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Fracture incidence rates and the association of rest with bone remodelling in Thoroughbred racehorses at the Hong Kong Jockey Club

Dr Tsim Christopher Sun

BVSc MRCVS

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Abstract

Fractures in Thoroughbred racehorses are an omnipresent welfare issue. Previous studies have often failed to adequately address the issue of fractures in racing and training because of the limitations associated with record keeping. Racehorses being rested from intensive exercise are also at greater risk of fracture on re-introduction to high intensity work. This thesis aims to accurately report first event fractures and determine racing and training fracture incidence rates in the highly controlled Thoroughbred racehorse population at the Hong Kong Jockey Club (HKJC) and to identify differences in bone remodelling (as defined in this thesis) between racehorses, which have been rested compared to horses in current high intensity exercise.

All fracture events from 1st July 2004 to 30th June 2011 were retrieved from veterinary and racing databases of the HKJC. Only first fracture events were included in this analysis. Fractures were classified as catastrophic if euthanasia occurred within five days of the fracture and non-catastrophic if euthanasia was not the outcome. Horses were considered to be at risk from time of importation into Hong Kong to date of fracture, retirement, or end of the study period, whichever was first. Incidence rates for racing were expressed as catastrophic or non-catastrophic fracture events per 1000 race starts (Chapter Three). Training incidence rates were expressed as catastrophic or non-catastrophic fracture events per 10,000 horse days at risk (Chapter Four). The incidence rate for catastrophic fractures during racing was 0.6 per 1000 race starts (95% CI 0.4 - 0.8) and for non-catastrophic fractures it was 2.2 per 1000 race starts (95% CI 1.8 - 2.6). The incidence rate for catastrophic fractures in training was 0.08 per 10,000 horse days at risk (95% CI 0.05 - 0.11), and for non-catastrophic fractures was 0.85 per 10,000 horse days at risk (95% CI 0.75 - 0.96). The incidence rate of catastrophic racing fractures at the HKJC were lower when compared to the results of studies conducted in the United States (Estberg, Stover et al. 1996b) and higher than in the United Kingdom (Parkin, Clegg et al. 2004a) and Australia (Boden, Anderson et al. 2006). The incidence rate for training fractures indicate that in a population of 1,000 horses in training, there would be approximately three catastrophic fractures and 31 non-catastrophic fractures every 365 training days at risk.

In another study, bones were obtained post-mortem from horses in Exercised (n = 6) and Rested (n = 6) Groups who died for reasons unrelated to fracture or the fracture study. Exercised horses had been euthanized within seven days of high intensity exercise while Rested horses had been retired for one to four months and whose work level was much reduced before retirement. Six bone blocks were cut from each horse at the following locations; right third metacarpal bone (MCIII) where samples were collected from the mid-diaphysis, distal lateral metaphysis and medial condyle; right third metatarsal bone (MTIII) where a sample was collected from the lateral condyle; distal left tibia, and mid-diaphysis of the left tenth rib. Each bone block was cut to 250 µm thick specimens using a diamond annular saw. Microradiographs were obtained using point projection digital microradiography (Faxitron) and analysed to identify radiolucent spaces indicative of recently formed resorption canals as a proxy for active bone remodelling. This study identified that resorption canals of all sections from MCIII and the tibia were significantly greater in the Rested Group compared with the Exercised Group ($P < 0.05$). There was no significant difference in the resorption canal density of the rib between the two groups. Resorption canals were seen to be at sites that were predisposed to fatigue fracture. Racehorses that have been rested for one to four months showed significantly greater resorption canals of the tibia and third metacarpal bone compared to exercised horses, and are therefore potentially more susceptible to fracture at predilection sites. This has important ramifications for the management of racehorses returning to high intensity exercise.

This thesis presents very detailed information about racehorse fractures at the HKJC. It emphasises the need for more stringent monitoring for fractures in horses in training and the importance of detecting non-catastrophic fractures before they become catastrophic. Highlighted in this thesis is the immediate need to introduce a monitoring program in horses that are returning to high intensity exercise after a period of rest. More research is needed to determine the safest way to reintroduce horses to exercise after a rest period.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

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Contributions by others to the thesis

The majority of the work integrated into this thesis was conducted by Dr Christopher Sun.

Dr John Alawneh (principal advisor) provided intellectual input on the study design, materials and methods, statistical analysis, interpretation of results, editorial comment and final review on the original research on which the thesis was based.

Dr Naomi Cogger (co-advisor) provided intellectual input on the study design, materials and methods, statistical analysis, interpretation of results, editorial comment and review on which chapters 2, 3 and 4 were based.

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Professor Alan Boyde provided intellectual input on materials and methods and expert experience in microradiography and scattered electron microscopy images in chapter 5.

Professor Mark Stevenson provided editorial comment on chapter 4.

Dr Kenneth Lam provided intellectual input on materials and methods in chapter 4.

Ms Iris Yu provided intellectual input and data collection on chapter 2, 3 and 4.

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Keywords

Fracture, catastrophic, non-catastrophic, incidence rate, equine, racehorse, rest period, bone, remodelling.

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List of abbreviations used in alphabetical order

CI	Confidence interval
HKJC	Hong Kong Jockey Club
IR	Incidence rate
IRR	Incidence rate ratio
MCIII	Third metacarpal bone
MSI	Musculoskeletal injury
MTIII	Third metatarsal bone
OVE	Official Veterinary Examination
P1	First phalanx
P2	Middle phalanx
P3	Distal phalanx

Chapter 1:

Introduction

1.1 Introduction of thesis

Fractures suffered by horses during racing and training constitute a serious welfare issue and are responsible for significant animal wastage and economic loss (Jeffcott, Rossdale et al. 1982, Riggs 2002). It is beholden of the racing industry to address welfare and wastage concerns but as many racing precincts do not maintain accurate injury records, it is difficult to identify and quantify the overall impact that fractures have on the racing industry (Parkin 2007). The analyses presented in this thesis utilised injury data systematically collected by staff of the Hong Kong Jockey Club (HKJC). Protocols mandated by the HKJC have resulted in the accumulation of highly accurate details describing fracture characteristics, horse, trainer and track information.

This chapter will be divided into two sections: the first section (current section) will introduce the structure of the thesis, and the second will introduce an overview of the Thoroughbred horse racing industry in Hong Kong and the HKJC.

Chapter 2 reviews the current literature relating to fracture incidence rates in racing and training. Also included is a review of the literature on bone repair and adaptation to exercise and rest, with particular emphasis on the response of bone to high intensity training.

Chapter 3 details the first event catastrophic and non-catastrophic fractures in horses while racing at the HKJC.

Chapter 4 details the first event catastrophic and non-catastrophic fractures in horses while in training at the HKJC.

Chapter 5 provides a comparison of the histology of bones at various sites harvested from 12 horses at the HKJC that were either being rested or were in race training and who were euthanised for reasons unrelated to fracture.

The thesis concludes with a general discussion of the results and recommends future directions of research. References cited in the MPhil are listed at the end of the thesis.

1.2 The Hong Kong Jockey Club

Thoroughbred horse racing was introduced to Hong Kong in 1841 by the British, who drained one of the few flat areas in the territory from a malarial swamp to form a racetrack at Happy Valley. With the exception of a few years during World War II, Thoroughbred racing in Hong Kong has seen non-stop action. The HKJC was founded in 1844 and is the only government approved organization in Hong Kong to regulate wagering activities including horse racing, lottery and football. In the 2013 to 2014 racing season, horse racing betting turnover was almost HK$104 billion (AUD$18.9 billion), of which the Club donated HK$3.6 billion to charities and was the largest payer of tax, contributing just under HK$20 billion to the Hong Kong government (HKJC 2015a). At the heart of the HKJC is the Thoroughbred racehorse of which there are approximately 1,200 at any time in flat race training, and roughly 200 at retired horse facilities such as riding schools.

1.3 Racehorse importation criteria

A lack of land and undesirable climatic conditions restrict horse breeding in Hong Kong, and as such, all Thoroughbreds are imported from overseas (Riggs 2015). Only Club members with a valid permit are able to own a horse, however, obtaining a permit only occurs annually and is highly competitive (Riggs 2015). There are also restrictions on the number or horses any individual may possess and as result, there is an expectation from horse owners that the Club will protect them as much as possible, from making a faulty investment (Riggs 2015).

A stringent pre-import process has been designed and enforced by the Club to restrict entry of horses that may prematurely become unsound, may be potentially unsafe, or have little realistic chance of racing under Hong Kong conditions (Riggs 2015). Horses may be imported directly from a pre-selected list of countries approved by the Club, such as Australia, New Zealand and Ireland which have demonstrated freedom from severe infectious diseases. There are restrictions imposed on other countries such as South Africa depending on the disease status at the time (HKJC 2015b).

There are two main racehorse permits available to Club members, previously raced horses, and privately purchased griffins, of which both must be imported into Hong Kong before they turn five years old (HKJC 2015b). Previously raced horses are horses which have raced successfully by having a Hong Kong performance rating of 70 or higher at the time of import (HKJC 2015b). There are also restrictions on the number of race starts for different age groups, for example two year olds must have no more than ten career starts prior to importation (HKJC 2015b). Privately purchased griffins are horses which are purchased unraced but must fulfil age requirements, for example northern hemisphere horses foaled in 2013 must arrive in Hong Kong before they turn four years of age (HKJC 2015b).

1.3.1 Racehorse importation protocol

Regardless of the type of permit, there are three stages to the pre-import process into Hong Kong. An initial veterinary examination must be conducted in the country of origin within 30 days prior to exportation and may be performed by any recommendable equine veterinarian (HKJC 2013b). This includes a clinical examination, trot up and flexion tests, strenuous exercise at half pace or faster listening for ‘wind’ problems, post-exercise auscultation, repeat clinical examination, endoscopic examination of the upper respiratory tract, ultrasonographic examination of the palmar metacarpal region, radiography of a pre-selected list of joints with a minimum of 46 views, and blood sampling for non-steroidal anti-inflammatories (HKJC 2013b). The results of this initial veterinary examination are then confirmed by a HKJC nominated veterinarian who are highly reputable equine veterinarians in each major exporting region on behalf of the Club. If the nominated veterinarian accepts the findings of the initial examination, a recommendation will be made to the HKJC on the suitability of the racehorse to race in Hong Kong, and the prospective owners and transport companies are notified for importation procedures (HKJC 2013b).

1.4 The racing season

The racing season runs from 1st of July to 30th of June the following year and apart from a two week hiatus between August and September, racing is year round. The Club is legally restricted to staging a maximum of 83 racing days per season which occur twice weekly in a clockwise direction between two racing centres; Happy Valley and Sha Tin. Racing at Happy Valley is normally on Wednesday nights and consists of eight or nine races, and day racing in Sha Tin is on Sunday and consists of ten or 11 races.

Racing in Sha Tin is typically run on the turf, however, approximately 70 races a year occur on the dirt all-weather track. Horses are trained to a race fit level and must prove their race fitness by performing a barrier trial which are race simulations and these also primarily occur on the dirt all-weather track. Barrier trials may be recommended voluntarily by the trainer for race preparation, or enforced by regulatory veterinarians to demonstrate the horse is free from injury after a period of rest. Trials are held twice a week at Sha Tin racecourse, and once a month in Happy Valley.

1.5 Racing and training

Happy Valley is used only for racing and barrier trials and has a single turf track. The Sha Tin centre has both training and racing facilities. Training occurs each day on the Sha Tin dirt all-weather race track in a clockwise direction but there is one day per week which is allocated to training in an anticlockwise direction. There are 24 professional racehorse trainers licenced by the Club and train at Sha Tin. Each trainer has a maximum of 65 racehorses in training and each stable is equipped with a walker and a small sand track, and all horses have access to a swimming pool. There are also several dirt based trotting rings situated throughout the training complex.

Training starts at fixed times between 4:30 and 8:30 am every day, in which horses are permitted to use the training tracks. The training activity and schedule of the racehorse is determined by the trainer, however all trainers are governed by the Rules of Racing and hefty penalties are enforced on those that do not comply. Horses requiring a rest period due to illness or injury may remain confined in their stable or spelled at a complex north of Sha Tin known as Bea’s River which also houses retired or pleasure horses.

1.6 Training data

During morning training sessions, a local commercial track work database group is employed for the collection of the track work from each horse and Club Stewards perform random inspections to verify correct horse identification (Lam, Parkin et al. 2007). Swimming activity is monitored separately from track work and activity within the stables is under the control of the trainer. Horses return to their stables after track work and there is continuous monitoring of the tracks by Club Stewards throughout the day. All track work records are consolidated into the track work database Microsoft Access database management system (Microsoft Office ® and Microsoft® Inc 2010) by 12 noon on the day of training and immediately made accessible to the public via the Club's website (HKJC 2015d).

1.7 Veterinary data and monitoring

Veterinary records for each horse are entered into a separate purpose built veterinary database by stable veterinarians who are employed by the Club. The database is accessible in all racing stables and veterinary hospitals allowing real time input of clinical records for example medications and diagnostics. Racehorses which succumb to injury during racing or training are further flagged by the veterinary database and examined rigorously by regulatory veterinarians before they can resume training. In addition, horses are flagged if they have not raced or trained for extended periods of times. Flagged horses are divided into either the 'To Watch' or 'Official Veterinary Examination' (OVE) category.

The 'To Watch' category is directed at horses with transient health problems, such as gastric ulceration which are unlikely to affect racing, while the OVE category is aimed at conditions that may seriously affect the welfare of the horse, such as a stress fracture diagnosed on nuclear scintigraphy. Furthermore, any racehorse at any time may be flagged with a 'To Watch' or OVE at the discretion of regulatory veterinarians who deem the horse to be at risk of injury. The horse may be required to prove its fitness with further clinical exams, barrier trials or diagnostic tests to demonstrate the injury has been resolved (HKJC 2012).

All horses which are scheduled to race have a compulsory trot up in front of regulatory veterinarians the day before race day. A horse that is flagged in the 'To Watch' or OVE category is heavily scrutinised during this examination. Horses that are considered to not be suitable to race will be withdrawn from the respected race at the discretion of the regulatory veterinarian.

1.8 Race day injury and fatality management

There are a minimum of seven veterinarians in attendance on each race day. In the event of a serious incident, there is an immediate response by veterinarians to attend to the horse's welfare. At the discretion of the veterinarian, the horse may be escorted to the veterinary hospital in Sha Tin where further examination may be performed. If euthanasia is elected, a mandatory post-mortem is conducted by the veterinarian and the results are entered directly into the veterinary database.

1.9 Racehorse retirement

Racehorses can be trained and raced in Hong Kong up to a maximum age of 10 years at which stage there is compulsory retirement. Other reasons for compulsory retirement include blindness, three episodes of epistaxis, three episodes of post-race heart irregularities, a Hong Kong performance rating of less than 20 at the end of the racing season, a horse in which the racing Stewards deem to be unsafe, or a horse that is of eight years old or greater that has not raced for an entire racing season (HKJC 2015c). Horses can also be retired prior to this time voluntarily by the owner for any reason. Horses may be exported, transferred to riding schools, retrained as lead horses, or donated to organisations in China or overseas (HKJC 2015c).

Chapter 2:

Literature Review

2.1 Introduction

Fractures in Thoroughbred racehorses are an omnipresent welfare issue. Studies of horses racing and training in California over a two year period reported fractures accounted for 95% and 91% of fatalities respectively (Estberg, Stover et al. 1996b, Estberg, Stover et al. 1998b). Fractures also incur direct financial losses as horses are forced into retirement prematurely. A study of New Zealand horses in training between 1997 to 2000 reported 42.9% of horses retired due to fractures (Perkins, Reid et al. 2005a). The welfare and financial costs make it desirable to understand factors that relate to the development of fractures.

A large body of studies have been published in the past three decades to describe the most common fractures with respect to local racing centres. The purpose of these studies is to generate hypotheses for analytical studies and make recommendations for minimising the risk of fracture occurrence. However, differences in fracture definition and methods of fracture confirmation make comparison between studies extremely difficult. There is also a paucity in the available literature on fractures which do not result in fatality and have gone undiagnosed by racing authorities. This review aims to firstly centralise and report the most common fractures globally and examine risk factors associated with fracture.

In addition to external risk factors, it is also important to understand the response of internal biological changes in bone’s adaptation to resist fracture. While there have been considerable advancements in our knowledge of how bone adapts to increased exercise in the past three decades, the reality of bone’s response to fluctuating high and low intensity exercise patterns are much less understood. This review further aims to collate the current understanding of how bone adapts internally to varying strains, with particular emphasis on the development of fatigue fractures in racehorses.

2.2 Racing and training fractures in Thoroughbred racehorses

The majority of studies that have been published originate from the United Kingdom and United States of America and studies which have provided the number of fractures have been tabulated below. Table 1 summarises fractures related to racing while Table 2 summarises the five published studies which report fractures related to training. Racing related fractures were often recorded by racing officials when the fracture occurred on the racetrack, and in instances where the fracture resulted in euthanasia, may have been sent for confirmatory post-mortem such as by the California Horse Racing Board in California (Johnson, Stover et al. 1994, Estberg, Stover et al. 1996b, Estberg, Stover et al. 1998b). Alternatively, fractures which did not occur on the racetrack or in training would have been managed by the racehorse trainer, in which the reporting or diagnosis of any fracture to any authority was not always compulsory (Verheyen and Wood 2004).

Table 1: Descriptive studies' attributes and bone involved in fracture event of Thoroughbred racehorse related to racing published between 1994 to 2014.

Study Source	Johnson et al. (1994)	Estberg et al. (1996b)	Estberg et al. (1998b)	Peloso et al. (1994)	Cohen et al. (1997)	Beisser et al. (2011)	Reardon et al. (2014)
Study period	1990-92	1991	1992	1992-93	1994-96	2000-06	1999-05
N. horses	174	79	78	117	216	124	344
Forelimb							
PSB	59	36	23	30	44	48	4
MCIII	36	19	20	11	21	25	#108
Carpal	9	8	10	4	12	27	NR
Radius	0	0	3	1	1	NR	NR
P1	4	1	NR	2	7	NR	78
Scapula	NR	1	2	1	3	NR	NR
Humerus	2	NR	2	2	3	2	NR
Hindlimb							
MTIII	6	3	4	0	2	NR	NR
Tarsus	NR	NR	2	0	1	NR	NR
Tibia	2	2	1	NR	0	NR	NR
Femur	1	NR	NR	NR	0	NR	NR
PSB	NR	1	NR	NR	1	NR	NR
P1	NR	2	1	1	3	NR	NR
Other							
Skull	NR	1	NR	NR	NR	NR	NR
Rib	NR	1	NR	NR	NR	NR	NR
Pelvis	5	2	1	1	NR	NR	NR
Vertebrae	NR	NR	NR	1	NR	NR	NR
Fetlock	NR	NR	NR	1	4	10	NR
Multiple	NR	22	57	NR	NR		154
Soft tissue	29	25	9	11	34	NR	Excluded
Total catastrophic	153	102	78	66	136	112	344

Key: N - number of horses; NR - not recorded; PSB - proximal sesamoid bone; MCIII - third metacarpal bone; P1- proximal phalanx; MTIII - third metatarsal bone; Fetlock includes soft tissue or bones of the metacarpophalangeal region; Soft tissue includes suspensory apparatus and superficial digital flexor tendons; #involves third metacarpal and third metatarsal bones.

