers

reported their horses had no prior exposure to the surface used on race-day, or only during an occasional preparatory gallop or trial. In addition, 20% (n=13) of trainers used hill work in training, 12% (n=8) exercised horses on firm beach sand, and 9% (n=6) on soft beach sand.

Eighty-nine per cent of trainers (n=59) used alternate methods of exercise in addition to ridden track-work. Sixty-eight per cent (n=45) regularly swam their horses, 50% (n=33) used a walker and 39% (n=26) a treadmill. Trainers that regularly swam horses did so a median of five times per week for each horse (IQR 2.75-6.5), with an additional four trainers only swimming horses after hard gallops and six only using swimming horses sporadically. Thirty-three trainers reported using a horse walker as part of their training regimens, with a median time spent by horses on the walker per day of 55 minutes (IQR 40-60; answered by 28 of the 33 users). Six percent (n=4) used water walking in regular training and an additional 6% (n=4) used water walkers just for pre-training or rehabilitation purposes. The majority of treadmill training was at trot or canter, but 10 of the 26 treadmill users (38%) also performed fast workouts. Treadmills were used a median of 1.75 times per week (IQR 1.25-2.0; reported by eight trainers), with nine trainers (35%) reporting only using treadmills on specific horses, four of which were based on horses being hard to handle, four reported using treadmill in circumstances of poor weather or lack of rider availability, and one reported using treadmills especially for fillies (reducing weight carried by lighter horses in workouts). Nine of the 26 trainers used treadmills to replace slow workouts for horses with tendon or soft tissue injuries, and five of these used treadmills for most or all fast workouts other than trialling for this specific group of horses (three of the 10 trainers using treadmills for fast work was exclusively for this group of horses). Treadmill slow work protocols consisted of a median of six minutes trotting (IQR 5-10) and five minutes cantering (IQR 4-5). Of the seven trainers galloping horses on treadmills, two monitored blood lactate concentration during high intensity exercise. Protocols involved one to three fast workout intervals, and inclines of four degrees for walking and trotting and up to six degrees for cantering

and faster. Maximal speeds were variable but ranged from 32kph to 45kph for one-minute intervals on an incline.

3.7 DISCUSSION

In Victoria, Australia, surveyed trainers use of track surfaces for training varied based on the anticipated speed of the exercise session and track availability. All combinations of turf, sand, synthetic and dirt were used, but sand or synthetic surfaces were most commonly used for slow workouts and most trainers galloped horses on turf or synthetic tracks. Approximately one third of trainers surveyed raced horses on surfaces they were regularly exposed to in training, with the remaining two-thirds racing horses on surfaces they were not accustomed to in their usual monthly training regimens. The majority of trainers employed some form of alternative exercise to overground ridden workouts.

Turf surfaces were used by 80% of trainers, but only for 34% of each horse's galloping exercise. In comparison, a cohort from a United Kingdom (UK) study (assessing tibial and pelvic fracture risk) had 81% of horses performing 70% or more of their high-speed work on turf or peat-moss training tracks [13]. Despite a large proportion of high-speed workouts being undertaken on synthetic surfaces by horses of more than half of the surveyed trainers (and up to 100% of gallop exercise in some cases), less than 10% of races and race meetings are conducted on this surface. Synthetic training surfaces in Victoria were used for galloping more than slow-workouts. Comparatively, all-weather (synthetic) surfaces in the UK were predominately used in workouts below high-speed exercise, with 51% of horses completing greater than 70% of total monthly distances on all-weather tracks and the remaining 49% on a combination of all-weather, turf and woodchip [13]. An equally distributed number of the horses presented for scintigraphic examination to a Canadian equine hospital trained on dirt and synthetic training tracks [4]. In our study, almost all trainers had horses undertake a high proportion of slow workouts on sand

training tracks, and a third of trainers utilised sand for a large proportion of fast workouts whereas less than 10% of trainers employed dirt surfaces for fast work. This is in contrast to apopulation of horses presenting to a United States of America (USA) equine hospital, where 64% had been trained on dirt training tracks with the remaining 36% training on turf tracks [4]. Exercise of horses on hill tracks were used by 20% of trainers in the present study, whereas UK training regimens more commonly incorporate a greater proportion of hill training [21].

Track surface properties have the potential to influence how loads are generated in the limb and therefore the development of bone fatigue injuries [4,15]. Bone adapts to its loading environment but the importance of skeletal adaptation to galloping on an individual surface is unknown [22]. A high proportion of trainers in the present study trained horses with limited exposure to race-day equivalent surfaces. For example, some trainers completed all high-speed gallop work on sand which is not used as a racetrack surface for Thoroughbreds in Australia. It is therefore possible that these horses' bones may not be appropriately adapted to the potential forces and surface properties encountered on race-day. There has been some indication of an association between the use of turf during training gallops and lower odds of lateral condylar third metacarpal/metatarsal fracture [23]. Additionally, all-weather (synthetic) training tracks have been shown to be associated with increased risk of pelvic and tibial stress fractures compared to turf [13]. However, through scintigraphic examination a higher incidence of stress fractures were identified in horses trained on synthetic compared to dirt surfaces [4]. Galloping exercise on sand and dirt surfaces is associated with higher risk of catastrophic MSI compared to turf-tracks [4,10], and impact force and surface stiffness is reportedly significantly higher for dirt surfaces compared to synthetic surfaces [11,12].

Alternative exercise methods to ridden track-work are widely used for achieving or maintaining fitness, as evidenced by the high percentage of the study group utilising such approaches in

typical training regimens. The most commonly used alternative exercise was swimming, followed by the use of mechanical walkers. The proportion of trainers using swimming and walkers as part of their typical training regimens in other countries is unknown although both appear commonly used in Australasia [24,25]. A New Zealand study of 14 trainers reported horses first entering racing having a median of one swim day preceding the start of racing and a median of 40 minutes per day on mechanical walkers [25]. This is compared to a median of five swim days a week per horse for trainers using swim training and a daily 55 minutes on mechanical walkers in the present study More than a third of trainers in the present study utilised treadmills in training. The extent to which this is comparable to other racing jurisdictions is undetermined.

Alternative training methods have been suggested to have potential benefits in mitigating the risk of injury by reducing the cumulative loading from ridden overground exercise while maintaining cardiovascular fitness and oxidative muscle capacity [6,26]. High speed treadmill exercise has been shown to generate adaptive bone modelling and one study demonstrated an association with improved racing performance compared with overground exercised horses [5,27]. Comparatively in the case of swimming the level of exertion has been suggested to be equivalent to a fast trot or slow canter rather than a gallop replacement, but provides much less skeletal loading for adaptation [28]. There has been little research into the role of walking distance on injury occurrence, but increasing time on mechanical walkers in one study was associated with greater risk of involuntary interruptions to training (both MSI and Dorsal Metacarpal Disease) [29].

This study had some limitations. Due to the sampling method and voluntary nature of the study selection bias may have been present. Trainers with an interest in the outcomes of the study may have been more willing to participate. Surface data was collected at the trainer level (i.e. general practices across his/her stable rather than for specific horses) and therefore the variation by individual horses could not be investigated. Trainers' access to certain facilities and specific track

types varied based on the location. However, many of the surveyed trainers were willing to travel to other training facilities, beach areas etc. to gain access to surfaces not available locally.

3.8 CONCLUSIONS

This study highlights the variation in surface use in training and alternate training practices used by a sample of Thoroughbred trainers in Victoria, Australia. The importance of skeletal adaptation to galloping on each individual surface is not clear, but given the large degree of variation in use, an understanding of the association between training environment surfaces and the injury risk posed by the respective surface is likely to be important for developing preventative strategies. Future research should focus on how such practices relate to injury risk and the importance of adaptation to specific race-day surfaces.

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Conflicts of Interest: The authors declare no conflict of interest.

3.9 POSTSCRIPT

This chapter described the typical surfaces employed by Victorian trainers for slow exercise and galloping horses and demonstrates that in many cases surfaces used for gallop work do not mimic those used on race-day. Alternative exercise methods were widely employed among the cohort surveyed, allowing for mental stimulation of horses as well as the potential for reduction in overground ridden workouts. In the following chapter I move on to examine racing workloads,

considering track surface and other factors such as distance, horse age and sex and how they influence the stride characteristics of horses galloping under racing conditions.

3.10 REFERENCES

[1] Georgopoulos, S.P. and Parkin, T.D.H. (2017) Risk factors for equine fractures in Thoroughbred flat racing in North America. *Prev Vet Med*, 99.

[2] Cohen, N.C., Berry, S.M., Pelso, J.G., Mundy, G.D. and Howard, I.C. (2000) Association of high-speed exercise with racing injury in Thoroughbreds. *J Am Vet Med Assoc* **216**, 1273-1278.

[3] Rosanowski, S.M., Chang, Y.M., Stirk, A.J. and Verheyen, K.L. (2016) Descriptive epidemiology of veterinary events in flat racing Thoroughbreds in Great Britain (2000 to 2013). *Equine Vet J* **49,** 275-281.

[4] MacKinnon, M.C., Bonder, D., Boston, R.C. and Ross, M.W. (2015) Analysis of stress fractures associated with lameness in Thoroughbred flat racehorses training on different track surfaces undergoing nuclear scintigraphic examination. *Equine Vet J* **47**, 296-301.

[5] Kobluk, C.N., Geor, R.J., King, V.L., Cronin, T. and Robinson, R.A. (1996) A case control study of racing Thoroughbreds conditioned on a high-speed treadmill. *J Equine Vet Sci* **16**, 511-513.

[6] Misumi, K., Sakamoto, H. and Shimizu, R. (1993) The validity of swimming training for two-year-old thoroughbreds. *J Vet Med Sci* **56**, 217-222.

[7] Verheyen, K.L., Wood, JL (2004) Descriptive epidemiology of fractures occuring in British Thoroughbred Racehorses in training. *Equine Vet J* **36**, 167-173.

[8] Arthur, R. (2010) Comparison of racing fatality rates on dirt, synthetic, and turf at four California racetacks. In: *American Association of Equine Practitioners Proceedings*, Baltimore, MD, USA. pp 405-408.

[9] Henley, W.E., Rogers, K. and Harkins, L. (2006) A comparison of survival models for assessing risk of racehorse fatality. *Prev Vet Med* **74**, 3-20.

[10] Parkin, T., Clegg , P., French , N., Proudman , C., Riggs, C., Singer, E., Webbon, P. and Morgan, K. (2004) Horse-level risk factors for fatal distal limb fracture in racing Thoroughbreds in the UK. *Equine Vet J* **36**, 513-519.

[11] Setterbo, J.J., Yamaguchi, A., Hubbard, M., Upadhyaya, S.K. and Stover, S.M. (2011) Effects of equine racetrack surface type, depth, boundary area, and harrowing on dynamic surface properties measured using a track-testing device in a laboratory setting. *Sports Eng.* **14**, 119-137.

[12] Setterbo, J.J., Fyhrie, P.B., Hubbard, M., Upadhyaya, S.K. and Stover, S.M. (2013) Dynamic properties of a dirt and a synthetic equine racetrack surface measured by a track-testing device. *Equine Vet J* **45**, 25-30.

[13] Verheyen, K.L.P., Newton, J.R., Price, J.S. and Wood, J.L.N. (2006) A case-control study of factors associated with pelvic and tibial stress fractures in Thoroughbred racehorses in training in the UK. *Prev Vet Med* **74**, 21-35.

[14] Dimock, A.N., Hoffman, K.D., Puchalski, S.M. and Stover, S.M. (2013) Humeral stress remodelling locations differ in Thoroughbred racehorses training and racing on dirt compared to synthetic racetrack surfaces. *Equine Vet J* **45**, 176-181.

[15] Oikawa, M. and Kusunose, R. (2005) Fractures sustained by racehorses in Japan during flat racing with special reference to track condition and racing time. *Vet J* **170**, 369-374.

[16] Racing Victoria Limited 2017 Annual Report, Flemington, Victoria, Australia.

[17] Harkins, J.D. and Kamerling, S.G. (1991) Assesment of tradmill internal training on fitness. *J Equine Vet Sci* **11**, 237-242.

[18] Self, Z.T., Spence, A.J. and Wilson, A.M. (2012) Speed and incline during thoroughbred horse racing: racehorse speed supports a metabolic power constraint to incline running but not to decline running. *J Appl Physiol* **113**, 602-607.

[19] Verheyen, K., Price, J., Lanyon, L. and Wood, J. (2006) Exercise distance and speed affect the risk of fracture in racehorses. *Bone* **39**, 1322-1330.

[20] Morrice-West, A., Hitchens, P., Walmsley, E., Stevenson, M. and Whitton, R. (2020) Training practices, speed and distances undertaken by Thoroughbred racehorses in Victoria, Australia. *Equine Vet J* **52**, 273-280

[21] Hodgson, D.R. and Rose, R.J. (1994) *The Athletic Horse: Principles and Practice of Equine Sports Medicine*, Saunders, Philidelphia, PA, USA.

[22] Nunamaker, D.M. and Reynolds, R.S. (2002) Relationships of exercise regimen and racetrack surface to modeling/remodeling of the third metacarpal bone in two year-old Thoroughbred racehorses. *Vet Comp Orthop Traumatol* **15**, 195-199.

[23] Parkin, T.D.H., Clegg, P.D., French, N.P., Proudman, C.J., Riggs, C.M., Singer, E.R., Webbon, P.M. and Morgan, K.L. (2004) Risk factors for fatal lateral condylar fracture of the third metacarpus/metatarsus in UK racing. *Equine Vet J* **37**, 192-193.

[24] Walmsley, E., Steel, C., Haines, G., Lumsden, J. and O'sullivan, C. (2011) Colic after swimming exercise in racehorses: an investigation of incidence, management, surgical findings and outcome. *Aust Vet J* **89**, 180-183.

[25] Bolwell, C.F., Rogers, C.W., French, N.P. and Firth, E.C. (2013) The effect of interruptions during training on the time to the first trial and race start in Thoroughbred racehorses. *Prev Vet Med* **108**, 188-198.

[26] Misumi, K., Sakamoto, H. and Shimizu, R. (1995) Changes in skeletal muscle composition in response to swimming training for young horses. *J Vet Med Sci* **57**, 959-961.

[27] McCarthy, R.N. and Jeffcott, L.B. (1992) Effects of treadmill exercise on cortical bone in the third metacarpus of young horses. *Res Vet Sci* **52**, 28-37.

[28] Murakami, M., Imahara, T., Inui, T., Amada, A., Senta, T., Takagi, S., Kubo, K., Sugimoto, O., Watanabe, H. and Ikeda, S. (1976) Swimming exercises in horses. *Experimental reports of Equine Health Laboratory* **1976**, 27-49.

[29] Bolwell, C.F., Rogers, C.W., French, N.P. and Firth, E.C. (2012) Associations between yearling exercise and interruptions during race training in Thoroughbred racehorses. *Am J Vet Res* **73**, 1601-1616.

CHAPTER 4. VARIATION IN GPS AND ACCELEROMETER RECORDED VELOCITY AND STRIDE PARAMETERS OF GALLOPING THOROUGHBRED HORSES

4.1 PREFACE TO CHAPTER 4

Chapters 2 and 3 detailed the strategies employed for training Thoroughbred racehorses in Australia. For the evaluation of racing workloads, speed and distance have typically been used for quantification purposes. Chapter 4 uses GPS data obtained for individual horses in race starts in Tasmania, Australia including speed and stride characteristics, which provides the opportunity to assess potential differences within a large cohort of horses. The primary objective for Chapter 4 was to establish the extent to which speed and distance of galloping predicts changes in stride characteristics. This information is important in determining whether speed and distance can be used as a proxy for the extent of skeletal loading incurred, or, whether an individual horse's strides need to be considered.

A version of this chapter has been accepted for publication in the Equine Veterinary Journal (2020).

Supplementary material is presented in Appendix B.

4.2 ABSTRACT

Background: With each stride galloping horses generate large skeletal loads which influence bone physiology, and may contribute to musculoskeletal injury. Horse speed and stride characteristics are related, but the usefulness of using horse speed and distance travelled as a proxy for stride characteristics is unknown.

Objectives: We aimed to determine stride characteristics, their variance, and their relationship with speed in horses performing maximally.

Study Design: A retrospective analysis of stride characteristics obtained using GPS and inertial sensors in Thoroughbred horses.

Methods: Data per 200 m race segment ("sectionals") for horses competing in races (N=25,259 race starts) were analysed to determine if speed predicted stride parameters. Multivariable mixed-effects linear regression models were fitted.

Results: Mean (±standard deviation, SD) stride length, stride count (number of strides per 200 m), duration and speed were 7.08±0.39 m, 28.32±1.56 strides/200m, 0.43±0.02 s/stride and 16.63±1.04 m/s across all sectionals and starts. Speed and stride length decreased, and stride count increased with race progression ($P<0.001$). Male sex, greater race distance, better finishing position, and firmer track surfaces were associated with less strides per 200 m and longer stride durations.

Main limitations: Lack of an independent-party validation of the measurement system used in this study.

Conclusions: There was substantial inter-horse variation in stride parameters, with speed predicting half or less of this variation. Speed alone does not fully explain stride characteristics in horses. Future studies aimed at investigating the impact of gait on bone biology and pathology would benefit from accounting for stride characteristics (e.g. length and duration).

4.3 INTRODUCTION

Galloping horses generate large loads through the musculoskeletal system during each stance phase of the stride [1,2]. The magnitude and frequency of skeletal loading have important effects on bone physiology and pathology [1,3-5]. Because of the historic difficulty in measuring stride characteristics, distance and speed galloped by horses has typically been used as a proxy for cycles of load that occur with each stride [6,7] but the validity of this approach is unknown.

Investigations of racehorse stride characteristics have focussed on treadmill locomotor testing and/or slower speed exercise, with a smaller subset assessed at or close to maximum speed [8-12]. Studies assessing maximum speed stride characteristics have relied on short segments of high speed videography with frame-by-frame analysis [13]. The combined use of Global Positioning Systems (GPS) and limb-mounted accelerometers have been shown to accurately measure stride data in small scale equine studies [14-16]. Accuracy for galloping horses is compromised by the use of light weight receivers and the vertical oscillations galloping induces, although within the desired 25 cm positional accuracy [17]. A radio tracking system (TurfTrax) monitoring speed and position during racing was shown to measure speed to an accuracy of 0.15 m/s [18]. This tracking system, however, does not measure stride characteristics and it has been suggested that the correlation between reference point and acquired data requires scaling factors which may introduce additional uncertainty to the positional recordings [17]. Full race analysis or use of combined GPS-accelerometer systems during racing would allow for a detailed understanding of stride parameters at maximal speeds. Use of GPS technology in monitoring training and competition loads in human sports research has been recently implemented and there is the potential for similar widespread introduction to horseracing [19,20].

The most frequently reported stride parameters are stride length and either duration (i.e. seconds per stride) or its inverse – stride frequency (i.e. the number of strides per second). Galloping horses can increase their velocity by increasing stride length and/or reducing the duration of each stride [8,10,21]. A linear relationship has been described between increasing stride length and speed as well as decreasing stride duration and speed [8,10,13,21,22]. It has been hypothesised that once a horse achieves its maximal intrinsic stride length at speed (based on the limb length and maximal angles between limbs and trunk), increasing the stride frequency is the only remaining mechanism by which an increase in velocity can be achieved [9,13]. Alternatively, stride duration may be limited by respiratory-locomotor coupling since a minimum time is required for inspiration [22,23].

In order to: (1) establish the association between speed and stride characteristics; (2) detail the variation of these factors across the population of racehorses; and (3) assess how race- and horse-level factors influence these findings, we undertook a retrospective descriptive analysis of stride characteristics of Thoroughbred racehorses competing over a five-year period in Tasmania, Australia. We hypothesised that there would be a horse-level correlation between speed and stride parameters, and that speed would be dependent on stride length, stride count (number of strides per 200 m) and duration, increasing proportionally more with stride duration than stride count (and therefore length) at higher speeds. Secondly, we hypothesised that these parameters would differ by horse-level characteristics as well as race-level factors such as race class and race distance.

4.4 MATERIALS AND METHODS

4.4.1 Data sources

Race start data from every Thoroughbred racehorse competing in 33,459 starts across three racing venues in Tasmania, Australia, between 10th of July 2011 and 21st of August 2016 were available for analysis, where all horses are routinely fitted with a stride measurement device. Race results were extracted from the official racing repository (Racing Australia Ltd.) including horse name, race date, barrier number, racetrack (venue), race number, race distance, track rating, finishing position and race time. A race meeting was defined as a series of races taking place at a single venue on a single day. Track surfaces were classified as turf (Launceston, Hobart) or synthetic (Devonport). Race classes were categorised as: (1) Maiden and Class 1 races, i.e. races where all starters have not previously won a race and have not won more than one race respectively; (2) Class 2-5, where starters have won no more than the respective number of races; (3) Restricted races- Benchmark (BM) and Handicap (HCP) races (races in which horses are assigned weights based on their rating); (4) Open races- no special conditions or restrictions; and (5) Listed and Group races. We obtained the summarised data (per 200 m segment of race; "sectional") for the number of strides, stride duration, stride lengths and margins (number of horse lengths) from the race leader. Data were collected by Tasmania's principal racing authority Tasracing using StrideMasterTM (Thoroughbred Ratings Pty Ltd, Romsey, Victoria, Australia) recording devices. Each Stridemaster device includes GPS, a Global Navigation Satellite system (GLONASS), and a three-axis accelerometer. The frequency of positional data capture was 5 Hz (five recordings per second) and an accelerometer frequency of 800 Hz. The device weighs approximately 100 g and has an internally-validated reported positional accuracy of approximately 10 cm after proprietary correction algorithms are applied. The device was mounted on saddle cloths of each horse in every race start.

The dataset was sorted by date within horse identification number and then each race start was assigned a race start number for each horse (n = 33,459 individual race starts). Erroneous values were identified and excluded from statistical analysis according to Figure 4.1. Biologically plausible speed and stride parameters were defined based on published data for galloping horses under non-race conditions [13], and manual assessment of detailed records of second-by-second GPS recordings provided by the manufacturer. The resulting exclusion criteria for the GPS and accelerometer derived data were: speeds below 12.57 m/s or above 21 m/s, stride lengths below 5.3 m or greater than 9.2 m, and stride durations below 0.37 seconds or greater than 0.49 seconds. As the present study aimed to describe characteristics of healthy horses only, we excluded horses that pulled up, lost a rider, fell, or were injured or disqualified. The official race result dataset was merged with the StrideMaster dataset using a one-to-one match on race date, race track, race number, and horse name. The final merged dataset for analysis consisted of 25,259 starts. This included 153,315 observations (200 m sectional recordings within race starts) for 2,678 individual horses (Figure 4.2).

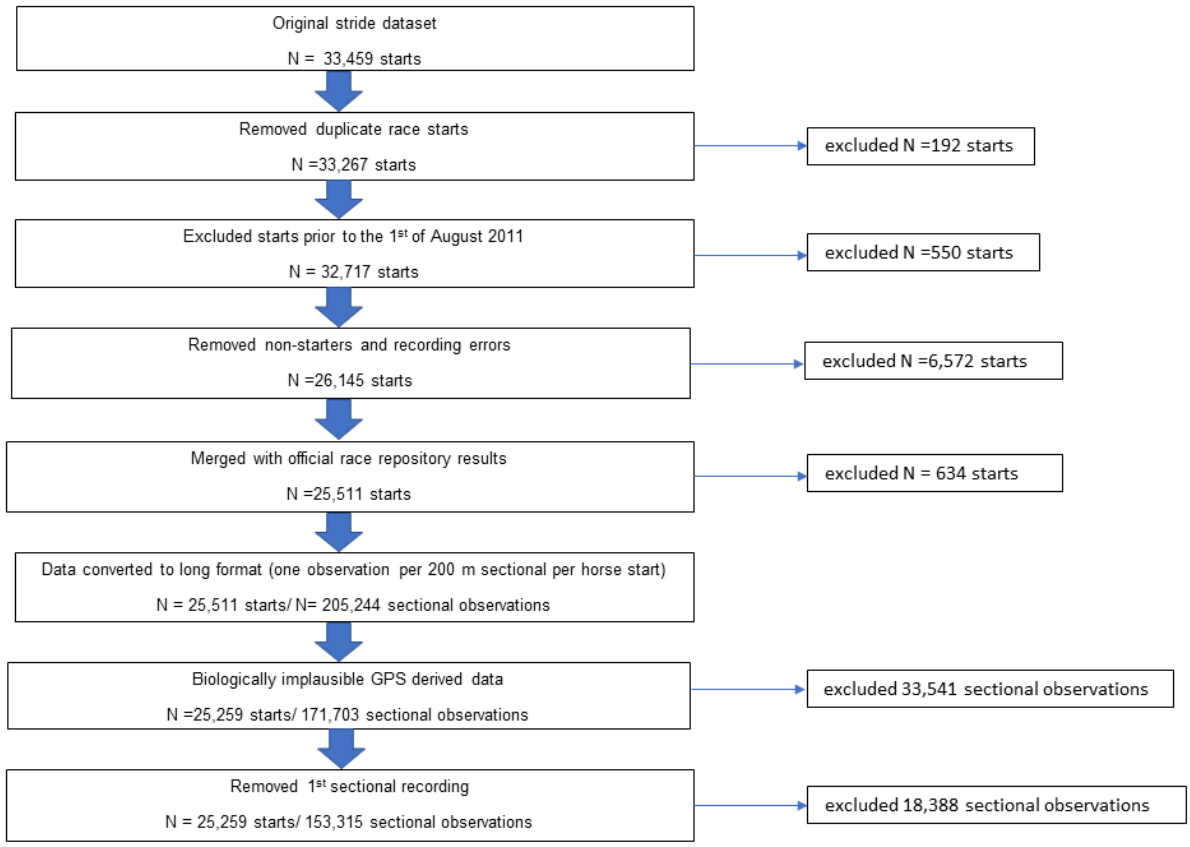

Figure 4.1. *Flowchart illustrating the size of the database used and sequential data exclusion.*

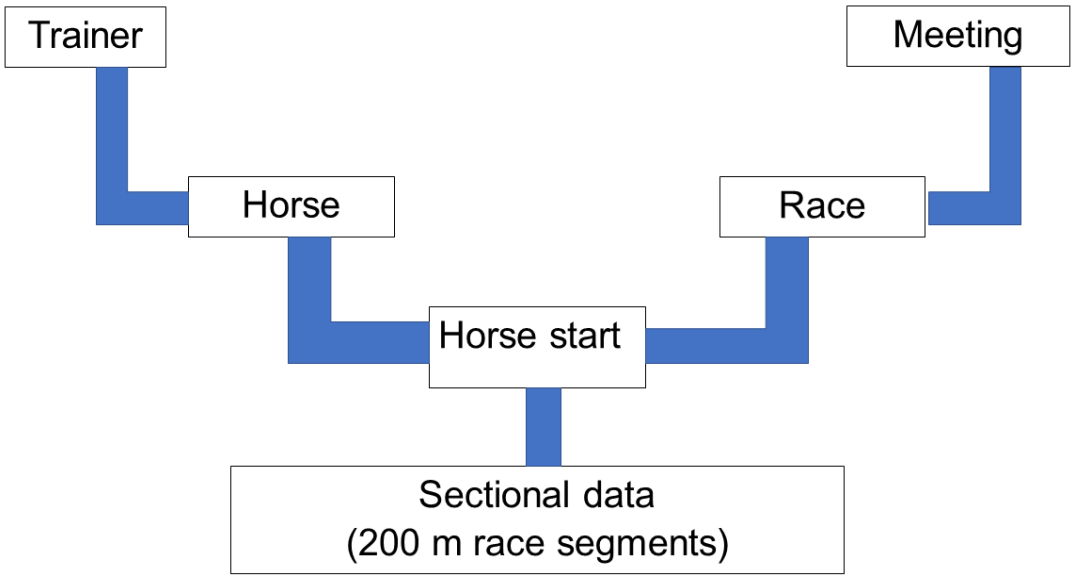

Figure 4.2. *Data structure showing the cross-classified hierarchy of 200 m race sectional stride and speed data of individual starts within individual horse and within race and meeting, for GPS recorded Thoroughbred races in Tasmania, Australia.*

The number of previous starts for horses that had commenced their racing career prior to the study period was extracted from the original official racing database. This was summed with the start number in the study period to generate a career start number by race start per horse. Horse-age was assessed both as official racing age according to race season (integer) and age in years/months according to its date of birth (decimal).

4.4.2 **Statistical analysis**

Analyses were conducted in two parts: (1) for each race stage at selected 200 m sectionals for the early, middle and late race (staged models); and (2) for all sectionals over the entire race. The staged models were employed to account for the unbalanced data across race distances and to reduce computation time. Early race stage = the second sectional (n = 24,978), middle = the half-way sectional (n = 25,220) and late = the final sectional (n = 25,040). Descriptive analyses were undertaken on the main outcomes of interest: speed, stride length, number of strides, stride duration. Stride length was calculated as 200 m divided by the number of strides per 200 m. Descriptive statistics were stratified by race distance and track surface type. Normality of continuous data was assessed using frequency histograms and Shapiro-Wilk tests.