Table 2: Descriptive studies' attributes and bone involved in fracture event of Thoroughbred racehorse related to training published between 1994 to 2015,

Study Source	Johnson et al. (1994)	Estberg et al. (1996b)	Verheyen et al. (2004)	Ramzan et al. (2011)	Hill et al. (2015)
Study period	1990-1992	1991	1998-2000	2005-2007	2009-2010
N. horses	185	78	1178	217	439
Catastrophic	150	101	11	7	27
Non-catastrophic	NR	NR	137	141	458
Forelimb					
PSB	40	36	4	2	32
MCIII	35	23	29	#34	39
Humerus	27	10	1	5	3
Carpal	3	NR	27	27	54
Radius	2	NR	5	NR	1
P1	12	9	16	35	32
Scapula	3	1	1	NR	NR
Hindlimb					
Tibia	5	1	21	50	39
Pelvis	11	3	23	26	4
MCII/MCIV	NR	NR	2	NR	17
MTIII	6	2	9	NR	2
Tarsus	NR	NR	7	9	1
P1	NR	4	NR	NR	NR
P2	1	NR	1	NR	1
P3	1	1	1	NR	2
Vertebrae	NR	NR	1	1	NR
Femur/patella	NR	NR	NR	1	1
Soft tissue	4	11	NR	48	135
Multiple	NR	23	NR	7	NR
Undiagnosed	NR	NR	NR	3	NR
Other	NR	NR	NR	NR	115
Total fractures	150	101	148	248	478

Key: N - number of horses; NR - not recorded; PSB - proximal sesamoid bone; MCIII - third metacarpal bone; P1 - proximal phalanx, P2 - middle phalanx, P3 - distal phalanx; MCII/MCIV - second and fourth metatarsal; MTIII - third metatarsal bone; Soft tissue includes suspensory apparatus and superficial digital flexor tendons; # third metacarpal and third metatarsal fractures; Other includes foot bruises, cellulitis, foot abscesses, lacerations, joint degeneration and osteoarthritis.

The term ‘catastrophic musculoskeletal injury’ or ‘catastrophic fracture’ has been used interchangeably in equine veterinary science clearly relating to a fatal injury (Boden, Anderson et al. 2006, Stover and Murray 2008, Reardon, Boden et al. 2014). Throughout this thesis the term of use will be catastrophic fracture. The nature of these fractures necessitates euthanasia of the racehorse on welfare grounds. Catastrophic fractures are common in racing. A recent American study reported that 92.8% (115/124) of all racing injuries that have been reported in three racetracks in Iowa, Kansas and Oklahoma between 2000 to 2006 were catastrophic fractures (Beisser, McClure et al. 2011).

Proximal sesamoid bones were the most common catastrophic fracture sustained in racing from studies in the United States published between 1994 to 2004, ranging from 21 to 58.8% of all catastrophic fractures (Johnson, Stover et al. 1994, Peloso, Mundy et al. 1994, Estberg, Stover et al. 1996b, Hernandez, Hawkins et al. 2001, Beisser, McClure et al. 2011). The most common anatomical configuration reported involved the mid-body fracture representing 56.5% (75/121) of all proximal sesamoid fractures between 1992 to 2002 in a Californian study (Anthenill, Stover et al. 2007). Alternatively, catastrophic fractures of the third metacarpal bone occurred most commonly in the United Kingdom between 1999 to 2005 representing 59.5% (148/262) of all distal forelimb fractures sustained in racing (Reardon, Boden et al. 2014). Lateral condylar fractures were the most common configuration representing 24.2% (46/190) of all single fracture sites in the United Kingdom (Reardon, Boden et al. 2014).

In contrast to catastrophic fractures, fractures which are non-catastrophic are less clearly defined in the literature. The term non-catastrophic fracture will be used preferentially in this thesis unless otherwise specified by the original authors. Non-catastrophic fractures have been included in a wide range of conditions including lameness (Rossdale, Hopes et al. 1985, Dyson, Jackson et al. 2008), musculoskeletal injury (Bailey, Reid et al. 1997b, Perkins, Reid et al. 2005a, Cogger, Evans et al. 2008a), injuries resulting in modified training (Bailey, Reid et al. 1999a), stress fractures (Stover, Johnson et al. 1992b, Verheyen and Wood 2004, Stover and Murray 2008, Ramzan and Palmer 2011) or a combination of the above (Hill, Blea et al. 2015).

Earlier fracture studies did not specifically report non-catastrophic fractures, however improvements in nuclear scintigraphy have allowed in the diagnosis of stress fractures which are defined as a non-catastrophic manifestation of fracture prior to becoming a catastrophic (Stover and Murray 2008). Stress fractures of either the pelvis, third metacarpal or tibia were the most common between 1998 and 2000 in the United Kingdom representing 56.8% (84/148) of all fractures in training (Verheyen and Wood 2004). Tibial stress fractures were the most common fracture reported representing 20.7% (50/241) of all training fractures in large scale study of three training yards in Newmarket United

Kingdom by Ramzan and Palmer (2011). In this study the most common anatomical configuration was the disto-caudal site representing 86% (43/50). This was in contrast to an Australian study which reported the diaphyseal location being the most common (77% (57/74); O'Sullivan and Lumsden 2003). Non-catastrophic fractures of the carpus also occur commonly in racing (Table 2). A study by the Japanese Racing Association showed that of 610 distal radius and carpal bone fractures between 1990 to 1994 only four resulted in euthanasia (Mizuno 1996).

2.3 The risk of fracture in racing

The risk reported for catastrophic fracture per 1000 racing starts in the past 30 years are in Table 3. Studies from the United States reported incidence rates between 0.99 to 3.21 per 1000 racing starts (Wilson, Jensen et al. 1996, Estberg, Stover et al. 1996b, Estberg, Stover et al. 1998b, Hernandez, Hawkins et al. 2001, Hill 2003, Beisser, McClure et al. 2011, Vallance, Case et al. 2012) and was similar to a Canadian study which reported 1.05 per 1000 racing starts (Cruz, Poljak et al. 2007). Both North American countries had greater incidence rates compared to studies from the United Kingdom: 0.34 to 0.9 per 1000 racing starts (Parkin, Clegg et al. 2004a, Henley, Rogers et al. 2006, Reardon, Boden et al. 2014) and studies from Australia: 0.3 to 0.6 per 1000 racing starts (Bailey, Reid et al. 1997b, Bailey, Reid et al. 1998, Boden, Anderson et al. 2006).

There are several explanations for the differences in the risk of fracture in the United States compared with other countries. Racing in the United States are conducted almost exclusively on all-weather dirt surfaces which are firmer compared to turf surfaces in the United Kingdom and Australia. Firmer surfaces has been shown to be a greater risk factor for catastrophic fractures in various studies published worldwide (Williams, Harkins et al. 2001, Parkin, Clegg et al. 2004a, Parkin, Clegg et al. 2004d, Oikawa and Kusunose 2005, Kristoffersen, Parkin et al. 2010b). Differences also exist in governance and racing rules. Each state in America has their own governing body which may vary vastly from pre-race physical examinations of horses, horse shoe allowance, and banned medications. Differences in incidence rates between American States may be explained by these variations in racing governance although more multi-centre research is required to determine whether the risk of fracture is true.

Another explanation for differences in incidence rates are the variations of fracture case definition. For example, in a Japanese study between 1985 to 1994, the case definition for fatality included both catastrophic fracture and joint dislocations which would have increased the incidence rate reported (Mizuno 1996). Similarly in another Japanese study between 1987 to 2000, the incidence rate included both catastrophic and non-catastrophic fractures (Oikawa and Kusunose 2005). In a Canadian study between 2004 and 2005, horses euthanised within 60 days of a racing related fracture were included in the case definition in contrast to a United Kingdom study which included only horses which sustained catastrophic fractures sustained on the racecourse (Parkin, Clegg et al. 2004a). Differences in case definition may either overestimate or underestimate the incidence rate reported which makes them difficult to compare. Researchers have attempted to objectively unify definition of fracture. For example at the 2005 Havemeyer conference held in Melbourne by equine veterinarians and veterinary epidemiologists, it was recommended that chip fractures less than five millimetres in size to be excluded from fracture analyses, and individual fractured bones be reported rather than joint fractures (Parkin 2007).

Table 3: Incidence rates for catastrophic fracture in racing from the past three decades.

Location	**IR**	**Study period**	**Source**
United States			
New York	1.50	1983-85	Hill, Carmichael et al. (1986)
	0.99-1.85	1984-02	Hill et al (2003)
Kentucky	1.40	1992-93	Peloso et al (1994)
California	1.70	1991	Estberg et al (1996b)
	1.66	1992	Estberg et al (1998b)
	2.00	1990-08	Vallance et al (2012)
Illinois	3.21	1987-92	Wilson et al (1996)
Florida	1.20	1995–98	Hernandez et al (2001)
Oklahoma	1.64	2000-06	Beisser et al (2011)
Iowa	1.31	2000-06	Beisser et al (2011)
Kansas	1.74	2002-06	Beisser et al (2011)
Australia			
New South Wales	0.30	1985–95	Bailey et al (1997b)
Victoria	0.60	1988–95	Bailey et al (1998)
	0.44	1989-04	Boden et al (2006)
United Kingdom			
	0.80	1995	McKee (1995)
	0.38	1999-05	Parkin et al (2004a)
	0.90	1990-99	Henley et al (2006)
	0.34	1999-05	Reardon, Boden et al. (2014)
Japan			
	3.20	1985-94	Mizuno (1996)
	18.30	1987-00	#Oikawa et al (2005)
Canada			
Ontario	1.05	2004-05	Cruz et al (2007)

Key: IR - Incidence rate per 1000 racing starts; #included both catastrophic and non-catastrophic fractures.

2.4 The risk of fracture in training

The risk of fractures have also been reported in training studies (Lindner and Dingerkus 1993, Bailey, Reid et al. 1999a, Verheyen and Wood 2004, Perkins, Reid et al. 2005a, Cogger, Evans et al. 2008a), however there are inconsistencies between studies in reporting the incidence risk and the incidence rate. In a prospective cohort study of German racehorses over nine months, the incidence risk of musculoskeletal injury was 57% over a nine month period (Lindner and Dingerkus 1993), while in the United Kingdom, the incidence risk was 45% for musculoskeletal injury during the 1980 flat racing season (Rossdale, Hopes et al. 1985). In these studies, Lindner and Dingerkus (1993) calculated the incidence risk using the mean number of horses stabled at the racetrack, while Rossdale, Hopes et al. (1985) used the total population of 314 horses in six stables.

However, racehorse populations are dynamic with horses contributing to different times at risk. Time at risk may differ for each horse as they may be entering the at risk population, leaving the at risk population temporarily due to injury or spelling, or to trainers not enrolled in the study and lost to follow up (Cogger, Evans et al. 2008a). Therefore the assumption that racehorses contribute equally to the risk period in the form of the incidence risk could be biased and the direction of this bias is further away from the null hypothesis. This would have resulted in an overestimation of the population incidence risk due to the differences in at risk experiences by each racehorse over time.

In training, the incidence rates of fracture have been reported as 4.78 (95% CI 4.17 - 5.39) per 1000 horse training days for first occurrence musculoskeletal injuries in New South Wales (Bailey, Reid et al. 1999a), 0.14 (95% CI 0.1 - 0.18) per 1000 horse training days for first occurrence fractures in New Zealand (Perkins, Reid et al. 2005b), and 0.94 (95% CI 0.71 - 1.24) per 100 horse months at risk for fractures in the United Kingdom (Verheyen and Wood 2004). Comparison of incidence rates should be conducted with caution as they may reflect differences in data collection or arbitrary definitions of time at risk. For example, initial comparison between the study from the United Kingdom, which reported 0.94 per 100 horse months (equates to 3.1 per 10,000 training days) Verheyen and Wood (2004), with the New Zealand study, which reported 0.14 per 1,000 horse training days (equates to 1.4 per 10,000 training days (Perkins, Reid et al. 2005a), may seem that training fracture rates are lower in New Zealand. However, the study by Verheyen and Wood (2004) excluded time at risk associated with ascending race training in contrast to the New Zealand study which incorporated all race training days into complete training preparations. Moreover, the incidence rate of both studies were likely to be an underestimation due to a lack of fracture diagnosis for non-catastrophic fractures. Recording of fractures in both studies were at the discretion of the trainers, and racehorses may have been spelled at the earliest sign of lameness, removed from training, resulting in selection or recall bias, and the direction of this bias would be away from the null hypothesis.

2.5 Risk factors for fractures in racing and training

2.5.1 Age

While there is evidence from descriptive studies suggesting that younger horses are predisposed to fractures, for example two year olds had the lowest incidence rate of catastrophic fracture between the ages of two and five (Wilson, Jensen et al. 1996), dorsometacarpal fractures in two and three year olds (Jeffcott, Rossdale et al. 1982, Rossdale, Hopes et al. 1985, Bailey, Reid et al. 1999a, Perkins, Reid et al. 2005a), tibial stress fractures in two year olds and humeral stress fractures in three year olds (O'Sullivan and Lumsden 2003), these studies did not adjust to potential confounding factors such as exercise history or training surface. When controlling for potential confounders using multivariable analyses, some studies showed that older horses seemed to be at greater risk in sustaining a catastrophic fractures in racing (Bailey, Reid et al. 1998, Carrier, Estberg et al. 1998, Estberg, Stover et al. 1998b) or that there was no relationship between fracture and age (Estberg, Gardner et al. 1998a, Cohen, Dresser et al. 1999a, Verheyen and Wood 2004).

Interpreting the true risk of age is difficult as studies may be confounded by previous exposure to race training. Race training involves a series of training preparations which aim to improve the fitness of the horse towards the first racing start preferentially as two year olds. There is strong evidence showing the protective effect of commencing training early to the two year old race milestone compared to the three year old race milestone (Bailey, Reid et al. 1999b, Tanner, Rogers et al. 2013). However, the pressure to push towards this milestone may result in large proportions of two year olds developing fractures if they are unable to adapt to race training stresses. A prospective cohort study in the United Kingdom investigated the risk of dorsometacarpal fracture using time-varying canter (≥ 15sec/furlong) and high speed (< 15 sec/furlong) variables for yearlings over two years (Verheyen, Henley et al. 2005). After adjusting for weekly high speed distance and trainer, average weekly canter distance resulted in an greater hazard ratio (HR) for every furlong increased (HR 1.03, 95% CI 1.00 - 1.07, P < 0.04), equating to a risk of 3.5% for every furlong increased (Verheyen, Henley et al. 2005). However, greater high speed distances showed a protective effect (RR 0.14, 95% CI 0.08 – 0.23, P < 0.001, Verheyen, Henley et al. 2005). This suggested that two year old horses may be at greater risk, or alternatively, may be confounded by adaptive changes in horses which have not adapted to the commencement of race training.

The complex relationship between age and training intensity therefore makes it difficult to examine the true risk of fracture in older versus younger horses. It is often that studies investigate other risk factors by reducing the confounding effect of age for example by restriction to the study of younger racehorses for specific injury or fracture types (Cogger, Evans et al. 2008a, Cogger, Perkins et al. 2008b, Reed, Jackson et al. 2012). A study of carpal and metacarpo/tarsophalangeal joint injuries in an United Kingdom study reported that after adjusting for training intensity, the incidence rate ratio (IRR) of either carpal or metacarpo/tarsophalangeal joint injuries were greater in two (IRR 2.5, 95% CI 1.2 - 5.2, P = 0.01) and three (IRR 3.2, 95% CI 1.5 - 7.0, P = 0.003) year olds when compared to yearlings (Reed, Jackson et al. 2012). An Australian study further showed that two year olds had a greater ratio of suffering dorsometacarpal stress fractures in race training compared to three year olds (IRR 5.10, 95% CI 2.24 - 11.60, Cogger, Evans et al. 2008a). Currently there is limited information on the incidence of fractures in older horses. It is likely that this is due to selection bias in which older horses still in training are generally healthier than horses that were removed from training at younger age (Delgado-Rodríguez and Llorca 2004). Differences in fracture incidence risk is unlikely to be explained by horse's age alone and it is likely that such difference are attributed to component causal pathway that includes age, differences in training, adaptation to exercise, previous injury or a combination of other factors.

2.5.2 Gender

Studies investigating the association between gender and risk of catastrophic fracture have produced conflicting results. A retrospective descriptive study of two American racing databases between 1987 to 1992 showed colts were at greater crude risk of sustaining a catastrophic fracture compared with fillies (RR 3.03, 95% CI 1.10 - 8.34, P < 0.04, Wilson, Jensen et al. 1996), but did not control for confounders. Other studies, after adjusting for the effect of potential confounding variables, either reported a lack of association between the risk of catastrophic fracture and gender (Mohammed, Hill et al. 1991, Bailey, Reid et al. 1997b, Cohen, Berry et al. 2000a, Perkins, Reid et al. 2005a), while others found that males were at greater risk than females (Estberg, Stover et al. 1996b, Estberg, Gardner et al. 1998a, Estberg, Stover et al. 1998b, Hernandez, Hawkins et al. 2001). In the study by Estberg, Stover et al. (1996b), the risk of sustaining catastrophic fracture during racing was as high as 4.26 (95% CI 1.88 - 9.64) for four year old males versus three year old females.

As with analytical studies investigating fractures and age, the relationship between gender and fracture risk is likely to be confounded by factors such as prospects of alternative careers resulting in a biased interpretation of the true risk of gender. A New Zealand retrospective cohort study found that male horses were more likely to discontinue racing compared to females (HR 0.85, 95% CI 0.78 – 0.92, P < 0.001, Tanner, Rogers et al. 2013). The reason may be that male horses, in particular for geldings, are limited by racing performance and retired from racing earlier. In contrast, females may have potentially longer careers and less likely to be euthanised given that they may retain some economic value for breeding.

2.5.3 Exercise intensity

The association of exercise history and intensity on fractures has changed dramatically in the last three decades. A large body of evidence supports the general positive correlation between excessive high speed exercise and the risk of fracture (Estberg, Gardner et al. 1995, Estberg, Stover et al. 1996a, Estberg, Gardner et al. 1998a, Cogger, Perkins et al. 2006a, Anthenill, Stover et al. 2007, Vallance, Entwistle et al. 2013). An age and gender matched case control study of Californian Thoroughbred racehorses reported that a horse that had accumulated a total of 35 furlongs of race and timed workouts compared with a horse that had accumulated 25 furlongs within the prior two months was 3.9 times more likely to sustain a catastrophic fracture (95% CI 2.1 - 7.1, Estberg, Gardner et al. 1995). The same authors later reported the relative risk (RR) of fracture was greatest within 30 days of a hazard period, which was defined as a 60 day exercise period in the top 25th *percentile* of average rate of distance accumulation (RR 4.2, 95% CI 3.0 - 5.8, Estberg, Gardner et al. 1998a). This equated to 46 to 57 furlongs accumulated within a two month period (Estberg, Gardner et al. 1998a).