Associations between stride parameters were quantified using pairwise Pearson correlation coefficients and presented as R-squared values. To assess whether a linear equation appropriately described the nature of the relationship between stride length and duration (independent variables) with speed (dependent variable), the Stata 'curve fit' package was employed which implements 34 alternative non-linear transformations. Model fit was assessed by correlation coefficients and minimisation of Akaike's information criterion (AIC) as well as graphically [24]. We generated a variable for the maximal sectional velocity for each horse over the entire data-set. We defined elite horses based on (1) the top ten percent of horses according to maximal sectional speed (vs the remaining 90% of horses), and (2) horses that won or placed

in each race start (vs the other starters in that race start). We used scatterplots to assess for an observable plateauing of either stride variable (length or duration), and then stratified our analysis by horse categorised as elite vs non-elite. In both stratifications no evidence of plateauing was detected. The relationship between speed and the number and duration of strides are presented as Sunflower plots (a density-based scatter plot) due to the large number of observations with overlapping speed-to-stride measure pairs observed [25]. Using the outcome of speed, three-way-interactions between the number of strides per 200 m, stride duration (s) and a series of race-level factors were analysed and assessed graphically to understand the strategies horses use to change speed during a race. The race-level variables assessed included race distance, track rating, stage of race, finishing position (win vs lose, place vs lose, place vs finishing in the bottom three), as well as elite horses vs the remaining cohort. Plots for each variable consisted of the linear prediction of the slope of each stride variable based on changes in the corresponding stride variable and the race-variable.

Two separate regression analyses were carried out to identify factors associated with each of the stride variables [number of strides per 200 m and stride duration (s)]. In the first, for 200 m sectionals from the early, middle and late stages of the race, the univariable association between the explanatory variables trainer, track surface type and condition, distance and class of race was assessed by fitting univariable mixed-effects linear regression models. Here, a zero-mean, Gaussian distributed random intercept term was included in the model to account for lack of independence in the data arising from repeated observations on individual horses over time. Explanatory variables from the univariable analyses described above that were associated with the study outcome with $P<0.2$ were then selected for inclusion in the multivariable analysis for which we used a backwards stepwise variable selection procedure. All explanatory variables that were unconditionally associated with the outcome with $P<0.2$ were entered into the model and then removed one at a time, beginning with the least significant, until only those at $P<0.05$

remained. Explanatory variables were then re-entered into the model and retained if there was more than a 10% change in the magnitude of the regression coefficients of the other variables. Variables retained were screened for biologically plausible interaction effects. Diagnostics conducted included evaluation of model residuals, linearity, heteroscedasticity, and goodness of fit. Descriptive statistics, univariable and multivariable analysis at 200 m sectionals for the early, middle and late race were analysed using Stata version 15.0.[a]

In the second analysis for all 200 m sectionals over the entire race, explanatory variables found to be significant in the final multivariable models described above were included in a cross-classified multi-level multivariable model for each stride measure using the lmer function in R (R Core Team 2017).[b] The hierarchal levels in this data set comprised sectional observations nested within horse start, horse starts nested within individual horses and horses nested within trainer. In addition, there was a cross-classified hierarchy with horse starts nested within races within meetings (Figure 4.2). Zero-mean, Gaussian distributed random effect terms were included in the model to account for these unmeasured influences on stride variables. As for the approach taken for the first analysis, backwards stepwise variable selection was used. Variance estimates of each of the random effect terms are reported as standard deviations, in addition to the intraclass correlation coefficient (ICC). The ICC quantifies the proportion of unexplained variation in the data attributable to each hierarchal level. Assessment of model fit was made on the basis of minimising the Bayesian information criterion (BIC) and visual assessment of scatter plots of observed versus predicted model outcomes. Model diagnostics were performed as per analysis (1).

4.5 RESULTS

Speed and stride characteristics are presented in Table 4.1 and Figure 4.3. R-squared correlations between speed and stride parameters are presented in Table 4.2. Speed correlated more strongly with the number of strides than with stride duration, but both stride variables had the greatest correlation in the final 200 m of each race ($P<0.001$; Table 4.3, Figure 4.3). The number of strides per 200 m and stride duration increased, and stride length and speed decreased with race progression ($P<0.001$). Mean (±SD.) stride length, number of strides, stride duration and speed were 7.08±0.39m, 28.32±1.56 strides/200 m, 0.43±0.02 s/stride and 16.63±1.04m/s across all sectionals and starts. Linear models, compared to the non-linear transformations implemented in 'curve fit' best described the relationship between stride length and speed and stride duration and speed. There was no observable deviation from linearity for all stride characteristics between the elite horses and the general cohort, nor with race distance or finishing position based on scatter plots and density scatter plots. Using three-way interactions, all stride variables responded similarly to increasing speed under differing conditions.

Table 4.1. *Descriptive analysis of speed and stride characteristics (mean ± SD.) determined by StrideMaster GPS and accelerometer derived data for n=25,259 Thoroughbred race starts, by 2,678 horses [totalling 153,315 sectionals observations (200 m race segments)] in Tasmania, Australia. Results are stratified by the distance (m) and the class of each race start.*

Track surface		n (sectionals)	Speed (m/s)	Stride count (strides per 200 m)	Stride length (m)	Stride duration (s)
Turf	**Race distance (m)**					
	≤1200	16,373	17.01±1.07	28.48±1.59	7.04±0.39	0.41±0.02
	>1200 - ≤1600	57,234	16.74±0.97	28.35±1.57	7.07±0.38	0.42±0.02
	>1600 - ≤2000	17,938	16.40±0.93	28.37±1.55	7.07±0.38	0.43±0.02
	>2000 - ≤2400	19,292	15.99±0.91	28.42±1.49	7.06±0.37	0.44±0.02
	>2400	1,699	15.92±0.88	28.33±1.46	7.08±0.36	0.44±0.02
	Race class					
	Maiden/Class 1	54,236	16.56±1.02	28.51±1.57	7.04±0.38	0.43±0.02
	Class 2-5	10,570	16.94±0.97	28.21±1.53	7.11±0.38	0.42±0.02
	HCP/BM[+]	38,362	16.49±1.02	28.35±1.55	7.07±0.38	0.43±0.02
	Group/Listed	4,540	16.44±1.03	28.03±1.39	7.15±0.35	0.44±0.02
	Open	4,828	16.96±1.01	28.00±1.43	7.16±0.37	0.42±0.02
Synthetic	**Race distance (m)**					
	≤1200	16,960	17.09±1.17	28.19±1.66	7.12±0.42	0.42±0.02
	>1200 - ≤1600	8,898	16.81±0.92	27.99±1.57	7.12±0.42	0.42±0.02
	>1600 - ≤2000	14,323	16.29±0.78	28.14±1.46	7.13±0.37	0.44±0.02
	>2000 - ≤2400	598	15.56±0.73	28.74±1.46	6.98±0.35	0.45±0.02
	Race Class					
	Maiden/Class 1	20,503	16.70±1.10	28.30±1.61	7.09±0.40	0.43±0.02
	Class 2-5	3,808	17.01±1.07	27.98±1.58	7.17±0.41	0.42±0.02
	HCP/BM	16,428	16.68±0.99	27.96±1.50	7.17±0.39	0.43±0.02
	Open	40	16.64±0.46	27.36±1.40	7.33±0.37	0.44±0.02

[+]Handicap/Benchmark races

Table 4.2. *Pearson correlation coefficients as R-squared values and their associated 95% confidence intervals (95%CI) for speed (m/s), number of strides per 200 m and stride duration (s) of n=25,259 Thoroughbred race starts in Tasmania, Australia using GPS and accelerometer derived data and stratified by three stages of each race.*

Outcome	Early[+]	Middle[+]	Late[+]	All race sectionals[+]
Number of strides to speed	0.423 (0.412 ,0.432)	0.375 (0.365 ,0.383)	0.536 (0.527 ,0.543)	0.510 (0.506, 0.513)
Stride duration to speed	0.203 (0.195 ,0.213)	0.166 (0.158 ,0.174)	0.269 (0.260 ,0.279)	0.270 (0.266 ,0.274)
Number of strides to stride duration	0.145 (0.137 ,0.154)	0.221 (0.213 ,0.230)	0.040 (0.035 ,0.44)	0.049 (0.048 ,0.051)

[+]All correlations $p<0.001$

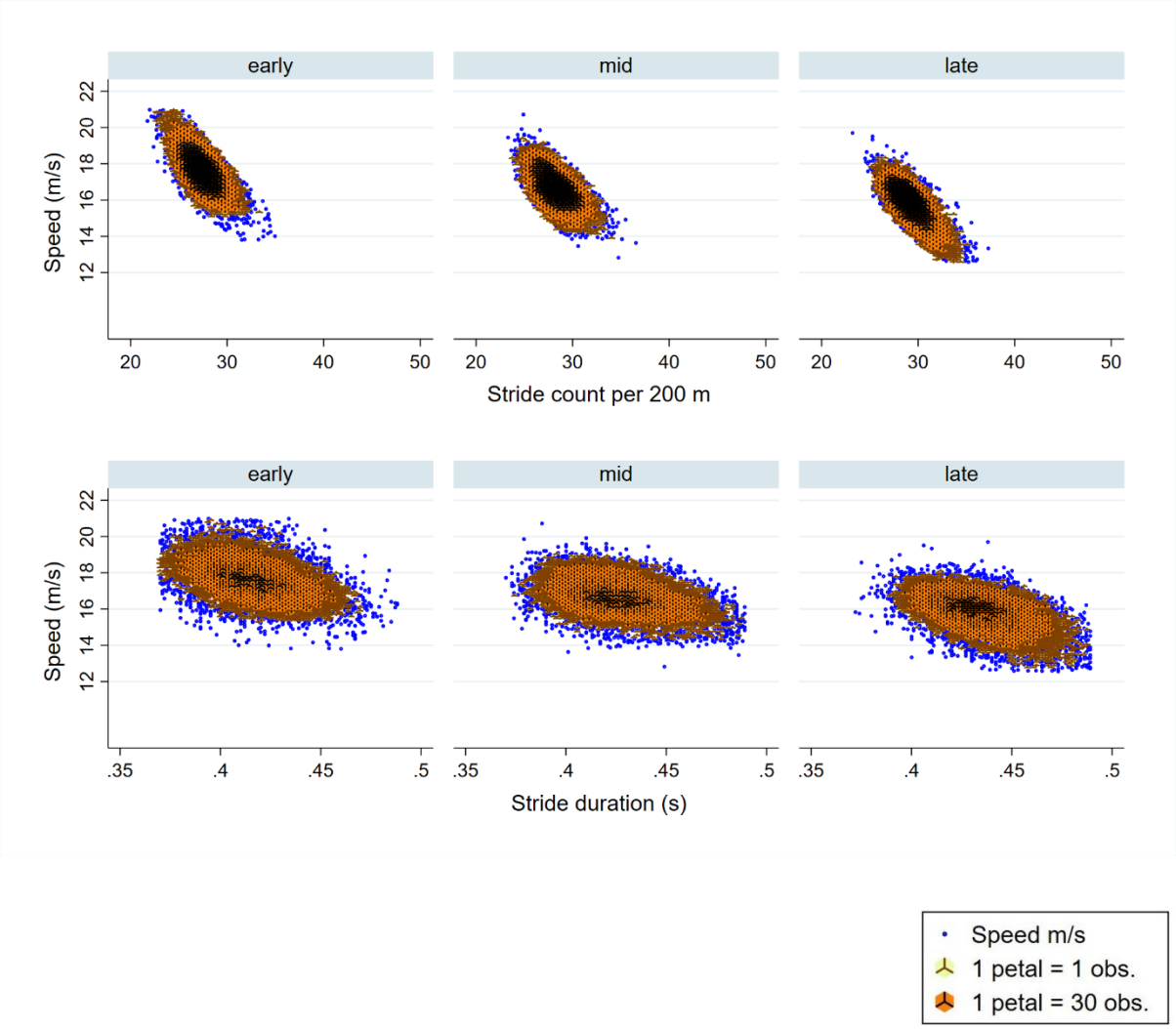

Figure 4.3. *Sunflower density plot showing the relationship of speed with sectional (200 m) averages for the number of strides per 200 m (top row) and stride frequency (bottom row) in Thoroughbred racing for n=25,259 race starts in Tasmania, Australia derived from GPS recordings. From low density (peripheral) to high density (central areas): blue areas represent one-two observations, followed by moderate density, where each brown segment of the region represents one observation. The high-density region is shown in orange, with each black segment representing 25 observations. The darkest middle region therefore represents the highest density of overlapping observations.*

Univariable associations between stride variables and horse- and race-level factors for early, mid and late race stages are presented in Table S1. In the multivariable staged models for the first set of analyses accounting for speed as a fixed effect, male sex, greater race distances, and firmer track surfaces were associated with fewer strides per sectional and longer duration of strides (Figure 4.4). Male sex (geldings and intact males) was associated with fewer strides per sectional and longer stride durations, with geldings having the lowest number and longest duration and mares and fillies having the greatest number of strides of the shortest duration ($P<0.001$). Horses competing in longer distance races took fewer strides and strides of longer duration per 200 m sectional, an effect which was strongest mid race ($P<0.001$). Horses' stride characteristics on the synthetic track surface were similar to harder turf tracks (Figure 4.4). On turf tracks, the number of strides per sectional increased and stride duration decreased with increasing track rating, where firm tracks had the lowest number of strides per sectional and heavy tracks the greatest number of strides ($P<0.001$). Horses racing in Maiden and Class 1 races (lower class races) had a greater number of strides in the early race stages, with Listed and Group races (high class races) associated with the least number of strides per sectional ($P=0.02$). Horses that finished in a better position took less strides per sectional of longer stride durations early and mid-race, with more strides of shorter duration in the final sectional ($P<0.01$). Horses with a greater number of career starts took more strides per sectional in the mid and final sectionals ($P<0.01$). Weight carried was influential in the early and mid-race stages, with higher weights associated with fewer strides and longer stride durations ($P<0.001$). In the early race stage, older horse age was associated with longer stride durations ($P=0.04$) and shorter stride durations mid race ($P<0.001$).

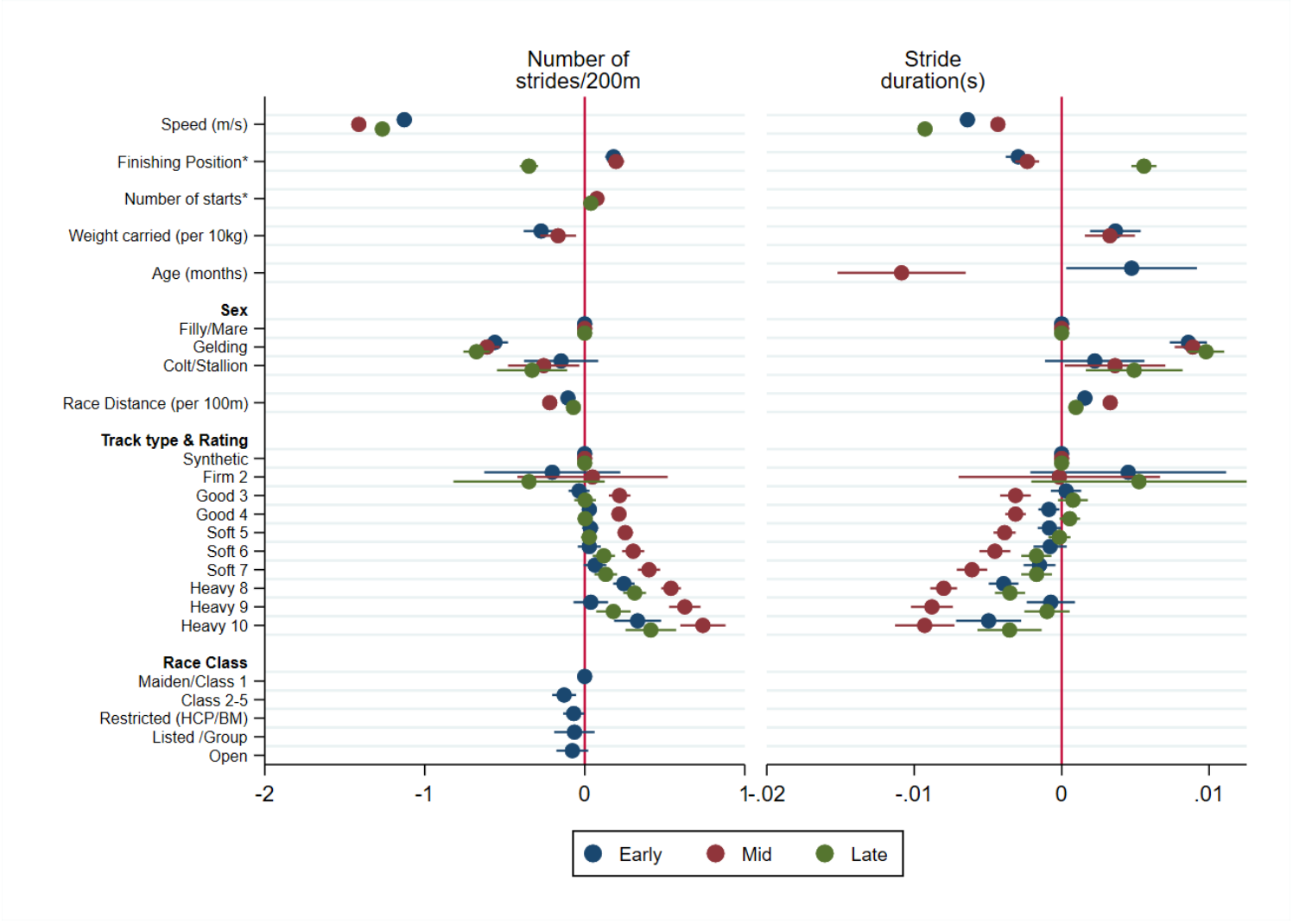

Figure 4.4. *Coefficient plot from multivariable linear regression modelling of speed in each of the 25,259 race starts to the number of strides taken in 200 m sectionals (left pane) and the duration of strides (right pane), showing the proportional change of horse and race-level factors on the respective stride parameters in the early, middle and late stages of Thoroughbred racing in Tasmania, Australia, plotted as coefficients and their 95% confidence intervals.*

The vertical zero red reference line indicates no effect or the reference category. For number of strides (left pane), points to the left imply less strides per 200 m (longer stride length) and to the right implies more strides. In the right pane, points to the left of the reference line implies shorter stride durations and to the right implies greater stride durations.

**Finishing position (where 1 is the winning horse) and number of career starts rescaled to per 10 places and per 10 starts, respectively.*

Missing points for weight carried, age and race class variables imply non significance in multivariable models. Interaction screening identified a relationship between a negative quadratic term for the percentage of race completed (i.e. a non-linear reduction in each respective stride parameter as horses approach the end of the race) and speed, with speed reducing as the horse approaches the end of the race, as well as an interaction between weight carried and race-class.

We identified two significant variable interactions. Firstly, between speed and the percentage of the race complete, speed was found to decrease in a non-linear (quadratic) fashion as the horse approached the end of the race, where with race progression there was a greater variability in strides according to speed. Horses racing at slower speeds took more strides towards the end of the race, compared to those racing at faster speeds that tended to maintain fewer strides. Secondly, an interaction between weight carried and race-class was identified, where in higher race classes the number of strides taken per sectional were maintained as weight carried increased. For other race classes there was a gradual reduction in the number of strides per sectional with increased weight, and in lower class races the rate of reduction in the number of strides per 200 m was more marked for every unit increase in weight carried.

In the cross-classified multi-level models across all 200 m sectionals race characteristics and horse sex influenced both the number of strides taken and the duration of strides (Table 3.3). Model fits were improved by the addition of a quadratic term for the percentage of the race complete interacting with the mean speed of each sectional recording, where speed gradually increased during each race start and then reduced as horses approached race completion. The cross-hierarchal multivariable models were improved by the addition of the interaction between class to weight carried described.

The majority of the unexplained variance in stride parameters was at the individual horse-level, with less variation at the start, race, meeting or trainer level (Table 3.3). The horse-level ICC for the number of strides taken and the duration of strides was 0.658 and 0.655, respectively. That is, sixty-six percent of the total unexplained variation in each stride variable was attributable to unmeasured horse-level effects.

Table 4.3. *Multivariable models of number of strides per 200 m sectional and stride duration of n=25,259 Thoroughbred race starts (totalling 153,315 sectional observations) in Tasmania, Australia using GPS and accelerometer derived data. Model results are presented as regression coefficients, with associated standard errors of the mean (s.e.m.), t-values, p-values and 95% confidence intervals. Variation at each hierarchal level (random effect terms) is displayed as the standard deviation (intraclass correlation coefficients [ICC]).*

	Number of strides per 200 m				Stride duration (s)			
	Regression coefficient (s.e.m)	**t value**	**p value**	**95%CI**	**Regression coefficient (s.e.m)**	**t value**	**p value**	**95%CI**
Fixed effects								
Speed (m/s)	-1.134 (0.002)	-609.97	<0.001	-1.138, -1.130	-0.009 (0.000)	-318.52	<0.001	-0.009, -0.009
Horse Sex								
Filly/Mare	(reference)				(reference)			
Gelding	-0.658 (0.032)	-20.25	<0.001	-0.722, -0.594	0.010 (0.001)	20.38	<0.001	0.009, 0.011
Colt/Stallion	-0.429 (0.103)	-4.15	<0.001	-0.632, -0.227	0.007 (0.002)	4.26	<0.001	0.004, 0.010
Race Distance (per 100 m)	-0.077 (0.001)	-63.82	<0.001	-0.079, -0.075	0.001 (0.000)	68.98	<0.001	0.001, 0.001
Track type & Rating								
Synthetic	(reference)				(reference)			
Firm 2	-0.005 (0.128)	-0.04	0.97	-0.257, 0.246	-0.0001 (0.002)	-0.06	0.96	-0.004, 0.004
Good 3	0.028 (0.025)	1.13	0.26	-0.021, 0.077	-0.0002 (0.0004)	-0.63	0.53	-0.001, 0.0005
Good 4	0.047 (0.017)	2.72	0.01	0.013, 0.081	-0.001 (0.0003)	-2.23	0.03	-0.001, -0.0001
Soft 5	0.081 (0.019)	4.36	<0.001	0.045, 0.117	-0.001 (0.0003)	-4.62	<0.001	-0.002, -0.001
Soft 6	0.179 (0.028)	6.47	<0.001	0.124, 0.233	-0.003 (0.0004)	-6.85	<0.001	-0.004, -0.002
Soft 7	0.293 (0.029)	10.15	<0.001	0.236, 0.349	-0.004 (0.0004)	-10.32	<0.001	-0.005, -0.004
Heavy 8	0.442 (0.027)	16.51	<0.001	0.389, 0.494	-0.006 (0.0004)	-15.91	<0.001	-0.007, -0.006
Heavy 9	0.508 (0.047)	10.76	<0.001	0.415, 0.601	-0.007 (0.0007)	-9.32	<0.001	-0.008, -0.005
Heavy 10	0.642 (0.067)	9.53	<0.001	0.510, 0.774	-0.008 (0.001)	-8.32	<0.001	-0.010, -0.006
Finishing position (per 10 places)	0.111 (0.007)	16.17	<0.001	0.097, 0.124	-0.002 (0.0001)	-15.61	<0.001	-0.002, -0.001

Percentage race complete (x)	104.874 (10.63)	9.87	<0.001	84.049, 125.699	10.194 (0.159)	48.61	<0.001	9.918, 10.470
Percentage race complete (x^2)	642.709 (9.376)	-68.55	<0.001	-661.086, -624.332	0.552 (0.141)	72.42	<0.001	0.548, 0.555
Weight carried (per 10kg)	-0.017 (0.019)	-0.91	0.36	-0.053, 0.019	0.0002 (0.0003)	0.87	0.39	-0.0003, 0.001
Race class								
Maiden/Class 1	(reference)				(reference)			
Class 2-5	0.067 (0.192)	-1.39	0.16	-0.221, 0.087	0.004 (0.003)	1.55	0.12	-0.001, 0.010
Restricted (HCP/BM)	-0.255 (0.134)	-1.91	0.06	-0.518, 0.007	0.004 (0.002)	2.05	0.04	0.0002, 0.008
Listed /Group	0.071 (0.659)	-0.56	0.58	-0.158, 0.299	0.009 (0.01)	0.97	0.33	-0.010, 0.029
Open	0.479 (0.444)	1.08	0.28	-0.391, 1.349	-0.006 (0.007)	-0.9	0.37	-0.019, 0.007
Intercept	48.592 (0.114)	427.63	<0.001	48.369, 48.814	0.552 (0.002)	324.71	<0.001	0.548, 0.555
Interaction terms								
Speed:Percentage race complete (x)	-3.782 (0.641)	-5.9	<0.001	-5.037, -2.526	-0.510 (0.010)	-53.1	<0.001	-0.529, -0.491
Speed:Percentage race complete (x^2)	39.435 (0.566)	69.74	<0.001	38.327, 40.544	-0.634 (0.008)	-74.72	<0.001	-0.651, -0.618
Weight carried:Maiden/Class 1	(reference)				(reference)			
Weight carried:Class 2-5	0.056 (0.034)	1.64	0.10	-0.011, 0.124	-0.001 (0.001)	-1.79	0.07	-0.002, 0.0001
Weight carried:Restricted (HCP/BM)	0.062 (0.566)	2.6	<0.001	0.015, 0.109	-0.001 (0.0004)	-2.74	0.01	-0.002, -0.0003
Listed /Group	0.071 (0.071)	0.61	0.54	-0.158, 0.299	-0.002 (0.002)	-1	0.32	-0.005, 0.002
Weight carried:Open	-0.067 (0.079)	-0.854	0.39	-0.221, 0.087	0.001 (0.001)	0.71	0.48	-0.001, 0.003
Random effects	SD. (ICC)				SD. (ICC)			
Horse start	0.178 (0.032)				0.003 (0.032)			
Horse	0.808 (0.658)				0.012 (0.655)			
Race	0.122 (0.015)				0.002 (0.013)			
Meeting	0.110 (0.012)				0.002 (0.013)			
Trainer	0.119 (0.014)				0.002 (0.015)			

4.6 DISCUSSION

We found that speed predicted approximately half of the variation in the number of strides per 200 m sectional and less of the variation in stride duration in this cohort of Thoroughbred racehorses galloping over a variety of distances. The largest degree of variation in stride parameters was at the individual horse level. Horse stride characteristics differed based on sex, age and race-level factors. Male sex, greater race distances, better finishing positions, and firmer track surfaces were associated with fewer strides per sectional and longer stride durations.

Previously, stride and gait parameters have been determined for horses galloping on treadmills where stride parameters are altered compared with overground galloping [8,26-29]. At racing-speeds, overground stride variables have been visually assessed through videography, but sophisticated recording methods have not been applied to race events where horses perform with maximal effort [10,13]. A single horse running at approximately 16.7 m/s for 860 metres took approximately 28 strides per 200 m (although this included an initial acceleration from rest) [15], similar to our mean reported stride count of 28.32 (±1.56) strides per 200 m. A larger high-speed video study of 3,008 horses undergoing short sprints (non-racing conditions) reported horses to have a mean maximum velocity of 16.3 m/s, with a mean stride length of 6.7 m [13]. This is similar to the present study where we found a mean sectional velocity of 16.6 m/s and stride length of 7.1 m, which may reflect the more competitive race-day environment. Leach *et al.* [22] analysed stride timing variables of five consecutive strides of 22 Thoroughbreds aged three years and above in the early stages of dirt racing on a 1,005 m track. Mean stride durations of 0.405 seconds (±0.027) were reported, similar to our early race stride durations of 0.42 (±0.02) for turf and 0.41 (±0.02) for synthetic tracks. Dirt tracks are not typically used in Australian racing, but the similarity in stride timing across these three racing surfaces is interesting given that our data highlights that track type and track surface influence stride duration.

In line with previous investigations we found a correlation between stride count (and therefore stride length) and speed [10,29], and a correlation with duration of stride and speed that was comparatively less strong [10,30]. However in horses bred for sprinting ability (Quarter Horses) speed was more influenced by stride duration than stride length at speeds of 10-15 m/s [31]. Additionally, these horses were not able to further increase stride length at high speeds, compared to their observed linearity at slower speeds [31]. Others have similarly observed a non-linear relationship between stride length and speed in individual horses with the rate of increase of stride length reduced at higher speeds [9]. Early locomotion reports across several quadrupedal species including horses showed that at all gallop speeds, stride duration is maintained, whereas others have identified stride duration as the limiting factor for a horse's maximal velocity [21,22]. The limiting effect of respiratory-locomotor coupling was not observed in our investigation based on a lack of plateauing of stride duration at high-speed. It is possible that our imposed limits of biological plausibility masked such an effect; however, Witte *et al.* [8] were also unable to demonstrate this phenomenon, albeit in a much smaller cohort of nine horses. Our results do, however, suggest that at the highest speeds, a horse must necessarily employ its maximal stride length and minimal stride duration, whereas at non-maximal galloping speeds it is possible to use a variety of strategies to achieve different speeds. The linear relationship we observed between these stride parameters and speed at the cohort level aligns with a recent study of speed influencers in non-maximal human running [32]. In that study, whilst individual participants' stride frequencies were best described by a quadratic change in speed, some subjects had a negative quadratic term whilst others had a positive term, which at the study population level generated an overall linear effect [32].

Over the course of a race start, horse speed and stride length reduced and stride count and stride duration increased. Leach and Sprigings [33] assessed the speed of 17 horses at the beginning

and end of their races (1200-1400 m) and, similar to our findings, all horses reduced speed and increased stride duration over the course of the race. Investigations of speed and racing position across a large number of race starts in the UK identified a similar reduction in speed with race progression [34]. In that study, speed was influenced by racing strategy, race distance and positioning within the field to reduce wind resistance [34]. Our finding of reducing speed and stride length during a race is comparable to data in human triathletes which the authors suggested was in response to fatigue [35]. Similarly, changes in stride length and frequency of horses at the end of a race were termed "gait fatigue" by Leach and Sprigings [33]. That study showed a consistent relationship between stride duration and speed, but divergent responses between stride length and speed; approximately half of the horses reduced, a third maintained, and the remainder increased their stride length despite reduced speed [33]. The authors described the latter category as "over-striding" indicative of poor running technique compared to the more energy efficient pattern of a shorter stride length at a higher stride frequency. As a cohort, our horses demonstrated both reduced stride length and increased duration (reduced frequency) in association with the reduction in speed.

Individual horse-level factors were associated with stride characteristics. Female horses took the greatest number of strides per sectional with the shortest stride duration. Differing stride characteristics based on horse-level factors were previously recorded in non-race galloping sessions, with fillies having shorter strides compared to colts, and 2-year-olds having shorter strides than older horses [13]. We postulate that this is in part due to the smaller body size and shorter limb length of female and younger horses [36-38]. Comparatively, age had a more variable effect on duration of stride by race stage in the present study and was not statistically significantly associated with the number of strides taken. Total race time decreases (i.e. horses run faster) for 3-year-olds compared with 2-year-olds [39]. Higher weight carried was associated with reduced number of strides of greater duration in the early and mid-race stages. Across all 200 m race

sectionals, this effect was more prominent in lower class races, with horses in high class races maintaining their stride characteristics as weight carried increased. There was no effect on stride duration of increasing weight carried in Warmbloods at walk, trot or canter, although carrying 10% additional bodyweight in Standardbreds was associated with an increased stride rate [29,40]. The effect of weight on stride length for galloping horses has not been analysed to the best of our knowledge. Finally, in the present study, for the late stages of a race better finishing positions were associated with greater stride counts (shorter stride lengths). The final 200 m sectional corresponds with the most competitive environment, and therefore it could have been expected that stride lengths would be longer for better performing horses. However, in this part of the race the shorter stride durations were associated with improved performance. In humans stride length is positively correlated with performance, which agrees with the association between finishing position and stride length we observed over whole race starts [35].

The majority of the unaccounted-for variance in the number of strides and duration of strides was at the individual horse level. There is limited data assessing the variation in strides between large groups of horses. A study of only three Thoroughbreds showed that stride length and duration had low intra-horse variability at a canter and gallop [9]. At the gallop, a high inter-horse variation for frequency of limb suspension (absence of hoof to ground contact) during a stride and limb/lead preference has also been demonstrated [41]. Studies of Standardbred horses trotting showed two to three times greater variation in stride characteristics between horses than within horse [42]. The applicability of trot-based studies on galloping locomotion is unclear; however, the high inter-horse variation in equine literature supports the notion of stride characteristics being an identifiable quality of individual horses.

A smaller proportion of the unaccounted-for variance in the number of strides and duration of strides was at the race and race meeting level. Important factors included track type and rating,

race distance, and class. There is limited published literature on the effect of race or race-day factors on stride characteristics. Shorter race distances were associated with a higher number of strides per sectional, but we are unaware of previous reports of the association between race distance and stride variables. Track surface has been shown to influence race speeds, with firmer tracks associated with faster race times [43]. Leach *et al.* [22] noted good agreement in stride parameters on different track surfaces which they suggested may indicate an innate breed-related stride characteristic. Although we found variation in the number of strides taken per sectional and stride duration according to track type in our univariable analyses (i.e. the binary turf vs synthetic track surface variable), this term was excluded due to collinearity with venue and surface rating in our multivariable models. It could be argued that the variation in the multivariable models was more of a difference based on the firmness of the surface rather than the surface type itself. In our study, horses on turf tracks had greater stride lengths of longer duration on firmer surfaces. The synthetic surface was also associated with greater stride lengths, however firmness was not recorded, and, because there was only one synthetic surface in our dataset, it was not possible to separate venue and track surface effects. Venue effects could include radius of turns and changes in gradient throughout each track. A study of pacing horses showed that stride length and velocity was lowest on the transition entering a curve and stride duration longest at the true curve segment of the turn [44]. In slower speed Thoroughbred studies (9-13 m/s), horses reduced their stride duration (greater frequency of strides) with larger inclines, and race-day evaluations on undulating tracks have shown that horse speed reduces on declines as well as on inclines compared to flat locomotion [29,45,46].

Equine limbs need to withstand large forces when galloping at racing speeds and the magnitude and duration of loading is associated with injury [1,3,4,47,48]. Therefore, variation in stride characteristics could be an important contributor to an individual's risk of injury. Of the horse- and race-level factors associated with stride characteristics in the present study, in particular

older age, male sex, and firmer turf track surfaces are demonstrated risk factors for race-day catastrophic musculoskeletal injuries [49]. The largest degree of variation in stride characteristics found was between individual horses; therefore, comparing horses in determining injury-risk may not be as important as longitudinal monitoring individual horses to recognise changes in stride parameters over time.

The main limitation to this study is the lack of independent-party validation and the potential for inaccuracy of GPS and accelerometer readings. The system was validated during the manufacturing process prior to becoming commercially available, with positional accuracy to 10 to 25 cm (personal communication David Hawke, Managing Director StrideMaster). Based on advice provided we excluded the first sectional reading due to potential interference of the metal starting gates and actions of the jockeys. A French product's validation (20 Hz GPS & GLONASS system) showed variation in accuracy of measurements with varying racetracks and it is unclear if similar factors may have influenced the Tasmanian data [17]. Those authors hypothesised that this was due to differences in terrain and infrastructure surrounding the track affecting satellite reception. Our data represented speed and stride parameters averaged over 200 m at different racetracks, and therefore turns and undulation/topography were not considered. Higher resolution data (by second or by metre) would be required to allow for inclusion of these factors. The sectional nature of the data also meant that it was not possible to report a maximal value. Race segments with stride lengths below our lower cut-off were excluded in the data cleaning phase which could have masked situations where the reduced stride lengths were due to injury, fatigue (with reduced speed), or slow starts. Due to the relatively complex hierarchical structure of our data, some analyses did not account for clustering at all levels; the staged models accounted only for clustering at the horse-level, whilst the analyses over all sectionals accounted for the other levels of meetings/races/trainers/horse-starts. We reasoned that the staged model horse-

level clustering was appropriate given that this was the level found to account for the greatest variance in stride parameters.

4.7 CONCLUSIONS

The first step in understanding the impact of stride characteristics at high to maximal speeds on equine bone biology is to document the extent of variation across a population. We have demonstrated that in line with previous investigations, as speed increases, stride lengths increase and stride duration reduces, however individual horses use variable strategies to achieve different speeds. Although stride variables are characteristics of individual horses, they are also influenced by factors such as the track conditions and distance raced. For future investigations to better assess the impact of racing history on bone biology and injury risk, stride variables should be considered.

Declarations:

Ethics: Data were sourced from existing collections of data and involved no direct work with animals. The animal ethics committee at the University of Melbourne Faculty of Veterinary and Agricultural Science gave an exemption for formal ethics approval on the 23rd of September 2016.

Competing interests*:* The authors have no competing interests to declare.

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Footnotes

a. Stata Version 15.0 StataCorp, College Station, TX: StataCorp LP

b. R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/).

4.8 POSTSCRIPT

Chapter 4 described large variation in stride characteristics between different horses. Horse factors such as male sex, and racing conditions such as longer race distances and firmer track surfaces were associated with less strides per 200 m of longer stride durations. Chapter 5 will next utilise the speed and stride data for this cohort of horses in racing to estimate the proportion of fatigue life accrued across race starts. I will then assess the association of the horse-and race-level factors influencing stride characteristics described in Chapter 4 on the accrued proportion of fatigue over those race starts.

4.9 REFERENCES:

[1] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2014) Evaluation of a subject-specific finite-element model of the equine metacarpophalangeal joint under physiological load. *J Biomech* **47**, 65-73.

[2] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2010) Relationship between muscle forces, joint loading and utilization of elastic strain energy in equine locomotion. *J Exp Biol* **213**, 3998-4009.

[3] Martig, S., Lee, P.V., Anderson, G.A. and Whitton, R.C. (2013) Compressive fatigue life of subchondral bone of the metacarpal condyle in thoroughbred racehorses. *Bone* **57**, 392-398.

[4] Nunamaker, D.M., Butterweck, D.M. and Provost, M.T. (1990) Fatigue Fractures in Thoroughbred Racehorses- Relationships with Age, Peak Bone Strain, and Training. *J Orthop Res* **8**, 604-611.

[5] Firth, E.C., Rogers, C.W., Doube, M. and Jopson, N.B. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 6. Bone parameters in the third metacarpal and third metatarsal bones. *N Z Vet J* **53**, 101-112.

[6] Estberg, L., Gardner, I.A, Stover, S.M et al (1998) A case-crosover study of intensive racing and training schedules and risk of catastrophic musculoskeletal injury and lay-up in Californian Thoroughbred racehorses. *Prev Vet Med* **33**, 159-170.

[7] Boston, R.C. and Nunamaker, D.M. (2000) Gait and speed as exercise components of risk factors associated with onset of fatigue injury of the third metacarpal bone in 2-year-old Thoroughbred racehorses. *Am J Vet Res* **61**, 602-608.

[8] Witte, T.H., Hirst, C.V. and Wilson, A.M. (2006) Effect of speed on stride parameters in racehorses at gallop in field conditions. *J Exp Biol* **209**, 4389-4397.

[9] Yamanobe, A., Hiraga, A. and Kubo, K. (1992) Relationships between Stride Frequency, Stride Length, Step Length and Velocity with Asymmetric Gaits in the Thoroughbred Horses. *Japanese Journal of Equine Science* **3**, 143-148.

[10] Ratzlaff, M., Shindell, R. and White, K. (1985) The interrelationships of stride lengths and stride times to velocites of galloping horses. *J Equine Vet Sci* **5**, 279-283.

[11] Ratzlaff, M., Grant, BD, Rathgeber-Lawrence, R et al (1995) Stride rates of horses trotting and cantering on a treadmill. *J Equine Vet Sci* **15**, 279-283.

[12] Ferrari, M., Pfau, T., Wilson, A.M. and Weller, R. (2009) The effect of training on stride parameters in a cohort of National Hunt racing Thoroughbreds: A preliminary study. *Equine Vet J* **41**, 493-497.

[13] Seder, J.A. and Vickery, C.E. (2003) Temporal and Kinematic Gait Variables of Thoroughbred Racehorses At or Near Racing Speeds. *J Equine Vet Sci* **23**, S82-S112.

[14] Witte, T.H. and Wilson, A.M. (2004) Accuracy of non-differential GPS for the determination of speed over ground. *J Biomech* **37**, 1891-1898.

[15] Pratt, G. (1997) Model for injury to the foreleg of the Thoroughbred racehorse. *Equine Vet J* **29**, 30-32.

[16] Fonseca, R.G., Kenny, D.A., Hill, E.W. and Katz, L.M. (2010) The association of various speed indices to training responses in Thoroughbred flat racehorses measured with a global positioning and heart rate monitoring system. *Equine Vet J Suppl*, 51-57.

[17] Blache, C., Baudoin, G., Somson, M., Taillandier-Loize, T., Versvisch-Picois, A. and Samama, N. (2018) An evaluation methodology to assess the accuracy of a tracking system in the case of horse races description and experimental validation. *Annals of Telecommunications*.

[18] Spence, A.J., Tan, H. and Wilson, A. (2008) Accuracy of the TurfTrax Racing Data System for determination of equine speed and position. *Equine Vet J* **40**, 680-683.

[19] Varley, M.C., Jaspers, A., Helsen, W.F. and Malone, J.J. (2017) Methodological considerations when quantifying high-intensity efforts in team sport using global positioning system technology. *Int J Sport Physiol* **12**, 1059-1068.

[20] Malone, J.J., Lovell, R., Varley, M.C. and Coutts, A.J. (2017) Unpacking the black box: applications and considerations for using GPS devices in sport. *Int J Sport Physiol* **12**, S2-18-S12-26.

[21] Heglund, N.C., Taylor, C.R. and McMahon, T.A. (1974) Scaling stride frequency and gait to animal size: Mice to horses. *Science* **186**, 1112-1113.

[22] Leach, D., Sprigings, E. and Laverty, W. (1987) Multivariate statistical analysis of stride-timing measurements of nonfatigued racing Thoroughbreds. *Am J Vet Res* **48**, 880-888.

[23] Butler, P., Woakes, AJ, Anderson, LS, Roberts, C.A. and Marlin, D.J. (1993) Stride length and respiratory tidal volume in exercising Thoroughbred horses. *Respiration Physiology* **93**.

[24] Liu, W. (2013) CURVEFIT: Stata module to produces curve estimation regression statistics and related plots between two variables for alternative curve estimation regression models.

[25] Dupont, W.D. and Plummer, W.D.J. (2003) Density Distribution Sunflower Plots *Journal of Statistical Software* **8**, 1-5.

[26] Ratzlaff, M.H., Grant, B.D., Rathgeber-Lawrence, R. and Kunka, K.L. (1995) Stride rates of horses trotting and cantering on a treadmill. *J Equine Vet Sci* **15**, 279-283.

[27] Corley, J. and Goodship, A. (1994) Treadmill training induced changes to some kinematic variables measured at the canter in Thoroughbred fillies. *Equine Vet J* **26**, 20-24.

[28] Rooney, J.R., Thompson, K. N, Shapiro, R. (1991) A contribution to the study of velocity, stride length, and frequency in the horse. *J Equine Vet Sci* **11**, 1991.

[29] Barrey, E., Galloux, P., Valette, J., Auvinet, B. and Wolter, R. (1993) Stride characteristics of overground versus treadmill locomotion in the saddle horse. *Cells Tissues Organs* **146**, 90-94.

[30] Rooney, J. (1984) Preliminary observations on stride length and frequencey in relation to velocity of horses. *J Equine Vet Sci* **4**, 33-34.

[31] Deuel, N. and Lawrence, L. (1986) Gallop velocity and limb contact variables of quarter horses. *J Equine Vet Sci* **6**, 143-147.

[32] Van Oeveren, B., De Ruiter, C., Hoozemans, M., Beek, P. and Van Dieën, J. (2019) Inter-individual differences in stride frequencies during running obtained from wearable data. *J Sports Sci*, 1-11.

[33] Leach, D.H. and Sprigings, E. (1979) Gait fatigue in the racing Thoroughbred. *The Journal of Equine Medicine and Surgery* **3**, 436-443.

[34] Spence, A.J., Thurman, A.S., Maher, M.J. and Wilson, A.M. (2012) Speed, pacing strategy and aerodynamic drafting in Thoroughbred horse racing. *Biol Lett* **8**, 678-681.

[35] Landers, G.J., Blanksby, B.A. and Rackland, T. (2011) Cadence, stride rate and stride length during triathlon competition. *Int J Exerc Sci* **4**, 40.

[36] Willoughby, D.P. (1975) *Growth and Nutrition in the Horse*, AS Barnes.

[37] Hintz, H., Hintz, R. and Van Vleck, L.D. (1979) Growth rate of thouroughbreds. Effects of age of dam, year and month of birth, and sex of foal. *J Anim Sci* **48**, 480-487.

[38] Thompson, Thompson, K.N. and Smith, B.P. (1994) Skeletal growth patterns of Thoroughbred horses. *J Equine Vet Sci* **14**, 148.

[39] Martin, G., Strand, E. and Kearney, M. (1996) Use of statistical models to evaluate racing performance in Thoroughbreds. *J Am Vet Med Assoc* **209**, 1900-1906.

[40] Sloet Van Oldruitenborgh-Oosterbann, M.M., Barneveld, A. and Schamhardt, H. (1995) Effects of weight and riding on workload and locomotion during treadmill exercise. *Equine Vet J* **27**, 413-417.

[41] Seder, J.A. and Vickery, C.E. (2003) Double and triple fully airborne phases in the gaits of racing speed thoroughbreds. *J Equine Vet Sci* **23**, S73-S81.

[42] Drevemo, S., Dalin, G., Fredricson, I. and Hjerten, G. (1980) Equine locomotion: 1. The analysis of linear and temporal stride characteristics of trotting Standardbreds. *Equine Vet J* **12**, 60-65.

[43] Maeda, Y., Tomioka, M., Hanada, M. and Oikawa, M.-a. (2012) Influence of Track Surface Condition on Racing Times of Thoroughbred Racehorses in Flat Races. *J Equine Vet Sci* **32**, 689-695.

[44] Crawford, W. and Leach, D. (1984) The effect of racetrack design on gait symmetry of the pacer. *Can J Comp Med* **48**, 374.

[45] Parsons, K.J., Pfau, T. and Wilson, A.M. (2008) High-speed gallop locomotion in the thoroughbred racehorse. I. The effect of incline on stride parameters. *J Exp Biol* **211**, 935-944.

[46] Self, Z.T., Spence, A.J. and Wilson, A.M. (2012) Speed and incline during thoroughbred horse racing: racehorse speed supports a metabolic power constraint to incline running but not to decline running. *J Appl Physiol* **113**, 602-607.

[47] Nunamaker, D., Butterweck, DM, and Black, J (1991) In vitro comparison of Thoroughbred and Standardbred Racehorses with regard to local fatigue failure of the third metacarpal bone. *Am J Vet Res* **52**, 97-100.

[48] Verheyen, K., Price, J., Lanyon, L. and Wood, J. (2006) Exercise distance and speed affect the risk of fracture in racehorses. *Bone* **39**, 1322-1330.

[49] Hitchens, P., Morrice-West, A.V., Stevenson, M. and Whitton, R.C. (2018) Meta-analysis of risk factors for racehorse catastrophic musculoskeletal injury in flat racing. *Vet J* **245**.

APPENDIX B. SUPPLEMENTARY INFORMATION TO CHAPTER 4

S1 UNIVARIABLE REGRESSION RESULTS FOR STRIDE PARAMETERS EARLY, MID AND LATE RACE.

Supplementary Table S1: *Univariable linear regression results of horse and race level factors on stride parameters [number of strides per 200m and stride duration (s)] during n=25,259 Thoroughbred race starts by 2,678 horses Thoroughbred racing in Tasmania, Australia presented as coefficient's and their associated 95% confidence intervals.*

Number of Strides per 200 m:

	Early			Mid			Late		
	coefficient	**95%CI**	**p-value**	**coefficient**	**95%CI**	**p-value**	**coefficient**	**95%CI**	**p-value**
Speed	-0.973	-.999, -.946	<0.001	-1.078	-1.107, -1.048	<0.001	-1.209	-1.232, -1.186	<0.001
Horse-factors									
Age (years)	-0.009	-.036, .018	0.513	-0.065	-.093, -.036	<0.001	-0.022	-.054, .010	0.185
Sex									
Female	(reference)			(reference)			(reference)		
Gelding	-0.589	-.675, -.503	<0.001	-0.706	-.794, -.619	<0.001	-0.667	-.764, -.570	<0.001
Intact Male	-0.216	-.485, .054	0.116	-0.186	-.439, .066	0.148	-0.113	-.452, .225	0.511
Number of career starts	0	.000, .000	0.45	0	.000, .000	0.413	0	.000, .000	0.025
Earnings per start	0	.000, .000	<0.001	0	.000, .000	<0.001	0	.000, .000	<0.001
Weight carried	-0.074	-.088, -.059	<0.001	-0.077	-.092, -.063	<0.001	-0.106	-.121, -.090	<0.001
Finishing position	0.035	.028, .042	<0.001	0.044	.037, .052	<0.001	0.105	.097, .113	<0.001
Race and Meet-factors									
Race Distance (m)									
≤1200	(reference)			(reference)			(reference)		
>1200-≤1600	0.673	.617, .728	<0.001	-0.757	-.812, -.703	<0.001	-0.169	-.228, -.110	<0.001
>1600 -≤2000	0.804	.718, .890	<0.001	-0.935	-1.026, -.844	<0.001	-0.084	-.178, .011	0.082
>2000 -≤2400	0.373	.251, .495	<0.001	-0.372	-.489, -.255	<0.001	-0.299	-0.441, -0.157	<0.001
>2400	0.632	.381, .882	<0.001	-0.669	-.914, -.425	<0.001	-0.102	-.382, .179	0.477

Venue									
Devonport Synthetic	(reference)			(reference)			(reference)		
Hobart Inside	0.666	.528, .805	<0.001	1.035	.872, 1.197	<0.001	0.313	.148, .483	<0.001
Hobart	0.337	.269, .405	<0.001	0.573	.497, .648	<0.001	0.227	.152, .301	<0.001
Launceston	0.671	.609, .733	<0.001	-0.224	-.298, -.151	<0.001	-0.385	-.443, -.327	<0.001
Track type									
Turf	(reference)			(reference)			(reference)		
Synthetic	-0.533	-.593, -.474	<0.001	-0.134	-.202, -.065	<0.001	0.117	.058, .176	<0.001
Track rating									
Synthetic	(reference)			(reference)			(reference)		
Turf:									
Firm 2	-0.688	-1.287, -.088	0.025	1.515	.977, 2.054	<0.001	-0.808	-1.347, -.269	0.003
Good 3	0.21	.119, .300	<0.001	-0.396	-.494, -.298	<0.001	-0.749	-0.835, -.664	<0.001
Good 4	0.427	.363, .492	<0.001	-0.301	-.374, -.228	<0.001	-0.674	-.734, -.613	<0.001
Soft 5	0.476	.408, .543	<0.001	0.134	.059, .209	<0.001	-0.269	-.335, -.203	<0.001
Soft 6	0.558	.464, .652	<0.001	0.425	.324, .525	<0.001	0.486	.391, .580	<0.001
Soft 7	0.788	.696, .880	<0.001	0.787	.686, .887	<0.001	0.828	.733, .922	<0.001
Heavy 8	1.112	1.027, 1.197	<0.001	1.203	1.114, 1.292	<0.001	1.572	1.481, 1.663	<0.001
Heavy 9	0.766	.624, .908	<0.001	1.606	1.461, 1.750	<0.001	1.589	1.423, 1.755	<0.001
Heavy 10	1.377	1.162, 1.593	<0.001	2.346	2.143, 2.550	<0.001	2.27	2.048, 2.492	<0.001
Number of starters per race	-0.06	-.073, -.048	<0.001	0.091	.078, .104	<0.001	0.067	.054, .079	<0.001
Class of race									
Maiden/Class 1	(reference)			(reference)			(reference)		
Class 2-5	-0.232	-.325, -.140	<0.001	-0.314	-.410, -.218	<0.001	-0.343	-.444, -.242	<0.001
Restricted (BM/HCP)	-0.079	-.519, .001	0.052	-0.34	-424, -.257	<0.001	-0.265	-.357, -.174	<0.001
Listed/Group	-0.389	-.538, -.241	<0.001	-0.366	-.499, -.233	<0.001	-0.77	-.923, -.616	<0.001
Open	-0.281	-.404, -.158	<0.001	-0.33	-.469, -.190	<0.001	-0.65	-.782, -.518	<0.001

Stride duration (*s*):

	Early			Mid			Late		
	coefficient	95%CI	p-value	coefficient	95%CI	p-value	coefficient	95%CI	p-value
Speed	-0.009	-.009, -.008	<0.001	-0.009	-.010, -.009	0	-0.01	-.010, -.010	<0.001
Horse-factors						<0.001			
Age (years)	0.002	.002, .003	<0.001	0.002	.001, .021	0	0.001	.001, .002	<0.001
Sex									
Female	(reference)			(reference)			(reference)		
Gelding	0.011	.010, .012	<0.001	0.011	.010, .013	<0.001	0.01	.009, .0117	<0.001
Intact Male	0.002	-.002, .007	0.262	0.004	.000, .009	0.114	0.007	.003, .010	0.001
Number of career starts	0	0.00, 0.00	<0.001	0	.000, .000	0.002	0	.000, .000	0.049
Earnings per start	0	.001, .001	<0.001	0	.000, .000	0.089	0	.000, .000	<0.001
Weight carried	0	.001, .001	<0.001	0.001	.001, .001	<0.001	0.001	.000, .001	<0.001
Finishing position	0	.000, .000	<0.001	0	.000, .000	0.002	0.002	.001,. 002	<0.001
Race and Meet-factors									
Race Distance (m)									
≤1200	(reference)			(reference)			(reference)		
>1200-≤1600	0.012	.011, .012	<0.001	0.009	.009, .010	<0.001	0.004	.003, .004	<0.001
>1600 -≤2000	0.021	.020, .022	<0.001	0.023	.022, .024	<0.001	0.011	.010, .012	<0.001
>2000 -≤2400	0.025	.023, .027	<0.001	0.037	.035, .039	<0.001	0.014	.012, .016	<0.001
>2400	0.029	.025, .032	<0.001	0.037	.033, .040	<0.001	0.017	.013, .021	<0.001
Venue									
Devonport Synthetic	(reference)			(reference)			(reference)		
Hobart Inside	0.004	.002, .007	<0.001	0	-.002, .003	0.651	0.002	-.000, .004	0.054
Hobart	0.003	.002, .004	<0.001	-0.002	-.003, -.001	<0.001	0.002	.001, .003	0.001
Launceston	0.004	.003, .004	<0.001	0	-.001, .001	0.555	-0.002	-.003, -.001	<0.001
Track type									
Turf	(reference)			(reference)			(reference)		
Synthetic	-0.003	-.004, -.002	<0.001	0.001	.000, .002	0.022	0	.000, .000	0.382
Track rating									

Synthetic	(reference)			(reference)			(reference)		
Turf:									
Firm 2	-0.001	-.009, .007	<0.001	-0.003	-.012, .005	0.451	0.001	-.009, .010	0.89
Good 3	0.004	.003, .005	<0.001	0	-.002, .001	0.679	-0.003	-.004, -.002	<0.001
Good 4	0.003	.002, 004	<0.001	-0.001	-.002, .000	0.151	-0.003	-.004, -.002	<0.001
Soft 5	0.003	.002, .004	<0.001	-0.001	-.002, .000	0.284	-0.001	-.002, .000	0.024
Soft 6	0.003	.002, .005	<0.001	-0.002	-.003, .000	0.026	0.002	.001, .003	0.001
Soft 7	0.004	.002, .005	<0.001	-0.002	-.003, -.001	0.004	0.005	.003, .006	<0.001
Heavy 8	0.002	.001, .004	<0.001	-0.003	-.004, -.002	<0.001	0.007	.006, .008	<0.001
Heavy 9	0.004	.002, .006	<0.001	-0.004	-.005, -.002	<0.001	0.01	.008, .0116	<0.001
Heavy 10	0.003	.000, .005	0.037	-0.002	-.004, .001	0.217	0.011	.009, .0135	<0.001
Number of starters per race	0	.000, .000	<0.001	0	.000, .000	0.934	0	.000, .001	<0.001
Class of race									
Maiden/Class 1	(reference)			(reference)			(reference)		
Class 2-5	0	-.001, .002	0.846	-0.005	-.006, -.003	<0.001	-0.003	-.004, -.001	<0.001
Restricted (BM/HCP)	0.007	.006, .008	<0.001	0.005	.003, .006	0	0.002	.001, .004	0.001
Listed/Group	0.01	.008, .012	<0.001	0.014	.011, .016	<0.001	0.002	-.001, .004	0.155
Open	0.001	.000, .003	0.144	-0.003	-.004, -.001	<0.001	-0.004	-.006, -.002	<0.001

S2 MULTIVARIABLE REGRESSION RESULTS FOR STRIDE PARAMETERS EARLY, MID AND LATE RACE.