These findings were supported by another Californian study which reported the relationship between excessive training and catastrophic proximal sesamoid fracture (Anthenill, Stover et al. 2007). The retrospective case control study between 1999 and 2002 used a different case definition compared to previous studies defining excessive exercise as greater time in active training and racing, and greater number of events in the previous 12 months (Anthenill, Stover et al. 2007). In the multivariable model, the best fitting model were for horses which had a greater accumulation of high speed distances within two months (OR 1.17, 95% 1.01 - 1.05, P = 0.01), and greater racing and training workouts (OR 2.07, 95% CI 1.01 - 1.32, P = 0.03). A further prospective cohort study from Australia investigated the risk of non-catastrophic injuries in two year old Thoroughbreds where the authors defined excessive exercise as speeds greater than 800 metres per minute over 27 months (Cogger, Perkins et al. 2006a). In the fixed trainer model, horses that had greater than 40 *percent* of days of excessive exercise were 1.71 times more likely to sustain a non-catastrophic musculoskeletal injury compared with horses that had less than 20 *percent* of days of excessive exercise (P < 0.006, Cogger, Perkins et al. 2006a). Interestingly, there were significant differences between trainers after adjusting for excessive exercise speed and days of exercise were accounted for, suggesting that other factors, such as training regimen may influence the rate of injury (Cogger, Perkins et al. 2006a). Despite the differences in case definition between studies, together they provide good evidence of the strong association between excessive high speed exercise and the risk of both catastrophic and non-catastrophic fractures.

Other studies reported results which contradicted those reported above (Boston and Nunamaker 2000, Cohen, Berry et al. 2000a, Parkin, Clegg et al. 2004a, Parkin, Clegg et al. 2004b). A case control study conducted in Kentucky found the odds of non-catastrophic fracture in racing to be negatively associated with high speed exercise one (OR 0.94, 95% CI 0.92 - 0.98, P = 0.003), and two months prior to racing injury (OR 0.98, 95% CI 0.96 - 0.99, P = 0.04, Cohen, Berry et al. 2000a). In this study, exercise intensity was defined as the number of furlongs of high speed exercise accumulated during a monthly period. This difference in case definition may partially explain the different results between Kentucky and California, as the Kentucky study allowed zero furlongs to be accumulated which was not detected in the Californian studies (Estberg, Gardner et al. 1995, Estberg, Gardner et al. 1998a). Alternatively, there may be a true effect suggesting that horses which did not exercise may have had pre-existing injuries or poor adaptation to their racing environment (Cohen, Berry et al. 2000a). However, a limitation of the study by Cohen, Berry et al. (2000a) was that there was no differentiation between horses which truly accumulated zero furlongs or whether the data were not recorded. The authors reported both zero inclusive and zero exclusive furlong values, both which reached statistical significance for the odds of non-catastrophic fracture between case and control horses. However, this misclassification bias would have directed the bias away from the null for horses which truly had zero furlongs and overestimating the effect of the risk of fracture (Delgado-Rodríguez and Llorca 2004).

Further studies from the United Kingdom add support to the risk of catastrophic fracture and reduced exercise intensity. Two retrospective case control studies showed the risk of distal limb catastrophic fracture (OR 3.1, 95% CI 1.1 – 8.9, P = 0.02, Parkin, Clegg et al. 2004c) and in particular with lateral condylar fractures was greatest for horses which accumulated zero furlongs per week (OR 5.26, 95% CI 1.86 - 14.90, P = 0.002, Parkin, Clegg et al. 2004b). In contrast to the Kentucky study, the United Kingdom studies also reported the age at first racing start which takes into account when racehorses were most adapted to start a race (Parkin, Clegg et al. 2004b, Parkin, Clegg et al. 2004c). Horses which started their racing careers at three or four were at greatest risk of catastrophic lateral condylar fracture when compared with two year olds (OR 2.71, 95% CI 1.36 - 5.42, P < 0.005). This was supported further by a case control study on scapular fractures in California where the odds of scapular fracture were significantly greater in Thoroughbreds which had not yet raced compared to those which had completed one or more races multivariable analysis was considered (OR 23.2, 95% CI 3.0 - 177.4, P < 0.001, Vallance, Entwistle et al. 2013). Given that it is industry standard for racehorses to start racing in their two year old season, a greater age at first start may be confounded by pre-existing injury or poor adaptation which would likely result in fracture before reaching race fitness (Riggs and Boyde 1999c). This is supported by a previous study suggesting that irrespective of age, horses in their first year of racing are significantly at greater risk of severe musculoskeletal injury (Mohammed, Hill et al. 1991).

However, a certain amount of exercise is essential in maintaining bone strength and fracture resistance (Boyde and Firth 2005). Parkin, Clegg et al. (2004c) reported that horses which did zero fast work were 3.13 times more likely to have catastrophic fracture of the distal limb compared to horses which galloped two to 7 furlongs per week (95% CI 1.10 - 8.91, P = 0.03). Short distances of gallop work were also shown to be protective against fracture and further supported by two other United Kingdom studies (Verheyen, Price et al. 2006a, Verheyen, Newton et al. 2006b). However, exercising at slower speeds such as at canter may increase the risk of fracture, with the greatest risk of pelvic or tibial fractures significantly associated with cantering within 30 days (OR 2.21, 95% CI 1.25 - 3.90, P = 0.006), although the linear trend seemed to level out in the highest distance category (Verheyen, Newton et al. 2006b). Likewise, several other studies support that high speed exercise increments over time may be protective against fracture (Boston and Nunamaker 2000, Perkins, Reid et al. 2005b, Henley, Rogers et al. 2006, Vallance, Entwistle et al. 2013).

2.5.4 Rest period

Resting a racehorse allows bones and soft tissue to remodel and heal and is an important component of race training (Jeffcott, Rossdale et al. 1982, Bailey, Reid et al. 1999a). However, compared with studies which show the risk of fracture and variations in exercise intensity as discussed above, there are limited studies which investigate the risk of rest and fracture outcome (Carrier, Estberg et al. 1998). A retrospective case crossover study in California found a large association of catastrophic humeral fracture within a hazard period of ten days after returning from a 60 day rest period (RR 71, 95% CI 32 - 158, Carrier, Estberg et al. 1998). Although the large size of the effect may suggest a causal relationship (Rothmann 2012; pages 32 - 34), there were no multivariable analyses performed which may account for confounders such as training history or previous injury which may have predisposed the horse to enter an initial rest period.

Evidence from observational studies have suggested that bone may take between two weeks and four months for remodelling to be complete and potentially inappropriate return to full exercise may result in fracture (Riggs 2002). A study from Florida seemed to support this hypothesis as horses which had greater than 33 days since their last race were 2.5 times more likely to sustain a catastrophic fracture compared to horses less than 14 days since their last race (OR 2.5, 95% CI 1.2 - 5.1, P = 0.01, Hernandez, Hawkins et al. 2001). However, similar to the earlier study by Carrier, Estberg et al. (1998), previous training history or injury records were not discussed.

2.5.5 Previous musculoskeletal injury

There is growing evidence that pre-existing musculoskeletal injury (MSI) increases the risk of fracture. A retrospective matched case control study in Kentucky between 1994 to 1996 found that horses with abnormalities detected on distal limb palpation during pre-race physical examinations were more likely to result in fatalities (OR 13.5, 95% CI 2.9 - 61.8, P < 0.001, Cohen, Peloso et al. 1997), of which 75% (102/136) of fatalities were catastrophic fractures. Similarly in a prospective cohort study conducted in New Zealand between 1997 and 2000, horses were at elevated risk of any fracture if there was previous MSI, compared to horses with no MSI history (RR 1.22, 95% CI 0.61 - 2.43, P = 0.7, Perkins, Reid et al. 2005a). Although the risk did not achieve statistical significance, this would have likely been an underestimation due to selection bias. The selection bias most was most likely a result of reporting bias and misclassification bias with the latter being attributed to the lack of imaging techniques used to confirm non-catastrophic fractures.

It is difficult to determine how much the initial MSI confounds the risk of subsequent fractures. Therefore the focus should be on the prevention of the initial MSI event which may significantly reduce the risk of subsequent and potentially catastrophic fractures. An advantage of the study by Perkins, Reid et al. (2005a) was the outcome of interest was the fracture event rather than the individual horse. This was in contrast to the study by Cohen, Peloso et al. (1997), in which horses could have experienced several injury events before becoming case horses. By restricting the focus to the event, clustering of unknown exposures around the individual is removed resulting in more accurate estimate of the incidence rate (Dohoo, Martin et al. 2003; pages 463 - 464). Removal of clustering around the horse is of particular importance given the first MSI may confound the subsequent injuries with other unknown exposures such as differences in bone loading, training schedule and resting period and therefore, prevention of the first MSI event may significantly reduce the risk of subsequent and potentially catastrophic injuries

2.6 Basic mechanical properties of bone

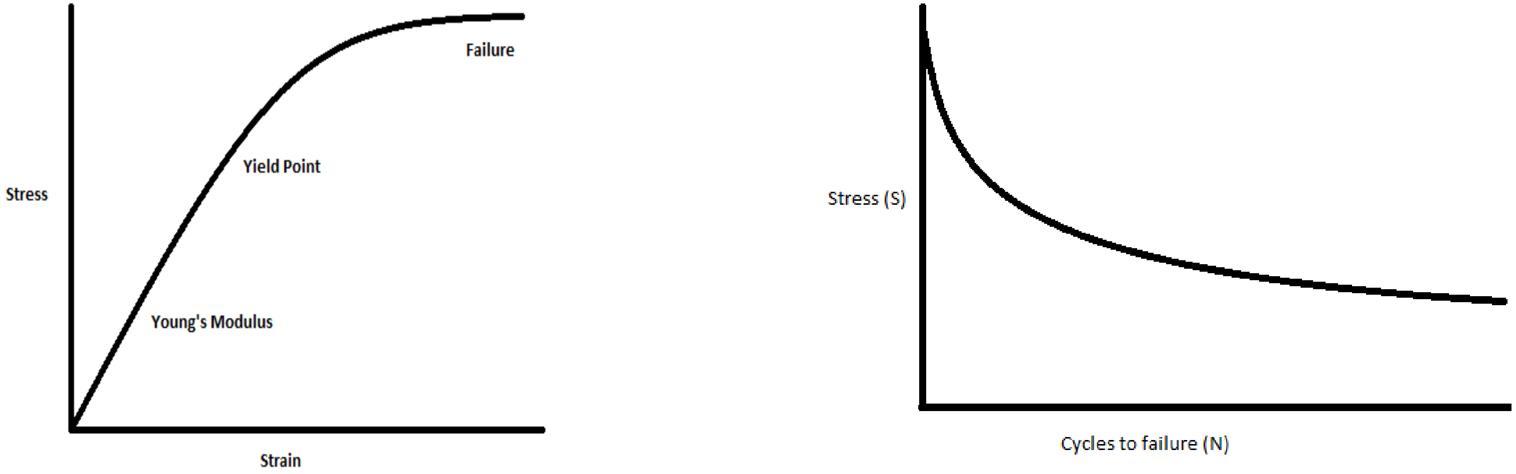
Bone is subject to varying laws of mechanics similar to other materials (Lanyon 1972, Rubin 1984). The change of shape when a load is applied to bone is termed deformation. The force of the load imposed onto bone is known as stress, while the difference between the original and deformed state is known as strain. The extent at which a material resists deformation is known as stiffness or toughness. Stress and strain initially exhibit a linear relationship in which deformation is elastic and is represented by the initial gradient of the curve, the Young's Modulus. However, past a particular point; the yield point, small increases in stress may cause permanent deformation and irreversible failure (Callister 2001; page 153). Figure 1A shows a typical stress strain curve for bone.

Fatigue refers to cyclical loading of a material where the force is below the threshold required for acute, or monotonic fracture. The material's resistance is described in terms of its fatigue life, the number of cycles required for it to fracture (Callister 2001; pages 255-259). Fatigue life can be demonstrated by an SN curve (Figure 1B), where S is stress, a measure of load onto a material, and N the number of cycles to failure. Fatigue life decreases exponentially with increasing stress and can be affected material properties, magnitude of the load and the architecture of the loaded structure (Martig, Chen et al. 2014).

2.7 Mechanical properties on equine bone

The dorsal aspect of the third metacarpal bone is a common site of injury in two to four year old Thoroughbred racehorses in race training (Nunamaker, Butterweck et al. 1990). Experimental studies on loading of cadaver specimens *in vitro* have aimed at investigating the differences in material properties between cortices of the mid-diaphysis of the third metacarpal bone (Gibson, Stover et al. 1995, Martin, Stover et al. 1996, Les, Stover et al. 1997, Martin, Gibson et al. 1997). Fatigue loading showed that the mechanical properties of the cortices of third metacarpal bone differed, with the dorsal cortex more resistant to bending forces compared to the medial and lateral cortices, and suggesting that the dorsal site adapted accordingly (Gibson, Stover et al. 1995). Although this demonstrated that there are regional differences inherent in bone properties, a further study showed that continual cyclical bending to -5000 microstrain at 100,000 loading cycles resulted only in marginally reduced the overall material properties of bone, and did not result in fracture (Martin, Gibson et al. 1997). The authors speculated that this degree of loading was estimated to be equivalent to a 'lifetime' of racing, and that other biological responses may be responsible in propagating fracture (Martin, Gibson et al. 1997).

An advantage of experimental studies is that there is often more control over the experimental settings and greater ability to ensure random allocation of subjects or exposure variables (Ellenberg 1994). In the studies above, potential confounding factors such as age, gender and breed were reduced through randomisation of samples, although the exact randomisation process was not discussed before the grouping stage (Gibson, Stover et al. 1995, Martin, Stover et al. 1996). Although it is difficult to comment on the precision of the above studies given that no confidence intervals were reported in the results (Rothmann 2012; page 149). Furthermore, while the results from the *in vitro* tests had reasonable internal validity, they may not be externally valid to the living equine athlete. Nevertheless, given the knowledge at the time, the above authors provided speculative evidence that material properties of bone may not necessarily equate to *in vivo* bone material properties, namely affected by bone modelling and remodelling.



(A) (B)

Figure 1: Stress strain curve for bone (A), and a typical stress as a function of cycles of failure (SN) curve for bone where fatigue life decreases exponentially with increasing stress (B). Adapted from Riggs (1990b).

2.8 Adaptation through bone modelling

Although the overall construction of bones is genetically pre-determined, their architecture, mass and material characteristics may be influenced by environmental factors such as with exercise (Goodship, Lanyon et al. 1979, Frost 1987, Lanyon 1987, Lanyon 1990). This is achieved in part by the modelling; bone adding, and remodelling; bone removing, processes. Remodelling, in contrast to modelling, occurs within the microstructure of the bone and is not discernible with digital radiography (Butler, Colles et al. 2009).

In the equine athlete, bones of the distal limbs are subjected to increasing loads as exercise intensity increases. A large focus of experimental studies *in vivo* have concentrated on the third metacarpal bone and metacarpophalangeal joint. Bones that constitute the metacarpophalangeal joint; the distal third metacarpal bone, proximal phalanx, and the proximal sesamoid bones, are commonly fractured in athletic horses (Stover 2003). In contrast to the cortical bone of the third metacarpal diaphysis, the architecture of the distal extremity of the third metacarpal bone consists of a highly mineralised cortical sub-articular surface, subchondral bone and deeper cancellous epiphysis (Boyde, Haroon et al. 1999), while the proximal sesamoid bone is largely of cancellous bone (Young, Nunamaker et al. 1991).

A large body of evidence demonstrates the effect of bone modelling in response to increasing limb loading from exercise. A series of descriptive cohort studies used rosette strain gauges mounted onto the periosteal surface of equine third metacarpal bone to demonstrate the linear relationship between compressive strains and increasing treadmill speed, with a later study by the same authors of 40 Thoroughbred horses in race training also showed that the radiographic thickness of the dorsal cortex plateaued after a mean of 501 days (Davies, McCarthy et al. 1993, Davies 2005, Davies 2006). Similarly, enlargement of the dorsomedial third metacarpal diaphysis was seen as tensile and shear strains increased from -670 to -1300 microstrain, and -670 to -1760 microstrain from walking to canter respectively (Rubin, Seeherman et al. 2013). An increase in bone mass is therefore stimulated by varying strains exposed in bone to reduce fatigue and a greater strain would equate to an increased modelling response.

However, increase in size is limited to the confines of anatomy for example within the metacarpophalangeal joint. An experimental study between horses in training versus untrained horses found that two year old horses in canter work showed increases in subchondral bone volume fraction, greater mineralisation and fewer marrow spaces in the palmar and dorsal cortical surfaces of the medial and lateral condyles using back scattered electron microscopy (Boyde and Firth 2005). Calcein labels highlighting active osteonal bone formation was mainly seen towards the dorsal epiphysis, suggesting that modelling occurred towards the cancellous regions of the condyle in horses in the training group rather than an increase in size (Boyde and Firth 2005). Bone modelling towards cancellous bone regions was also seen in another experimental study of proximal sesamoid bones, with microradiography showing densely compacted cancellous bone in both the proximal sesamoid fracture and non-proximal sesamoid fracture groups (Anthenill, Gardner et al. 2010). Similar to earlier *in vitro* bone studies discussed earlier, these studies reduced confounding by restriction or matching to gender, breed and age (Boyde and Firth 2005, Davies 2005, Davies 2006, Anthenill, Gardner et al. 2010). It is therefore not unreasonable to assume that the increased exposure to exercise would be directly proportional to increased bone modelling, in particular towards the region of highest strain (McCarthy and Jeffcott 1992, Carstanjen, Lepage et al. 2003, Hiney, Nielsen et al. 2004, Firth, Rogers et al. 2005b). However, the strain stimulus is reduced as bone mass increases and improves fatigue life. Continual peak strains experienced by equine athletes may not be sufficient stimulus to induce further modelling.

2.9 Adapting through bone remodelling

In contrast to bone modelling, bone remodelling is considerably more complex and much less understood. Bone remodelling has three main functions; to provide mineral homeostasis particularly for calcium; skeletal adaptation to environmental changes; and reparation of microdamage created by repetitive fatigue loading, with the latter two being critical in the development of fatigue fractures in racehorses (Burr 2002a).

Material properties within cortical and trabecular bone structure are affected by the remodelling process, as bone multicellular units resorb and form bone in response to microdamage (Lee, Staines et al. 2002, Martin 2003). Microdamage occurs synonymously with routine daily loading activity (Burr, Schaffler et al. 1988, Schaffler, Radin et al. 1989) and is also a function of time dependent damage (Guo, Gibson et al. 1994, Bowman, Guo et al. 1998). A material's fatigue life is negatively affected by the accumulation of microdamage (Cui 2002), but in bone, microdamage also contributes to stiffness and resistance to fatigue failure.

At the molecular level, microdamage occurs in the form of microcracks caused by cleavage of bone mineral and collagen fibre bonds, and increased loading exacerbates molecular damage resulting in more extensive propagation of microcracks (Burr, Forwood et al. 1997). Microcracks consist of a frontal process zone and wake zone (Vashishth, Behiri et al. 1997). The frontal process zone facilitates amplification of the crack in response to increased loads and the wake zone shields and redistributes energy away from the crack tip to the surrounding microstructure (Sakai and Bradt 1993). Further studies have shown that frequent formation of microcracks at lower stresses is advantageous at increasing resistance of fatigue fracture (Akkus and Rimnac 2001, Vashishth 2004, Zimmermann, Launey et al. 2010). However, it is unknown why some cracks merge to cause fatigue failure while others remain microscopic.