Supplementary Table S2. *Coefficients and 95% confidence intervals of the number of strides taken per 200m and the duration of strides (s) for 200 m race segments at three stages of n=25,259 Thoroughbred race starts by 2,678 horses in Tasmania, Australia, in 2011-2016, generated through multivariable linear regression modelling.*

	Number of Strides/200 m			Stride Duration (s)		
	Early	**Mid**	**Late**	**Early**	**Mid**	**Late**
Speed (m/s)	-1.128*** [-1.148,-1.107]	-1.412*** [-1.435,-1.390]	-1.265*** [-1.293,-1.238]	-0.006*** [-0.007,-0.006]	-0.004*** [-0.005,-0.004]	-0.009*** [-0.010,-0.009]
Finishing position (per 10 places)	0.180*** [0.128,0.233]	0.195*** [0.144,0.247]	-0.349*** [-0.405,-0.292]	-0.003*** [-0.004,-0.002]	-0.002*** [-0.003,-0.002]	0.006*** [0.005,0.006]
Number of starts (per 10 starts)		0.076*** [0.050,0.102]	0.039** [0.012,0.065]			
Weight carried (per 10 kg)	-0.272*** [-0.382,-0.163]	-0.166** [-0.279,-0.053]		0.004*** [0.002,0.005]	0.003*** [0.002,0.005]	
Age (months)				0.005* [0.000,0.009]	-0.011*** [-0.015,-0.007]	
Horse Sex						
Filly/Mare	(reference)	(reference)	(reference)	(reference)	(reference)	(reference)
Gelding	-0.562*** [-0.644,-0.479]	-0.610*** [-0.690,-0.531]	-0.676*** [-0.759,-0.594]	0.009*** [0.007,0.010]	0.009*** [0.008,0.010]	0.010*** [0.009,0.011]
Colt/Stallion	-0.147 [-0.380,0.085]	-0.256* [-0.479,-0.034]	-0.329** [-0.548,-0.109]	0.002 [-0.001,0.006]	0.004* [0.000,0.007]	0.005** [0.002,0.008]
Race Distance (per 100 m)	-0.104*** [-0.114,-0.095]	-0.218*** [-0.228,-0.209]	-0.071*** [-0.081,-0.061]	0.002*** [0.001,0.002]	0.003*** [0.003,0.003]	0.001*** [0.001,0.001]
Track type & Rating						
Synthetic	(reference)	(reference)	(reference)	(reference)	(reference)	(reference)
Firm 2	-0.203 [-0.628,0.223]	0.049 [-0.421,0.519]	-0.348 [-0.821,0.125]	0.005 [-0.002,0.011]	-0.000 [-0.007,0.007]	0.005 [-0.002,0.013]
Good 3	-0.035 [-0.101,0.030]	0.218*** [0.151,0.286]	0.003 [-0.065,0.070]	0.000 [-0.001,0.001]	-0.003*** [-0.004,-0.002]	0.001 [-0.000,0.002]
Good 4	0.029 [-0.017,0.075]	0.214*** [0.168,0.260]	0.003 [-0.044,0.049]	-0.001* [-0.002,-0.000]	-0.003*** [-0.004,-0.002]	0.001 [-0.000,0.001]
Soft 5	0.035	0.253***	0.028	-0.001*	-0.004***	-0.000

	[-0.016,0.086]	[0.204,0.303]	[-0.022,0.077]	[-0.002,-0.000]	[-0.005,-0.003]	[-0.001,0.001]
Soft 6	0.028	0.303***	0.120***	-0.001	-0.005***	-0.002**
	[-0.044,0.101]	[0.233,0.372]	[0.050,0.189]	[-0.002,0.000]	[-0.006,-0.003]	[-0.003,-0.001]
Soft 7	0.064	0.402***	0.132***	-0.002**	-0.006***	-0.002**
	[-0.007,0.136]	[0.333,0.471]	[0.061,0.203]	[-0.003,-0.000]	[-0.007,-0.005]	[-0.003,-0.001]
Heavy 8	0.245***	0.540***	0.312***	-0.004***	-0.008***	-0.004***
	[0.178,0.312]	[0.478,0.601]	[0.241,0.383]	[-0.005,-0.003]	[-0.009,-0.007]	[-0.005,-0.002]
Heavy 9	0.038	0.626***	0.179**	-0.001	-0.009***	-0.001
	[-0.070,0.147]	[0.528,0.724]	[0.072,0.287]	[-0.002,0.001]	[-0.010,-0.007]	[-0.003,0.001]
Heavy 10	0.331***	0.739***	0.413***	-0.005***	-0.009***	-0.004**
	[0.184,0.478]	[0.598,0.881]	[0.255,0.571]	[-0.007,-0.003]	[-0.011,-0.007]	[-0.006,-0.001]
Race class						
Maiden/Class 1	(reference)					
Class 2-5	-0.129***					
	[-0.204,-0.053]					
Restricted (HCP/BM)	-0.069*					
	[-0.134,-0.003]					
Listed /Group	-0.064					
	[-0.191,0.062]					
Open	-0.077					
	[-0.177,0.022]					
Observations	24,978	25,220	25,039	24,978	25,220	25,039

95% confidence intervals in brackets

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

CHAPTER 5. RELATIONSHIP BETWEEN THOROUGHBRED WORKLOADS IN RACING AND THE FATIGUE LIFE OF EQUINE SUBCHONDRAL BONE

5.1 PREFACE TO CHAPTER 5

Strides in racing varied under differing race conditions in Chapter 4. Whilst there was also variation according to horse factors such as sex, stride characteristics were found to be innate for individual horses. Workloads have been used to quantify musculoskeletal injury risk, but workload variables have been restricted to speed and distance. Chapter 5 assesses the variation in estimated proportion of fatigue life used, as a function of the number of strides undertaken in individual race starts and the speed of those individual strides. This provides a better estimate for quantifying the skeletal impact of each start on a horse. The mathematical modelling approach used for Chapter 5 allowed exploration of the relative importance of stride and speed variables in the development of injury.

Supplementary information is provided in Appendix C.

5.2 ABSTRACT

Bone fatigue life (FL) is the number of cycles of load sustained by a material before failure, dependent on the load magnitude. For athletes, 'cycles' translate as the number of strides, with load proportional to the speed of gait. To improve previous investigations estimating training load based on distance, we aimed to use speed per stride as a proxy for limb load to investigate factors associated with FL, using Thoroughbred race starts as a model. Speed (m/s, x), measured using 5Hz GPS/800Hz accelerometer sensors for strides in 25,245 race starts, were investigated using a combination of mathematical and regression modelling. Fore-limb vertical force (NKg^{-1}) was estimated using a published equation for speed: Vertical force = $2.778 + 2.1376*x - 0.0535*x^2$. Joint load (σ) was estimated based on the vertical force scaled according to the maximum speed and defined experimental loads as a sensitivity analysis for the expected variation in load distribution across a joint surface (54-90 MPa): σ=vertical force*experimental load/24.13. Percentage FL was estimated using a published equation for cycles to failure (N_f) summed across each race start: $N_f=10^{(\sigma-134.2)/-14.1.}$ Multivariable mixed-effects linear regression models were generated with FL as the outcome, adjusting for horse-level clustering. Females, older age, longer race distances and firmer track surfaces were associated with greater percentage FL accumulated ($P<0.001$). Deviations from injury risk studies highlight areas for future model improvement, but most variables associated with fatigue accumulation are risk factors for injury supporting the model validity. Monitoring strides in racehorses may therefore allow identification of horses at risk, enabling early detection of injury.

5.3 INTRODUCTION

Numerous studies have investigated associations between workload and musculoskeletal injuries in Thoroughbred racehorses, but are limited by the practicality of measuring workload itself [1-8]. Most have relied on speed and distance travelled both in training and racing to quantify workload, and often use subjective estimates of speed which lack precision [9,10]. For human athlete monitoring, GPS data with distance travelled categorised according to speeds achieved have been used and proposed to be beneficial in tracking training and competition workloads [11,12]. GPS data for speed and distance have been used to estimate workloads in a limited number of equine studies but for small sample sizes under non-competition conditions [13-16].

Racehorse bone injury is most commonly a result of bone fatigue, a process leading to the degradation of the bones' overall integrity generating microdamage and microcracks which can propagate, resulting in bone failure [17-20]. The fatigue life of a material relates to the number of cycles of a defined load able to be incurred before partial or complete failure [17,21]. In racehorses this translates to the number of strides accrued before a bone lesion or fracture occurs. The fatigue life of bone is dependent on the magnitude of load via an inverse exponential relationship and has been investigated in cortical, trabecular and subchondral bone [22-24]. It is not possible to measure load in limbs while horses are competing, but load on the equine limb is directly proportional to speed [25], therefore, as galloping speed increases, a substantially lower number of stride cycles are required to induce injury.

We have previously described a large variation in the stride characteristics of a cohort of Australian Thoroughbreds during racing [26]. By generating a quantitative estimate of the number of cycles actually incurred during racing we aim to determine the loading history of equine bones *in vivo*. Because of the variation in stride parameters, it is likely that individual

horse-factors, as well as race-day factors, result in variation between horses and racing conditions in the degree of bone damage accrued and therefore the propensity for injury. We aimed to use published fatigue equations to assess the effect of racing workloads as determined by distance and speed on equine subchondral bone fatigue. We hypothesised that a higher percentage of bone fatigue life would be used for (1) longer distance races; (2) harder track surfaces and synthetic surfaces compared to turf; (3) higher classed races; and that (4) there would be individual horse variation in the cumulative fatigue life across multiple race starts over the study period.

5.3 MATERIALS AND METHODS

5.3.1 Data sources

Speed and stride data (stride length, duration) from Thoroughbred racehorses in race starts between 11th of January 2011 and 21st of August 2016 were retrospectively sourced from Tasracing and the product and software manufacturer (StrideMaster™; Thoroughbred Ratings Pty Ltd, Romsey, Victoria, Australia). Data for the present study were provided as SQLite files by individual stride, collected from 5 Hz positional recording and 800 Hz accelerometer recordings via sensors mounted on the saddle cloth of each horse in every race start, and smoothed through StrideMaster™ proprietary algorithms. Individual stride data were matched with the sectional (200 m race segment) data that was previously used to assess stride characteristic variation across this population of racehorses [26]. This dataset included race results from the official racing repository (Racing Australia Ltd) for finishing position, weight carried, track type and surface, race class and distance and previous number of starts, in addition to the average stride characteristics in the early, middle and late stages of each start. Track surfaces were classified as synthetic or turf, with turf tracks rated from firmest to most water-logged in ordinal categories 2-10). Race classes were categorised as: (1) Maiden and Class 1 races (containing horses that had won ≤1 race); (2) Class 2-5 (where starters have won ≤2-5 races respectively); (3) Benchmark

(BM) and Handicap (HCP) races (Restricted races in which horses are assigned weights based on their rating); (4) Open races (available to all horses); and (5) Listed and Group races (high classed races). Recordings were excluded where there were recording errors or biologically implausible data as previously described [26]. Resultingly, 25,245 race starts were available for analysis.

5.3.2 **Mathematical modelling**

Vertical force (NKg^{-1}) exerted on the fore-limb at each stride was estimated according to the formula by Witte *et al.* [25], equation (1), based on speed (m/s; x) given that stance duration was not available, adjusting the sign of the b_0 (constant) term to reflect the quadratic relationship displayed graphically in that paper:

$$Estimated\ vertical\ force = 2.778 + 2.1376*x - 0.0535*x^2 \quad (1)$$

Equation 1 resulted in a maximum vertical force (at maximum speed of 20.99 m/s) of 24.13 NKg^{-1}. To scale to the load at a distal limb joint for the calculated vertical force at each stride, we referred to previously published ex-*vivo* joint loads (MPa) at the metacarpal condyle, which has been reported to be representative of 49 to 80% of yield stress (i.e. the singular stress required to induce failure) [22,27]. Because load will vary across a joint surface [23], we ran a sensitivity analysis where estimated joint loads were calculated based on maximally defined experimental loads of 90, 78, 66 and 54 MPa as per equation (2) [22]. Joint load (MPa; σ) was estimated as the product of the conversion factor and the estimated vertical force from equation (1).

$$Conversion\ factor = experimental\ load / 24.13\ NKg^{-1} \quad (2)$$

$$\sigma = Conversion\ factor * estimated\ vertical\ force \quad (3)$$

The number of cycles to failure (N_f) was calculated according to the fatigue life curve for equine metacarpal subchondral bone with known load, equations (4) and (5) [22].

$$\sigma = 134.2 - 14.1 \cdot log10(Nf) \quad (4)$$

$$N_f = 10^{(\sigma - 134.2)/-14.1} \quad (5)$$

The proportion of fatigue life accrued during each recording (i.e. each stride) for each scaled load was calculated as the quotient of the number of strides (one) and the number of cycles to failure (N_f), equation (7). The sum of the proportions of fatigue life for each recording were then calculated for each race start at each scaled load, and converted to a percentage to generate the race percentage fatigue life equation (8).

$$Proportion\ FL\ per\ recording\ = \ 1/N_f \tag{7}$$

$$Race\ percentage\ FL = \ sum(proportion\ FL) * 100 \tag{8}$$

5.3.3 **Statistical analysis**

Data analysis was performed using Stata (Stata Version 15.0 StataCorp, College Station, TX: StataCorp LP). Data were assessed for normality via histograms and accordingly presented as means (standard deviation; sd.) and ranges. Data were collapsed by race start, and summary statistics for the race percentage fatigue life at each scaled load (54, 66, 78, 90, MPa) were generated, stratified by race factors of class, distance and track surface.

Using the collapsed data to assess the effect of horse and race level factors on the percentage fatigue life accrued over each race start, univariable linear regression models, adjusting for clustering at the horse-level, were generated using the highest scaled load (90 MPa). To assess whether linear regression on the outcome variable percentage fatigue life was appropriate, we assessed predicted values to ensure they did not fall outside the bounds of 0 and 100%. Continuous predictor variables were assessed for linearity of association with the outcome variable, with potential transformations assessed according to improvement in AIC and BIC values, model specification tests (linktest) and normality of residuals assessed via histograms. A Box-Tidwell (power) transformation was applied to the predictor race distance (per 100 m), with

a new variable generated for use in further modelling where the transformed distance variable, equation (9) [28].

$$Transformed\ distance = Race\ distance^{0.3531} - 1.11833823 \quad (9)$$

Study factors assessed included horse sex and age, weight carried, finishing position, track type/rating, race class, and race distance. All variables assessed in univariable analysis were $P<0.2$ and were retained in multivariable analysis following backwards stepwise elimination. Potential interaction terms were assessed for statistical significance. Statistically significant interaction terms were then assessed graphically. Model diagnostics were conducted for assessment of residuals and goodness of fit. Statistical significance was set at $P<0.05$.

5.4 RESULTS

The estimated percentage of fatigue life accumulated over each race start stratified by race distance, track surface type and rating are presented in Table 5.1. The sensitivity analysis to account for variation in force distribution across a joint surface demonstrated the exponential relationship between the joint surface load and percentage fatigue life accrued over each race start, Figure 5.1.

Table 5.1. *Estimated percentage of bone fatigue life accrued over Thoroughbred race starts in Tasmania, Australia as means (sd.) based on speed and stride data obtained by GPS and accelerometer devices. Results are stratified by distance of race and track surface type and rating (firmest to softest). Loads were estimated as a sensitivity analysis of varying pressure across a joint surface according to pre-determined experimental joint loads.*

Scaled load (MPa)	**54**	**66**	**78**	**90**
	Race percentage fatigue life accrued			
All starts	0.03 (0.01)	0.20(0.04)	1.38(0.25)	9.34(1.64)
Race distance (m)				
≤1200	0.03 (0.00)	0.18(0.02)	1.20(0.11)	8.16(0.83)
>1200 - ≤1600	0.03 (0.00)	0.21(0.02)	1.44(0.13)	9.70(0.95)
>1600 - ≤2000	0.04 (0.00)	0.24(0.02)	1.63(0.12)	10.91(0.87)
>2000 - ≤2400	0.04 (0.00)	0.29(0.02)	1.92(0.16)	12.71(1.17)
Track type and rating				
Synthetic Turf	0.03 (0.01)	0.20(0.04)	1.32(0.24)	8.96(1.55)
Firm 2	0.02 (0.00)	0.17(0.01)	1.16(0.07)	7.95(0.47)
Good 3	0.03 (0.01)	0.22(0.04)	1.48(0.26)	10.03(1.73)
Good 4	0.03 (0.01)	0.21(0.04)	1.46(0.24)	9.89(1.59)
Soft 5	0.03 (0.01)	0.21 (0.04)	1.41(0.25)	9.51(1.62)
Soft 6	0.03 (0.01)	0.20 (0.03)	1.33(0.21)	8.91(1.34)
Soft 7	0.03 (0.01)	0.20 (0.04)	1.33(0.24)	8.86(1.55)
Heavy 8	0.03 (0.00)	0.19 (0.03)	1.29(0.20)	8.55(1.29)
Heavy 9	0.03 (0.01)	0.19 (0.03)	1.24(0.21)	8.21(1.33)
Heavy 10	0.03 (0.00)	0.18 (0.03)	1.14(0.19)	7.42(1.24)
Race class				
Maiden/Class 1	0.03 (0.01)	0.20 (0.03)	1.32(0.22)	8.93(1.45)
Class 2-5	0.03 (0.00)	0.19 (0.02)	1.30(0.13)	8.87(0.92)
Restricted (HCP/BM)	0.03 (0.01)	0.22 (0.04)	1.48(0.26)	9.98(1.71)
Open	0.03 (0.01)	0.20 (0.04)	1.36(0.27)	9.28(1.76)
Listed /Group	0.04 (0.01)	0.26 (0.05)	1.72(0.35)	11.58(2.23)

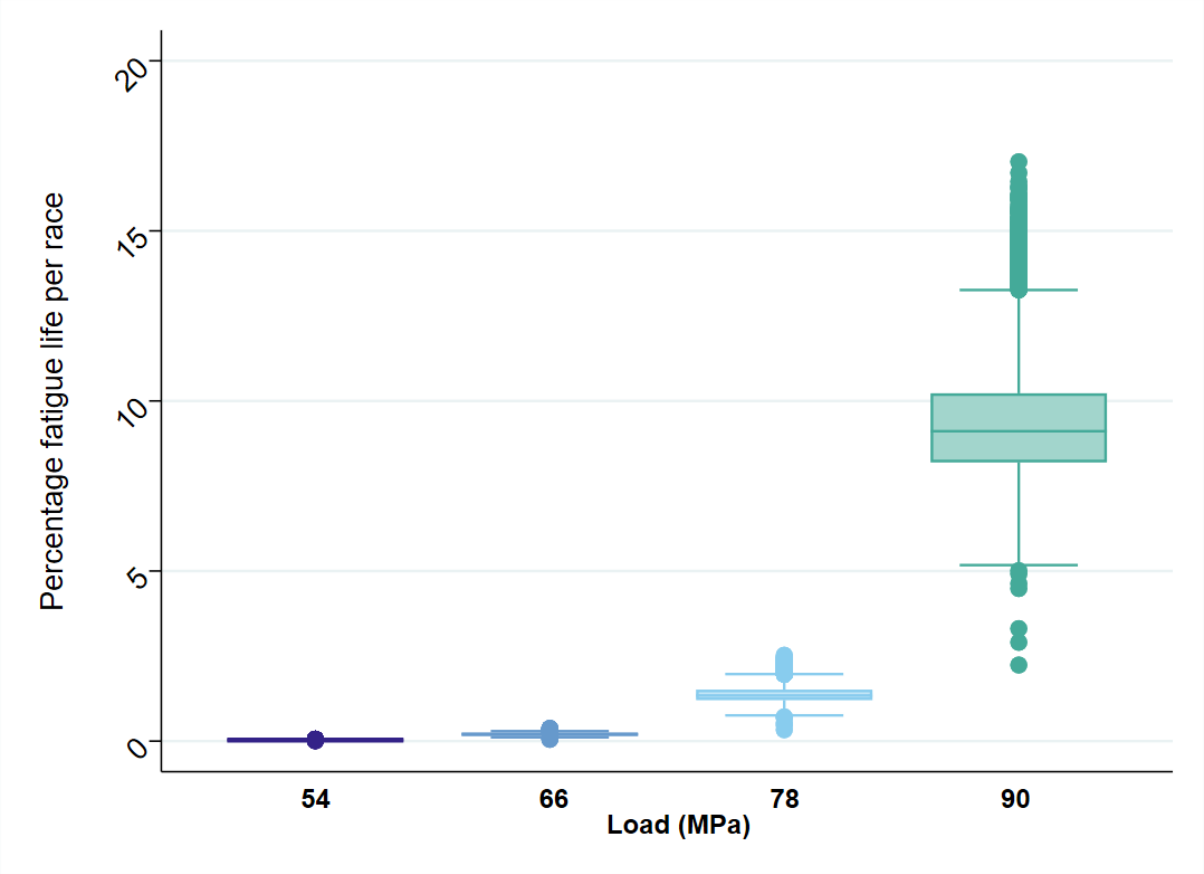

Figure 5.1. *Box-plot showing the percentage fatigue life accrued in 25,245 Thoroughbred race starts in Tasmania, Australia when scaled to pre-determined experimental joint loads.*

Univariable regression results for the horse- and race-level factors predicting the percentage fatigue life accrued per race start according to scaled to 90 MPa joint force loading are presented in Supplementary Table S1. In multivariable analysis, horse-level factors of age and sex were associated with the percentage of fatigue life accrued, with more fatigue life accrued per race as age of horse increased, and females using greater proportions than males, Table 5.2. The change in direction of relationship between horse sex and estimated fatigue life used in races in multivariable models (where geldings univariably used more fatigue life to females but less in multivariable analysis) can be explained in part because a higher proportion of geldings competed in longer distances races, and geldings tended to carry heavier weights, Supplementary Table S2. Greater race distances were associated with greater percentage of

fatigue life accumulated in a non-linear fashion (Box-Tidwell transformation of distance to the power of 0.351; $P<0.001$), therefore doubling the distance raced did not equate to double the percentage fatigue life accrued, Figure 5.2. Firmer track surfaces were associated with greater fatigue life accrued. Synthetic tracks were statistically different from all turf condition categories, with estimated accrued fatigue life for synthetic tracks lying between a turf condition of soft 5 and 6, Figure 5.3 ($P<0.001$). Better finishing positions were associated with a greater percentage of fatigue life accumulated ($P<0.001$). An interaction was present between weight carried and race class, whereby lower class and restricted races maintained the percentage of fatigue life accrued as weight carried increased, with some reduction in race percentage fatigue life for high class races (Listed/Group races) as weight increased,. However, for open class races (races with no special conditions or restrictions), the greater the weight carried the higher the race percentage fatigue life, Figure 5.4. This class of race is available to horses of all abilities (i.e. races with the greatest variation in horse ability).

Table 5.2. *Multivariable linear regression results showing the association between horse and race-level factors on the percentage of fatigue life accrued over Thoroughbred race starts in Tasmania, Australia, according to estimated joint loads scaled to a maximum of 90 MPa.*

Race percentage fatigue life	Coef.	[95% Conf	Interval]	p-value
Horse factors				
Sex				
Female	(reference)			
Gelding	-.159	-.197	-.121	<0.001
Colt/Stallion	-.132	-.233	-.032	.001
Age (years)	.028	.015	.041	<0.001
Finishing position	-.045	-.048	-.042	<0.001
Weight carried (per 10 kg)	-.079	-.165	.006	.070
Race Factors				
Race Distance ±	7.353	7.263	7.444	<0.001
Track type & Rating				
Synthetic	(reference)			
Firm 2	-.131	-.29	.029	.109
Good 3	.472	.433	.511	<0.001
Good 4	.425	.401	.449	<0.001
Soft 5	.119	.094	.145	<0.001
Soft 6	-.358	-.395	-.32	<0.001
Soft 7	-.465	-.502	-.427	<0.001
Heavy 8	-.764	-.805	-.724	<0.001
Heavy 9	-1.092	-1.170	-1.015	<0.001
Heavy 10	-1.896	-1.999	-1.794	<0.001
Race Class				
Maiden/Class 1	(reference)			
Class 2-5	.030	-.739	.799	.939
Restricted (HCP/BM)	-.427	-1.080	.225	.199
Listed /Group	2.480	-2.104	7.065	.289
Open	-5.087	-6.791	-3.383	<0.001
Interaction effects:				
Race Class: Weight Carried (per 10 kg)				
Maiden/Class 1: Weight Carried	(reference)			
Class 2-5: Weight Carried	.034	-.104	.172	.631
Restricted (HCP/BM): Weight Carried	.115	-.002	.232	.054
Listed /Group: Weight Carried	-.353	-1.167	.462	.396
Open: Weight Carried	.938	.635	1.242	<0.001

± Race distance scaled per 100 m and transformed to the power of 0.3531 according to a Box-Tidwell transformation

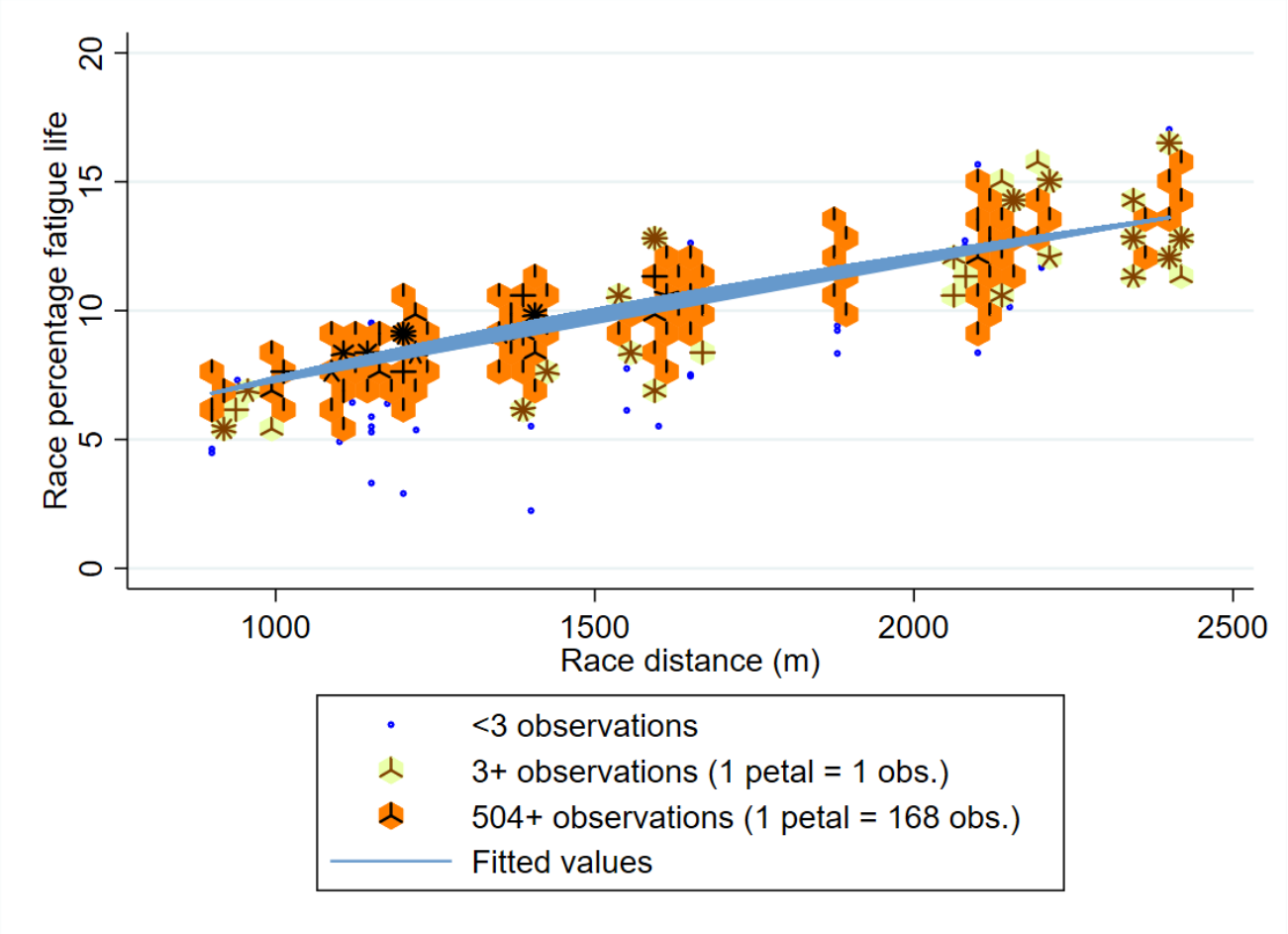

Figure 5.2. *Scatter density plot of race distance to the percentage of fatigue life accrued per race with Box-Tidwell power transformed fitted regression line (distance transformed to the power of 0.3531). Petals of shaded areas represent the number of observations, where the number of observations increase from blue to yellow to orange, and overlapping lines (therefore displayed as asterisks indicating greater number of petals) equate to the highest density regions.*

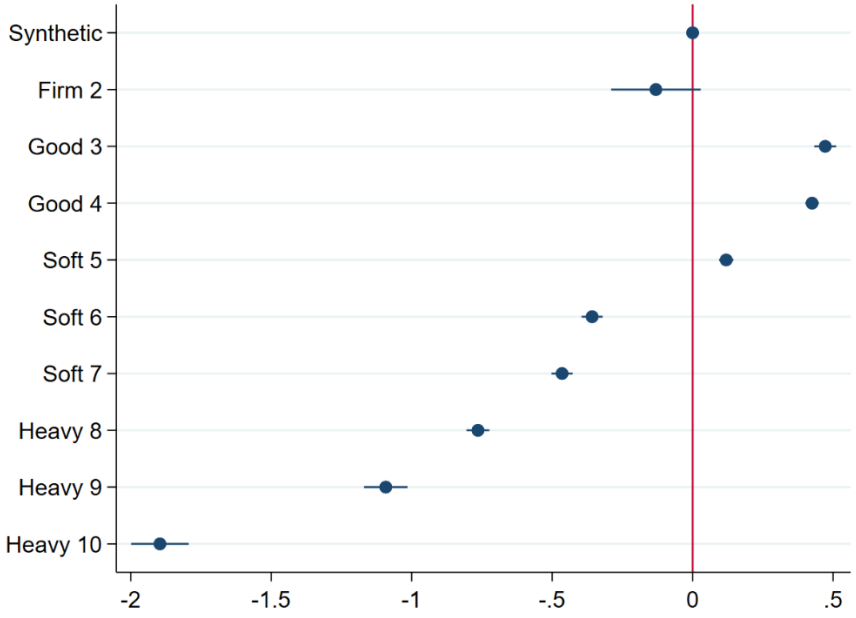

Figure 5.3. *Coefficient plot (regression coefficients and associated 95% confidence intervals) showing the proportional effect of track surface type and rating (synthetic vs turf tracks rated from firmest to softest) on the percentage of fatigue life accrued over Thoroughbred race starts in Tasmania, Australia, according to estimated joint loads scaled to a maximum of 90 MPa.*

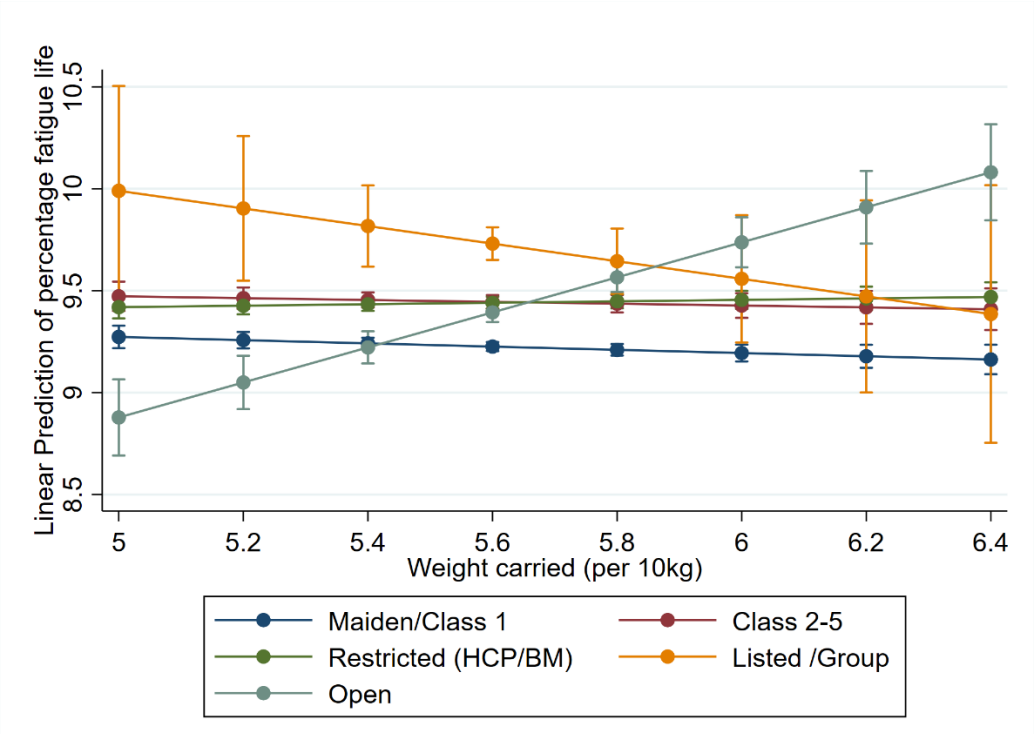

Figure 5.4. *The interaction between weight carried and race class on the percentage of fatigue life accrued over Thoroughbred race starts in Tasmania, Australia in multivariable linear regression modelling, according to estimated joint loads scaled to a maximum of 90 MPa.*
*HCP/BM= Handicap/Benchmark races

5.5 DISCUSSION

Using individual stride characteristics recorded during racing in a large population of horses, we aimed to estimate potential variations in the proportion of subchondral bone fatigue life consumed per race. Models produced for different joint surface loads demonstrated that the proportion of fatigue life per race increased exponentially based on the magnitude of the scaled load, but there was substantial variation between horses. Older horses, females, better finishing positions, firmer track surfaces, and longer race distances were estimated to have a greater percentage fatigue life accrued over each race start.