At a cellular level, remodelling involves a strict sequential process involving the activation, resorption and formation processes performed by the bone multicellular unit (Parfitt 1984, Schaffler and Jepsen 2000), which normally advances through cortical bone at 11µm per day (Boyde and Firth 2005). Within bone multicellular units, cells known as osteoclasts form the cutting cone and resorb bone. This creates a temporary area of porosity, known as a resorption canal, and when seen in cross section is about 200-300µm in diameter (Cooper, Turinsky et al. 2003). Closely behind the osteoclasts are osteoid producing osteoblasts which form new bone at a rate of 1.23 µm per day (Boyde and Firth 2005).

2.9.1 Remodelling to a high strain environment

The equine athlete provides a useful model in understanding the skeleton's response to continual high strain, high intensity exercise. There is evidence that exercise reduces bone resorption in horses (McCarthy and Jeffcott 1992, Murray, Vedi et al. 2001, Boyde and Firth 2005, Firth, Rogers et al. 2005b). Experimental studies using microradiography and histomorphometry in treadmill trained horses showed reduced cortical porosity in the dorsal third metacarpal bone mid-diaphysis (McCarthy and Jeffcott 1992), and reduced subchondral osteoid seam width of the dorsal intermediate carpal bone (Murray, Vedi et al. 2001) compared with untrained horses. Exercise has been shown to be accompanied by bone modelling in these horses (McCarthy and Jeffcott 1992, Murray, Vedi et al. 2001). Significantly fewer resorption canals and reduce bone porosity were observed in the third metacarpal diaphysis of the exercised group (pasture: 1.36 per mm, high exercise: 0.408 per mm, $P < 0.001$), and the diameter of resorption canals reduced with increasing fast exercise (pasture: 161 µm, medium exercise: 148 µm, high exercise: 144 µm, Firth, Rogers et al. 2005b). Lower bone porosities are consistent with reduced bone remodelling, as temporary porosity is created as part of normal bone multicellular unit function following the activation phase. Another study by the same authors, it was shown that canter exercise was enough to reduce bone remodelling (Boyde and Firth 2005)

The consequences of reduced remodelling are amplified by microdamage accumulation within bone. An experimental study showed through staining microcracks with basic fuchsin, that specimens from actively raced Thoroughbreds had significantly greater resorptive areas associated with microcracks in the condylar groove, compared to the non-athletic group (Muir, Peterson et al. 2008). Microcrack density also varied significantly throughout the subchondral bone of the actively raced group, although the targeted resorption response was only seen directly above the area of articular fracture (Muir, Peterson et al. 2008). These findings were supported by previous studies, which showed that horses that died during active race training had stronger resorptive responses in focal areas of the third metacarpal bone condyles (Riggs, Whitehouse et al. 1999b, Muir, McCarthy et al. 2006, Norrdin and Stover 2006). In particular, Riggs, Whitehouse et al. (1999b) described the pathology of condylar fractures originating from distopalmar or plantar third metacarpal and metatarsal condyles. Fracture lines passed through linear defects of damaged articular cartilage in close proximity to the junction between actively resorbing and dense subchondral bone (Riggs, Whitehouse et al. 1999b). The differences in bone material properties at the interface may therefore succumb to shear strains allowing the preference of the fracture line to propagate proximally (Riggs, Whitehouse et al. 1999b).

The emphasis on replacing bone microdamage in a timely fashion is therefore of paramount importance. There is evidence that resorption may occur in unison with bone modelling. Whitton, Trope et al. (2010) demonstrated that horses with condylar fatigue fractures had significantly increased surrounding epiphyseal bone modelling when compared with actively training horses that died from non-fracture related reasons. In addition, it was found that the area of trabecular bone directly surrounding fracture sites was significantly greater when compared with control horses (81 ± 2%, 72 ± 2%, P = 0.002, Whitton, Mirams et al. 2013). Bone is therefore able to offset areas of weakness by locally maintaining yield strength and fatigue resistance, allowing areas of high microdamage to proceed with the resorption process. This response of balancing bone properties is also seen on a whole-bone scale. A post-mortem study investigating material properties of equine humeri compared the diaphysis; a site not predisposed to stress fracture, to the proximocaudal site; a site prone to stress fracture (Entwistle, Sammons et al. 2009). It was observed that with decreasing yield strength of the proximocaudal site, the material properties at the distal diaphyseal site increased (P = 0.075, Entwistle, Sammons et al. 2009).

2.9.2 Remodelling to a low strain environment

In contrast to studies investigating the effects of increasing exercise on bone, there are limited studies on the consequences to bone when removed from a high strain environment. With the removal of high strain, remodelling continues with microdamage resorption and subsequent bone formation. In humans, this process lasts between six to seven weeks (Schaffler 2001), and resorption canals formed during this process may exponentially decrease cortical and trabecular bone material properties (Schaffler and Burr 1988, McCalden, McGeough et al. 1997, Wachter, Krischak et al. 2002, Hernandez, Gupta et al. 2006).

In racehorses, rest periods are commonplace in training schedules, in particular for rehabilitation from injury or spelling between racing seasons. Resting the racehorse is complicated by the history of bone loading and the ultimate requirement for bone resorption of microdamage. As discussed previously, changes in bone density may predispose to fracture propagation (Riggs, Whitehouse et al. 1999b, Muir, McCarthy et al. 2006, Norrdin and Stover 2006) and computational models also suggest that excessive resorption may act as potential stress risers for fracture (Hernandez, Gupta et al. 2006).

A series of experimental studies from New Zealand investigated bone density fluctuations during the training of two year old Thoroughbred racehorses (Firth, Rogers et al. 2007, Rogers, Firth et al. 2008, Firth, Doube et al. 2009, Firth, Rogers et al. 2011, Firth, Rogers et al. 2012). Peripheral quantitative computed tomography was used to measure changes in third metacarpal bone and first phalanx bone mineral density, bone area and bone strength in eight pastured and 11 horses in ascending intensity race training. In the initial study, Firth, Rogers et al. (2007) found third metacarpal diaphyseal bone mineral density in the trained group decreased significantly ($P = 0.02$) after 145 ± 10 days from the end of eight months of training, however, no significant changes in density were found at the epiphysis when compared to pastured horses. A further study in these horses found no difference in bone mineral density between two year old horses in training and horses after spelling, although bone area continued to increase, maintaining bone strength parameters (Firth, Rogers et al. 2012). Although the duration of the rest period between and two and three year old race training seasons was not described, this study suggests that enough time elapsed to allow some bone resorption to occur at the end of the two year old season (Firth, Rogers et al. 2012).

A recent study by Holmes, Mirams et al. (2014) examined the resorption activity in the subchondral bone of third metacarpal lateral condyles in 24 actively training and 24 horses rested from training. Resorption was measured as the eroded bone surface percentage, the hypothesis being that this would be less in the trained group. As expected, trained horses had significantly less eroded surfaces in the lateral condyle (training: 11.1%, rested: 20.8%, $P < 0.001$), but within the training group, horses with greater than 20 weeks training had significantly greater eroded surfaces in the lateral condyle when compared with those trained less than 20 weeks ($R^2 = 0.26$, $P = 0.001$). In contrast, eroded bone in the rested group was highly variable with no significance detected between time rested and eroded bone surface ($R^2 = 0.02$, $P = 0.48$).

Although the trained horses in the above studies varied in the time spent in continuous race training (eight months; Firth, Rogers et al. 2007, < 20 weeks; Holmes, Mirams et al. 2014), the evidence indicates that the initial adaptive processes are better tolerated and repair more rapidly if given an opportunity to rest (Firth, Rogers et al. 2012), and that continual training without adequate rest periods may increase the risk of condylar fracture (Holmes, Mirams et al. 2014). Moreover, the time required for bone to complete the remodelling process is unknown, although it has been hypothesised to be between two weeks to four months (Riggs 2002). The potentially catastrophic consequences of loading bone during a period where porosity is at its highest warrants further research.

2.10 Summary

Fractures have been identified as a pertinent welfare concern for Thoroughbred racehorses worldwide. Common fractures such as catastrophic fractures of the proximal sesamoid bone and third metacarpal bone in racing (Johnson, Stover et al. 1994, Estberg, Stover et al. 1996b, Reardon, Boden et al. 2014), and non-catastrophic fractures of the third metacarpal bone, tibia and humerus (O'Sullivan and Lumsden 2003, Verheyen and Wood 2004, Ramzan and Palmer 2011) incur direct financial costs resulting in removal from the racing industry, or interference with race training milestones.

After reviewing the literature, it is clear that there is a need to improve existing fracture collection systems particularly with non-catastrophic fractures to enhance the understanding of how a single risk factor or a set of risk factors are involved in the causal pathways of fractures in these athletes. Therefore there is an urgency to identify the exact number of fractures in a Thoroughbred population to initiate and facilitate the design of analytical studies that may reduce the occurrence and impact of both catastrophic and non–catastrophic fractures in racing and training Thoroughbreds.

There is also a need to understand the biology of bone remodelling in response to fluctuating demands of race training on the equine skeleton. While there is a large body of literature investigating the effect of increasing exercise intensity on bone modelling and remodelling (Estberg, Stover et al. 1996a, Estberg, Gardner et al. 1998a, Riggs, Whitehouse et al. 1999b, Parkin, Clegg et al. 2004c, Firth, Rogers et al. 2005b), there is paucity in the literature which examine the effect of rest periods in the racehorse skeleton (Carrier, Estberg et al. 1998, Firth, Rogers et al. 2007). Understanding the role of rest periods and withdrawal from high strain exercise will benefit the understanding of appropriate re-introduction of racehorses back to full race training.

The aims of this thesis were to:

a) Report the counts and incidence rates of racing and training fractures in a highly monitored group of race training Thoroughbreds at the Hong Kong Jockey Club.
b) Examine bone remodelling activity in a group of recently deceased active racehorses compared with a group withdrawn from race training.

To accomplish these general aims, there were three specific objectives; describing catastrophic and non-catastrophic fractures in racing; describing catastrophic and non-catastrophic fractures in training; describe the difference in bone remodelling in a group of recently deceased active racehorses compared with a group withdrawn from race training using bone samples representative of the equine appendicular and axial skeleton.

The overall hypothesis of the thesis is that the incidence rate of catastrophic and non-catastrophic fractures reported for Thoroughbred horses during racing and training at the HKJC are consistent with those reported in the literature. Furthermore, we hypothesise that there is greater bone remodelling activity in rested racehorses compared with horses that has been withdrawn from race training.

Chapter 3:

Non-catastrophic and catastrophic fractures in racing Thoroughbreds at the Hong Kong Jockey Club

Abstract

The aim of this study was to describe the incidence rate and anatomical configuration of catastrophic and non-catastrophic fractures related to racing Thoroughbreds at the Hong Kong Jockey Club over seven racing seasons. Electronic fracture injury records were obtained from the Hong Kong Jockey Club veterinary database and racing starts data extracted from the Hong Kong Jockey Club racing registry. Catastrophic fractures were confirmed if euthanasia was the outcome on the injury report within five days of racing and had agreeable post mortem reports which are mandatory at the Club. Non-catastrophic fractures were confirmed with an injury record which did not include euthanasia as an outcome within five days of racing and had supporting diagnostic imaging reports of fracture also mandatory at the Club. The first fracture event was determined and non-catastrophic and catastrophic fracture incidence rates and incidence rate ratios were calculated and reported per 1000 racing starts for racetrack, age, racing season, gender and trainer. There were 179 first fracture events and 64,807 racing starts over seven racing seasons. Proximal sesamoid bone fractures represented 71% of catastrophic fracture while the most common non-catastrophic fractures were bones of the carpus and first phalanx. The incidence rate of non-catastrophic fractures was 2.17 per 1000 racing starts and catastrophic fractures was 0.6 per 1000 racing starts. Statistical differences were detected in non-catastrophic incidence rates between gender, trainer and racing season. Non-catastrophic fractures contribute to a large proportion of fractures in racing at the Hong Kong Jockey Club. The ratio of non-catastrophic fractures to catastrophic fractures are almost four to one. Increases in the non-catastrophic fracture incidence rate over seven racing seasons correlated with a decreased catastrophic fracture incidence rate over the same time period.

Key words: Racehorse, non-catastrophic, catastrophic, racing, Hong Kong Jockey Club.

3.1 Introduction

Catastrophic fractures consistently remain one of the most significant welfare issue facing the Thoroughbred flat racing industry worldwide. The risk of fracture has been reported by major racing centres in the form of incidence rates of fracture per 1000 racing starts and varies between studies. In Victoria, Australia there were 0.44 catastrophic musculoskeletal injuries per 1000 racing starts in the period between 1989 and 2004 (Boden, Anderson et al. 2006), while starts in the United Kingdom, the incidence rate of distal limb catastrophic fracture between 1999 and 2005 was 0.38 per 1000 racing (Parkin, Clegg et al. 2004a).

Studies have also shown that the type of fractures varies between countries for example the most common catastrophic fracture in the United States are of the proximal sesamoid bone (Johnson, Stover et al. 1994, Peloso, Mundy et al. 1994, Estberg, Stover et al. 1996b, Cohen, Peloso et al. 1997, Beisser, McClure et al. 2011), where as in the United Kingdom the third metacarpal and first phalanx are more commonly fractured (Mckee 1995, Parkin, Clegg et al. 2004a, Reardon, Boden et al. 2014).

In contrast, few studies have reported on the risk of non-catastrophic fractures in racing (Peloso, Mundy et al. 1994, Mizuno 1996), despite being the primary reason for horses leaving the industry (Perkins, Reid et al. 2005a). Reporting of racing fractures largely occurs trackside by regulatory veterinarians, but data are limited on fractures which occur as a result of racing, but diagnosed away from the racecourse. Identifying of the first fracture is of particular focus as the prevention of its occurrence may result in a reduced risk of future catastrophic injury (Cohen, Mundy et al. 1999b, Perkins, Reid et al. 2005a). The aim of this study was to describe, the incidence rate and anatomical configuration of catastrophic and non-catastrophic fractures related to racing Thoroughbreds at the Hong Kong Jockey Club (HKJC) over seven racing seasons.

3.2 Materials and Methods

3.2.1 Study period

This was a retrospective descriptive analysis of reported fractures in all Thoroughbred racehorses at the HKJC from 2004 to 2011 racing seasons. The start date was July 1st 2004 to June 30th 2011. Details of the Hong Kong racing industry have been previously described.

3.2.2 Race day injury and fatality management

All horses which are scheduled to race have a compulsory trot up in front of regulatory veterinarians the day before race day. Horses are heavily scrutinised during this examination and will be withdrawn from the respected race at the discretion of the regulatory veterinarian. There are a minimum of seven veterinarians in attendance on each race day. In the event of a serious incident, such as collapse of a horse during racing, there is an immediate response by veterinarians to attend to the horse's welfare. If euthanasia is elected, a mandatory post-mortem is conducted by the veterinarian in the Sha Tin Hospital and the results are entered directly into the veterinary database. Horses which have pulled up lame after a race may also be flagged resulting in mandatory inspections the day after race day.

3.2.3 Data Collection

Racing season: The racing season runs from July 1st of a given calendar year to June 30th of the following calendar year. Although there is a break from racing between mid-July to early September, training activities still continue. Therefore, any racing starts made between 1st September and 30th July are assigned to one season

Race day data: Information of racing starts was obtained from the centralised purpose built racing registry which is also available to the public online (HKJC 2013a). They were identified by the racing season, racing date, horse number, race location (Sha Tin or Happy Valley), and racing surface (turf or all-weather).

Veterinary data: The method and protocol of veterinary injury reporting has been previously discussed. In this study, records were identified by the racing season, horse number, age, gender, trainer, date of fracture, bone(s) fractured, limb, fracture location, outcome of fracture, activity at time of fracture (racing or training, or unreported), racing surface and racing location.

Fracture records: A fracture case was identified from an electronic fracture report and confirmed on diagnostic imaging reports (radiographic, ultrasonography or nuclear scintigraphy images). All diagnostic investigations must be reported using a specific template and these records are reviewed weekly by the Head of Department of Veterinary Clinical Services, who produces a summary for senior management at the Club. Veterinary surgeons are required to make an entry into a dedicated injury record database for every fracture or other significant injury. Fractures were removed from analysis if they were associated with an accident unrelated to racing (n = 17) and were further identified as either catastrophic or non-catastrophic. Catastrophic fracture was defined as a fracture in which euthanasia was listed on the outcome of the record within five days of the fracture. A non-catastrophic fracture was defined as a fracture which did not have euthanasia as an outcome. All catastrophic fracture records were confirmed with post-mortem reports which are compulsory at the Club, and all non-catastrophic fracture records were confirmed by the absence of post-mortem reports.

Limb preference: The limb involved in the fracture were also recorded as left fore, left hind, right fore, right hind, both fore, both hind, or multiple limb combinations such as; right fore left hind, left fore right hind or miscellaneous (axial skeleton fractures).

Anatomical configuration: The exact description of the fracture was identified from the injury record and cross referenced with diagnostic images from the candidate. Where injury records reported a joint was involved in the fracture (e.g. fetlock), the relative report was retrieved from and examined by the candidate to determine the bones involved. Carpal fractures had confirmed radiographic evidence of fractures of any of the carpal bones. Where possible, the fracture was described in detail from either pre-existing injury reports or from digital radiographs. Descriptions were dependent on the type of bone fractured i.e. lateral condylar fracture of the third metacarpal bone. Where more than one fracture description occurred on the fracture record the description was considered ‘comminuted’. A bone was classified as ‘unrecorded’ if there was no record of the bone in the injury record or diagnostic reports. Fracture records were collectively tabulated using Microsoft Excel (Microsoft Office Professional Plus© 2010).

First fracture event: Only the first fracture event was of interest in this study. The first fracture event was cross referenced between multiple dates of fracture at the level of the horse allowing only the first recorded date to be included. If the horse sustained multiple fractures on the first day of fracture, the event would be recorded as ‘multiple’.

3.2.4 Statistical analysis

The time at risk equated to one horse-race-day which equalled to once horse-racing start. Calculation of fracture incidence rates was based on fracture events from the veterinary database and the racing starts from the racing registry. The fracture event was cross referenced with racing registry to confirm that the horse started a race. Catastrophic and non-catastrophic fracture incidence rates were reported per 1000 racing starts. The influence of trainer on fracture events was identified and trainers were ranked in ascending order of fracture occurrence differentiating between catastrophic and non-catastrophic fracture events.

Statistical analysis of fracture events was performed. Crude incidence rate with 95% CI were calculated based on *poisson* distribution approximation implemented within the Wald method in the epiR package to enable comparisons between non-catastrophic and catastrophic fracture incidence rates for racetrack, season, age, gender and trainer. The association between racetrack, season, age, gender and trainer and the overall risk of fracture (catastrophic and non-catastrophic) was assessed using the likelihood ratio test implemented with a generalised linear model frame work with *poisson* link function. Statistical significance was declared at an alpha < 0.05. Statistical analyses were carried out using the epiR (Stevenson, Nunes et al. 2014) and epicalc (Chongsuvivatwong 2008) packages in R (R Development Core Team 2013).

3.3 Results

In the period from 1st July 2004 until 30th June 2011 there were 179 fracture events recorded in 64,516 racing starts: 162 involved a single bone; 13 involved two bones and four involved three bones. Of the 162 fractures involving a single bone 34 were catastrophic (21%), 164 of the fractures involved the forelimb and of those involving the forelimb 92 occurred in the left limb and 56 occurred on the right limb with the remaining 16 being bilateral. Left sided fractures were statistically significant went compared to the right. The most common fracture sites were the proximal sesamoid (44/162) and the carpus (36/162; Table 4). Of the 17 fractures involving more than one bone, five were catastrophic (Table 5).