Recent studies assessing training and competition workloads in human athletes have largely used GPS data with categorised speed ranges to quantify the distance travelled by the athletes as a proxy for 'load' [11,12]. In assessing race-day workload in equine athletes, we wanted to include the knowledge that bone fatigue injuries are typically the result of cumulative loading cycles at areas of high stress. Because it is the most common mechanism for injury, we included a measure of bone fatigue rather than just distance and speed. As we were unable to measure load on bone itself, we used the horse speed for each stride as a proxy for the load incurred. Loads were scaled based on joint surface loads expected to be incurred during high-speed galloping. Maximal joint surface pressures *in vivo* are yet to be determined owing to the difficulty to make such measurements in the live animal, therefore we modelled a range of loads [22,23]. This method of using speed and cycles to calculate a training/racing load based on the fatigue process, whilst subject to limitation, improves upon previous quantitative estimates using just speed and distance.

The exponential relationship between the estimated fatigue accrued for each race start and the magnitudes of the potential loading emphasises the importance of the magnitude of load for injury risk. Limb loading is directly proportional to speed, therefore greater bone damage would

be expected to occur with greater race speeds [22-24]. These relationships explain why distances accumulated at high speed, where loads on the limb are greater, have a greater impact on injury than distances at lower speed [8]. When loads were scaled to 54 MPa the mean race start fatigue accumulation was only 0.03% of total fatigue life, but when that load was increased by two-thirds, the mean race start fatigue accumulation increased to 9.34% of fatigue life, a greater than 300-fold increase. Based on our previous analysis of strides and the work of others, greater speed is associated with fewer stride cycles/ greater stride lengths [25,26,29,30]. For higher speed our estimates have a small reduction in the proportion of fatigue life due to fewer cycles of load, but this linear effect is overwhelmed by the increase in fatigue accumulation due to the higher load estimated according to the quadratic relationship of speed to force in our first equation. The relationship between load and fatigue accumulation also explains the strong spatial association between areas of high load across a joint surface and subchondral bone injury [23].

Horse level factors of age, sex and performance (as indicated by finishing position) influenced the percentage fatigue life accrued over each race start but in different ways; i.e. differences in numbers of strides, differences in speed, or a combination of the two. Based on our model, females accumulate greater fatigue per race than male horses. This was due to the greater number of strides female horses took per race for similar speeds, and supported by a study of 2-year-olds galloping (under non-race conditions) where for any given speed, colts had longer stride length than fillies [26,29]. Greater horse age was associated with greater estimated bone fatigue per race. However, age was not associated with the number of strides, therefore the relationship demonstrated here is due to an increase in speed of older horses [26]. Older racehorses tend to have higher stride frequencies which is consistent with higher speed if stride length is unchanged [26,31,32]. Average race speed has also been reported to increase with age until 4.5 years followed by a plateau period [33,34]. The effect of finishing position on strides is variable depending on location in the race, but overall horses with better finishing positions take similar

or slightly fewer strides than the rest of the field and average higher speed over race starts [26,35].

With increasing race distance total bone fatigue accumulation increased but not at a proportional rate. This was because both the number of strides per 200 m reduced, and so did mean speed [26]. Horses racing on a softer surface used up less bone fatigue life than those racing on firm surfaces, since the slower speeds over-ride the effect of greater numbers of strides on softer surfaces [26]. The stride characteristics of synthetic tracks correlated with good rated turf tracks, but the fatigue life estimate here aligned more with the soft track ratings, therefore a combination of speed and stride characteristics may be contributing to this effect.

The relationship of weight carried on fatigue accrual was dependent on the class of race, where greater weight carried did not necessarily result in greater fatigue damage. Overall the number of strides per race tended to decrease with increasing weight carried, and greater weight carried is reported to be associated with slower racing times [26,36]. For the lower classed races, the static percentage of fatigue life accrued with increased weight was due to a slight increase in speed compensating for fewer strides. A similar effect has been described in a Japanese cohort, where for young horses entering racing their speed increased despite additional weights carried [33]. The authors speculated this was likely due to horse growth in the early racing years outweighing the effects of carried weight [33]. Comparatively, the estimated fatigue accrual for open class races increased with weight carried due to a greater increase in speed. Therefore, weight carried is an indicator of the ability of a horse as open class races tend to have the largest variation in horse ability.

The results presented here largely agree with injury risk factor studies, especially for speed, race level factors and horse age. This likely reflects the important contribution of speed and stride characteristics in injury development and supports the validity of the models presented. Race-factors of longer race distances and firmer turf track surfaces were associated with greater fatigue life, in agreement with risk factor studies in Australia [37,38]. For track surface type, although some studies have reported a higher risk for specific fracture site locations on synthetic/all-weather tracks [39-43], in pooled meta-analysis there was no difference in catastrophic musculoskeletal injury (CMI) risk for turf tracks compared to synthetic (P=0.991) [6]. This is consistent with fatigue accumulation for synthetic tracks equivalent to the mid-range of turf track ratings. Better finishing position's association with greater fatigue damage aligns with findings that horses expected to be better performers in race starts (as defined by better "Odds ranks") were at higher risk of fracture [44]. Greater horse age was associated with greater estimated accumulated bone damage per race and similarly reported to be a risk factor for CMI in pooled meta-analysis [6]. Given that bone injuries are typically the result of damage accumulation over time, increased risk with age may be due to accumulated galloping distance. However, more fatigue damage may also accrue with each start in older horses. The lack of consistent association between weight carried and fatigue life is also interesting given that there is limited literature suggesting an association between weight carried and risk of injury. Of the 11 epidemiological studies in Thoroughbreds that have assessed the effect of weight carried on risk of CMI, 10 found no significant association, with only one study reporting greater carried weights to be a (univariable) risk factor [1,6,37,38,45-53].

Where our results do not mimic injury risk studies suggest areas where our modelling methods may be improved upon. In estimating fatigue accrual by horse sex, females used a greater percentage fatigue life over race starts. However males are typically higher risk of CMI [6]. Speeds achieved between male and female mature horses has been shown to be largely equivalent, but

females undertake such speed at a greater stride frequency [29]. Investigation of stride characteristics in Thoroughbreds is a recent area of investigation, but in human athletics it has been recognised that in order to reduce injury risk, it is preferential for athletes to increase their running cadence (stride frequency) and to reduce their stride length to reduce limb loading [54]. Our modelling will underestimate any protective effect of the higher stride frequency in female horses because the effect of stride frequency on limb load is not taken into account. Other aspects such as increased weight carried will likely increase limb loading if speed is maintained due to a direct effect on the Ground Reaction Force (GRF). Additional factors that are not taken into account with the current modelling method may contribute to these apparently conflicting results by affecting limb loads include muscle forces, bone shape and quality.

The current modelling approach would be improved by the addition of stance duration data (time that the hoof is in contact with the ground) as this would enable the measurement of duty factor (proportion of the stride the limb is in contact with the ground) from which GRF can be calculated [55]. Moreover, the equations we used do not have confidence intervals around the coefficients. Given the variation in strides between individual horses, the inclusion of a sensitivity analysis for vertical force estimates would account for further variation in these parameters.

5.6 CONCLUSIONS

The modelling approach described here builds on previous methods for determining training and racing loads by adding a bone fatigue function. The validity of this approach is demonstrated by the good agreement of the outputs with the results of previous risk factor studies and has enabled identification of areas where modelling inputs can be improved. We have previously demonstrated a large inter-horse variation in stride measures suggesting the stride pattern of individual horses is highly specific. The results presented here suggest that there is also

substantial variation across horse- and race-level factors of fatigue accrual accumulation in Thoroughbred racing which explains why horses with similar racing histories may have very different outcomes. An individual horse's innate stride characteristics in combination with loading estimates derived from its racing history may be beneficial for future assessment of a horse's suitability to race.

5.7 POSTSCRIPT

The results presented in Chapter 5 demonstrate the importance of developing methods for quantifying load in galloping horses given that the proxy used for load (speed) had a large effect on bones' fatigue life consumed per distance. The implications for measured workloads undertaken by individual horses in training and racing are explored in Chapter 7.

5.8 REFERENCES

[1] Cohen, N.C., Berry, S.M., Pelso, J.G., Mundy, G.D. and Howard, I.C. (2000) Association of high-speed exercise with racing injury in Thoroughbreds. *J Am Vet Med Assoc* **216**, 1273-1278.

[2] Estberg, L., Gardner, I.A., Stover, S.M., Johnson, B.J., Case, J.T. and Ardans, A. (1995) Cumulative racing-speed exercise distance cluster as a risk factor for fatal musculoskeletal injury in Thoroughbred racehorses in California. *Prev Vet Med* **24**, 253-263.

[3] Estberg, L., Stover, S.M., Gardner, I.A., Rake, C.M., Johnson, B. and Ardans, A. (1996) High-speed exercise history and catastrophic racing fracture in Thoroughbreds. *Am J Vet Res* **57**, 1549-1555.

[4] Estberg, L., Gardner, I.A, Stover, S.M . and and Johnson, B.J. (1998) A case-crosover study of intensive racing and training schedules and risk of catastrophic musculoskeletal injury and lay-up in Californian Thoroughbred racehorses. *Prev Vet Med* **33**, 159-170.

[5] Hitchens, P.L., Hill, A.E. and Stover, S.M. (2018) Relationship between historical lameness, medication usage, surgery, and exercise with catastrophic musculoskeletal injury in racehorses. *Front Vet Sci* **5**, 217.

[6] Hitchens, P., Morrice-West, A.V., Stevenson, M. and Whitton, R.C. (2018) Meta-analysis of risk factors for racehorse catastrophic musculoskeletal injury in flat racing. *Vet J* **245**.

[7] Reed, S.R., Jackson, B.F., Wood, J.L., Price, J.S. and Verheyen, K.L. (2013) Exercise affects joint injury risk in young Thoroughbreds in training. *Vet J* **196**, 339-344.

[8] Verheyen, K., Price, J., Lanyon, L. and Wood, J. (2006) Exercise distance and speed affect the risk of fracture in racehorses. *Bone* **39**, 1322-1330.

[9] Rogers, C.W. and Firth, E.C. (2004) Musculoskeletal responses of 2-year-old Thoroughbhred horses to early training. 2. Measurement error and effect of training stage on the Relationship between objective and subjective criteria of training workload. *N Z Vet J* **52**, 272-279.

[10] Rogers, C.W., Rivero, J.L.L., van Breda, E., Lindner, A. and Sloet van Oldruitenborgh-Oosterbaan, M.M. (2007) Describing workload and scientific information on conditioning horses. *Equine and Comparative Exercise Physiology* **4**, 1-6.

[11] Stares, J., Dawson, B., Peeling, P., Heasman, J., Rogalski, B., Drew, M., Colby, M., Dupont, G. and Lester, L. (2018) Identifying high risk loading conditions for in-season injury in elite Australian football players. *J Sci Med Sport* **21**, 46-51.

[12] Cummins, C., Welch, M., Inkster, B., Cupples, B., Weaving, D., Jones, B., King, D. and Murphy, A. (2019) Modelling the relationships between volume, intensity and injury-risk in professional rugby league players. *J Sci Med Sport* **22**, 653-660.

[13] Bazzano, M., Giudice, E., Rizzo, M., Congiu, F., Zumbo, A., Arfuso, F., Di Pietro, S., Bruschetta, D. and Piccione, G. (2016) Application of a combined global positioning and heart rate monitoring system in jumper horses during an official competition - A preliminary study. *Acta Vet Hung* **64**, 189-200.

[14] Fonseca, R.G., Kenny, D.A., Hill, E.W. and Katz, L.M. (2010) The association of various speed indices to training responses in Thoroughbred flat racehorses measured with a global positioning and heart rate monitoring system. *Equine Vet J Suppl*, 51-57.

[15] Vermeulen, A., Evans, DL (2006) Measurements of fitness in Thoroughbred racehorses using field studies of heart rate and velocity with a global positioning system. *Equine Vet J* **38**, 113-117.

[16] Kingston, J., Soppet, GM, Rogers, CW, Firth, EC (2006) Use of a global positioning and heart rate monitoring system to assess training load in a group of thoroughbred racehorses. *Equine Vet J 7* **38**, 106-109.

[17] Martig, S., Chen, W., Lee, P.V. and Whitton, R.C. (2014) Bone fatigue and its implications for injuries in racehorses. *Equine Vet J* **46**, 408-415.

[18] Muir, P., Peterson, A.L., Sample, S.J., Scollay, M.C., Markel, M.D. and Kalscheur, V.L. (2008) Exercise-induced metacarpophalangeal joint adaptation in the Thoroughbred racehorse. *J Anat* **213**, 706-717.

[19] Cui, W. (2002) A state-of-the-art review on fatigue life prediction methods for metal structures. *J Mar Sci Technol* **7**, 43-56.

[20] Carter, D.R., Hayes, W.C. (1977) Compact bone fatigue damage—I. Residual strength and stiffness. *J Biomech* **10**, 325-337.

[21] Salkind, M. (1972) Fatigue of composites. In: *Composite Materials: Testing and Design (Second Conference)*, ASTM International. pp 333-364.

[22] Martig, S., Lee, P.V., Anderson, G.A. and Whitton, R.C. (2013) Compressive fatigue life of subchondral bone of the metacarpal condyle in thoroughbred racehorses. *Bone* **57**, 392-398.

[23] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2014) Evaluation of a subject-specific finite-element model of the equine metacarpophalangeal joint under physiological load. *J Biomech* **47**, 65-73.

[24] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2010) Relationship between muscle forces, joint loading and utilization of elastic strain energy in equine locomotion. *J Exp Biol* **213**, 3998-4009.

[25] Witte, T.H., Hirst, C.V. and Wilson, A.M. (2006) Effect of speed on stride parameters in racehorses at gallop in field conditions. *J Exp Biol* **209**, 4389-4397.

[26] Morrice-West, A.V., Hitchens, P.L., Walmsley, E.A., Stevenson, M.A., Wong, A.S.M. and Whitton, R.C. (2020) Variation in GPS and accelerometer recorded velocity and stride parameters of galloping Thoroughbred horses. *Equine Vet J***.**

[27] Rubio-Martínez, L.M., Cruz, A.M., Gordon, K. and Hurtig, M.B. (2008) Mechanical properties of subchondral bone in the distal aspect of third metacarpal bones from Thoroughbred racehorses. *Am J Vet Res* **69**, 1423-1433.

[28] Royston, P. (2013) BOXTID: Stata module to fit Box-Tidwell and exponential regression models.

[29] Seder, J.A. and Vickery, C.E. (2003) Temporal and kinematic gait variables of Thoroughbred racehorses at or near racing speeds. *J Equine Vet Sci* **23**, S82-S112.

[30] Ratzlaff, M., Shindell, R. and White, K. (1985) The interrelationships of stride lengths and stride times to velocites of galloping horses. *J Equine Vet Sci* **5**, 279-283.

[31] Parkes, R.S., Weller, R., Pfau, T. and Witte, T.H. (2019) The effect of training on stride duration in a Cohort of Two-Year-Old and Three-Year-Old Thoroughbred Racehorses. *Animals* **9**, 466.

[32] Ferrari, M., Pfau, T., Wilson, A.M. and Weller, R. (2009) The effect of training on stride parameters in a cohort of National Hunt racing Thoroughbreds: A preliminary study. *Equine Vet J* **41**, 493-497.

[33] Takahashi, T. (2015) The effect of age on the racing speed of Thoroughbred racehorses. *J Equine Sci* **26**, 43-48.

[34] Oki, H., Willham, R. and Sasaki, Y. (1994) Genetics of racing performance in the Japanese Thoroughbred horse: I. Description of the data. *J Anim Breed Genet* **111**, 121-127.

[35] Spence, A.J., Thurman, A.S., Maher, M.J. and Wilson, A.M. (2012) Speed, pacing strategy and aerodynamic drafting in Thoroughbred horse racing. *Biol Lett* **8**, 678-681.

[36] Martin, G., Strand, E. and Kearney, M. (1996) Use of statistical models to evaluate racing performance in Thoroughbreds. *J Am Vet Med Assoc* **209**, 1900-1906.

[37] Boden, L.A., Anderson, G.A., Charles, J.A., Morgan, K.L., Morton, J.M., Parkin, T.D.H., Clarke, A.F. and Slocombe, R.F. (2007) Risk factors for Thoroughbred racehorse fatality in flat starts in Victoria, Australia (1989-2004). *Equine Vet J* **39**, 430-437.

[38] Bailey, C.J., Reid, S. W. J., Hodgson, D. R., Bourke, J. M., Rose, R. J. (1998) Flat, hurdle and steeple racing risk factors for musculoskeletal injury. *Equine Vet J* **30**, 498-503.

[39] Williams, R.B., Harkins, L.S., Hammond, C.J. and Wood, J.L.N. (2001) Racehorse injuries, clinical problems and fatalities recorded on British racecourses from flat racing and National Hunt racing during 1996, 1997 and 1998. *Equine Vet J* **33**, 478-486.

[40] Kristoffersen, M., Parkin, T. and Singer, E. (2010) Catastrophic biaxial proximal sesamoid bone fractures in UK Thoroughbred races (1999–2004): Horse characteristics and racing history. *Equine Vet J* **42**, 420-424.

[41] Reardon, R.J., Boden, L., Stirk, A.J. and Parkin, T.D. (2014) Accuracy of distal limb fracture diagnosis at British racecourses 1999-2005. *Vet Rec* **174**, 477.

[42] Parkin, T.D., Clegg, P.D., French, N.P., Proudman, C.J., Riggs, C.M., Singer, E.R., Webbon, P.M. and Morgan, K.L. (2006) Catastrophic fracture of the lateral condyle of the third metacarpus/metatarsus in UK racehorses - fracture descriptions and pre-existing pathology. *Vet J* **171**, 157-165.

[43] Parkin, T., French, N., Riggs, C., Morgan, K., Clegg, P., Proudman, C., Singer, E. and Webbon, P. (2004) Risk of fatal distal limb fractures among thoroughbreds involved in the five types of racing in the United Kingdom. *Vet Rec* **154**, 493-497.

[44] Georgopoulos, S.P. and Parkin, T.D.H. (2017) Risk factors for equine fractures in Thoroughbred flat racing in North America. *Prev Vet Med*, 99.

[45] Bailey, C.J., Reid, S. W. J., Hodgson, D. R., Suann, C. J., Rose, R. J. (1997) Risk factors associated with musculoskeletal injuries in Australian Thoroughbred racehorses. *Prev Vet Med* **32**, 47-55.

[46] Bolwell, C., Rogers, C., Gee, E. and McIlwraith, W. (2017) Epidemiology of musculoskeletal injury during racing on New Zealand racetracks 2005–2011. *Animals* **7**, 62.

[47] Allen, S., Rosanowski, S., Stirk, A. and Verheyen, K. (2017) Description of veterinary events and risk factors for fatality in National Hunt flat racing Thoroughbreds in Great Britain (2000–2013). *Equine Vet J* **49**, 700-705.

[48] Cohen, N., Peloso, J., Mundy, G., Fisher, M., Holland, R., Little, T., Misheff, M., Watkins, J., Honnas, C. and Moyer, W. (1997) Racing-related factors and results of prerace physical inspection and their association with musculoskeletal injuries incurred in thoroughbreds during races. *J Am Vet Med Assoc* **211**, 454-463.

[49] Cohen, N.D., Mundy, G.D., Peloso, J.G., Carey, V.J. and Amend, N.K. (1999) Results of physical inspection before races and race-related characteristics and their association with musckuloskeletal injuries in Thoroughbreds during races. *J Am Vet Med Assoc* **215**, 654-661.

[50] Henley, W.E., Rogers, K. and Harkins, L. (2006) A comparison of survival models for assessing risk of racehorse fatality. *Prev Vet Med* **74**, 3-20.

[51] Hernandez, J., Hawkins, DL, Scollay, MC (2001) Race start characteristics and risk of musculoskeletal injury in Thoroughbred racehorses. *J Am Vet Med Assoc* **218**, 83-86.

[52] Parkin, T., Clegg , P., French , N., Proudman , C., Riggs, C., Singer, E., Webbon, P. and Morgan, K. (2004) Horse-level risk factors for fatal distal limb fracture in racing Thoroughbreds in the UK. *Equine Vet J* **36**, 513-519.

[53] Parkin, T., Clegg, P., French, N., Proudman, C., Riggs, C., Singer, E., Webbon, P. and Morgan, K. (2005) Risk factors for fatal lateral condylar fracture of the third metacarpus/metatarsus in UK racing. *Equine Vet J* **37**, 192-199.

[54] Schubert, A.G., Kempf, J. and Heiderscheit, B.C. (2014) Influence of stride frequency and length on running mechanics: a systematic review. *Sports Health* **6**, 210-217.

[55] Witte, T., Knill, K. and Wilson, A. (2004) Determination of peak vertical ground reaction force from duty factor in the horse (Equus caballus). *J Exp Biol* **207**, 3639-3648.

APPENDIX C. SUPPLEMENTARY INFORMATION TO CHAPTER 5

S1 UNIVARIABLE ASSOCIATIONS

Supplementary Table S1. *Univariable associations between horse and race-level factors on the percentage of fatigue life accrued over Thoroughbred race starts in Tasmania, Australia, according to estimated joint loads scaled to a maximum of 90 MPa.*

Race percentage fatigue life	Coef.	[95% Conf	Interval]	p-value
Horse factors				
Sex				
Female	(reference)			
Gelding	.194	.086	.302	<0.001
Colt/Stallion	-.167	-.478	.144	.291
Age (years)	.297	.264	.329	<0.001
Finishing position	-.033	-.042	-.025	<0.001
Weight carried (per 10 kg)	.025	-.154	.203	0.270
Race Factors				
Race Distance ±	7.586	7.475	7.696	<0.001
Track type & Rating				
Synthetic	(reference)			
Firm 2	-1.016	-1.23	-.802	<0.001
Good 3	1.065	.95	1.180	<0.001
Good 4	.928	.855	1.000	<0.001
Soft 5	.547	.469	.625	<0.001
Soft 6	-.049	-.147	.049	.327
Soft 7	-.099	-.212	.014	.086
Heavy 8	-.411	-.502	-.320	<0.001
Heavy 9	-.749	-.885	-.614	<0.001
Heavy 10	-1.546	-1.727	-1.365	<0.001
Race Class				
Maiden/Class 1	(reference)			
Class 2-5	-.063	-.130	.003	.061
Restricted (HCP/BM)	1.043	.948	1.139	<0.001
Listed /Group	2.649	2.426	2.873	<0.001
Open	.346	.177	.515	<0.001

± Race distance scaled per 100 m and transformed to the power of 0.3531 according to a Box-Tidwell transformation

S2 CROSS-TABULATION OF SEX AGAINST RACE DISTANCE, RACE CLASS AND WEIGHT CARRIED

Supplementary table S2. *Cross-tabulation of the number of females, geldings and intact male horses competing in varying race distance categories, race classes and weights carried.*

		Horse Sex			
Race Distance (m)		**Filly/Mare**	**Gelding**	**Colt/Stallion**	**Total**
≤1200	n	3,526	3,392	176	7,094
	% race distance	*50*	*48*	*2*	*100*
	% horse sex	*32.1*	*24.7*	*34.11*	*28.11*
>1200 - ≤1600	n	5,097	6,380	227	11,704
	% race distance	*44*	*55*	*2*	*100*
	% horse sex	*46.41*	*46.45*	*43.99*	*46.38*
>1600 - ≤2000	n	1,575	2,629	82	4,286
	% race distance	*36.75*	*61.34*	*1.91*	*100*
	% horse sex	*14.34*	*19.14*	*15.89*	*16.99*
>2000 - ≤2400	n	743	1,222	29	1,994
	% race distance	*37*	*61*	*1*	*100*
	% horse sex	*6.77*	*8.9*	*5.62*	*7.9*
>2400	n	42	112	2	156
	% race distance	*26.92*	*71.79*	*1.28*	*100*
	% horse sex	*0.38*	*0.82*	*0.39*	*0.62*
Total	n	10,983	13,735	516	25,234
	% race distance	*43.52*	*54.43*	*2.04*	*100*
	% horse sex	*100*	*100*	*100*	*100*
Race Class					
Maiden/Class 1	n	6,451	6,193	289	12,933
	% race distance	49.88	47.89	2.23	100
	% horse sex	58.74	45.09	56.01	51.25
Class 2-5	n	1,157	1,472	60	2,689
	% race distance	43.03	54.74	2.23	100
	% horse sex	10.53	10.72	11.63	10.66
Restricted (HCP/BM)	n	2,742	5,299	145	8,186
	% race distance	33.5	64.73	1.77	100
	% horse sex	24.97	38.58	28.1	32.44
Listed /Group	n	265	301	7	573
	% race distance	46.25	52.53	1.22	100
	% horse sex	2.41	2.19	1.36	2.27
Open	n	368	470	15	853
	% race distance	43.14	55.1	1.76	100
	% horse sex	3.35	3.42	2.91	3.38
Total	n	10,983	13,735	516	25,234
	% race distance	43.52	54.43	2.04	100
	% horse sex	100	100	100	100
Weight carried (kg)					
50- 52	n	957	555	27	1,539
	% race distance	62.18	36.06	1.75	100
	% horse sex	8.71	4.04	5.23	6.1

52.5- 54.5	n	3,766	2,377	101	6,244
	% race distance	60.31	38.07	1.62	100
	% horse sex	34.29	17.31	19.57	24.74
55- 57	n	5,704	5,921	241	11,866
	% race distance	49.9	2.03	100	
	% horse sex	51.93	43.11	46.71	47.02
57.5- 59.5	n	534	4,642	141	5,317
	% race distance	10.04	87.3	2.65	100
	% horse sex	4.86	33.8	27.33	21.07
≥60	n	22	240	6	268
	% race distance	8.21	89.55	2.24	100
	% horse sex	0.2	1.75	1.16	1.06
Total	n	10,983	13,735	516	25,234
	% race distance	43.52	54.43	2.04	100
	% horse sex	100	100	100	100

CHAPTER 6. EFFECT OF HIGH SPEED TRAINING VOLUME, AND DURATION AND FREQUENCY OF REST PERIODS, OF AUSTRALIAN THOROUGHBRED RACEHORSES ON RACING PERFORMANCE

6.1 PREFACE TO CHAPTER 6

Chapters 2 and 3 demonstrate the wide array of strategies adopted by trainers in preparing and maintaining horses for racing campaigns. The effect of training workloads on subsequent horse performance has not previously been reported in Australian Thoroughbreds. Injury risk factor studies assessing the effect of Thoroughbred workloads are limited, but those that have been conducted report low and high workloads being associated with greater risk of MSI, as discussed in Chapter 1. Any advised manipulation to training and racing regimens, for the sake of injury mitigation, has the capacity to affect racing performance. Therefore, the potential impact of workload changes must be considered relative to performance.

The following Chapter assesses, for Australian Thoroughbred racehorses, whether the variation between workloads prescribed by a cohort of 66 surveyed Victorian trainers was associated with racing success.

Supplementary information is provided in Appendix D.

6.2 ABSTRACT

It is important to investigate the relationship between Thoroughbred racehorse training practices and racing performance to understand the impact of advice given to trainers for injury prevention or management. We assessed the effects of intended volume and speed of gallop training and rest practices on official trainer career and previous season performance measures (percentage wins, places and prize money per start). Sixty-six Australian Thoroughbred trainers were surveyed. For career and previous season, multivariable negative binomial regression models were employed for the outcomes of wins and places, and linear regression models for prize money per start. Training workload was not associated with prize money outcomes when other factors were taken into account. Pre-trial galloping distances between 7,500 m and 15,000 m were associated with a greater rate of career wins, previous season wins and places ($P<0.05$). Slow-speed galloping distance to trial at distances between 5,000 m to 12,500 m was associated with greater rate of career placing, with reduced performance thereafter ($P=0.003$). Frequency of racing up to three weeks between racing starts was associated with previous season wins and prize money, with decline in performance thereafter ($P<0.05$). Greater frequency of rest breaks was associated with greater prize money earnt in the previous season ($P\leq0.01$). These results suggest that modifications to training aimed at injury prevention, such as avoiding long galloping distances, should not adversely affect horse performance.