The incidence rate for catastrophic fractures was 0.60 per 1,000 racing starts (95% CI 0.43 – 0.83). This did not vary significantly by track, season or age (Table 6). Nor did the incidence rate for catastrophic factures during a race vary significantly between trainers (Figure 2; $P = 0.38$). The incidence rate for non-catastrophic fractures was 2.17 per 1,000 racing starts (95% CI 1.83 to 2.56). Like catastrophic racing fractures the incidence rate was not significantly different between race tracks or age groups (Table 6). In contrast, to catastrophic fractures, the incidence rate for non-catastrophic fractures varied significantly by trainer (Figure 3; $P < 0.001$), gender (Table 7; $P < 0.05$) and racing season (Table 7; $P = 0.03$). The highest incidence rates were recorded in 2006/2007 and 2010/2011 racing seasons (Table 7).

Table 4: Count of all fracture events in Thoroughbred horses racing at the Hong Kong Jockey Club involving only one bone (n = 162) and the number that were catastrophic stratified by location and type of fracture. Data were from 162 fracture events from 1st of July 2004 to 30th of June 2011.

Location	**Type**	**No. fracture events**	**Limb**			**No. catastrophic**
			Left	**Right**	**Both**	
PSB	Comminuted		12	6	0	14
	Basilar		6	4	0	4
	Other		14	2	0	6
	Subtotal	**44**	32	12	0	24
Carpus	Chip		9	10	3	
	Slab		6	0	0	
	Other		5	2	1	2
	Subtotal	**36**	20	12	4	2
P1	Chip		14	11	7	
	Other		0	2	0	1
	Subtotal	**34**	14	13	7	1
MCIII	Lateral condylar		3	2	0	
	Medial condylar		1	0	0	
	Other		3	5	0	
	Subtotal	**14**	7	7	0	0
Radius	Distal		0	2	0	
	Chip		5	3	1	
	Other		1	0	0	
	Subtotal	**12**	6	5	1	0
Humerus	Distal		1	0	0	0
	Proximal		3	0	0	0
	Subtotal	**4**	4	0	0	2
Pelvis		**4**	0	0	4	0
Tibia		**3**	1	2	0	0
Scapula		**3**	1	2	0	3
MTIII		**2**	0	2	0	2
MTIV		**2**	0	2	0	0
Tarsus		**1**	1	0	0	0
MCII		**1**	0	1	0	0
P3		**1**	1	0	0	0
Unrecorded		**1**	1	0	0	0
Total fracture events		**162**	**88**	**58**	**16**	**34**

Key: PSB - proximal sesamoid bone; carpus - involving either one or more of the radial, intermediate carpal, ulnar carpal, second, third or fourth carpal bones; P1 - first phalanx; MCIII - third metacarpal bone; MTIII - third metatarsal bone; MTIV - fourth metatarsal bone; Tarsus - involving either one or more of the talus, calcaneus, central tarsal, first/second, third or fourth tarsal bones; MCII - second metacarpal, P3 - third phalanx; Unrecorded - one injury record with no supporting diagnostic imaging report.

Table 5: Counts and description of fracture events involving more than one bone in Thoroughbred horses racing at the Hong Kong Jockey Club. Data were from 17 fracture events from 1st of July 2004 to 30th of June 2011.

Fracture Number	Fracture details	Bilateral	Catastrophic
#1	Third metacarpal and first phalanx	Yes	No
#2	Third metacarpal and first phalanx	Yes	No
#3	Third metacarpal and first phalanx	No	No
#4	Third metacarpal and first phalanx	No	No
#5	Carpus and radius	No	No
#6	Carpus and radius	No	No
#7	Carpus and radius	No	No
#8	Radius and other	No	Yes
#9	Proximal sesamoid and third metacarpal	No	Yes
#10	Humerus and scapula	No	Yes
#11	Radius and second metacarpal	No	No
#12	First phalanx and proximal sesamoid	No	No
#13	Radius and humerus	Yes	No
#14	First phalanx, third metacarpal and proximal sesamoid	Yes	Yes
#15	First phalanx, third metacarpal and proximal sesamoid	Yes	Yes
#16	First phalanx, carpus and second metacarpal	No	No
#17	Tibia, third metacarpal and other	No	No

Table 6: Number of catastrophic racing fractures, number of racing starts, incidence rate (IR) and incidence rate ratio (IRR) stratified by track, racing season, age and gender in Thoroughbred horses racing at the Hong Kong Jockey Club. Data were from 39 fracture events resulting in death over 64,807 racing starts from 1st of July 2004 to 30th of June 2011.

Variable	**No. fracture events**	**No. racing starts**	**IR per 1,000 starts(95% CI)**	**IRR (95% CI)**	**P-value[a]**
Track					**0.5**
Happy Valley Turf	10	21,386	0.47 (0.22-0.86)	Reference	
Sha Tin Turf	23	36,382	0.63 (0.4-0.95)	1.82 (0.66-5.02)[b]	0.25
Sha Tin All-weather	6	7,039	0.85 (0.31-1.86)	1.35 (0.64-2.84)	0.43
Racing Season					**0.14**
2004/2005	7	9,153	0.76 (0.31-1.58)	Reference	
2005/2006	3	9,018	0.33 (0.07-0.97)	0.43 (0.11-1.68)	0.23
2006/2007	5	9,083	0.55 (0.18-1.28)	0.72 (0.23-2.27)	0.57
2007/2008	12	9,136	1.31 (0.68-2.29)	1.72 (0.68-4.36)	0.26
2008/2009	5	9,179	0.54 (0.18-1.27)	0.71 (0.23-2.24)	0.56
2009/2010	3	9,736	0.31 (0.06-0.9)	0.4 (0.1-1.56)	0.19
2010/2011	4	9,502	0.42 (0.11-1.08)	0.55 (0.16-1.88)	0.34
Age					**0.36**
2 to 3	8	8,664	0.92 (0.4-1.82)	Reference	
4 to 5	16	34,576	0.46 (0.26-0.75)	0.5 (0.11-1.17)	0.11
6 to 7	13	17,351	0.75 (0.4-1.28)	0.81 (0.18-1.96)	0.64
≥8	2	4,216	0.47 (0.06-1.71)	0.51 (0.16-2.42)	0.4
Gender					**0.7**
Gelding	37	62,560	0.59 (0.43-0.82)	Reference	
Male	2	2,015	0.99 (0.31-3.59)	1.68 (0.4-6.9)	0.47
Female	0	232	0	0	NA

Key: No. Number; 95% CI - 95% Confidence Interval.

[a] Bold P-value is for the log-likelihood test statistic and non-bold is for the Wald test statistic.

[b] Interpretation – The rate of non-catastrophic fractures on the Sha Tin Turf was 1.8 times higher than on Happy Valley turf but this was non-significant as the 95% confidence interval ranged from 0.66 to 5.02 (i.e. the 95% Confidence interval crossed one).

Table 7: Number of non-catastrophic racing fractures, number of racing starts, incidence rate (IR) and incidence rate ratio (IRR) stratified by track, racing season, age and gender in Thoroughbred horses racing at the Hong Kong Jockey Club. Data were from 140 fracture events over 64,807 racing starts from 1st of July 2004 to 30th of June 2011.

Variable	**No. of fracture events**	**No. of racing starts**	**IR per 1,000 starts(95% CI)**	**IRR (95% CI)**	**P-value[a]**
Track					**0.38**
Happy Valley Turf	39	21,386	1.82 (1.3-2.49)	Reference	
Sha Tin Turf	83	36,382	2.28 (1.82-2.83)	1.4 (0.80-2.45)[b]	0.24
Sha Tin All-weather	18	7,039	2.56 (1.52-4.04)	1.25 (0.86-1.83)	0.25
Season					**0.03**
2004/2005	6	9,153	0.66 (0.24-1.43)	Reference	
2005/2006	17	9,018	1.89 (1.1-3.02)	2.88 (1.13-7.29)	0.03
2006/2007	27	9,083	2.97 (1.96-4.32)	4.53 (1.87-10.98)	0.00
2007/2008	19	9,136	2.08 (1.25-3.25)	3.17 (1.27-7.94)	0.01
2008/2009	18	9,179	1.96 (1.16-3.10)	2.99 (1.19-7.54)	0.02
2009/2010	24	9,736	2.47 (1.58-3.67)	3.76 (1.54-9.20)	0.00
2010/2011	29	9,502	3.05 (2.04-4.38)	4.66 (1.93-11.21)	0.00
Age					**0.56**
2 to 3	24	8,664	2.77 (1.77-4.12)	Reference	
4 to 5	74	34,576	2.14 (1.68-2.69)	0.77 (0.49-1.22)	0.27
6 to 7	35	17,351	2.02 (1.41-2.81)	0.73 (0.43-1.22)	0.23
≥8	7	4,216	1.66 (0.67-3.42)	0.6 (0.26-1.39)	0.23
Gender					**<0.05**
Gelding	127	62,560	2.03 (1.7-2.40)	Reference	
Male	12	2015	5.96 (3.4-10.40)	3.0 (1.60-5.10)	0.00
Female	1	232	4.31 (0.1-24.00)	2.4 (0.10-10.60)	0.44

Key: No. Number; 95% CI 95% Confidence Interval.

[a] Bold P-value is for the log-likelihood test statistic and non-bold is for the Wald test statistic.

[b] Interpretation – The rate of non-catastrophic fractures on the Sha Tin Turf was 1.4 times higher than on Happy Valley turf but this was non-significant as the 95% confidence interval ranged from 0.8 to 2.45 (i.e. the 95% Confidence interval crossed one).

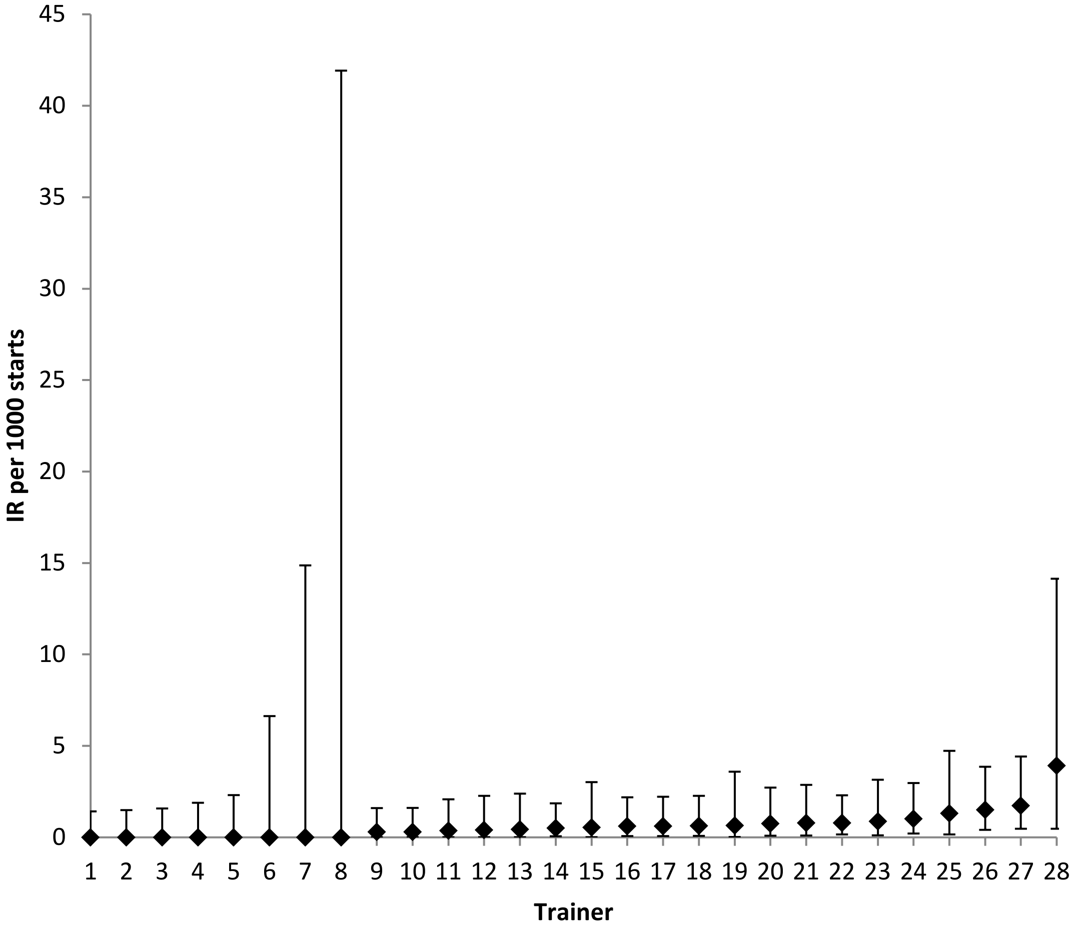


Figure 2: Incidence Rate (IR), per 1,000 starts, for catastrophic fractures by HKJC trainers. Data were from 39 fracture events resulting in death over 64,516 racing starts in Thoroughbred horses racing in Hong Kong from 1st of July 2004 to 30th of June 2011. Error bars represent the 95% Confidence Interval for the incidence rate. Fracture event by trainer is plotted as an ascending incidence rate.

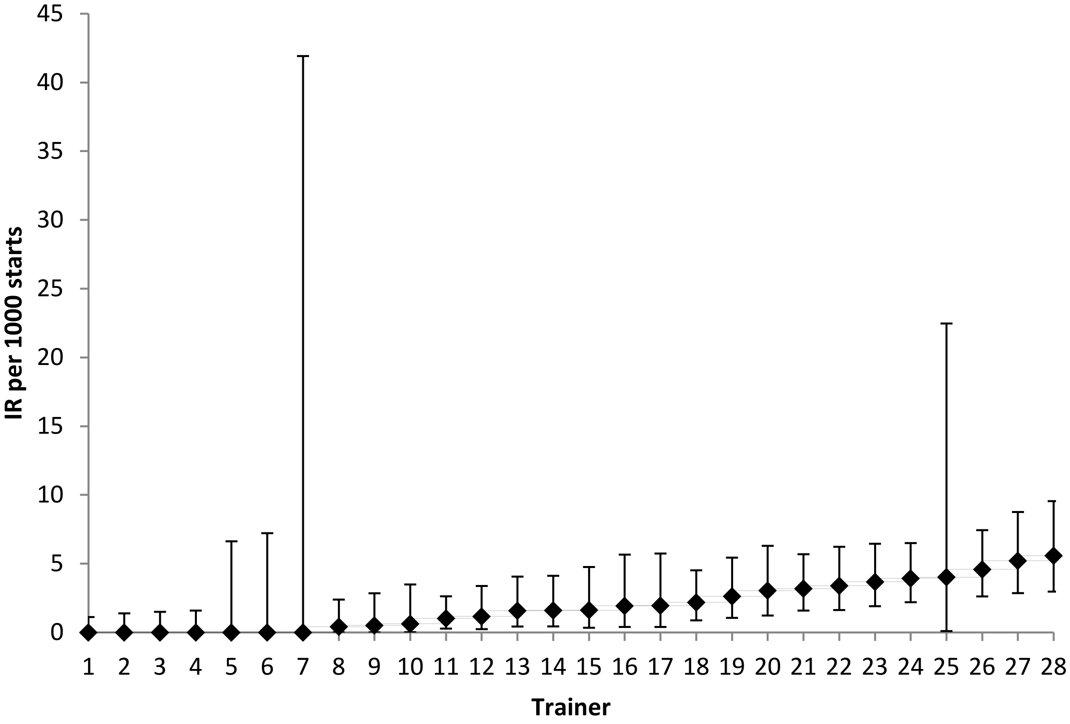


Figure 3: Incidence Rate (IR), per 1,000 starts, for non-catastrophic fractures by HKJC trainers. Data were from 140 fracture events resulting in death over 64,516 racing starts in Thoroughbred horses racing in Hong Kong from 1st of July 2004 to 30th of June 2011. Error bars represent the 95% Confidence Interval for the incidence rate. Fracture event by trainer is plotted as an ascending incidence rate.

3.4 Discussion

The most common catastrophic fracture at the Hong Kong Jockey Club involved the proximal sesamoid bones representing 70.6% (24/34) of all single site catastrophic fractures. Proximal sesamoid bones fractures were also the most common catastrophic fracture in a number of US studies; ranging from 21-58.8% of all catastrophic fractures (Johnson, Stover et al. 1994, Peloso, Mundy et al. 1994, Estberg, Stover et al. 1996b, Hernandez, Hawkins et al. 2001, Beisser, McClure et al. 2011). Comminuted proximal sesamoid fractures were the most common configuration in the current study (58%; 14/24), while American studies reported mid-body (Anthenill, Gardner et al. 2010) and basilar fractures (Parente, Richardson et al. 1993) being more common.

Racing in Hong Kong and America may have similar risk factors which increase the proportion of catastrophic proximal sesamoid bone fractures. The risk of proximal sesamoid bone fractures was observed to be greater on all-weather tracks when compared with turf tracks (Parkin, Clegg et al. 2004a, Kristoffersen, Parkin et al. 2010b). Although there were no statistical differences detected between catastrophic fractures and racing in Hong Kong racetracks, the hardness of turf tracks in Hong Kong may be more similar to dirt surfaces in America. The turf track in Hong Kong is a sand based track which is similar to all-weather tracks in the United States (Riggs 2015).

Alternatively, fractures of the carpal bones, first phalanx and third metacarpal bone were largely non-catastrophic. The majority of carpal and first phalanx fractures were defined as chip fractures although the definition of a chip fracture size was variable to interpretation and dependant on the veterinarian filing the report. Chip fractures may not necessarily remove horses from race training but are a major cause of morbidity in particularly in the carpal and metacarpophalangeal joints (Reed, Jackson et al. 2012). The large number of non-catastrophic chip fractures in the present study highlights the significance of these injuries in the broader population and warrants further analytical studies to be conducted to identify risk factors such as corticosteroid injections (Whitton, Jackson et al. 2014).

Interestingly, no fractures of the third metacarpal bone were catastrophic which is in stark contrast to the United Kingdom where third metacarpal or metatarsal fractures accounted for more than half of all single limb catastrophic racing fractures (56.8%, 108/190; Reardon, Boden et al. 2014). This may be partly explained by the restrictive and highly regulated entry requirements of racehorses into Hong Kong. Given that third metacarpal fractures most commonly occurred in racehorses which did no gallop work during training or were in their first year of racing (Mohammed, Hill et al. 1991, Parkin, Clegg et al. 2004b), the importation process would have in theory selectively reduced the entry of horses which have not adapted their bones adequately to racing conditions, creating a bias in favour of better adapted horses to race in Hong Kong.

Our study showed that forelimb fractures occurred more commonly than hindlimb fractures and that left sided fractures were significantly greater than right sided fractures. It was previously hypothesized that the greatest peak vertical force occurs on the lead limb and may predispose to fracture (Ratzlaff, Hyde et al. 1990, Ueda 1991), however, kinematic studies show that overall impact forces while galloping were greater in the hindlimb rather than the forelimb, suggesting that other forces associated with limb vibration may result in greater risk of fracture (Gustas, Johnston et al. 2001, Parsons, Spence et al. 2011). As racing occurs clockwise in Hong Kong, the lead limb may often be the right limb while the left limb may be predisposed to injury as a result of vibrational forces mid-air. The distal limb, in particular the bones encompassing the metacarpophalangeal region may be subject to greater forces imposed by lack of muscle for vibration attenuation (Wilson, McGuigan et al. 2001) which explains a greater proportion of distal limb fractures (Parkin, Clegg et al. 2004a, Perkins, Reid et al. 2005b).

The incidence rate of catastrophic fracture at the Hong Kong Jockey Club was 0.6 per 1000 racing starts which was higher than that reported in Australia (Boden, Anderson et al. 2006) and United Kingdom (Parkin, Clegg et al. 2004a, Reardon, Boden et al. 2014), but lower than North American studies (Peloso, Mundy et al. 1994, Estberg, Stover et al. 1996b, Hernandez, Hawkins et al. 2001, Cruz, Poljak et al. 2007, Beisser, McClure et al. 2011). Differences may be associated with a different time frame of euthanasia compared to the current study of five days post-race. Furthermore, the exact bone was recorded in contrast to previous studies which may have allowed for fetlock fractures as one fracture (Peloso, Mundy et al. 1994, Cohen, Peloso et al. 1997). We believed it was important to eliminate misclassification bias of injuries and the environment at the Hong Kong Jockey Club provided a unique opportunity for the exact count of fractures. Racehorse ownership is regulated by the Hong Kong Jockey Club and trainers, owners and veterinarians are governed by the rules and regulations of the Club. Horses which sustain catastrophic fractures are subjected to a mandatory post mortem which occurs at the Equine hospital with the results filed electronically into the veterinary database. Previous studies may not have had mandatory post mortem (Boden, Anderson et al. 2006) or the decision to euthanise was determined by a regulatory veterinarian on track (Peloso, Mundy et al. 1994, Cohen, Mundy et al. 1999b). In effect, the rules and regulations of the Hong Kong Jockey Club are ideal for descriptive analysis given the high degree of rigor imposed.

The incidence rate of non-catastrophic fracture was 2.17 per 1000 racing starts which was similar to a retrospective study on New York racing tracks which reported the incidence rate from 3.5 to 7.3 per 1000 racing starts, although comparisons are difficult given the limited case definitions for non-catastrophic injury or the method in which the data was collected (Hill 2003). The ratio of non-catastrophic fractures versus catastrophic fractures in our study was 3.6:1, emphasising that for every catastrophic fracture on the racetrack, almost four non-catastrophic fractures occurred. While this study was not designed to identify relationships between risk factors and fracture, differences in incidence rate may direct future studies in examining risk factors specific to Hong Kong racing. No statistical significance was detected in any of the catastrophic fracture variables, but for non-catastrophic fractures, statistical differences were detected within trainers, gender and season.

Trainers at the Hong Kong Jockey Club had autonomy into the selection of race meeting according to the horse's performance rating. Differences in non-catastrophic racing incidence rate may reflect training practice differences as suggested by previous studies (Verheyen and Wood 2004, Perkins, Reid et al. 2005b, Cogger, Evans et al. 2008a, Ramzan and Palmer 2011). Trainers with the highest non-catastrophic incidence rate did not correlate to trainers with the highest catastrophic incidence rate, for example trainer number 28 (Figure 3) had zero catastrophic fractures. As trainers were not convenience sampled, the incidence rate reported was the true incidence rate of first fracture events between 2004 and 2011. However, given only 24 trainers are licenced by the Hong Kong Jockey Club every racing season, not all 28 trainers would have trained throughout the study period and may have biased the overall incidence rate reported towards trainers which were at the Club for a longer period of time.

Differences in gender were also statistically different between non-catastrophic incidence rates. It is unlikely that female horses are at a greater risk of fracture when compared to geldings but rather confounded by the preference to import male horses into Hong Kong. Alternatively, racing starts in geldings represented 97% of all racing starts made during the study period. Given the lack of breeding prospects for entire males in Hong Kong, geldings may be encouraged to continue racing despite non-catastrophic fracture. The increased risk of entire males and geldings is difficult to explain although hormonal differences may influence the rate of injury and warrants further investigation.

For racing seasons, non-catastrophic fracture incidence rates increased during the study period while catastrophic fracture incidence rates decreased. This may reflect changes in racehorse monitoring systems (To Watch), which was implemented in the 2005 to 2006 racing season designed to flag horses with transient health problems. Subsequently, this may have improved detection of non-catastrophic fractures post-race and prevented the development of subsequent catastrophic fractures in later seasons. Although no direct relationships can be made due to the design of the study, earlier and more regular detection of non-catastrophic fractures may assist in confirming a reduction in the catastrophic fracture incidence rate.

Limitations of our study included our focus on fatigue fractures and exclusion of fractures which were accidental. Fractures associated with accidents were not specific to racing or training Thoroughbreds

(Riggs 2002) and is consistent with definitions in previous studies (Hernandez, Hawkins et al. 2001, Verheyen and Wood 2004). The interest of this current study was to examine fatigue fractures which may be a result of end stage orthopaedic disease sustained during racing or training (Riggs 2002). Furthermore, the unit of interest in this study was the first fracture event as we were interested in determining the incidence rate of fracture rather than for individual horses (Cumming, Kelsey et al. 1990, Eisen 1999). Other studies may have reported on the incidence risk of fracture (Mizuno 1996, Oikawa and Kusunose 2005) or allowed for first or second fracture events and may not be directly comparable.

3.5 Conclusion

The descriptive analysis of racing fractures at the Hong Kong Jockey Club suggests that non-catastrophic fractures contribute to a large proportion of fractures in racing. Although catastrophic fracture incidence rates have been well reported in the literature, our results show that the ratio of non-catastrophic fractures to catastrophic fractures are almost four to one. Increases in non-catastrophic fracture incidence rate over seven racing seasons correlated with a decreased catastrophic fracture incidence rate over the same time period. Rising non-catastrophic fracture incidence rates may provide added support for racing centres that implementation strategies of catastrophic fractures in racing are effective.

Chapter 4:

Non-catastrophic and catastrophic fractures in training Thoroughbreds at the Hong Kong Jockey Club

Abstract

The aim of this chapter was to describe the types of fractures and calculate the incidence rate of catastrophic and non-catastrophic fractures related to training Thoroughbreds from 2004 to 2011 at the Hong Kong Jockey Club over seven racing seasons. Electronic fracture injury records were obtained from the Hong Kong Jockey Club veterinary database and racing starts data extracted from the Hong Kong Jockey Club racing registry. Catastrophic fractures were confirmed if euthanasia was the outcome on the injury report within five days of racing and had agreeable post mortem reports which are mandatory at the Club. Non-catastrophic fractures were confirmed with an injury record which did not include euthanasia as an outcome within five days of racing and had supporting diagnostic imaging reports of fracture also mandatory at the Club. The first fracture event was determined and calculation of non-catastrophic and catastrophic fracture incidence rates and incidence rate ratios were performed per 10,000 training days for racing season, age and gender, while incidence risk was calculated for trainer. There were 292 first fracture events and 3,153,223 training days over seven racing seasons. Proximal sesamoid bone were the most common fracture fractures in 19% of fractures while the most common non-catastrophic fractures were bones of the carpus and first phalanx and primarily chip fractures. The incidence rate of non-catastrophic fractures was 0.85 per 10,000 training days at risk and catastrophic fractures was 0.08 per 10,000 training days at risk, suggesting that in a population of 1,000 horses in training, three catastrophic fractures and 31 non-catastrophic fractures every 365 training days. Statistical differences were detected in non-catastrophic incidence rates for age, and trainer incidence risk. Non-catastrophic fractures are an important part of fractures sustained in racing but previously been underreported. Detecting non-catastrophic fractures in training is important in reducing catastrophic fractures both in training and racing.

Key words: Racehorse, non-catastrophic, catastrophic, training, Hong Kong Jockey Club.

4.1 Introduction

Musculoskeletal injuries in Thoroughbred racehorses are the most common cause of days lost from race training and often resulting in permanent removal from the racing industry (Jeffcott, Rossdale et al. 1982, Lindner and Dingerkus 1993). In contrast to the protocols placed for detecting racehorses which sustain catastrophic racing fractures (Boden, Anderson et al. 2006, Reardon, Boden et al. 2014), training fractures may not receive the same rigorous degree of monitoring or reporting, resulting in many conditions being undiagnosed or unrecorded (Jeffcott, Rossdale et al. 1982, Rossdale, Hopes et al. 1985, Verheyen and Wood 2004, Perkins, Reid et al. 2005a).

Fractures in training are largely non-catastrophic. It was estimated that fractures were the most common cause of musculoskeletal injury contributing 21- 30% of days lost from race training (Dyson, Jackson et al. 2008).with chip fractures and stress fractures representing 12% and 57% of all fractures in a United Kingdom study respectively (Verheyen and Wood 2004). Anatomically, tibial fractures were the most common fracture sustained in training in the United Kingdom representing 26% of all fractures (Ramzan and Palmer 2011), while in the United States, carpal chip fractures were the most common fracture type representing 8.6% of all musculoskeletal injuries in training (Hill, Blea et al. 2015).

Previous studies measuring the frequency of training injuries have reported both the incidence risk (Rossdale, Hopes et al. 1985, Lindner and Dingerkus 1993, Bailey, Reid et al. 1999a), and incidence rate (Bailey, Reid et al. 1999a, Verheyen and Wood 2004, Perkins, Reid et al. 2005a, Cogger, Evans et al. 2008a). An advantage of the incidence risk is that the measurement is readily understood to an audience less familiar with epidemiology, for example 45% of Thoroughbreds training in 1982 in the United Kingdom suffered musculoskeletal injury (Rossdale, Hopes et al. 1985). However, the incidence rate has a further advantage in that it accounts for the time at risk for each individual horse, and may be a more appropriate measurement given the dynamic fluctuations in population at risk in Thoroughbred racing (Cogger, Evans et al. 2008a). The aim of this study was to describe the types of fractures and calculate the incidence rate of catastrophic and non-catastrophic fractures related to training Thoroughbreds from 2004 to 2011 at the Hong Kong Jockey Club. The availability of such information will expand our understanding of the true frequency of training related fractures in Thoroughbred racehorses which will assist in the management of fracture prevention strategies.

4.2 Materials and methods

4.2.1 Study period and population

This was a retrospective descriptive study quantifying fractures in Thoroughbred racehorses at the Hong Kong Jockey Club from 2004 to 2011. The study population was all horses which were stabled in Sha Tin training complex for the purposes of flat race training. The start date was July 1st 2004 to June 30th 2011. Details of the Hong Kong racing industry have been previously described.

4.2.2 Trainers and training facilities

Trainers are licensed by the Hong Kong Jockey Club, which restricts trainer numbers to a maximum of 25 per year. Each trainer is allowed a maximum of 65 horses in their training care. Horses can potentially remain in training and racing until ten years of age, at which stage there is compulsory retirement. There are also numerous international trainers participating in Hong Kong international group races each season. For the purposes of this study only trainers licenced by the Hong Kong Jockey Club will be included.

Training largely takes place on one of two all-weather tracks: the inner track is restricted to slow work (trotting, light cantering) and the larger outer for fast work (cantering, galloping). Training on turf is permitted but limited specific times and restricted to a small number of horses per trainer per week. All training occurs in a clockwise direction six days per week and anti-clockwise training one day per week. There are also two sand based trotting rings used predominantly as a warm up facility, and each training stable is supplied with their own stable walker used at the trainer's discretion. Barrier trials are a form of race practice involving high speed gallops under simulated race conditions, and are held twice a week at Sha Tin and once every month at Happy Valley. The majority of are held on the all-weather track although turf trials for a limited number of horses are held four times a month. For the purposes of this study, barrier trials will also be included as part of training.

4.2.3 Data Collection

Racing season: The racing season runs from July 1st of a given calendar year to June 30th of the following calendar year. Although there is a break from racing between mid-July to early September, training activities still continue. Therefore, any training records made between 1st July and 30th June are assigned to one season

Training data: Information on training were obtained from the centralised purpose built racing registry (HKJC 2013a). Training starts at fixed times between 4:30 and 8:30 am every day, in which horses are permitted to use the training tracks. Specific training activities are recorded by an experienced independent commercial track work database group with all daily training overseen by Club Stewards who perform random inspections to confirm horse identification (HKJC 2012). All training records are consolidated into the racing registry by 12 noon on the day of the training and immediately accessible to the public via the Club's website (HKJC 2015d). Horses return to their stables after track work where training may continue informally and is under the jurisdiction of the trainer.

Veterinary data: Veterinary records for each horse are entered into a separate purpose built veterinary database by stable veterinarians who are employed by the Club and the method and the protocol of fracture reporting has been discussed previously (Chapter 1. section 5). Veterinary surgeons are required to make an entry into a dedicated injury record database for every fracture or other significant injury, for example catastrophic suspensory ligament rupture. In this study, records were identified by the racing season, horse number, age, gender (male or female), trainer, date of fracture, bone(s) fractured, limb, fracture location, outcome of fracture (whether euthanasia was performed or not).

Fracture records: All electronic fracture records were extracted from the veterinary database between 1st of July 2004 to 30th of June 2011. A fracture case was subsequently confirmed on diagnostic imaging reports by the candidate (Christopher Sun). Fractures were removed from the analysis if they were accident related according to the fracture record (n = 17). The remaining fractures were further identified as either catastrophic or non-catastrophic. Catastrophic fracture was defined as a fracture in which euthanasia was a direct outcome of the fracture event within five days of the date of the fracture event. A non-catastrophic fracture was defined as a fracture which did not have euthanasia as an outcome. All catastrophic fracture records were further cross referenced with post-mortem reports to ensure the accuracy of the fracture description of the original fracture record.

Limb involvement: The limb involved in the fracture were also recorded as left fore, left hind, right fore, right hind, both fore, both hind, or multiple limb combinations such as; right fore left hind, left fore right hind or miscellaneous (non-limb).

Anatomical configuration: The description of the fracture was identified from the injury record and cross referenced with diagnostic images from the candidate. Where injury records reported a joint was involved in the fracture (e.g. fetlock), the relative report was retrieved from and examined by the candidate to determine the bones involved. Carpal fractures had confirmed radiographic evidence of fractures of any of the carpal bones. Where possible, description was made of the site of fracture. Descriptions were dependent on the type of bone fractured i.e. lateral condylar fracture of the third metacarpal bone. Where more than one fracture description occurred on the fracture record the description was considered comminuted. A bone was classified as unrecorded if there was no record of the bone in the injury record or diagnostic reports. Fracture records were collectively tabulated using Microsoft Excel (Microsoft Office ® and Microsoft® Inc 2010).

First fracture event: Only the first fracture event was of interest in this study. If the horse sustained multiple fractures on different bones on the first day of fracture, the event would be recorded as multiple.

4.2.4 Definition of training time at-risk

Training in Hong Kong occurs throughout the year either on the racetracks, trotting rings or respective training yards and is continually monitored by Club Stewards. Horses also have the possibility of training on race day although this was dependent on individual trainers.

There is continual importation and retirement of racehorses throughout the year and transfer of racehorses between trainers. Importation protocol has previously been discussed. Briefly, racehorses permitted into Hong Kong must satisfy performance criteria and veterinary examination prior to importation (HKJC 2015b). Although there are quarantine protocols in place for new imports, racehorses are permitted to commence training at specifically allocated times at the request of the trainer. In effect, racehorses imported into Hong Kong will contribute to time at risk immediately from the day it is imported into Hong Kong.

In this study, time at risk begins at the day of importation or the 1st of July 2004, and ends at the date of retirement or fracture; or 30th June 2011. Importation and retirement dates were extracted from the racing registry while fracture records were extracted from the veterinary database. Horses with fracture records were flagged with the dates adjusted so that the time at risk ended on the fracture date. Fractured horses and non-fractured horses were combined and tabled using Microsoft Excel (Microsoft Office ® and Microsoft® Inc 2010).

4.2.5 Statistical analysis

Calculation of fracture incidence rates was based on the first fracture event from the veterinary database and the time at risk. Catastrophic and non-catastrophic fracture incidence rates were reported per 10,000 horse days at risk. Incidence rate ratios were calculated for racing seasons, age and gender.

Fracture incidence risks were calculated for each HKJC trainer that had horses in race training during the study period. The number of horses per trainer were identified from existing Microsoft Access (Microsoft Office ® and Microsoft® Inc 2010) databases as discussed earlier (Chapter 1 section 6), and recorded on Microsoft Excel (Microsoft Office ® and Microsoft® Inc 2010). Catastrophic and non-catastrophic fracture incidence risk and 95% confidence intervals were calculated and expressed as a proportion per 65 horses given that a maximum of 65 horses are permitted in each stable.

Statistical analysis of fracture events was performed. Crude incidence rate with 95% CI were calculated based on *poisson* distribution approximation implemented with the Wald method in the epiR package to enable comparisons between non-catastrophic and catastrophic fracture incidence rates for season, age and gender and trainer. The association between season, age, gender and trainer and the overall risk of fracture (catastrophic and non-catastrophic) was assessed using the likelihood ratio test implemented with a generalised linear model frame work with *poisson* link function. Statistical significance was declared at an alpha < 0.05. Statistical analyses were carried out using the epiR (Stevenson, Nunes et al. 2014), epiTools (Aragon, Fay et al. 2012) and epicalc (Chongsuvivatwong 2008) packages in R (R Development Core Team 2013).

4.3 Results

In the period from 1st July 2004 until 30th June 2011 there were 3,612 horses in active race training at the Hong Kong Jockey Club. There were 292 fracture events recorded in 3,153,223 training days at risk: 268 involved a single bone; 20 involved two bones; two involved three bones; and two involved four bones. Of the 268 fractures involving a single bone 17 were catastrophic (6.3%), 217 of the fractures involved the forelimb and of those involving the forelimb 118 occurred in the left limb and 81 occurred on the right limb (P = 0.002) with the remaining 18 being bilateral. The most common fracture sites were the proximal sesamoid (53/268) and the first phalanx (43/268; Table 8). Of the 24 fractures involving more than one bone there were seven that were catastrophic (Table 9).

The overall fracture incidence rate reported in our study was 0.93 per 10,000 training days at risk (95% CI 0.85 - 1.04). The incidence rate for catastrophic fractures was 0.08 per 10,000 training days at risks (95% CI 0.05 – 0.11). This did not vary significantly by season and gender, but a significant association was detected for age (Table 10). The incidence risk for catastrophic factures during training did not differ between trainers (P = 0.07; Figure 4). The incidence rate for non-catastrophic fractures was 0.85 per 10,000 training days at risk (95% CI 0.75 - 0.96). Like catastrophic racing fractures the incidence rate was not significantly different between season or gender but a significant association was detected for age (Table 11). The incidence risk for non-catastrophic fractures varied significantly by trainer (P < 0.001; Figure 4).

Table 8: Count of all fracture events involving only one bone (n = 268) and the number and percentage that were catastrophic stratified by location and type of fracture in Thoroughbred racehorse training records at the Hong Kong Jockey Club from 1st of July 2004 to 30th of June 2011.