Keywords: equine; workload; exercise; trainer; winnings; prize money; earnings

6.3 INTRODUCTION

For racing career success and longevity, a combination of cardiorespiratory fitness and musculoskeletal adaptation is required. The volume and type of workload to optimise racing performance is unknown and this is reflected in the lack of universality in training regimens implemented by Thoroughbred trainers [1]. Both high and low workloads are associated with injury in Thoroughbred racehorses indicating that workload modification may contribute to musculoskeletal injury rate reduction [2-4]. However optimising workloads to prevent injury is unlikely to have a high uptake by trainers if these strategies compromise performance outcomes.

A correlation between longer distances exercised at sub-maximal speeds and greater race winnings have been observed [5-7]. A quadratic relationship between galloping distance (in training and racing) and performance measures has been reported, with higher and lower distances associated with poorer performance outcomes [6]. But when examining the effect of training volume on performance in the individual horse, the confounding effect of injury on workload needs to be considered. A 'healthy horse effect' has been described whereby horses with less underlying injury undertake higher workloads [8].

Along with the workloads undertaken by race-fit horses, other training practices may affect horse performance. These include the effect of the rapidity of progression from unfit to race-fit, or of rest frequency and duration which have not been investigated previously.

The present study aimed to assess the effect of intended volume and speed of gallop training and duration and frequency of rest periods reported by Victorian Thoroughbred trainers on their horses' subsequent performance outcomes. We hypothesised that there is an optimal workload volume whereby (1) too high or too low maintenance gallop workloads, (2) too rapid progression

or too high workloads in the lead up to trialling, and (3) too short/ low frequency of rest periods would be associated with poorer performance.

6.4 MATERIALS AND METHODS

6.4.1 Workload data

Briefly, 66 (of 889 registered) trainers representative of all licence levels (Class A, General, Restricted) and regional classifications (Metropolitan, Provincial, Country) participated in a survey (2016/2017 race season). These survey methods of trainer reported Thoroughbred racehorse training regimens have been described previously in Chapter 2 [1].

We defined galloping workloads as distances (m/month) at speeds of 13.3 m/s and above ("total galloping"), and categorised them into four speeds (13.3-14.3 m/s "slow-speed galloping", 14.4-15.4 m/s "medium-speed galloping", 15.5-16.7 m/s "high-speed galloping", ≥16.8 m/s "very high-speed galloping"). Information on ages and general intended race distance (sprint, middle distance, stay) for horses by trainer were recorded. Descriptions of the typical training track surface, speed (m/s) and distance (m) for horses pre-trial and during maintenance workloads for each age and intended race distance were interpreted to generate a dataset of general workloads for the different categories of horses. Cluster analyses previously conducted by our group showed three groups of pre-trial programs for mature (3-year-old and above) horse workloads [1]. These were; (1) high volume with large amounts of slow-speed gallop; (2) moderate volume and (3) fast and light programs (low workloads over the shortest time period) [1]. Additional pre-trial variables included number of weeks from resting to trial, number of weeks in slow versus fast workouts, distances galloped at each stage of progression by speed (m/s), and average weekly gallop distance (m) by speed. Maintenance workload programs (race-fit horses) were categorised as (1) low volume; (2) medium volume; (3) medium volume with greater high-speed work; and

(4) high volume [1]. Trainers were ranked according to their maintenance workload programs and distribution of horses in their stable, detailed methods are in supplementary item S1. Trainers also provided information on the typical frequency and duration of rest periods for horses under their care (in the absence of injury or illness).

6.4.2 **Performance data**

Total career and previous season (01/08/2016-31/07/2017) race-data (wins, places, prize money, number of race starts, race distance, race class) for the 66 surveyed trainers were obtained through the official repository for Australian racing results (accessed 13- 29/03/2018).[a] Results from specific race distances (≤1,200 m, 1,201-1,400 m, 1,401-1600 m, 1601-2000 m, >2000 m) and classes (Group 1-3, Listed) were obtained. Distances were further categorised into sprint (≤1,400 m), middle distance (1,401-2000 m), and staying races (>2000 m).

We calculated percentage wins, places, and prize money per start (AUD) as these were key trainer-level parameters identified by a systematic-review of racehorse performance measures [9].

6.4.3 **Data Analysis**

Data analyses were conducted using Stata/SE version 15.0.[b] Discrete or continuous variables were assessed for normality using histograms and Shapiro-Wilk tests.

Spearman correlations (r) were used to compare workloads, trainer workload-based ranking, and rest period ranking with performance outcomes. Trainer categorical variables (licence, region, cluster groups) were considered as ordinal variables for the purposes of correlation

calculations. Univariable analyses were performed for the six outcomes: [1] career wins, [2] career places, [3] career prize money per start, [4] previous season wins, [5] previous season places, and [6] previous season prize money per start.

Predictor variables included trainer factors, progressive pre-trial fitness workload factors (timeframes, distances, clustered workload intensities), maintenance workload factors (clustered workload intensities, trainer workload intensity rank), and rest-period factors (total weeks per year, frequency).

Regression models of the above predictors on each of the six performance outcomes were generated. Models [1], [2], [4] and [5] were conducted using Negative Binomial regression according to the number of wins/places over an exposure of the logarithm of the number of starts, given the overdispersion generated when a Poisson model was employed (where overdispersion implies greater variation than predicted by the model, i.e. variance larger than the mean) [10]. Prize money analyses ([3],[6]) were conducted using linear regression. These models utilised a transformed outcome variable of the natural log of prize money per start to improve residual normality [6]. For trainers where previous season prize money was zero, 1AUD was substituted. Model residuals were checked for normality via Shapiro-Wilk tests and assessing histograms. Natural log (number of horses) and quadratic (total gallop distance, distance at 13.3-14.3 & 15.5-16.7m/s trained prior to trialling, frequency of racing) transformations were applied to continuous predictor variables based on a departure from linearity when investigating their association with outcome variables. Variables with $p \leq 0.2$ in univariable models were considered in multivariable models and retained where $p \leq 0.05$ following backwards and forward stepwise elimination. Model fit was assessed by minimisation of AIC and BIC values. Biologically plausible first-order interaction terms were screened for statistical significance, assessed graphically and included in the multivariable models after the determination of appropriate main effect terms.

Regression coefficients and their 95% confidence intervals (95%CI) are reported. For interpretation, the predictions for log transformed prize money variables were back-transformed accounting for the variance of the errors of each predicted model. For Negative Binomial models, coefficients are reported in their exponentiated form (Incident Rate Ratios, IRR). As monthly reported workloads (maintenance programs) were not uniform across each training stable and depended on the intended race distance and class of horse, sub-set univariable analyses were performed of maintenance workloads by horse program type (sprint, middle, stay, elite) on the previous season performance results. High class races were defined as Listed and Group races.

6.5 RESULTS

Licenced trainers had a median 1,220 career horse starts (IQR 261-3,409), and 108 previous season horse starts (IQR 33-244). Median career prize money was 3,500,000 AUD (IQR 450,000-13,000,000) and last racing season prizemoney was 1,300,000 AUD (IQR 630,000-2,200,000). Trainers had a median of 140 (IQR 22-40) career wins, 380 career places (IQR 70-1,218), 10 previous season wins (IQR 4-31) and 36 previous season places (IQR 7-85). Trainers had a mean 11% (SD 4%) career wins, 31% (SD 8%) places, and 10% (SD 5%) previous season wins and 31% (SD 12%) places per start.

Weak to moderate correlations between trainer-category predictor variables were present: experience of trainers increased with larger stables ($r=0.62$) and from country to provincial to metropolitan areas ($r=0.42$; $P<0.01$). Trainers with more horses tended to have higher rates of weekly distance accumulation and higher total monthly distances ($r=0.29$; $P=0.02$). Pre-trial total gallop and the slow-speed gallop (13.3-14.3m/s) distance variables were strongly correlated ($r=0.90$, $P<0.001$). Increasing pre-trial gallop distance correlated with maintenance workloads based on trainer ranking (from low to high) ($r=0.68$, $P<0.001$) and maintenance workload cluster

group (r=0.70, P<0.001). Designation of trainers into pre-trial cluster groups was moderately correlated with maintenance cluster group classification (r=0.45, P<0.001).

Univariable associations between trainer-level variables and performance outcomes are presented in Supplementary Table S2, Supplementary Figure S3. Multivariable associations are presented in Table 1, with prediction plots for the quadratic transformations displayed in Figure 6.1.

6.5.1 **Pre-trial workload factors**

Univariable

In the pre-trial period, all performance measures (career wins [1], places [2], prize money [3]; previous season wins [4], places [5], prize money [6]) improved at moderate distances and reduced at higher and lower distances galloped (P<0.05, Supplementary Table S2, Supplementary Figure S3). High-speed galloping was associated with performance outcomes ([1]-[3] P<0.05). For slow-speed gallop distances in the pre-trial period, horse performance was stable and then reduced at higher distances for most univariable models ([1],[2] P<0.001; [4],[5] P=0.03).

Multivariable

Pre-trial total galloping distances between 7,500 m and 15,000 m were associated with a greater rate of career wins (P=0.02) and previous season wins and places (P<0.05, Figure 6.1). Slow-speed galloping distance to trial (13.3-14.3m/s) was also an indicator of previous season wins, where due to its co-linearity with total distance it was interchangeable in multivariable model [1]. Pre-trial distance of 5,000 m to 12,500 m was associated with greater rate of career placing, with reduced performance at distances greater than 12,500 m ([2] P=0.003).

6.5.2 **Maintenance workloads, racing frequency and rest period factors**

Univariable

Maintenance cluster group and ranked maintenance training intensity were not associated with performance outcomes in any models. For all outcomes there was improving performance until three weeks between races with a decline in performance thereafter (Supplementary Figure S1, P<0.05). Shorter rest periods were associated with improved performance ([1]-[3],[6] P<0.05).

Multivariable

For previous season wins and prize money there was improving performance until three weeks between races with a decline in performance thereafter. Higher frequency of rest periods was associated with greater previous season prize money (P=0.01).

6.5.3 **Trainer-level factors**

Univariable

Trainer-level variables including higher licence level (P<0.01) and trainer location (metropolitan > provincial > country regions, P<0.05) were associated with some performance measures ([1]-[3],[6]), and larger stable size was associated with better performance in all models (P<0.05). Trainers that raced horses on track-surfaces not used in training (compared to those who only race on surfaces they regularly train on) had a higher rate of wins and places (P=0.02).

Multivariable

Larger stable sizes were associated with more career wins and places and previous season prize money (P<0.01), and larger stable size was the only variable associated with greater career prize money ([3] P<0.001).

Table 6.1. *Multivariable modelling of career and previous season trainer race performance outcomes from 66 surveyed Victorian thoroughbred trainers. Wins and places were analysed as negative binomial models for the number of wins/places with an exposure variable of the number of starts and presented as exponentiated coefficients to show IRR's and their associated 95% Confidence intervals (CI). Prize money per start outcome variables were log-transformed and analysed via linear regression and therefore presented as point estimates and their associated 95% CI's.*

	Career			**Previous season**		
	[1] Wins	**[2]** Places	**[3]** Prize money	**[4]** Wins	**[5]** Places	**[6]** Prize money
	IRR	IRR	Coef.	IRR	IRR	Coef.
Stable size (number of horses)	1.154** [1.038,1.283]	1.116*** [1.051,1.186]	0.50 *** [0.400, 0.596]			2.718*** [1.844,3.592]
Gallop distance (per 1000 m at >13.3 m/s) to trial *x*	1.087* [1.012,1.167]			1.141* [1.007,1.292]	1.084* [1.019,1.153]	
Gallop distance (per 1000 m at >13.3 m/s) to trial x^2	0.996* [0.993,0.999]			0.994* [0.988,1.000]	0.996** [0.994,0.999]	
Slow-speed gallop distance (per 1000 m at 13.3-14.3 m/s) to trial *x*		1.044** [1.014,1.075]				
Slow-speed gallop distance (per 1000 m at 13.3-14.3 m/s) to trial x^2		0.998** [0.996,0.999]				
Weeks between starts *x*				3.353* [1.017,11.059]		10.498* [0.375,20.621]
Weeks between starts x^2				0.795* [0.637,0.993]		-2.343* [-4.257,-0.429]
Number of rest periods/year						2.376** [0.699,4.053]

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

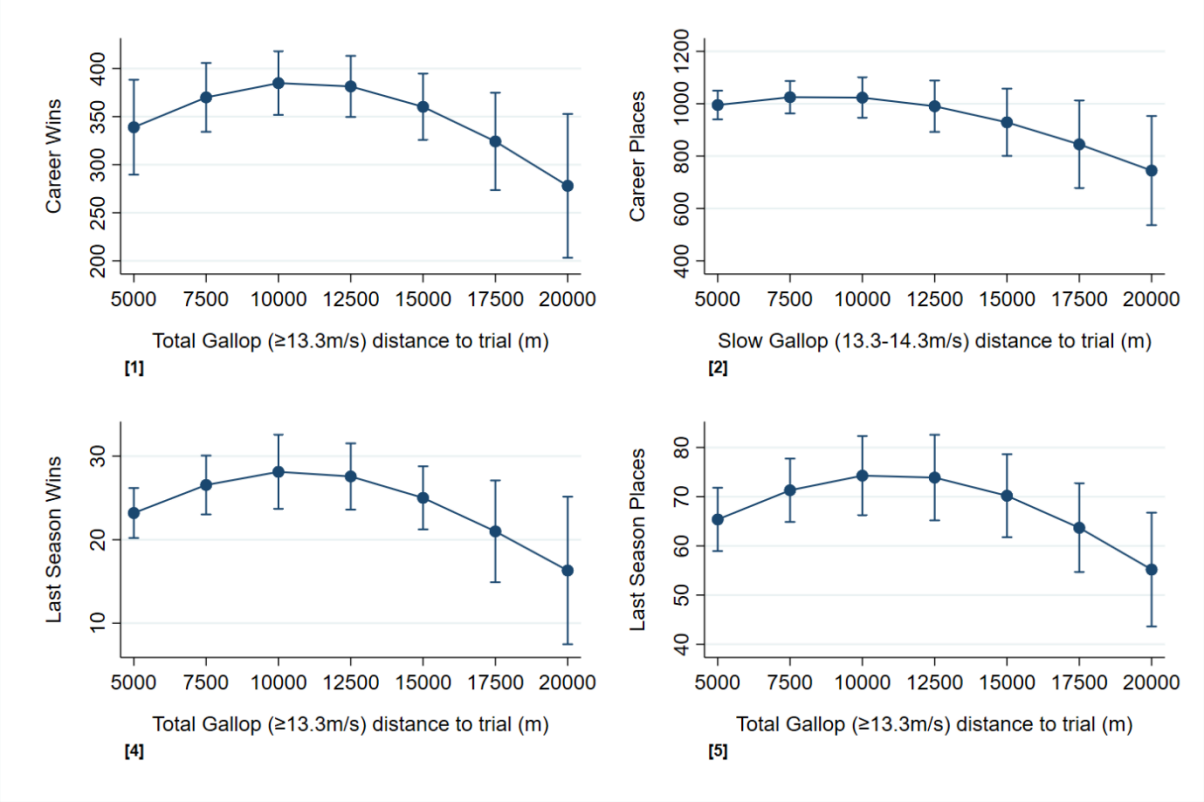

Figure 6.1. *Quadratically transformed workload variables (as galloping distance in preparation for trialling) significant in multivariable negative binomial model's for trainer performance as career [1] wins and [2] places, and previous season [4] wins and [5] places from 66 surveyed Victorian Thoroughbred trainers, accounting for an exposure variable of number of starts.*

6.5.4 **Maintenance workloads per 1,000 m (according to specific horse types)**

In a univariable subset analysis, sprint horse performance models were not affected by maintenance gallop distances, and no group's workloads (race distance categories or elite horses) significantly affected prize money per start (Supplementary Table S4). After adjusting for stable-size the effect of high-speed galloping distance did not retain significance for middle-distance horses, with stable size significantly associated with performance for this category of horses. Staying horse models, adjusted for stable size, showed a modest effect of increased slow-speed galloping (13.3-14.3 m/s) with increased places [IRR 1.02 (95%CI 1.00,1.05), P=0.02]. However, there were small but opposite effects of high-speed galloping and very high speed galloping; higher win rates associated with both lower and higher volumes of high-speed galloping [IRR 1.01 (95%CI 1.01,1.02), P<0.001], whereas higher win rates were associated with mid-volumes of very high-speed galloping, with win rates reduced for lower and higher volumes [IRR 0.99 (95%CI

0.99-1.0), P=0.01]. Although, the proportion of trainers exercising stayers at very high-speeds was small (n=6). For elite horse programs adjusted for stable size, places were increased with increased maintenance total gallop distance [>13.3 m/s, IRR 1.06 (95%CI 1.01, 1.10), P=0.01; win rate P=0.06], and wins increased as fast-galloping (15.5-16.7 m/s) increased, with a reduction for the highest distances of fast-galloping [IRR 0.94 (95%CI 0.90, 0.98), P=0.01].

6.6 DISCUSSION

We investigated the effect of training practices on measures of success for racehorse trainers in Victoria, Australia. There were few multivariable associations between training workloads and trainer success rates. Training workloads had no effect on prize money variables when other factors were taken into account, whereas the trainers who utilised the lowest and highest total or slow-speed galloping workloads as horses gained fitness and prepared for racing had the least wins and places. Similarly, the lowest and highest racing frequency was associated with less success in last season performance outcomes, with 2.5 to 3.5 weeks between starts appearing to be optimal.

Pre-trial galloping workloads were associated with performance, with performance compromised for those that galloped less or more than most of the surveyed cohort. In the pre-trial period slow-speed galloping correlated strongly with total distance galloped which likely reflects the typical Australian training pattern of a high proportion of gallop workouts at even-time (15 s/200 m; 13.3-14.3 m/s), with a short sprint finish (typically high speed and above) [1]. This is consistent with total galloping and even-time galloping being the predominant distance measures associated with performance. The pre-trial short sprint distance (fast galloping of high or very high speeds) comparatively held no multivariable associations. Galloping exercise is necessary for appropriate bone adaptation to tolerate racing loads, but our findings suggest there

is no benefit to performance through extended high-speed galloping pre-trial [11-13]. Further work is required to elucidate the optimal ranges for introduction of high-speed galloping relative to performance and injury.

We found few associations between maintenance workloads and performance outcomes, with no associations based on stable-level data. Previous work examining actual distance galloped by horses in training found a quadratic effect of high-speed galloping volume in the previous 30 days on winning a race or earning prize money in the UK [6]. Although similar to our pre-trial workload findings, which were to some extent correlated with maintenance workloads, maintenance factors which related to a trainer's overall training intensity had no effect on performance outcomes. The UK study was likely to be influenced by a healthy horse effect with horses that were performing well and remaining injury free racing more, whereas we report findings on intended rather than actual workloads in an effort to minimise the direct effect of injury. The discrepancy may also be a result of differences in training and racing environments and/or training philosophies and methodologies in different racing jurisdictions. Additionally the UK study reported a quadratic effect of distance raced in the previous 30 days on prize money [6]. We considered the frequency of racing which could be regarded as a proxy for racing intensity at the stable-level, where moderate time between races was associated with performance. Whether changes to an individual horse's racing frequency affects their performance could not be assessed, but a study using other performance measures reported a greater number of days between starts was associated with longer racing career duration [14].

It is possible that the effect of workload on performance differs for horses prepared for different distances. For instance, there are varying energy and oxygen consumptive requirements for horses racing over different distances [15]. We therefore conducted a subset analysis to stratify performance results by training programs for horses targeted to specific races. We previously

demonstrated that in this cohort, sprinters were trained over shorter distances at slow-speed gallops but there was no difference in high-speed galloping by intended race distance [1]. In the current study we found no association between maintenance galloping workloads and performance measures in sprinting horses. After adjusting for stable size, stayer's places were mildly improved by greater maintenance distances of slow-speed galloping. For stayers, both the longest and the lowest gallop distances at high-speed (15.6-16.7 m/s) were associated with better performance than mid distances at high speed. There may therefore be little benefit in extended workloads. The univariable association between greater slow-speed galloping distances and performance for elite horse programs, after adjusting for stable size, may reflect the potential for elite horses to tolerate higher workloads, but we cannot rule out other reasons for this observation.

A greater number, but not longer duration, of rest periods was associated with greater prize money per start. There is little information published on the effect of rest on performance. Periods without training have demonstrated benefits on rates of bone remodelling and therefore replacement of fatigued bone accumulated during active racing campaigns [16]. Our finding suggests that increasing the total amount of rest is best achieved by adding breaks from training rather than increasing the duration of each rest period. This relationship warrants further investigation.

Greater training stable size, and univariably, metropolitan stable locations were associated with improved performance. These findings corroborate results from Thoroughbred racing performance in New Zealand and that it was important to correct for stable size and location in the multivariable analysis where appropriate [17,18]. In both Australian and UK racing jurisdictions both horse and trainer have been associated with performance, even after accounting for different workloads between trainers [7,19].

Our findings and those of others are consistent with the lowest and highest volumes of galloping not being conducive to maximising performance. However, in horses in this study it was the volume of galloping in preparation for training that demonstrated that effect rather than gallop volumes once horses were fit to race. It is possible low workloads are not sufficiently preparing horses for race-level fitness and that horses trained over long distances are over-trained. Some trainer's low workloads in preparation for trial may also be offset by using races to gain fitness which would present as poorer performance at the beginning of campaigns. Whilst pre-trial workloads were consistent within stables, maintenance workloads were highly variable for different types of horses. At the stable-level in multivariable analysis for maintenance workloads we could only assess ranking of training intensity and clustered workload levels. Had we assessed the maintenance workloads of individual horses, we may have been able to more closely mimic the findings of previous studies.

This study has certain limitations. Firstly, as per Chapter 2 training and rest period data was obtained via in-person interviews and represents holistic training approaches to a range of horses in each stable rather than verified workload data from specific horses [1]. Injuries directly compromise workload in addition to performance. By looking at performance across entire stables and assessing intended workloads, we aimed to reduce the effect of individual horses' inability to cope with prescribed programs. The present study did not assess injury rates which clearly need careful consideration when assessing any perceived benefit to performance. The frequency of use of varying performance variables were recently reported to achieve consistency between future veterinary studies, the first and second most frequent being return to racing (yes/no) and number of starts over a set period [9]. These variables are less applicable at the trainer-level compared to studies following individual horses. We therefore chose the commonly reported rate variable measures relating to wins, places and prize money. Finally, the relatively

small sample size and the multi-collinearity, specifically with inter-changeability between workload variables and stable size, led to difficulty fitting multivariable models. Sample size calculations were prospectively conducted with the intention of having sufficient power to detect differences in workloads between groups of trainers [1].

6.7 CONCLUSIONS

When advising trainers on management practices that will minimise musculoskeletal injury, it is critical that the impact of that advice on success rates is considered. Here we found limited data linking training or rest factors in the management of Thoroughbred racehorses with trainer success according to wins, places or earnings per start. Only the very low or very high workloads were associated with poorer performance but not consistently. Therefore there is substantial potential for manipulation of workload quantity and intensity without the risk of compromising trainer, industry personnel or horse owner earnings.

Conflict of interest statement

The authors have no conflicts of interest to disclose.

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Footnotes

a. Racing Victoria 2017, www.racing.com

b. StataCorp. 2017. Stata Statistical Software: Release 15. College Station, TX: StataCorp LP

6.8 POSTSCRIPT

Chapter 6 demonstrates that the large variation in training workloads, especially for maintaining horses during a race campaign, was not associated with a trainer's overall level of success. These results are of benefit to future studies aimed at identification of risks for, and mitigation of, MSI in Thoroughbred racehorses in Australia.

A general discussion of the findings presented across this thesis, assimilating the conclusions and implications from the training and racing workloads under investigation follows and forms the final chapter of this thesis.

6.9 REFERENCES

[1] Morrice-West, A., Hitchens, P., Walmsley, E., Stevenson, M. and Whitton, R. (2020) Training practices, speed and distances undertaken by Thoroughbred racehorses in Victoria, Australia. *Equine Vet J* **52**, 273-280.

[2] Verheyen, K., Price, J., Lanyon, L. and Wood, J. (2006) Exercise distance and speed affect the risk of fracture in racehorses. *Bone* **39**, 1322-1330.

[3] Estberg, L., Stover, S.M., Gardner, I.A., Rake, C.M., Johnson, B. and Ardans, A. (1996) High-speed exercise history and catastrophic racing fracture in Thoroughbreds. *Am J Vet Res* **57**, 1549-1555.

[4] Hitchens, P., Morrice-West, A.V., Stevenson, M. and Whitton, R.C. (2018) Meta-analysis of risk factors for racehorse catastrophic musculoskeletal injury in flat racing. *Vet J* **245**.

[5] Berkman, C., Teixeira, L.G., Pereira, M.C., Sampaio, R.d.C.d.L., Bernardi, N.S., Lacerda Neto, J.C.d., Queiroz Neto, A.d. and Ferraz, G.d.C. (2015) Distance exercised during submaximal training on race winnings for Thoroughbred racehorses. *Ciência Rural* **45**, 1268-1273.

[6] Verheyen, K.L., Price, J.S. and Wood, J.L. (2009) Exercise during training is associated with racing performance in Thoroughbreds. *Vet J* **181**, 43-47.

[7] Ely, E.R., Price, J.S., Smith, R.K., Wood, J.L. and Verheyen, K.L. (2010) The effect of exercise regimens on racing performance in National Hunt racehorses. *Equine Vet J Suppl*, 624-629.

[8] Verheyen, K.L., Newton, J.R., Price, J.S. and Wood, J.L. (2006) A case-control study of factors associated with pelvic and tibial stress fractures in Thoroughbred racehorses in training in the UK. *Prev Vet Med* **74**, 21-35.

[9] Wylie, C.E. and Newton, J.R. (2018) A systematic literature search to identify performance measure outcomes used in clinical studies of racehorses. *Equine Vet J* **50**, 304-311.

[10] Hinde, J. and Demétrio, C.G. (1998) Overdispersion: models and estimation. *Comput Stat Data Anal* **27**, 151-170.

[11] Firth, E.C., Rogers, C.W., Doube, M. and Jopson, N.B. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 6. Bone parameters in the third metacarpal and third metatarsal bones. *N Z Vet J* **53**, 101-112.

[12] Firth, E.C. and Rogers, C.W. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 7. Bone and articular cartilage response in the carpus. *N Z Vet J* **53**, 113-122.

[13] Riggs, C. and Boyde, A. (1999) Effect of exercise on bone density in distal regions of the equine third metacarpal bone in 2-year-old Thoroughbreds. *Equine Vet J* **31**, 555-560.

[14] Bailey, C., Reid, S., Hodgson, D. and Rose, R.J. (1999) Factors associated with time until first race and career duration for Thoroughbred racehorses. *Am J Vet Res* **60**, 1196-1200.

[15] Eaton, M.D., Evans, D.L., Hodgson, D.R. and Rose, R.J. (1995) Maximal accumulated oxygen deficit in thoroughbred horses. *J Appl Physiol (1985)* **78**, 1564-1568.

[16] Holmes, J.M., Mirams, M., Mackie, E.J. and Whitton, R.C. (2014) Thoroughbred horses in race training have lower levels of subchondral bone remodelling in highly loaded regions of the distal metacarpus compared to horses resting from training. *Vet J* **202**, 443-447.

[17] Perkins, N., Reid, S. and Morris, R. (2004) Effect of training location and time period on racehorse performance in New Zealand. 1. Descriptive analysis. *N Z Vet J* **52**, 236-242.

[18] Perkins, N., Reid, S. and Morris, R. (2004) Effect of training location and time period on racehorse performance in New Zealand. 2. Multivariable analysis. *N Z Vet J* **52**, 243-249.

[19] More, S.J. (1999) A longitudinal study of racing Thoroughbreds: performance during the first years of racing. *Aust Vet J* **77**, 105-112.

APPENDIX D. SUPPLEMENTARY INFORMATION TO CHAPTER 6

S1 SUPPLEMENTARY METHODS

Trainer ranking for race-fit maintenance workloads

Each trainer was grouped into their primary workload level (the level in which the majority of their reported maintenance programs were categorised as). Where trainers had equal proportions of programs across two groups (n = 4) the group to which the volume of high-speed gallops most closely matched was selected. Trainers were ranked according to the proportion of maintenance workloads in each of the described cluster volume groups from lowest to highest training intensities. For each trainer, we generated a standardised score as follows. The proportion of the stable trained at each intensity level was multiplied by cluster groups' median total monthly gallop distance, a z-score was then generated and converted into a percentage. For example, a trainer with low level programs across all of the horse demographics in his stable would have resulted in 100% of programs at 4,800 m/month, and thus being ranked in the 1st percentile of workload intensity compared to the cohort. Other maintenance workload variables included frequency of racing (number of weeks between starts). Rest period variables included frequency of rest periods per year, total number of weeks in rest per year, and a rank based on the total annual weeks in rest (as least number of weeks off per year to highest weeks off per year).