Fracture Location	**Type**	**Fracture events (*N*)**		**Limb**		**Catastrophic fracture (*n*)**
			Left	**Right**	**Both**	
PSB	Basilar		13	5	0	3
	Apical		3	7	0	1
	Mid-body		5	4	1	2
	Comminuted		7	1	1	6
	Other		6	0	0	
	Subtotal	**53**	34	27	3	12
P1	Chip		19	11	10	
	Other		2	0	0	
	Subtotal	**43**	21	12	10	
Carpus	Chip		18	8	3	
	Other		7	5	0	
	Subtotal	**41**	25	13	3	
MCIII	Lateral		8	9	0	
	Proximal		6	7	0	
	Other		5	4	1	
	Subtotal	**40**	19	20	1	2
Humerus	Distal		8	4	0	
	Proximal		2	5	0	
	Subtotal	**19**	10	9	0	
Tibia	Distal		6	5	1	
	Mid-body		1	1	1	
	Proximal		1	0	0	
	Subtotal	**16**	8	6	2	
Radius		**10**	3	6	1	
Pelvis		**8**	0	0	8	
MTIII		**8**	6	2	0	
MTIV		**5**	2	3	0	
MCII		**4**	3	1	0	
HP1		**4**	2	2	0	2
HP3		**4**	2	2	0	
P3		**3**	2	1	0	
Femur		**2**	1	1	0	
MCIV		**2**	1	1	0	
Navicular		**1**	1	0	0	
HP2		**1**	0	1	0	1
P2		**1**	0	1	0	
Scapula		**1**	0	1	0	
Unknown		**2**	1	0	1	
Total fracture events		**268**	141	99	28	17

Key: PSB - proximal sesamoid bone; carpus - involving either one or more of radial, intermediate, ulnar, second, third or fourth carpal bones; P1 - first phalanx; MCIII- third metacarpal bone; MTIII - third metatarsal bone; MCII - second metacarpal bone; HP1 - first phalanx hindlimb; HP3 - third phalanx hindlimb; MTIV - fourth metatarsal bone; P3 - third phalanx; MCIV - fourth metacarpal; HP2 - second metacarpal hindlimb; P2 - second metacarpal; P3 - third phalanx; Unknown - two injury records with no supporting diagnostic imaging report.

Table 9: A description of fracture events involving more than one bone. Data were from 24 fracture events in Thoroughbred horses racing in Hong Kong from 1st of July 2004 to 30th of June 2011.

Fracture number	**Fracture details**	**Bilateral**	**Catastrophic**
#1	Proximal sesamoid and third metacarpal bone	No	Yes
#2	Humerus and hind first phalanx	No	No
#3	Proximal sesamoid the third metacarpal bone	No	Yes
#4	First phalanx and tibia	No	No
#5	Humerus and radius	No	No
#6	Humerus and third metacarpal, radius and ulnar	Yes	No
#7	Proximal sesamoid and third metacarpal bone	No	Yes
#8	Both third metacarpal bones	Yes	Yes
#9	First phalanx and proximal sesamoid bone	No	Yes
#10	Radius and tibia	Yes	No
#11	Humerus, radius and carpus	No	No
#12	Humerus, radius and third metacarpal bone	No	No
#13	Third metacarpal and proximal sesamoid bone	No	Yes
#14	Humerus and third metacarpal bone	Yes	No
#15	Radius and third metacarpal bone	Yes	No
#16	Tibia and third metacarpal bone	No	No
#17	Femur and second metacarpal bone	No	No
#18	Third metacarpal bone and tibia	Yes	No
#19	Both third metacarpal bones	No	Yes
#20	Fourth metacarpal and proximal sesamoid bone	No	No
#21	Humerus and radius	No	No
#22	Carpus and third metacarpal bone	No	No
#23	Carpus and third metacarpal bone	No	No
#24	Third metatarsal bone, navicular, pelvis and femur	Yes	No

Table 10: Count of catastrophic training fractures, count of training days at risk, crude incidence rate (IR) and incidence rate ratio (IRR) stratified by racing season, age and gender. Data were from 24 fracture events resulting in death over 3,153,223 training days at risk in Thoroughbred horses training in Hong Kong from 1st of July 2004 to 30th of June 2011.

Variable	**Number**		**IR per 10,000 days at risk (95% CI)**	**IRR (95% CI)**	**P-value**[a]
	Fracture Events	**Training days**			
Season					**0.10**
2004/2005	6	445073	0.13 (0.05- 0.29)	Reference	
2005/2006	4	431323	0.09 (0.03- 0.24)	0.69 (0.19-2.44)[b]	0.56
2006/2007	5	425776	0.12 (0.04-0.27)	0.87 (0.27-2.85)	0.82
2007/2008	2	431978	0.05 (0.01-0.17)	0.34 (0.07-1.70)	0.19
2008/2009	4	456342	0.09 (0.02-0.08)	0.65 (0.18-2.30)	0.51
2009/2010	0	483289	0	0	0
2010/2011	3	479442	0.06 (0.01-0.18)	0.46 (0.12-1.86)	0.28
Age					**<0.05**
2 to 3	3	1408813	0.02 (0.01-0.06)	Reference	
4 to 5	11	1198377	0.09 (0.04-0.16)	4.15 (1.28-19.23)	0.16
6 to 7	9	454700	0.20 (0.09-0.38)	9.0 (2.63-42.60)	0.87
≥8	1	91333	0.11 (0.02-0.61)	5.6 (0.19-48.20)	0.57
Gender					
Male	24	3142756	0.08 (0.05-0.11)	NA	
Female	0	10467	0		

Key: 95% CI - 95% Confidence Interval; NA – no risk calculations applicable.

[a] Bold P-value is for the log-likelihood test statistic and non-bold is for the Wald test statistic.

[b] Interpretation – The rate of catastrophic fractures in the 2005/2006 season was 0.69 times the 2004/2005 season (IRR 0.69 95% CI 0.19 to 2.44, P = 0.56).

Table 11: Count of non-catastrophic training fractures, crude incidence rate (IR) and incidence rate ratio (IRR) stratified by racing season, age and gender. Data were from 268 fracture events over 3,153,223 training days at risk in Thoroughbred horses training in Hong Kong from 1st of July 2004 to 30th of June 2011.

Variable	**Number**		**IR per 10,000 days at risk (95% CI)**	**IRR (95% CI)**	**P-value**[a]
	Fracture Events	**Training days**			
Season					**0.75**
2004/2005	34	445073	0.76 (0.53-1.07)	Reference	
2005/2006	41	431323	0.95 (0.68-1.29)	1.24 (0.79-1.96)[b]	0.35
2006/2007	39	425776	0.92 (0.65-1.25)	1.2 (0.76-1.9)	0.44
2007/2008	41	431978	0.95 (0.68-1.29)	1.24 (0.79-1.96)	0.35
2008/2009	31	456342	0.68 (0.46-0.96)	0.89 (0.55-1.45)	0.64
2009/2010	43	483289	0.89 (0.64-1.20)	1.16 (0.74-1.83)	0.51
2010/2011	39	479442	0.81 (0.58-1.11)	1.06 (0.67-1.69)	0.79
Age					**<0.05**
2 to 3	68	1408813	0.45 (0.35-0.58)	Reference	
4 to 5	147	1198377	1.23 (1.04-1.32)	2.54 (1.90-3.40)	0.00
6 to 7	45	454700	0.99 (0.72-1.32)	2.1 (1.40-3.00)	0.00
≥8	8	91333	0.88 (0.38-1.73)	1.8 (0.80-3.60)	0.11
Gender					**0.31**
Male	266	3142756	0.85 (0.75-0.95)	Reference	
Female	2	10467	1.91 (0.23-6.90)	2.4 (0.40-7.50)	0.25

Key: 95% CI - 95% Confidence Interval.

[a] Bold P-value is for the log-likelihood test statistic and non-bold is for the Wald test statistic.

[b] Interpretation – The rate of non-catastrophic fractures in the 2005/2006 season 1.24 times higher than in the 2004/2005 season (IRR 1.24 95% CI 0.79 to 1.96; P = 0.35).

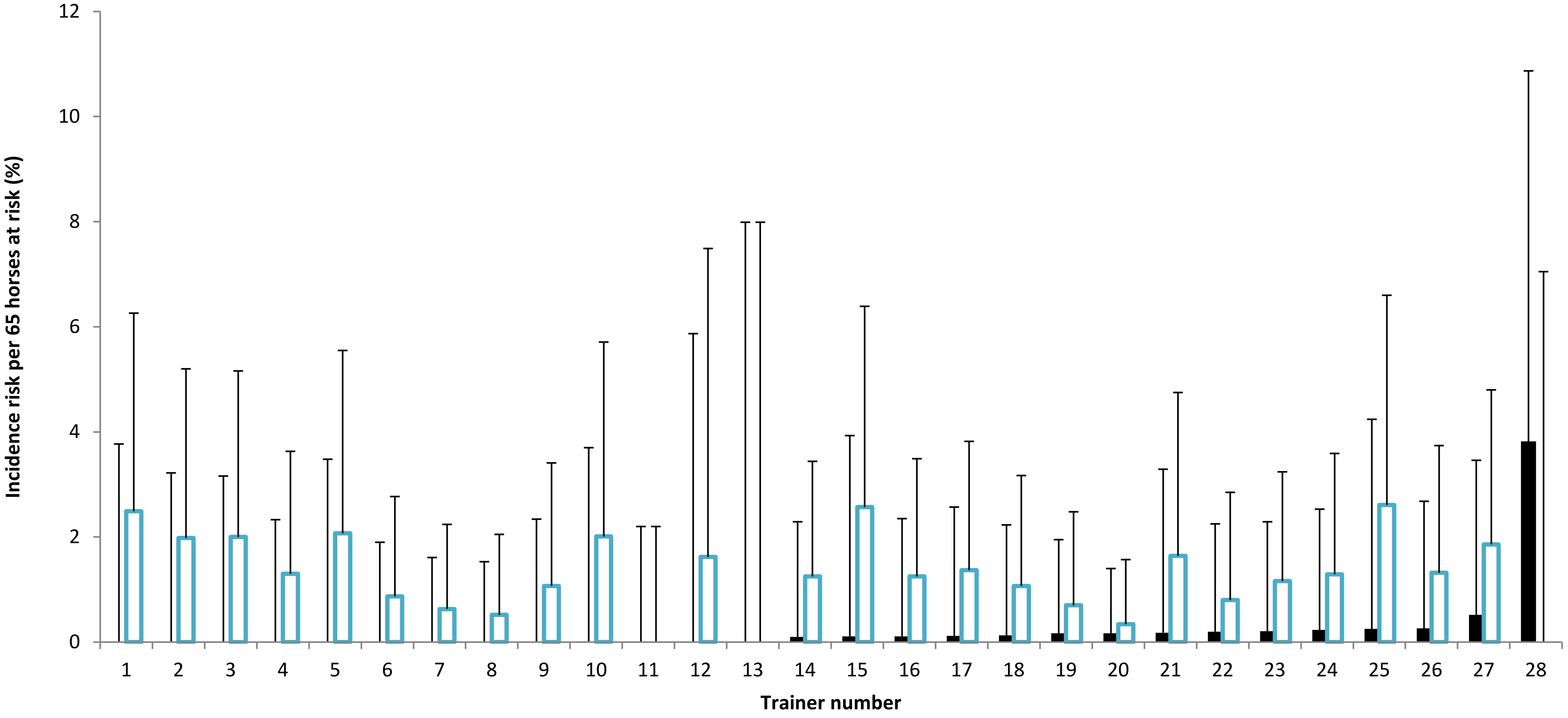


Figure 4: Incidence risk per 65 horses at risk for catastrophic (solid boxes) and non-catastrophic (non-solid boxes) fractures for HKJC trainers. Data from 292 fracture events over 11,904 horses at risk in Hong Kong from 1st of July 2004 to 30th of June 2011. Error bars represent 95% confidence intervals and incidence risks are in ascending order for catastrophic fracture.

4.4 Discussion

The overall fracture incidence rate reported in our study was 0.93 per 10,000 training days at risk (95% CI 0.85 - 1.04). This compared favourably to similar studies in the United Kingdom, which reported 0.94 per 100 horse months (equates to 3.1 per 10,000 training days) Verheyen and Wood (2004), and to New Zealand 0.14 per 1,000 horse training days (equates to 1.4 per 10,000 training days (Perkins, Reid et al. 2005a)). To our knowledge we are the first to report catastrophic and non-catastrophic fracture incidence rates for horses in training with the catastrophic fracture and non-catastrophic incidence rates being 0.08 and 0.85 per 10,000 training days respectively. This suggests that in a population of 1,000 horses in training, we would see three catastrophic fractures and 31 non-catastrophic fractures every 365 training days.

The most common fracture sustained in training at the Hong Kong Jockey Club involved the proximal sesamoid bone representing 19.8% (53/268) of all single site fractures. In comparable studies, fractures sustained in training in the United Kingdom reported non-catastrophic tibial fractures (20.7% (50/241); Ramzan and Palmer 2011) and third metacarpal bone fractures (19.6% (29/148); Verheyen and Wood 2004) to be the most common fracture, while a recent Californian study reported non-catastrophic carpal fractures to be the most common fracture in all training injuries (8.6%; Hill, Blea et al. 2015). The greater proportion of proximal sesamoid bone fractures in training in Hong Kong is of great concern given that they accounted for 71% (12/17) of all single site catastrophic fractures. This is similar to descriptive studies on catastrophic training fractures from the United States which have also reported proximal sesamoid fractures being the most common fracture sustained in training being 30% (Johnson, Stover et al. 1994) and 46% (Estberg, Stover et al. 1996b). The training environment in Hong Kong may be a greater risk of sustaining a catastrophic fracture of the proximal sesamoid bone as horses begin training almost immediately upon arrival would result in a greater number of training days at risk in order to reach racing milestones (Velie, Stewart et al. 2013b). Horses which sustained proximal sesamoid bone fractures were the result of a higher number of workouts and training events compared to those without fracture (Anthenill, Stover et al. 2007).

Carpal (43/268) and first phalanx (41/268) were also common fractures in Hong Kong. This may be due to the large number of non-catastrophic chip fractures which represented 48% of carpal and 61% of first phalanx fractures respectively, and was considerably greater compared a United Kingdom study in which chip fractures accounted for only 9.5% (14/148) of all fractures (Verheyen and Wood 2004). Variations in case definition between studies may account for some differences, but it may be that the training environment in Hong Kong may lead to a greater proportion of non-catastrophic chip fractures. While other studies in the United Kingdom and Australia report fractures of the tibia (O'Sullivan and Lumsden 2003, Ramzan and Palmer 2011), pelvis (Verheyen and Wood 2004, Verheyen, Newton et al. 2006b) and humerus (O'Sullivan and Lumsden 2003) to be common non-catastrophic fractures in their training populations, non-catastrophic injury to carpal joints and the metacarpophalangeal joint occur commonly in training horses in Hong Kong. The training environment in Hong Kong is on sand based surfaces but lacks the soft turf training surfaces prevalent in United Kingdom and Australia (Riggs 2015). Previous studies in the United States have also shown an association between training track surfaces and a variation of fracture types which may increase development for specific configurations and fracture prognosis (Dimock, Hoffman et al. 2013, Mackinnon, Bonder et al. 2014). Further research is warranted for the prognosis of chip fractures and the relationship to catastrophic fracture.

Fractures most commonly occurred in the distal forelimbs which is consistent with other training studies in the United Kingdom (Rossdale, Hopes et al. 1985, Verheyen and Wood 2004), New Zealand (Perkins, Reid et al. 2005b) and Australia (Cogger, Evans et al. 2008a). There was a significant association detected in the left compared to the right limbs which is in contrast with previous training studies which suggest no predilection (Robinson, Kobluk et al. 1988, Bathe 1994, Verheyen and Wood 2004, Anthenill, Stover et al. 2007, Cruz, Poljak et al. 2007). There were limited studies examining the effect of training direction and limb predilection, with descriptive studies suggesting that the direction of training may have an effect on right or left limb fractures (Schneider, Bramlage et al. 1988, Dallap, Bramlage et al. 1999, Ramzan and Palmer 2011). In Hong Kong, the direction of training occurs primarily in a clockwise direction while racing also occurs in a clockwise direction. The similarities between the Hong Kong racing and training environment may predispose to left sided fracture, however an important consideration is whether limb predilection of fractures in training translates to catastrophic racing fractures in the respective limb during racing. Although not within the scope of this study, future analytical studies may be focused on detection of fractures in the left limb in training.

It was interesting that both non-catastrophic and catastrophic fracture incidence rates had a significant association between age groups. For non-catastrophic fractures the risk was greatest in four to five year olds while the risk was greatest in six and seven year olds for catastrophic fractures. A possible explanation for this is that horses may be more likely to sustain non-catastrophic fractures if they have not adapted sufficiently to training (Verheyen, Henley et al. 2005, Cogger, Perkins et al. 2006a), and clinical signs such as lameness or absence from training are flagged by the stewards at the Club. In essence, horses with non-catastrophic fracture are selectively removed from time at risk at an earlier age, while continual training and fatigue loading of bone may progress to catastrophic fracture in older horses (Estberg, Gardner et al. 1995, Anthenill, Stover et al. 2007).

The incidence risk rather than the incidence rate of catastrophic and non-catastrophic fracture was calculated for trainers (Figure 4). Although fracture records from the veterinary database specified the trainer at the time of the fracture event, it was not possible to discern the exact date at which the time at risk began or ended for that particular trainer due to the inaccurate and sometimes unknown date of racehorse transfers. The decision to transfer racehorses between trainers rested largely with the owner’s perception of the trainer’s ability to maximise racing performance, and racehorses may transfer up to several times per racing season and sometimes returned to the original trainer. This would have resulted in an overestimation of the incidence risk in those trainers. However, given that trainers are governed by the rules of racing equally, shared training facilities, and used the same training tracks at the Club, differences of incidence risk may also be associated with the style of training. Interestingly, there was a significant association between trainers for non-catastrophic fracture incidence risk but not for catastrophic fracture. This may suggest that a certain aspect of catastrophic fracture risk is inherent in training in Hong Kong, while differences in training patterns may influence the risk of non-catastrophic fracture.

The focus of this study was to calculate incidence rates in catastrophic and non-catastrophic fractures in which the definition of time at risk started from the date of importation or beginning of the study, to the date of fracture, retirement, or end of the study period. This was in contrast to previous definitions of time at risk which excluded training days where horses were lost to trainers not involved in the study (Perkins, Reid et al. 2005a), or days in ascending training (Verheyen and Wood 2004). Racehorses at the Hong Kong Jockey Club are imported for the sole purpose of race training and only horses which reach health and performance requirements would be permitted into Hong Kong. Furthermore, unless retired from racing or fractured, horses would contribute to time at risk on either training tracks which are regulated, or reduced regulated activities in training stables. The incidence rates reported are therefore suitable for the environment in Hong Kong and high in internal validity, but may not be generalized to training populations which focus on two year old racing such as Australia and the United Kingdom.

4.5 Conclusion

Catastrophic fractures of the proximal sesamoid bone occur commonly in training racehorses in Hong Kong as do non-catastrophic chip fractures of the carpus and first phalanx. For every 1,000 horses in training there are three catastrophic and 31 non-catastrophic fractures per 365 training days. Horses may develop non-catastrophic fractures at a younger age than catastrophic fractures. Monitoring of non-catastrophic fracture incidence rates may be an important method in preventing catastrophic fractures in training.