S2 UNIVARIABLE ASSOCIATIONS

Table S2: *Univariable regression models of career and previous season trainer race performance outcomes from 66 surveyed Victorian thoroughbred trainers. Wins and places were analysed as negative binomial models for the number of wins/places with an exposure variable of the number of starts and presented as exponentiated coefficients to show IRR's and their associated 95% Confidence intervals (CI). Prize money per start outcome variables were log-transformed and analysed via linear regression and therefore presented as point estimates and their associated 95% CI's.*

	Performance Outcomes																			
	Career										*Last season*									
	Wins				Places			Prizemoney per start				Wins			Places			Prizemoney per start		
Trainer variables	IRR	95% CI		*p-value*	IRR	95% CI		*p-value*	Coefficent	95% CI		*p-value*	IRR	95% CI		*p-value*	IRR	95% CI		*p-value*	Coefficent	95% CI		*p-value*
Licence																				
Class A	(reference)																			
General	0.90	0.77 ,	0.05	*0.19*	0.94	0.84 ,	1.05	*0.29*	-0.46	-0.91 ,	-0.02	*0.04*	1.01	0.83 ,	1.23	*0.94*	1.04	0.90 ,	1.19	*0.58*	-5.22	-8.46 ,	-1.98	*<0.01*
Restricted	0.67	0.52 ,	-0.14	*<0.01*	0.74	0.63 ,	0.87	*<0.01*	-1.18	-1.63 ,	-0.72	*<0.01*	0.87	0.66 ,	1.16	*0.35*	0.78	0.63 ,	0.98	*0.03*	-7.97	-11.25 ,	-4.69	*<0.01*
Regional classification																				
Metropolitan	(reference)																			
Provincial	0.84	0.70 ,	0.02	*0.09*	0.90	0.79 ,	1.03	*0.13*	-0.54	-1.01 ,	-0.08	*0.02*	0.87	0.71 ,	1.06	*0.16*	0.93	0.80 ,	1.08	*0.35*	-3.33	-6.57 ,	-0.1	*0.04*
Country	0.70	0.54 ,	-0.08	*0.01*	0.79	0.65 ,	0.95	*0.01*	-0.89	-1.51 ,	-0.27	*0.01*	0.90	0.64 ,	1.26	*0.51*	0.79	0.63 ,	1.00	*0.05*	-8.5	-12.76 ,	-4.24	*<0.01*
Number of horses[#]	1.17	1.05 ,	0.27	*<0.01*	1.13	1.05 ,	1.20	*<0.01*	0.5	0.4 ,	0.6	*<0.01*	1.13	1.01 ,	1.27	*0.04*	1.13	1.02 ,	1.25	*0.02*	2.95	2.06 ,	3.83	*<0.01*
Workload Variables																				
Progressive:																				
Progressive workload levels (clusters)																				
1. Moderate workload	(reference)																			
2. High volume, slower speed gallops	0.71	0.49 ,	1.03	*0.07*	0.86	0.68 ,	1.09	*0.23*	0.47	0.24 ,	0.93	*0.03*	0.80	0.50 ,	1.27	*0.35*	0.84	0.61 ,	1.17	*0.3*	-3.15	-8.35 ,	2.05	*0.23*
3. Fast & Light	0.86	0.71 ,	1.04	*0.12*	0.92	0.81 ,	1.05	*0.22*	0.79	0.51 ,	1.23	*0.29*	0.93	0.76 ,	1.15	*0.51*	0.98	0.83 ,	1.16	*0.83*	-1.79	-5.03 ,	1.46	*0.28*
Time in fast phase	1.00	0.95 ,	1.05	*0.9*	1.01	0.98 ,	1.04	*0.51*	1.00	0.90 ,	1.13	*0.93*	0.10	0.07 ,	0.15	*<0.01*	1.02	0.98 ,	1.07	*0.33*	-0.13	-0.98 ,	0.72	*0.76*
Timeto trial	1.03	0.96 ,	1.09	*0.43*	1.02	0.97 ,	1.06	*0.41*	0.97	0.84 ,	1.12	*0.62*	1.01	0.94 ,	1.08	*0.77*	1.01	0.95 ,	1.06	*0.84*	-0.29	-1.31 ,	0.72	*0.57*
Cumulative program distance (m [§]) x	1.13	1.05 ,	1.20	*<0.01*	1.07	1.03 ,	1.12	*<0.01*	1.23	1.06 ,	1.42	*0.01*	1.16	1.03 ,	1.30	*0.01*	1.08	1.02 ,	1.15	*0.01*	1.19	0.11 ,	2.26	*0.03*
Cumulative program distance (m [§]) x^2	0.99	0.99 ,	1.00	*<0.01*	1.00	1.00 ,	1.00	*<0.01*	0.99	0.98 ,	1.00	*<0.01*	0.99	0.99 ,	1.00	*0.02*	1.00	0.99 ,	1.00	*0.01*	-0.05	-0.09 ,	0	*0.04*
Total distance at: (m/s[§])																				
13.3-14.3[±] x	1.06	1.01 ,	1.12	*0.01*	1.05	1.02 ,	1.08	*<0.01*	0.08	-0.06 ,	0.22	*0.25*	1.12	1.01 ,	1.23	*0.03*	1.06	1.01 ,	1.11	*0.02*	0.85	-0.15 ,	1.85	*0.1*
13.3-14.3[±] x^2	1.00	0.99 ,	1.00	*<0.01*	1.00	1.00 ,	1.00	*<0.01*	-0.01	-0.01 ,	0.00	*0.09*	0.99	0.98 ,	1.00	*0.03*	1.00	0.99 ,	1.00	*<0.01*	-0.05	-0.1 ,	0	*0.07*
14.4- 15.4 [±] x	0.76	0.34 ,	1.65	*0.48*	0.79	0.47 ,	1.31	*0.35*	-2.11	-4.79 ,	0.57	*0.12*	0.82	0.28 ,	2.44	*0.72*	0.30	0.10 ,	0.90	*0.03*	-17.33	-36.06 ,	1.4	*0.07*
14.4- 15.4 [±] x^2	1.23	0.81 ,	1.88	*0.34*	1.19	0.91 ,	1.55	*0.2*	1.33	-0.25 ,	2.91	*0.1*	1.16	0.64 ,	2.10	*0.63*	1.90	1.03 ,	3.53	*0.04*	10.53	-0.5 ,	21.57	*0.06*
15.5-16.7[±] x	1.17	1.05 ,	1.32	*0.01*	1.07	1.00 ,	1.15	*0.04*	0.33	0.02 ,	0.63	*0.03*	1.05	0.90 ,	1.22	*0.56*	1.04	0.90 ,	1.20	*0.54*	1.27	-0.92 ,	3.46	*0.25*
15.5-16.7[±] x^2	0.98	0.96 ,	0.99	*0.01*	0.99	0.98 ,	1.00	*0.02*	-0.04	-0.08 ,	0.00	*0.03*	0.99	0.97 ,	1.01	*0.45*	0.99	0.98 ,	1.01	*0.41*	-0.14	-0.42 ,	0.14	*0.32*
16.8+[±] x	1.21	1.01 ,	1.45	*0.03*	1.13	0.99 ,	1.30	*0.08*	0.48	-0.13 ,	1.09	*0.12*	1.08	0.85 ,	1.39	*0.52*	1.11	0.93 ,	1.32	*0.23*	3.43	-0.81 ,	7.67	*0.11*
16.8+[±] x^2	0.97	0.95 ,	1.00	*0.06*	0.99	0.96 ,	1.01	*0.19*	-0.06	-0.17 ,	0.04	*0.24*	0.99	0.96 ,	1.03	*0.71*	0.99	0.96 ,	1.02	*0.45*	-0.37	-1.11 ,	0.36	*0.32*
Average weekly distance at: (m/s [§])																				
>13.3m/s x	1.55	0.94 ,	2.59	*0.09*	1.23	0.90 ,	1.70	*0.2*	0.52	-0.67 ,	1.71	*0.38*	1.43	0.81 ,	2.53	*0.22*	1.06	0.72 ,	1.57	*0.75*	6.85	-1.42 ,	15.13	*0.1*
>13.3m/s x^2	0.90	0.79 ,	1.01	*0.06*	0.94	0.88 ,	1.02	*0.17*	-0.14	-0.42 ,	0.14	*0.31*	0.91	0.79 ,	1.05	*0.2*	0.98	0.89 ,	1.07	*0.61*	-1.39	-3.34 ,	0.56	*0.16*
13.3-14.3	0.94	0.81 ,	1.09	*0.41*	0.95	0.86 ,	1.06	*0.41*	-0.21	-0.54 ,	0.11	*0.2*	0.93	0.77 ,	1.14	*0.51*	0.94	0.84 ,	1.06	*0.34*	0.09	-2.3 ,	2.48	*0.94*
14.4- 15.4	1.19	0.44 ,	3.16	*0.74*	1.15	0.55 ,	2.36	*0.71*	-0.03	-4.77 ,	4.7	*0.99*	1.23	0.46 ,	3.29	*0.67*	0.41	0.07 ,	2.41	*0.33*	-1.89	-35.21 ,	31.42	*0.91*
15.5-16.7	1.04	0.79 ,	1.35	*0.78*	1.00	0.84 ,	1.20	*0.99*	0.25	-0.39 ,	0.9	*0.44*	0.98	0.71 ,	1.35	*0.9*	0.97	0.74 ,	1.27	*0.83*	2.94	-1.62 ,	7.51	*0.2*
16.8+	1.49	1.02 ,	2.18	*0.04*	1.39	1.11 ,	1.75	*<0.01*	1.01	-0.34 ,	2.35	*0.14*	1.36	0.92 ,	1.99	*0.11*	1.42	1.08 ,	1.86	*0.01*	9.82	0.5 ,	19.15	*0.04*

Table S2 continued:

	Performance Outcomes																			
	Career								*Last season*											
	Wins				Places				Prizemoney per start				Wins				Places				Prizemoney per start			
Race-fit:																				
Maintenance workload levels (clusters)																				
(1) Low Volume	(reference)																			
(2) Medium Volume	1.07	0.85 ,	1.363	*0.54*	1.00	0.86 ,	1.16	*0.98*	-0.06	-0.62 ,	0.5	*0.83*	1.08	0.86 ,	1.38	*0.49*	0.95	0.81 ,	1.13	*0.59*	2.21	-1.64 ,	6.06	*0.26*
(3) Medium Volume + greater fast	1.07	0.80 ,	1.45	*0.63*	1.05	0.89 ,	1.25	*0.58*	0.17	-0.52 ,	0.86	*0.63*	1.21	0.91 ,	1.58	*0.18*	1.04	0.86 ,	1.26	*0.69*	4.66	-0.35 ,	9.68	*0.07*
(4) High Volume	1.05	0.78 ,	1.42	*0.74*	1.05	0.84 ,	1.31	*0.68*	0.11	-0.75 ,	0.96	*0.81*	0.88	0.55 ,	1.40	*0.59*	0.94	0.67 ,	1.31	*0.71*	2.36	-3.55 ,	8.28	*0.43*
Ranking x	2.23	0.63 ,	7.85	*0.21*	1.11	0.47 ,	2.61	*0.82*	0.64	-2.52 ,	3.79	*0.69*	3.42	0.88 ,	13.46	*0.08*	1.13	0.39 ,	3.25	*0.83*	12.09	-9.88 ,	34.06	*0.28*
Ranking x^2	0.46	0.15 ,	1.38	*0.16*	0.90	0.41 ,	1.97	*0.81*	-0.51	-3.38 ,	2.36	*0.72*	0.30	0.08 ,	1.15	*0.08*	0.86	0.30 ,	2.41	*0.77*	-8.4	-28.36 ,	11.55	*0.4*
Frequency of racing* (weeks between starts) x	3.78	1.48 ,	9.58	*0.01*	1.70	1.04 ,	2.77	*0.03*	2.15	0.27 ,	4.02	*0.03*	4.10	1.46 ,	11.47	*0.01*	1.97	0.98 ,	3.97	*0.06*	16.35	2.99 ,	29.72	*0.02*
Frequency of racing* (weeks between starts) x^2	0.79	0.66 ,	0.93	*<0.01*	0.90	0.83 ,	1.00	*0.04*	-0.37	-0.72 ,	-0.01	*0.04*	0.77	0.64 ,	0.92	*<0.01*	0.87	0.76 ,	1.00	*0.04*	-3.19	-5.73 ,	-0.66	*0.01*
Rest period factors																				
Frequency/year	1.08	0.94 ,	1.25	*0.24*	1.05	0.96 ,	1.15	*0.25*	0.24	-0.07 ,	0.55	*0.13*	1.06	0.92 ,	0.2	*0.37*	0.97	0.87 ,	1.08	*0.55*	2.35	0.23 ,	4.46	*0.03*
length (weeks)	0.93	0.89 ,	0.98	*0.01*	0.96	0.93 ,	0.99	*0.01*	-0.13	-0.21 ,	-0.04	*0.01*	0.97	0.92 ,	0.03	*0.31*	0.97	0.94 ,	1.00	*0.07*	-0.81	-1.46 ,	-0.16	*0.01*
Track surface type use prior to racing:																				
Don't race on surfaces if not used in training	(reference)																			
Will only have trial or occassional gallop on racing surfaces	0.90	0.70 ,	1.16	*0.44*	0.96	0.81 ,	1.14	*0.64*	-0.3	-0.82 ,	0.22	*0.25*	0.92	0.70 ,	0.18	*0.54*	0.97	0.78 ,	1.21	*0.77*	0.07	-3.77 ,	3.9	*0.97*
Will race on surfaces not used in regular training	1.26	1.04 ,	1.52	*0.02*	1.17	1.03 ,	1.35	*0.02*	0.28	-0.21 ,	0.78	*0.25*	0.96	0.77 ,	0.18	*0.71*	1.09	0.94 ,	1.28	*0.25*	1.71	-1.94 ,	5.37	*0.35*

[§] Natural log transformed

[‡] Per 1000 m

x and x^2 terms refer to quadratic transformations

S3 QUADRATIC TRANSFORMATIONS FOR WORKLOAD VARIABLES

Figure S3: *Quadratically transformed workload variables (as galloping distance (m) in preparation for trialling at various speeds, and frequency of racing as weeks between starts) significant in univariable models for trainer performance as career [1] wins, [2] places and [3] prize money per start and previous season [4] wins, [5] places and [6] prize money per start from 66 surveyed Victorian Thoroughbred trainers. For [1], [2], [4] and [5] we generated as negative binomial regression models accounting for an exposure variable of number of starts. Prize money per start ([3] and [6]) were analysed with log transformed outcome variables and back transformed for graphical interpretation purposes accounting for variance in the standard errors of the models. Model [6] graphs are presented excluding the trainers who did not earn prize money in the previous season.*

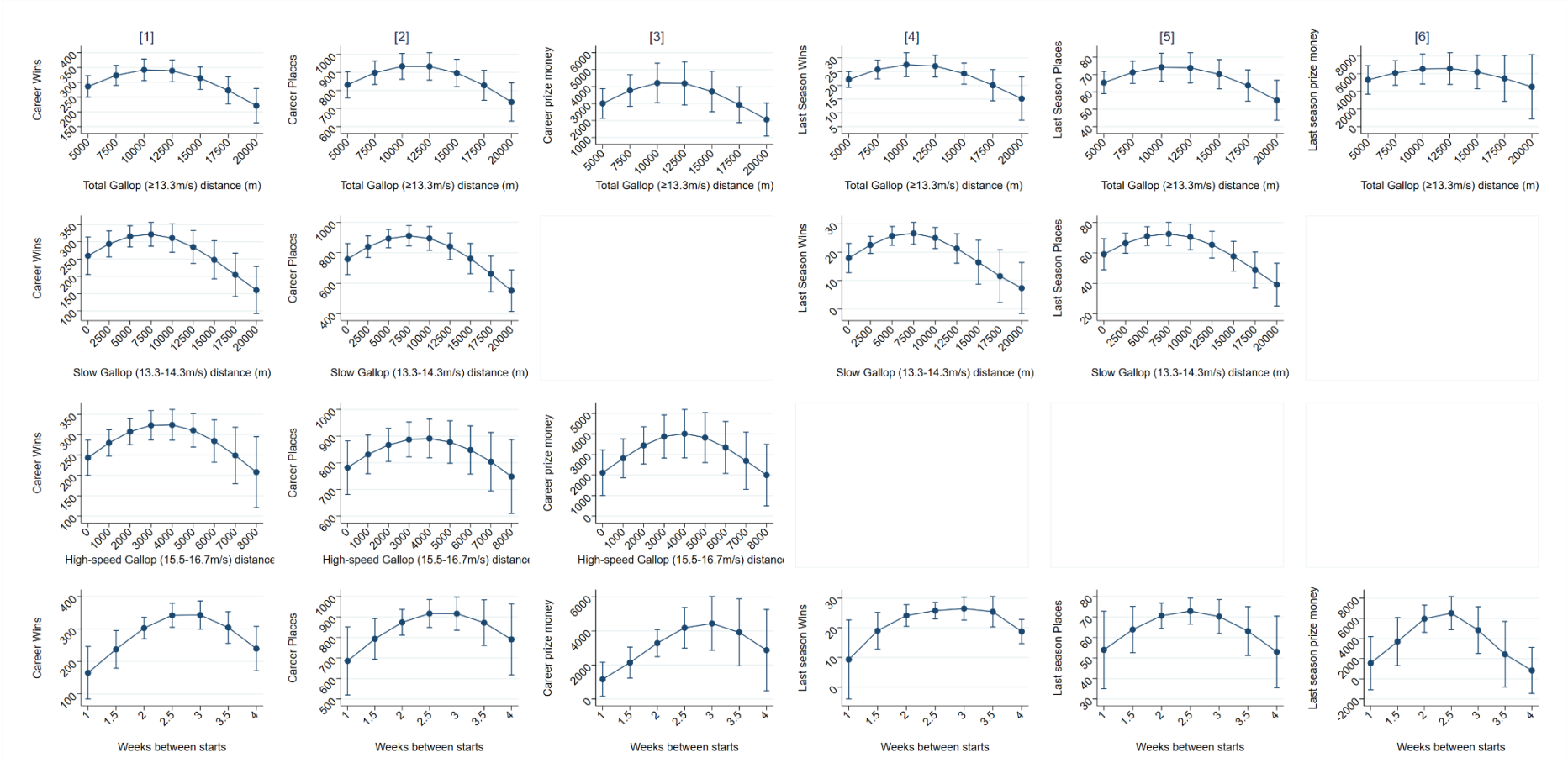

Table S4: *Previous season trainer performance outcomes as wins, places and prize money per start (log transformed) according to monthly distances galloped by subsets of horses within each training stable based on intended race distance from short to long distance (sprint/middle/stay) and elite horses from a surveyed cohort of 66 Thoroughbred trainers in Victoria, Australia.*

	Sprint												Middle distance											
	Wins				Places				Prize money per start				Wins				Places				Prize money per start			
	IRR	95% CI		*p-value*	IRR	95% CI		*p-value*	Coefficient	95% CI		*p-value*	IRR	95% CI		*p-value*	IRR	95% CI		*p-value*	Coefficient	95% CI		*p-value*
Number of horses[+]	1.03	0.80	, 1.31	*0.83*	0.99	0.90	, 1.07	*0.76*	633.28	-1763.75	, 0.59	*0.59*	1.26	1.09	, 1.46	*<0.01*	1.12	1.03	, 1.20	*<0.01*	2226.80	172.82	, 0.03	*0.03*
Total monthly distance at (m/s): Linear predictors																								
>13.3	1.01	0.98	, 1.04	*0.50*	1.01	0.99	, 1.03	*0.52*	81.35	-372.38	, 535.07	*0.71*	1.02	0.99	, 1.04	*0.18*	1.01	1.00	, 1.03	*0.12*	81.82	-193.64	, 357.29	*0.54*
13.3-14.3	1.03	0.99	, 1.06	*0.17*	1.01	0.99	, 1.03	*0.30*	157.46	-360.54	, 675.45	*0.54*	1.01	0.97	, 1.04	*0.70*	1.01	0.98	, 1.03	*0.63*	-4.77	-384.96	, 375.42	*0.98*
14.4- 15.4																								
15.5-16.7	1.04	0.95	, 1.13	*0.42*	1.01	0.98	, 1.04	*0.52*	15.04	-738.88	, 768.97	*0.97*	1.03	1.00	, 1.07	*0.08*	1.02	1.00	, 1.04	*0.10*	189.19	-298.37	, 676.76	*0.43*
16.8+	1.01	0.96	, 1.05	*0.83*	1.01	0.99	, 1.03	*0.54*	185.41	-674.65	, 1045.48	*0.66*	1.02	0.98	, 1.07	*0.30*	1.03	0.99	, 1.06	*0.11*	224.59	-607.36	, 1056.54	*0.58*
Quadtratic transformations																								
>13.3 x	0.97	0.77	, 1.21	*0.78*	0.94	0.84	, 1.04	*0.24*	-815.72	-2747.59	, 1116.15	*0.39*	1.15	0.98	, 1.34	*0.08*	1.04	0.95	, 1.14	*0.35*	487.35	-838.85	, 1813.55	*0.45*
>13.3 x2	1.00	0.99	, 1.01	*0.67*	1.00	1.00	, 1.01	*0.14*	49.57	-54.18	, 153.33	*0.33*	1.00	0.99	, 1.00	*0.10*	1.00	1.00	, 1.00	*0.48*	-15.83	-66.41	, 34.76	*0.52*
13.3-14.3 x	1.03	0.87	, 1.22	*0.69*	0.96	0.90	, 1.02	*0.23*	-579.75	-2011.77	, 852.27	*0.41*	1.00	0.89	, 1.13	*0.94*	0.98	0.91	, 1.04	*0.51*	158.24	-1264.11	, 1580.59	*0.82*
13.3-14.3 x^2	1.00	0.99	, 1.01	*0.91*	1.00	1.00	, 1.01	*0.05*	73.67	-59.83	, 207.16	*0.26*	1.00	0.99	, 1.01	*0.83*	1.00	1.00	, 1.01	*0.34*	-11.92	-111.95	, 88.11	*0.81*
14.4- 15.4 x																								
14.4- 15.4 x^2																								
15.5-16.7 x	1.21	0.93	, 1.55	*0.15*	1.02	0.92	, 1.13	*0.71*	1482.19	-948.99	, 3913.37	*0.22*	1.08	0.95	, 1.22	*0.22*	1.04	0.96	, 1.13	*0.33*	-14.35	-1423.96	, 1395.26	*0.98*
15.5-16.7 x^2	0.97	0.94	, 1.01	*0.14*	1.00	0.98	, 1.01	*0.84*	-247.75	-638.58	, 143.09	*0.20*	1.00	0.99	, 1.00	*0.34*	1.00	0.99	, 1.00	*0.48*	16.76	-91.82	, 125.35	*0.75*
16.8+ x	1.07	0.89	, 1.30	*0.48*	1.02	0.93	, 1.12	*0.63*	1836.36	-452.08	, 4124.81	*0.11*	1.12	1.02	, 1.23	*0.02*	1.07	0.99	, 1.16	*0.07*	1499.94	-1004.65	, 4004.54	*0.23*
16.8+ x^2	0.99	0.97	, 1.01	*0.40*	1.00	0.99	, 1.01	*0.67*	-279.19	-639.58	, 81.19	*0.12*	0.98	0.97	, 0.99	*<0.01*	0.99	0.98	, 1.00	*0.10*	-262.85	-749.91	, 224.22	*0.27*

Table S4 continued:

	Staying horses										Elite horses									
	Wins				Places			Prize money per start			Wins				Places			Prize money per start		
	IRR	95% CI		*p-value*	IRR	95% CI	*p-value*	Coefficient	95% CI	*p-value*	IRR	95% CI		*p-value*	IRR	95% CI	*p-value*	Coefficient	95% CI	*p-value*
Number of horses[+]	1.01	0.84 , 1.20		*0.94*	1.06	0.95 , 1.19	0.29	4154.98	116.96 , 0.04	*0.04*	1.48	0.93 , 2.34		*0.1*	1.42	1.09 , 1.82	*0.01*	9306.77	-2032.92 , 0.10	*0.1*
Total monthly distance at (m/s): Linear predictors																				
>13.3	1.02	1.00 , 1.03		*0.11*	1.01	1.00 , 1.03	*0.13*	219.49	-366.52 , 805.49	*0.45*	1.08	1.00 , 1.19		*0.04*	1.05	1.02 , 1.08	*<0.01*	1837.41	-104.90 , 3779.73	0.06
13.3-14.3	1.02	0.99 , 1.04		*0.20*	1.02	1.00 , 1.04	*0.02*	268.30	-489.60 , 1026.20	*0.48*	1.00	0.90 , 1.09		*0.93*	1.00	0.93 , 1.06	*0.94*	563.85	-1823.94 , 2951.64	0.63
14.4- 15.4	0.98	0.94 , 1.01		*0.22*	0.95	0.92 , 0.98	*<0.01*	-262.97	-6601.84 , 6075.90	*0.93*	1.14	1.08 , 1.21		*<0.01*	1.11	1.08 , 1.13	*<0.01*	2878.29	-186.62 , 5943.20	0.06
15.5-16.7	0.99	0.93 , 1.05		*0.80*	0.99	0.95 , 1.04	*0.75*	627.31	-811.13 , 2065.75	*0.38*	1.08	0.92 , 1.27		*0.33*	1.12	1.04 , 1.19	*<0.01*	3244.36	-478.84 , 6967.56	0.08
16.8+	1.05	1.02 , 1.08		*<0.01*	1.01	0.96 , 1.07	*0.72*	-277.41	-1784.85 , 1230.04	*0.71*	1.11	0.88 , 1.38		*0.41*	1.02	0.91 , 1.15	*0.67*	-715.59	-5019.21 , 3588.04	0.73
Quadtratic transformations																				
>13.3 x	1.01	0.93 , 1.09		*0.81*	1.01	0.96 , 1.06	*0.66*	1448.39	-635.86 , 3532.64	*0.17*	1.34	0.78 , 2.29		*0.29*	1.04	0.89 , 1.21	*0.64*	-989.93	-12459.15 , 10479.29	0.86
>13.3 x2	1.00	1.00 , 1.00		*0.86*	1.00	1.00 , 1.00	*0.99*	-36.87	-96.92 , 23.18	*0.22*	0.99	0.97 , 1.02		*0.46*	1.00	0.99 , 1.01	*0.88*	140.16	-419.74 , 700.05	0.6
13.3-14.3 x	1.05	0.98 , 1.13		*0.19*	1.03	0.98 , 1.08	*0.26*	1129.94	-885.46 , 3145.34	*0.26*	0.98	0.71 , 1.36		*0.91*	0.99	0.77 , 1.27	*0.95*	-1115.03	-8723.89 , 6493.84	0.76
13.3-14.3 x^2	1.00	1.00 , 1.00		*0.23*	1.00	1.00 , 1.00	*0.67*	-36.94	-116.98 , 43.09	*0.36*	1.00	0.98 , 1.03		*0.92*	1.00	0.98 , 1.02	*0.96*	161.71	-532.15 , 855.58	0.63
14.4- 15.4 x											2.36	2.03 , 2.75		*<0.01*	1.30	1.17 , 1.42	*<0.01*			
14.4- 15.4 x^2											0.93	0.91 , 0.94		*<0.01*	0.98	0.98 , 0.99	*<0.01*			
15.5-16.7 x	0.85	0.78 , 0.94		*<0.01*	0.92	0.84 , 1.03	*0.15*	1001.01	-2681.40 , 4683.41	*0.58*	1.70	1.19 , 2.41		*<0.01*	1.17	0.97 , 1.40	*0.1*	2004.49	-10553.68 , 14562.66	0.74
15.5-16.7 x^2	1.01	1.01 , 1.02		*<0.01*	1.01	1.00 , 1.01	*0.09*	-30.72	-308.66 , 247.22	*0.82*	0.94	0.90 , 0.99		*0.01*	0.99	0.98 , 1.01	*0.47*	189.20	-1635.25 , 2013.65	0.83
16.8+ x	1.15	1.06 , 1.26		*<0.01*	1.17	1.08 , 1.27	*<0.01*	-90.60	-5126.29 , 4945.09	*0.97*	1.49	1.02 , 2.16		*0.04*	1.25	1.01 , 1.54	*0.04*	2827.24	-9798.00 , 15452.47	0.64
16.8+ x^2	0.99	0.99 , 1.00		*0.01*	0.99	0.98 , 0.99	*<0.01*	-14.74	-393.27 , 363.79	*0.94*	0.94	0.90 , 0.99		*0.02*	0.96	0.94 , 0.99	*0.01*	-570.22	-2475.11 , 1334.67	0.54

+ natural log transformed predictor variable

CHAPTER 7. GENERAL DISCUSSION

7.1 GENERAL AIMS AND APPROACHES

Basic quantitative data is readily available for horses on race-day, but there are many other contributing factors that occur in the training environment that need to be considered to assess the total number of loading cycles a horse's limbs are subjected to. This thesis aimed to quantify workloads and the variation in training and management practices within a representative population of Australian trainers, and investigate the variation in stride characteristics between horses whilst racing and under different environmental conditions. The impact of these features on the accumulation of fatigue damage as a proportion of projected fatigue life were estimated. Finally, the potential impact of alteration of workloads (and therefore a horses' fitness and preparedness for racing) on race performance was assessed. The following chapter will discuss how these research questions have been addressed through the findings detailed in the preceding chapters, as well as practical implications of these findings and suggestions for future research.

7.2 TRAINING AND RACING WORKLOADS

The nature of equine bone damage, adaptation and repair involves numerous interactions and therefore examining aspects of training or racing in isolation is subject to limitations. Areas of bone subjected to highest stress were estimated to use a mean of 9.34% of fatigue life per race and therefore under the same conditions and, in the absence of any bone repair, could be expected to fail within 11 race starts (Chapter 5). Failure would be expected sooner when training gallops and additional exercise are taken into consideration. Mature horses undertook a mean of 5.9 weeks of fast work in preparation for trialling, galloping a mean of twice per week, therefore undertaking approximately 12 galloping sessions before achieving trial fitness alone (Chapter 1). Horses were then maintained with training gallops in combination with races at a mean of 2.3 weeks between starts. The average fast phase preparation and racing campaign last for 16 weeks, based on the annual exclusion of a mean of 1.9 rest periods per year

of 6.3 weeks and 4.0 weeks slow work upon re-entering training. While most horses under this average yearly program would therefore not be undertaking 11 starts in a single preparation, the combination of galloping sessions and races would exceed the fatigue life of subchondral bone. This is supported by the high prevalence of microdamage in recent Thoroughbred post-mortem histopathological investigations [1,2].

Equine bone has the capacity to adapt to loading [2-4]. An understanding of the rate of introduction to workload is therefore important in understanding a horse's preparedness for tolerating the high loads incurred under racing conditions. The three categories of gallop training introduction in the pre-trial period (Chapter 2) were divergent and these variations have the potential to influence bone modelling responses. Accumulation of moderate gallop distances in the pretrial period was associated with improved racing performance (Chapter 6). This may be indicative of better performance for trainers whose horses' bones were appropriately modelled but not overloaded in the pre-trial period, however the effects described may also be a result of cardiovascular preparedness for racing.

Although low galloping distances can be an MSI risk due to poor adaptation, numerous studies have demonstrated that increased distance at higher speeds is associated with increasing risk of musculoskeletal failure [5-13]. This is consistent with equine biomechanical investigations that show increased speed increases the force and torque on the joints, particularly at articular surfaces, and as presented in Chapter 5, higher workloads at higher speeds were associated with greater accumulated fatigue [14-16]. Victorian Thoroughbred racehorses were found to undertake relatively high monthly gallop distances in training compared to reports from other countries (Chapter 2) [17-19]. Despite this, Australia is reported to be among the nations with the lowest Thoroughbred race-day fatality rates [20]. As injury risk is multifactorial, other contributing factors need to be concurrently assessed, including the rate of workload introduction and rest periods from training. For example, Australian trainers rest horses more frequently compared to reports of international training practices (Chapter 2). Substantial

variation in workload existed across trainers in maintaining fitness, with a four-fold difference in the monthly gallop distance for horse programs in the lowest compared to the highest volume groups. Further, this variation did not translate to enhanced racing performance (Chapter 6). More research on the effect of training on injury risk is required. However, there were limited associations between workloads and performance, there is significant scope to modify training practices for the benefit of the Thoroughbred Racing Industry in general.

Alternative exercise methods such as swimming provide an opportunity for reduction of concussive cycles of loading incurred during overground exercise and have therefore been proposed as tools for controlling injury risk [21,22]. Chapter 3 and Steel and Morrice-West [23] showed that swimming in particular was frequently undertaken as a part of Victorian training regimens. Swimming reportedly generates heart rate responses similar to slower speed exercise, and therefore may be beneficial either as an additional measure or as a replacement of trot/canter workouts, however sufficient galloping trackwork to stimulate appropriate skeletal adaptation is still required [24].

Overall, training distances increase with intended race distance, but this was not the case for the high-speed/ race-speed galloping portion of workouts which was not different across designated sprint, middle and staying horses (Chapter 2). Comparatively, under race conditions, high-speed galloping is maintained for substantially longer than during training sessions and therefore the degree of bone fatigue accumulation across race distances is substantial. This is illustrated through an example of a horse's training session compared to a 1,400 m race using GPS data, Figure 7.1. The left panel shows a training workout where there is a staged progression after initial cantering, slow speed galloping and then an increasing speed sprint to the finish line. The right panel conversely shows a typical racing workload, consisting of an acceleratory period from stationary as the horse leaves the starting gate and then maintaining a high-speed gallop for as long as possible with a gradual deceleration to the finish line. For the example workout session, at a scaled joint load of 90 MPa the estimated percentage fatigue life used

was 6.27%, compared to the mean race percentage fatigue life of 9.46% for 1,400 m race starts. Comparison between, and amalgamation of, training and racing workloads warrant further investigation, but this example highlights the differences in the loading patterns between non-competition and competition galloping.

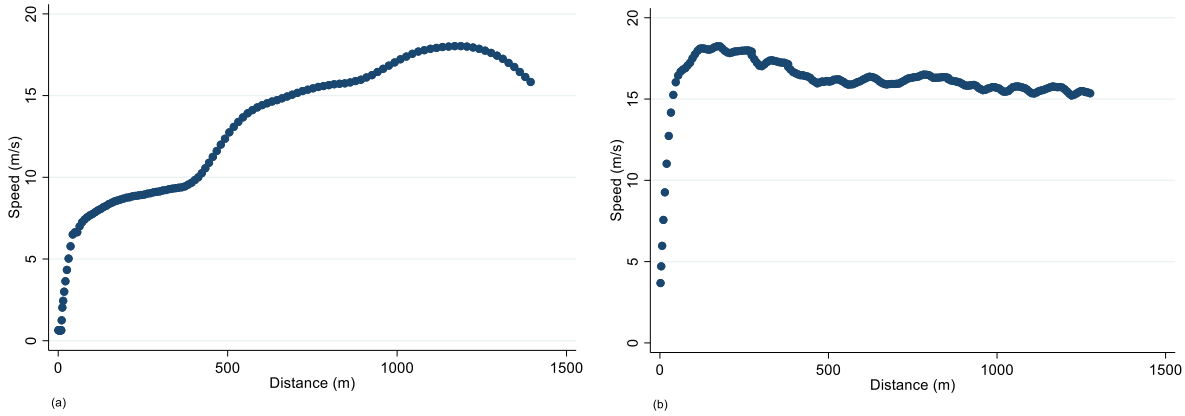

Figure 7.1. *An example of the speeds undertaken during a 1,400 m galloping session by an Australian Thoroughbred racehorse in a training session (a) vs racing (b).*

7.3 TRACK AND RACE CONDITIONS

Track surface is consistently shown to be a risk factor for MSI, with firmer tracks associated with faster racing times and increased fracture rates [19,20,25-35]. Potential mechanisms for this relationship include faster speeds being associated with higher loads on bone, greater impact forces at hoof strike with harder surfaces, and differences in distal limb stability and hoof slide [36-39]. It is also possible that a lack of adaptation to the track surface type or conditions influences injury risk if horses have not had previous exposure. Despite this, there was a lack of awareness amongst the surveyed population of Australian trainers about the potential importance of skeletal adaptation to surface conditions in preparation for racing. Track surface and rating consistently affected racing stride characteristics and the proportion of fatigue life estimated to be used per start, with horses racing on firmer tracks accruing a

greater proportion of fatigue life (Chapters 4-5). Because the results of the fatigue life calculations, which were predominantly driven by galloping speeds, mimic the relationship between surface and injury risk, this is further evidence that speed is the main mechanism resulting in greater injury risk on hard surfaces.

Race distance is another risk factor for MSI [20]. For every additional 1,000 m in a race there is reported to be 1.45 times greater odds of fatality (95% CI 1.05, 2.01) [40]. The findings of this thesis confirm that horses racing over greater distances also train over greater distances (although without greater distances at high speeds) so would therefore be expected to consume a greater proportion of fatigue life during a race and in the lead up to a race. However, these horses have different stride characteristics in racing, taking less strides of longer length and duration per sectional compared to horses competing over shorter distances (Chapters 2 and 4). The variation in strides, coupled with the lower average speeds, meant that as race distance increases horses were not estimated to accrue fatigue at the same rate (Chapter 5). Horses are therefore likely to have a greater risk of fatigue injury in longer races, but not directly proportional to the distance raced over, aligning with previous injury risk factor investigations.

7.4 INDIVIDUAL HORSE VARIATION

This thesis has highlighted the substantial variation in skeletal loading between horses and therefore the difficulty in predicting musculoskeletal injury in an individual horse. Chapter 2 highlighted the variation in workload between trainers irrespective of stable size, trainer licence or location. There was also variation within a training stable with 2-year-olds undertaking lower workloads compared to mature horses, and monthly workloads increasing as intended race distance increased. It must be considered then; are two horses exposed to the same conditions and the same workload at the same risk of injury? Besides innate differences between two individual horses such as size and weight, genetics, previous bone loading history etc., stride characteristics are a potentially important factor that could be related to an individual's innate injury risk.

Chapter 4 demonstrated that even accounting for variation across races and race meetings, the highest proportion of variation in stride characteristics was attributable to variation between individual horses. As expected based on previous investigations, stride parameters were correlated with speed. However, speed predicted only some of the variance in these parameters over race starts. High correlations would have supported the established proxy of speed and distance in representing the loading history of bone. Chapter 6 showed that the horse-level variation in stride characteristics translated to variation in the estimated percentage fatigue life accrued over race starts. Given the large variation in strides between horses, to best estimate the biological and potential pathologic state of an individual horse's bone after a series of galloping events, the individual stride characteristics must be considered.

In addition to the variation identified in this thesis, the process of material fatigue is inherently stochastic [41]. Also, bone properties such as stiffness, porosity, mineralisation, and trabecular lamellae orientation vary between individuals and across anatomical locations within an individual bone [42,43]. Therefore, two horses with seemingly identical racing histories, would not be expected to be at the same level of injury risk based on the state of accumulated bone damage incurred through individual cycles of loading in racing.

7.5 LIMITATIONS

As a series of epidemiological studies, this thesis has the following limitations that should be borne in mind. All data were retrospectively collected. Data presented in three chapters were collected via surveying trainers (Chapters 2, 3 and 6). Surveys have their limitations which can be broadly categorised into (i) observational errors due to measurement or processing faults, or; (ii) non-observational errors where some of the population is not represented by the study group because of selection bias or nonresponse errors, or alternatively adjustment errors (made in an attempt to minimise the impacts of

poor coverage, sampling and nonresponse) [44,45]. Data and analyses based on racing results (Chapters 4-6) and GPS and accelerometer devices (Chapters 3 and 4) explored associations rather than investigating causality. There was the potential for measurement error of either the predictor or outcome variables. Owing to the large number of external factors influencing race-day events, the possibility of confounders or other effect modifiers that were not recorded or considered cannot be dismissed.

7.5.1 **Selection bias and generalisability**

Selection bias is a type of systematic error which may occur when the sample group does not accurately represent the source population [46,47]. The survey was advertised to all trainers in Victoria, Australia. However, participation was voluntary, which may have resulted in selection bias. Trainers with an interest in scientific evidence-based training methods may have been more likely to participate which would result in a biased study population. Similarly, some trainers were actively targeted based on veterinarian recommendations for willingness to participate, and therefore the sampling was not conducted at random. In examining the results in these chapters, caution should be exercised if generalising to the broader population as although it showed large variation between training programs, it may not be entirely representative of training practices over the state of Victoria or Australia.

The survey had a 7.4% response rate (66 participants from a possible 889 trainers licenced in Victoria). The precision and accuracy for answering study hypotheses may have been reduced as the sample size was relatively small. The practicalities of in-person interviewing of participants restricted the number of trainers that could be interviewed. However, in-person interviewing (as opposed to a larger online survey) enabled greater detail to be collected over a large number of questions, and minimised nonresponse errors, where participants may have otherwise answered a smaller proportion of the questionnaire. Moreover, sampling from all licence categories and regions within the state was an attempt to ensure that the study population represented the demographic profile of the target population [47].

7.5.2 **Recall and misclassification bias**

Recall bias is a typical feature of retrospective studies, referring to situations where study subjects provide erroneous responses based on an inability to correctly recall previous activities [48,49]. Trainers were asked to describe typical practices used for all horses under their care. Verified quantitative data on individual horses would give less-biased and more accurate estimates of workloads. However, this was impractical due to the number of trainers surveyed (and therefore large number of horses that would have needed to be longitudinally monitored), time constraints in undertaking this thesis, and an anticipated inability to differentiate horses undertaking low workloads as an intended practice vs low workloads because of injury or other performance limiting condition. Now that we have confirmation of the importance of workloads, future studies should aim to confirm these findings, implementing more objective methods.

7.5.3 **Measurement error**

Measurement error occurs when device inaccuracy or environmental conditions lead to a difference between observed and actual values [49]. For Chapters 4 and 5, which used data collected by accelerometer and GPS recording during racing, this may have occurred due to potential inaccuracies in the collected data, especially given there was no independent-party validation of the recording system. In such cases, the errors would likely be random in nature and therefore would be minimised by the extremely large sample size of race starts available [46]. However these potential errors could not be controlled for, except to exclude biologically implausible values from the data analysed. Similarly, workloads for the fatigue life estimation were based on speed for each individual stride by horses in each race start rather than measured bone load (Chapter 5). Whilst this methodology improves on previous workload estimation methods of race-day speed and distance, it is still subject to limitation and therefore results need to be interpreted with caution.

7.5.4 **Confounding**

Confounding is a systemic error occurring when certain factors (either measured or unmeasured) are related to both the exposure and outcome variables creating a spurious association [46]. In the studies using race speed and stride data (Chapters 4 and 5), there may have been relevant independent variables (confounders or effect modifiers) present that we did not have information on causing omitted variable bias. Horse or race-level factors not assessed in the data sets available, for example horse weight, jockey pacing decisions and riding style/degree of urging the horse, as well as track undulation, or turn radius may have had an effect on the dependant variables (stride parameters), with that effect attributed to variables we had in our models, potentially resulting in biased coefficient estimates.

7.6 **IMPLICATIONS**

This thesis has the following practical implications.

The large variation in workloads, exercise methods and surfaces used in training highlights a lack of agreement or understanding of the most suitable training regimens. Moreover, no one training method was associated with peak race performance. Such diversity provides scope to modify training regimens so factors that are found to increase the risk of injury can be modified without a detrimental effect on performance.

The inter-horse variation in stride characteristics demonstrates that individuals load their bones differently. The degree of estimated fatigue damage in Chapter 5 was more sensitive to the effect of speed than the number of cycles. In order to fully elucidate the effect of load on fatigue of bone, a more accurate proxy for load is required.

There are race-level variations in the proportion of fatigue life accrued over horse race starts. Previous *in vitro* investigations have shown that the fatigue properties of bone are highly variable and there is substantial variation in how horses apply load to their limbs through varying training and racing regimens [41,50]. The combination of variation in training practices and variation in bone loading during racing illustrates the complexity in assessing an individual horse's propensity for injury. Therefore, training and racing workloads need to be tailored to the individual horse and population-based injury preventative measures need to be combined with effective monitoring methods to identify those individuals that are accumulating bone damage at rates much higher than the majority of the population.

7.7 RECOMMENDATIONS FOR FUTURE RESEARCH

Following this thesis, the fundamental question to be addressed in future research is: what is the most appropriate range of workloads and rest periods to optimise preparedness for racing while avoiding excessive overloading, and, is this the same for every horse? The first step would be to compare workload data for individual horses with the rate of injury occurrence. Understanding how training methodologies influence the propensity for musculoskeletal injury will allow for the development of evidence-based recommendations to trainers and industry personnel to aid in decision making and ultimately risk reduction.

Other measures of estimating bone and joint surface loading warrant further investigation for the accurate quantification of *in vivo* stress on bone. This may include the analysis of stance duration to attain a more accurate representation of the effect of speed and individual horse parameters on bone loading.

Universal monitoring of stride and speed variables during racing is possible as shown by Tasracing and should be implemented in all racing jurisdictions. Given the variation in stride parameters between

individuals identified in this thesis, changes in stride characteristics over time may be a better indicator of impending injury than a one-off measurement. In addition, monitoring the accumulation of bone fatigue in each horse appears to be a useful method of assessing injury risk.

Galloping exposes equine bones and joint surfaces to the highest forces and therefore racing was an appropriate starting point for exploring stride variables. Moreover, the size and longitudinal nature of the data-set available provided considerable opportunity to assess inter and intra-horse variation. Future investigations would benefit from similar data collected during training and is a key step in progressing the research presented here. However, few trainers in the geographic research area of this thesis (Victoria, Australia) use GPS systems during regular training, so in order to achieve sufficient datasets for meaningful analysis, GPS system usage would need to be standardised and increase substantially.

The recent consensus statement for monitoring training loads in human athletes highlighted the need for individualised monitoring, the monitoring not just of total workloads, but also acute to chronic workload ratios, and the need for quantification of both training- and competition-load data [51]. In line with this, over varying sporting disciplines recent research efforts looking at assessing workload on injury risk have focussed on quantifiable (GPS recorded) data combining all training data and competition workloads [52,53]. Future equine analytics would likewise benefit from the synthesis of detailed training and racing workload data.

7.8 CONCLUSIONS

It was my experience in talking to trainers that there was a lack of awareness of aspects of training that influence injury risk. There is no benefit to a trainer to have a horse injured in training or racing, and most participants in our survey wanted direct feedback on their training programs, asking “is that ok” or “is that too much?” With the Racing Industry under ever increasing scrutiny there is a pressing need for

investigations and subsequent implementation of protective policies but also dissemination of findings to trainers. When a horse sustains a CMI on a race track it is too late; we need to work with trainers to find practical and easily implementable ways to modify approaches to help mitigate injury risk before the catastrophe occurs.

Strategies implemented by trainers in preparing horses for racing and how they are maintained during and between racing campaigns are incredibly diverse, yet the overall fitness and performance of the cohort are not dissimilar. Speed and distance worked in training is highly variable for different types of horses, and differing racing campaigns result in differences in the workloads horses are exposed to. When the strides of horses galloping in these races are considered, further variation exists, even for the horses in the same races, based on innate qualities of the individual horse which translated into variation in the estimated degree of bone fatigue accrued by individual horses over each race start.

The findings presented here warrant further investigation to enable the development of industry-based guidelines for managing all aspects of horses' workloads and developing appropriate monitoring methods to identify horses at high risk of injury.

7.9 REFERENCES

[1] Whitton, R., Ayodele, B., Hitchens, P. and Mackie, E. (2018) Subchondral bone microdamage accumulation in distal metacarpus of Thoroughbred racehorses. *Equine Vet J* **50**, 766-773.

[2] Whitton, R.C., Trope, G.D., Ghasem-Zadeh, A., Anderson, G.A., Parkin, T.D., Mackie, E.J. and Seeman, E. (2010) Third metacarpal condylar fatigue fractures in equine athletes occur within previously modelled subchondral bone. *Bone* **47**, 826-831.

[3] Firth, E.C., Rogers, C.W., Doube, M. and Jopson, N.B. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 6. Bone parameters in the third metacarpal and third metatarsal bones. *N Z Vet J* **53**, 101-112.

[4] Boyde, A. and Firth, E.C. (2005) Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 8. Quantitative back-scattered electron scanning electron microscopy and confocal fluorescence microscopy of the epiphysis of the third metacarpal bone. *N Z Vet J* **53**, 123-132.

[5] Parkin, T. (2008) Epidemiology of Racetrack Injuries in Racehorses. *Vet Clin Equine* **24**, 1-19.

[6] Verheyen, K.L., Newton, J.R., Price, J.S. and Wood, J.L. (2006) A case-control study of factors associated with pelvic and tibial stress fractures in Thoroughbred racehorses in training in the UK. *Prev Vet Med* **74**, 21-35.

[7] Cogger, N., Perkins, N., Hodgson, D.R., Reid, S.W. and Evans, D.L. (2006) Risk factors for musculoskeletal injuries in 2-year-old Thoroughbred racehorses. *Prev Vet Med* **74**, 36-43.

[8] Verheyen, K., Price, J., Lanyon, L. and Wood, J. (2006) Exercise distance and speed affect the risk of fracture in racehorses. *Bone* **39**, 1322-1330.

[9] Parkin, T.D.H., Clegg, P.D., French, N.P., Proudman, C.J., Riggs, C.M., Singer, E.R., Webbon, P.M., Morgan, K.L., (2006) Analysis of horse race videos to identify intra-race risk factors for fatal distal limb fracture. *Prev Vet Med* **74**, 44-55.

[10] Oikawa, M., Ueda, Y., Inada, S. (1994) Effect of restructuring of a racetrack on the occurance of racinginjuries in Thoroughbred Horses. *J Equine Vet Sci* **14**, 262-268.

[11] Cogger, N., Perkins, N., Hodgson, D.R., Reid, S.W.J. and Evans, D.L. (2006) Risk factors for musculoskeletal injuries in 2-year-old Thoroughbred racehorses. *Prev Vet Med* **74**, 36-43.

[12] Estberg, L., Gardner, I.A, Stover, S.M et al (1998) A case-crosover study of intensive racing and training schedules and risk of catastrophic musculoskeletal injury and lay-up in Californian Thoroughbred racehorses. *Prev Vet Med* **33**, 159-170.

[13] Estberg, L., Gardner, I.A., Stover, S.M., Johnson, B.J., Case, J.T. and Ardans, A. (1995) Cumulative racing-speed exercise distance cluster as a risk factor for fatal musculoskeletal injury in Thoroughbred racehorses in California. *Prev Vet Med* **24**, 253-263.

[14] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2010) Relationship between muscle forces, joint loading and utilization of elastic strain energy in equine locomotion. *J Exp Biol* **213**, 3998-4009.

[15] Witte, T.H., Hirst, C.V. and Wilson, A.M. (2006) Effect of speed on stride parameters in racehorses at gallop in field conditions. *J Exp Biol* **209**, 4389-4397.

[16] Brown, N.A., Pandy, M.G., Kawcak, C.E. and McIlwraith, C.W. (2003) Force-and moment-generating capacities of muscles in the distal forelimb of the horse. *J Anat* **203**, 101-113.

[17] Boston, R.C. and Nunamaker, D.M. (2000) Gait and speed as exercise components of risk factors associated with onset of fatigue injury of the third metacarpal bone in 2-year-old Thoroughbred racehorses. *Am J Vet Res* **61**, 602-608.

[18] Pagan, J.D., Mulvey, E., Oneill, K., Ireland, N. and Davies, M. (2017) Intensity and distance of exercise during training in advanced three-day event horses and thoroughbred racehorses assessed using KER ClockIt smartphone application. *J Equine Vet Sci* **52**, 67-68.

[19] Verheyen, K.L., Wood, JL (2004) Descriptive epidemiology of fractures occuring in British Thoroughbred Racehorses in training. *Equine Vet J* **36**, 167-173.

[20] Hitchens, P., Morrice-West, A.V., Stevenson, M. and Whitton, R.C. (2018) Meta-analysis of risk factors for racehorse catastrophic musculoskeletal injury in flat racing. *Vet J* **245**.

[21] Misumi, K., Sakamoto, H. and Shimizu, R. (1993) The validity of swimming training for two-year-old thoroughbreds. *J Vet Med Sci* **56**, 217-222.

[22] Misumi, K., Sakamoto, H. and Shimizu, R. (1995) Changes in skeletal muscle composition in response to swimming training for young horses. *J Vet Med Sci* **57**, 959-961.

[23] Steel, C. and Morrice-West, A. (2019) A survey of trainers on the use of swimming and other water-based exercise for Thoroughbred racehorses in Australia. *Comp Exerc Physiol* **15**, 1-8.

[24] Murakami, M., Imahara, T., Inui, T., Amada, A., Senta, T., Takagi, S., Kubo, K., Sugimoto, O., Watanabe, H. and Ikeda, S. (1976) Swimming exercises in horses. *Experimental reports of Equine Health Laboratory* **1976**, 27-49.

[25] Georgopoulos, S.P. and Parkin, T.D.H. (2017) Risk factors for equine fractures in Thoroughbred flat racing in North America. *Prev Vet Med* **139**, 99-104.

[26] Cohen, N.C., Berry, S.M., Pelso, J.G., Mundy, G.D. and Howard, I.C. (2000) Association of high-speed exercise with racing injury in Thoroughbreds. *J Am Vet Med Assoc* **216**, 1273-1278.

[27] Arthur, R. (2010) Comparison of racing fatality rates on dirt, synthetic, and turf at four California racetacks. In: *American Association of Equine Practitioners Proceedings*, Baltimore, MD, USA. pp 405-408.

[28] Rosanowski, S.M., Chang, Y.M., Stirk, A.J. and Verheyen, K.L. (2016) Descriptive epidemiology of veterinary events in flat racing Thoroughbreds in Great Britain (2000 to 2013). *Equine Vet J* **49**, 275-281.

[29] Henley, W.E., Rogers, K. and Harkins, L. (2006) A comparison of survival models for assessing risk of racehorse fatality. *Prev Vet Med* **74**, 3-20.

[30] Parkin, T., Clegg , P., French , N., Proudman , C., Riggs, C., Singer, E., Webbon, P. and Morgan, K. (2004) Horse-level risk factors for fatal distal limb fracture in racing Thoroughbreds in the UK. *Equine Vet J* **36**, 513-519.

[31] Verheyen, K.L.P., Newton, J.R., Price, J.S. and Wood, J.L.N. (2006) A case-control study of factors associated with pelvic and tibial stress fractures in Thoroughbred racehorses in training in the UK. *Prev Vet Med* **74**, 21-35.

[32] MacKinnon, M.C., Bonder, D., Boston, R.C. and Ross, M.W. (2015) Analysis of stress fractures associated with lameness in Thoroughbred flat racehorses training on different track surfaces undergoing nuclear scintigraphic examination. *Equine Vet J* **47**, 296-301.

[33] Dimock, A.N., Hoffman, K.D., Puchalski, S.M. and Stover, S.M. (2013) Humeral stress remodelling locations differ in Thoroughbred racehorses training and racing on dirt compared to synthetic racetrack surfaces. *Equine Vet J* **45**, 176-181.

[34] Maeda, Y., Tomioka, M., Hanada, M. and Oikawa, M.-A. (2012) Influence of Track Surface Condition on Racing Times of Thoroughbred Racehorses in Flat Races. *J Equine Vet Sci* **32**, 689-695.

[35] Oikawa, M. and Kusunose, R. (2005) Fractures sustained by racehorses in Japan during flat racing with special reference to track condition and racing time. *Vet J* **170**, 369-374.

[36] Setterbo, J.J., Fyhrie, P.B., Hubbard, M., Upadhyaya, S.K. and Stover, S.M. (2013) Dynamic properties of a dirt and a synthetic equine racetrack surface measured by a track-testing device. *Equine Vet J* **45**, 25-30.

[37] Setterbo, J.J., Garcia, T.C., Campbell, I.P., Reese, J.L., Morgan, J.M., Kim, S.Y., Hubbard, M., Stover, S.M., (2009) Hoof accelerations and ground reaction forces of Thoroughbred racehorses measured on dirt, synthetic, and turf track surfaces. *Am J Vet Res* **70**, 1220-1229.

[38] Ratzlaff, M.H., Hyde, M.L., Hutton, D.V., Rathgeber, R.A. and Balch, O.K. (1997) Interrelationships between moisture content of the track, dynamic properties of the track and the locomotor forces exerted by galloping horses. *J Equine Vet Sci* **17**, 35-42.

[39] Harrison, S.M., Whitton, R.C., Kawcak, C.E., Stover, S.M. and Pandy, M.G. (2014) Evaluation of a subject-specific finite-element model of the equine metacarpophalangeal joint under physiological load. *J Biomech* **47**, 65-73.

[40] Boden, L.A., Anderson, G.A., Charles, J.A., Morgan, K.L., Morton, J.M., Parkin, T.D.H., Clarke, A.F. and Slocombe, R.F. (2007) Risk factors for Thoroughbred racehorse fatality in flat starts in Victoria, Australia (1989-2004). *Equine Vet J* **39**, 430-437.

[41] Martig, S., Lee, P.V., Anderson, G.A. and Whitton, R.C. (2013) Compressive fatigue life of subchondral bone of the metacarpal condyle in thoroughbred racehorses. *Bone* **57**, 392-398.

[42] Martig, S., Chen, W., Lee, P.V. and Whitton, R.C. (2014) Bone fatigue and its implications for injuries in racehorses. *Equine Vet J* **46**, 408-415.

[43] Carter, D.R., Caler, W.E., Spengler, D.M. and Frankel, V.H. (1981) Uniaxial fatigue of human cortical bone. The influence of tissue physical characteristics. *J Biomech* **14**, 461-470.

[44] Coughlan, M., Cronin, P. and Ryan, F. (2009) Survey research: process and limitations. *Int J Ther Rehabil* **16**, 9-15.

[45] Umbach, P.D. (2005) Getting back to the basics of survey research. *New Directions for Institutional Research* **2005**, 91-100.

[46] Dohoo, I.R. (2014) Bias—Is it a problem, and what should we do? *Prev Vet Med* **113**, 331-337.

[47] Kelley, K., Clark, B., Brown, V. and Sitzia, J. (2003) Good practice in the conduct and reporting of survey research. *Int J Qual Health Care* **15**, 261-266.

[48] Lilienfeld, A.M. (1983) Practical limitations of epidemiologic methods. *Environ Health Perspect* **52**, 3-8.

[49] Althubaiti, A. (2016) Information bias in health research: definition, pitfalls, and adjustment methods. *J Multidiscip Healthc* **9**, 211.

[50] Martin, R., Gibson, V., Stover, S., Gibeling, J. and Griffin, L. (1997) Residual strength of equine bone is not reduced by intense fatigue loading: mplications for stress fracture. *J Biomech* **30**, 109-114.

[51] Bourdon, P.C., Cardinale, M., Murray, A., Gastin, P., Kellmann, M., Varley, M.C., Gabbett, T.J., Coutts, A.J., Burgess, D.J., Gregson, W. and Cable, N.T. (2017) Monitoring Athlete Training Loads: Consensus Statement. *Int J Sport Physiol* **12**, S2161-S2170.

[52] Stares, J., Dawson, B., Peeling, P., Heasman, J., Rogalski, B., Drew, M., Colby, M., Dupont, G. and Lester, L. (2018) Identifying high risk loading conditions for in-season injury in elite Australian football players. *J Sci Med Sport* **21**, 46-51.

[53] Cummins, C., Welch, M., Inkster, B., Cupples, B., Weaving, D., Jones, B., King, D. and Murphy, A. (2019) Modelling the relationships between volume, intensity and injury-risk in professional rugby league players. *J Sci Med Sport* **22**, 653-660.