Chapter 5:

Resorption canal densities in bones from Thoroughbred racehorses in race training and rested from training

Abstract

The aim of this post-mortem study was to describe and compare resorption canal densities, used as a proxy for bone remodelling, in selected bones from horses in active race training and in horses after a period of rest. Resorption canal density was compared between Exercised Group (n=6) and Rested Group (n=6) Thoroughbred horses who died from non-fracture related causes. Exercised Group horses were euthanized within seven days of high intensity exercise, while Rested Group horses had been retired from racing between one and four months prior to death. For all horses, six blocks were cut from four bones at the following locations; mid-diaphysis of the right third metacarpal bone (MCS); distal lateral metaphysis (MCD) and medial condyle (MCC) of the right third metacarpal bone; lateral condyle of the right third metatarsal bone (MT); left distal tibia, and left tenth rib. Each bone block was then cut into 250 µm thick slices using a diamond annular saw. Images were obtained using point projection digital microradiography and examined for radiolucent spaces indicative of recently formed resorption canals. Statistical significance was declared at alpha < 0.05 using the Mann-Whitney U test. Resorption canal densities were greater in the Rested Group for all sections of the third metacarpal bone, third metatarsal bone and the tibia compared with the Exercised Group. Resorption canals were most commonly present in the dorsal aspect of the third metacarpal bone, palmar and plantar condyles of the third metacarpal/ metatarsal bone and caudal aspect of the tibia. Horses in the Rested Group showed greater bone remodelling activity compared with horses in the Exercised Group. Increased resorption at regions of increased loading may result in overt bone fracture. This has implications for the management of racehorses returning to work after prolonged periods of rest.

Key words: Bone, resorption canal, remodelling, rest, exercise

5.1 Introduction

Bone fatigue results from repeated cyclical loading during intense exercise (Riggs 2002, Martig, Lee et al. 2013, Pinchbeck, Clegg et al. 2013). Understanding the mechanisms involved in bone fatigue is imperative as fatigue fractures occur if the reparative processes in bone cannot adapt timely to loading requirements. Adaptation of bone to loading occurs via the coupled processes of bone modelling and remodelling. Bone modelling attempts to maximise material properties by adding bone mass to maintain strain vectors at safe levels. A typical example of bone modelling in horses occurs with normal development in young horses between one to three years of age where bone mass is added dorsomedially to the diaphysis of the third metacarpal bone (Nunamaker, Butterweck et al. 1989, Davies 2005, Davies 2006). Bone remodelling differs from bone modelling, although both can occur concurrently, in that it repairs microdamage created by cyclical loading by way of a strictly sequential process of bone activation, resorption and formation (Parfitt 1984, Schaffler and Jepsen 2000). Fatigue fractures develop when microdamage accumulation exceeds the rate of remodelling repair.

The resorption of microdamage is an active process conducted by osteoclasts, which are cells that form a cutting cone to create a resorption canal. Resorption canals can be seen histologically as well-defined circular radiolucencies measuring about 200 to 300µm in diameter (Cooper, Turinsky et al. 2003). This process inadvertently creates a temporary area of porosity within bone before trailing osteoblasts replace the deficit with new bone. With intense exercise, the resorption process is halted (McCarthy and Jeffcott 1992, Boyde and Firth 2005, Whitton, Trope et al. 2010), but resumes and accelerates once high strain loading is removed (Holmes, Mirams et al. 2014). While a temporary inhibition in resorption may be insignificant for bone integrity, complications arise when extended periods of high strain loading occur leading to large accumulations of microdamage, which may predispose to fatigue fracture development (Muir, Peterson et al. 2008, Whitton, Trope et al. 2010). Hence, fatigue fractures occur in consistent locations and follow predictable paths through bones exemplified by lateral and medial condylar fractures of third metacarpal/tarsal bones (Riggs 2002), mid-body fractures of proximal sesamoid bones (Anthenill, Gardner et al. 2010), distal tibia and proximal humerus (O'Sullivan and Lumsden 2003). The mechanisms by which the equine skeleton adapts to decreasing demands of exercise or periodical intervals of rest are less well understood. Resorption canals created by accelerated remodelling may lead to bone failure earlier than is the case in fully adapted bone.

The aim of this study is to describe and compare bone resorption canal density, a proxy for bone remodelling, in selected bones from horses in active race training with those from horses who have ceased training.

5.2 Materials and Methods

5.2.1 Study material

This retrospective case series study used bones obtained post-mortem from Thoroughbred racehorses at the Hong Kong Jockey Club (HKJC) from December 2012 to February 2013. These horses died from non-fracture related causes or were euthanised for welfare reasons (Table 12). Horses sustaining catastrophic fractures or musculoskeletal injuries during racing or in race training at the HKJC are diagnosed pre-mortem. The HKJC mandates that all horses within its precinct are autopsied at the Equine Hospital in Sha Tin. All autopsies follow a set protocol and are conducted by an experienced veterinarian who is required to upload a report to a digital database within 24 hours of the autopsy.

Study horses (*n*=12) were assigned to one of two groups: exercised (*n*=6) and rested (*n*=6). The Exercised Group was defined by having had a recorded period of intense exercise within seven days of death. Intense exercise was defined as a race, barrier trial, training gallop or training canter on at least four occasions in the preceding 30 days. The Rested Group was defined by having had a similar period of intense exercise to that of the Exercised Group but was either being rested or was in retirement for one to four months since that period of exercise. Exercise and racing histories, age, gender and rest days were sourced from the centralised racing registry as previously described in Chapter 3 section 2.3.

Table 12: Reason for euthanasia or cause of death in Exercised or Rested Group horses.

Study Group	Horse identification	Reason for euthanasia/ cause of death
Rested	7, 10	advanced osteoarthritis
	8	tendon rupture
	9, 12	chronic lameness
	11	unsuitable temperament
Exercised	1	drug anaphylaxis
	2	tendon rupture
	3, 4	collapse during racing
	5	Colic
	6	severe exercise-induced pulmonary haemorrhage

5.2.2 Bone processing

Bones selected for evaluation were the third metacarpal bone, third metatarsal bone, tibia, humerus and proximal sesamoid bone, all of which are located in the appendicular skeleton, and are common sites for fatigue fractures (Riggs 2002). The tenth rib was also selected because it is part of the axial skeleton and not normally associated with fatigue fractures. Sites from where bone samples were collected are described in Table 13 and the stages involved in bone processing are described in Figure 5A-E using the mid-diaphyseal region of the third metacarpal bone as an example. Bones were removed in entirety immediately post-mortem (5A). Each section was first cut with a band saw (Model ST-WBS 180, Equine Hospital, Hong Kong Jockey Club) to generate a 20 mm thick slice. Slices were cleaned of soft tissue and fat and the periosteum removed (5B) and placed in a bacterial pronase detergent (Tergazyme 10% alkaline pronase detergent, Alconox Inc, NY, USA) at 37°C for five days to remove all cells and unmineralised cartilage matrix before being fixed in 70% ethanol for seven days (5C). Sections were mounted onto a stub using adhesive (Equilox International 2012) and cut using an annular saw (Leica Microsystems SP1600) to produce three 250 µm thick plane-parallel slices per bone section in the same plane as the gross section (5D-E). Microradiographs were obtained from each section by point projection digital microradiography at 26 kV (Faxitron QADOS, Sandhurts, Berkshire, UK; Boyde 2012).

One section from the mid-diaphysis of the third metacarpal bone (Horse 8), the proximal sesamoid bone (Horse 12) and the humerus (Horse 3) was processed for scanning electron microscopy (SEM; Zeiss UK, Welwyn Garden City, Herts, UK). The three sections were mounted onto polymethyl methacrylate (PMMA) blocks, micromilled and carbon coated before being scanned digitally with back scattered electrons (BSE; KE Electronics, Toft, Cambs., UK; Boyde 2012).

Table 13: Location and description of bone sections evaluated in the study and the magnification used to produce microradiographs of these sections.

Location and description of bone sections	**Microradiograph magnification**
Transverse section of the mid-diaphysis of the right third metacarpal bone (MCS)#*	2x
Transverse section of the lateral distal metaphysis of the right third metacarpal bone (MCD)#	3x
Parasagittal 30-40^{O} palmar wedge section of the medial condyle of the right third metacarpal bone (MCC)#	3x
Parasagittal 30-40^{O} plantar wedge section of the lateral condyle of the right third metatarsal bone (MT)#	2x
Transverse section of the distal third region of the right tibia (TIB)#	4x
Transverse section of the mid-diaphysis of the left tenth rib (RIB)#	5x
Transverse section of the proximal left humerus (HUM)# *	3x,5x
Parasagittal section of the right fore medial proximal sesamoid bone (PSB)#*	3x

Key: #Processed for microradiography
*Processed for scanning electron microscopy.

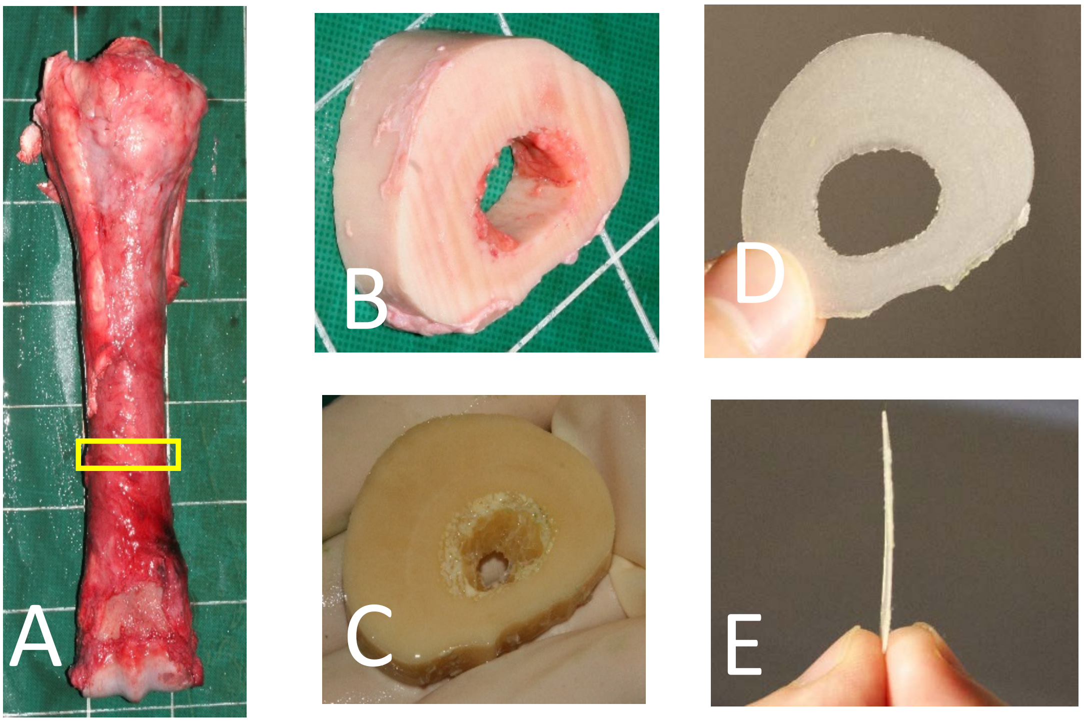


Figure 5: Processing the mid-diaphyseal section of the right third metacarpal bone (MCS) for image analysis A: Dorsal view of the right third metacarpal bone immediately post mortem. The section was collected 13 cm proximal to the distal articular surface. B: A transverse 20 mm thick slice was cut with a band-saw. C: Appearance of the slice after five days of immersion in bacterial pronase detergent and subsequent fixation for seven days in 70% ethanol. D and E: 250 µm thick sections cut with an annular saw.

5.2.3 Image Analysis

Multiple microradiographs were obtained of each section but only one microradiograph, selected by picking a number out of a hat, was analysed. Two dimensional radiolucent resorption canals were used to assess bone remodelling (Parfitt 2002). Resorption canals were evaluated proximo-distally in transverse sections, and latero-medially in parasagittal sections (Table 13). Resorption canals were selected if they were circular or oval and roughly 0.2 to 0.3 mm in diameter, radiolucent, or surrounded by mineralised bone or if they extended to the bone surface. Resorption canals were counted manually with the assistance of imaging software (PaintShopPro version 6.1, JascSoftWare, Inc. 1998). Microradiographs were analysed quantitatively using Image J software (Rasband, W.S., ImageJ, U. S. National Institutes of Health). Sampled bones were sectioned so that specific areas of interest could be examined: the periosteal and endosteal regions of the mid-diaphysis of the third metacarpal bone and distal tibia; the dorsal and palmar regions of the lateral metaphysis of the third metacarpal bone; the palmar region of the medial condyle of the third metacarpal bone, and the plantar region of the lateral condyle of the third metatarsal bone.

Area was calculated from each microradiograph using Image J software. Microradiograph calibrations were based on recommendations by expert opinion of pixel aspect ratio: magnification 2x = 25 µm per pixel; 3x = 16.7 µm per pixel; 4x = 12.5 µm per pixel, and 5x = 10 µm per pixel (Boyde, A., personal communication January 3, 2013). Entire area and specific regions of interest were determined per μm^2 and converted to cm^2 in Microsoft Excel (Microsoft Office ® and Microsoft® Inc 2010). Densities of resorption canals were determined by dividing the number of resorption canals by the entire area or area of the specific region of interest (RC/cm^2).

5.2.4 Statistical Analysis

Age and days to euthanasia and density of resorption canals (RC/cm^2) for each section was reported using median values. Comparisons of resorption canal densities were conducted between Exercised and Rested Groups, and within group by using Mann-Whitney U test. Statistical analysis was performed using R software (2013). Statistical significance was set at alpha < 0.05.

5.3 Results

Resorption canal densities of the Rested Group differed in the periosteal regions compared with the endosteal regions of MCS ($P < 0.001$) and TIB ($P < 0.005$), and dorsal to the palmar regions of MCD ($P < 0.005$) (Table 14). The densities of resorption canals in MCS ($P = 0.004$), MCD ($P = 0.002$), MCC ($P = 0.03$) and TIB ($P = 0.004$) differed between Rested and Exercised Groups (Table 15).

Table 14: Crude median and range of resorption canals, bone area and resorption canal densities (RC/cm^2) obtained from specific areas of interest in microradiographs of sections of the third metacarpal bone, tibia, third metatarsal bone and tenth rib bone of twelve Thoroughbred racehorses at the Hong Kong Jockey Club.

Bone	Specific area of interest	Exercised Group median (range)			Rested Group median (range)		
		RC	cm^2	RC/cm^2	RC	cm^2	RC/cm^2
MCS	Periosteal	13.5 (4,126)	1.23 (0.76, 2.07)	13.72 (2.49, 100.10)	46 (3, 196)	1.22 (0.57, 2.38)	39.41 (2.64, 122.66)^{a}
	Endosteal	4 (0, 12)	0.80 (0.49, 1.30)	5.77 (0, 16.34)	18 (0, 87)	0.79 (0.44, 1.46)	23.72 (0, 66.77)^{a}
TIB	Periosteal	24 (2, 91)	2.82 (2.52, 3.13)	8.52 (0.78, 31.54)	109 (27, 330)	3.02 (2.63, 3.96)	33.12 (10.26, 83.41)^{b}
	Endosteal	7 (1, 44)	2.06 (1.75, 2.43)	3.69 (0.44, 25.14)	28 (7, 67)	2.12 (1.79, 2.78)	13.14 (3.07, 24.12)^{b}
MCD	Dorsal	42 (12, 115)	1.45 (1.19, 1.93)	30.21 (8.59, 61.40)	326 (259, 473)	1.59 (1.35, 1.69)	207.55 (153.41, 315.07)^{c}
	Palmar	17 (12, 56)	1.23 (1.03, 1.65)	14.81 (9.08, 41.50)	42 (25, 152)	1.00 (0.75, 1.35)	50.31 (24.22, 122.68)^{c}
MCC	Palmar	14 (5, 20)	0.30 (0.26, 0.33)	43.77 (19.42, 66.62)	41 (17, 69)	0.26 (0.17, 0.36)	114.16 (57.85, 396.60)
MT	Plantar	17.5 (2, 31)	0.27 (0.24, 0.31)	60.24 (7.58, 122.50)	21.5 (12, 68)	0.26 (0.26, 0.29)	81.65 (46.73, 243.56)
RIB		60.5 (15, 156)	0.90 (0.83, 0.98)	65.38 (18.00, 158.67)	60.5 (53, 142)	0.88 (0.77, 1.03)	69.92 (60.38, 161.43)

Key: Resorption canal densities of the Rested Group differed in the periosteal regions compared with the endosteal regions of ^{a}MCS ($P < 0.001$) and ^{b}TIB ($P < 0.005$), and dorsal to the palmar regions of ^{C}MCD ($P < 0.005$).

MCS- mid-diaphysis of the third metacarpal bone; MCD- lateral aspect of the distal metaphysis of the third metacarpal bone; MCC- lateral condyle of the third metacarpal bone; MT- medial condyle of the third metatarsal bone; TIB- distal tibia; RIB- mid-diaphysis of the tenth rib.

RC – resorption canal.

RC/cm^2 – resorption canal density calculated by the number of resorption canals divided by the specific area of interest.

Table 15: Resorption canal densities (RC/cm^2) obtained from microradiographs of sections of the third metacarpal bone, third metatarsal bone, tibia, tenth rib bone, crude days of rest and age of twelve Thoroughbred racehorses at the Hong Kong Jockey Club.

Bone Section	RC/cm^2														P-values
	Exercised Group							Rested Group							
	1	2	3	4	5	6	Median	7	8	9	10	11	12	Median	
MCS	6.85	14.38	10.54	28.17	7.85	9.42	9.98	24.33	55.73	40.63	34.97	65.82	45.21	42.92	0.00
MCD	25.89	20.76	52.22	44.4	11.41	8.85	23.33	143.74	202.63	105.08	133.91	187.17	152.74	148.24	0.00
MCC	26.54	65.9	19.42	22.25	61.01	66.62	43.78	n/a	57.85	396.6	298.63	95.58	114.16	104.87	0.03
MT	104.54	35.83	34.1	122.5	7.58	84.64	60.24	243.56	88.24	61.12	75.06	161.4	46.73	81.65	0.30
TIB	15.13	3.75	8.06	19.18	1.49	11.39	9.73	20.19	45.88	20.49	31.35	n/a	28.71	24.6	0.00
RIB	158.67	18	104.05	18.45	52.87	77.9	65.39	72.85	72.49	67.35	64.98	60.38	161.43	69.92	0.69
Days of rest	0	0	3	1	0	0	0	35	91	82	45	79	94	81	0.00
Age	5	6	6	5	5	4	5	8	6	8	8	5	6	7	0.05

Key: MCS- mid-diaphysis of the third metacarpal bone; MCD- lateral aspect of the distal metaphysis of the third metacarpal bone; MCC- lateral condyle of the third metacarpal bone; MT- medial condyle of the third metatarsal bone; TIB- distal tibia; RIB- mid-diaphysis of the tenth rib.

RC – resorption canal; n/a: sections unavailable due to processing damage; P-Value derived from Mann-Whitney U test.

Mid-diaphysis of the third metacarpal bone (MCS)

There were significant differences in resorption canal densities between the Exercised and Rested Groups. Horse 1 had the lowest recorded MCS resorption canal densities (6.85 RC/cm^2). In the Rested Group, resorption canals were seen in all horses throughout the cortex and concentrated in the dorsal region of the bone, while the palmar region of the bone was largely devoid of resorption canals. The periosteal regions had significantly more resorption canals compared to the endosteal regions. Resorption canals were seen in close proximity to each other and were between 100 to 300 µm in diameter (Figure 8).

Lateral metaphysis of the third metacarpal bone (MCD)

Figure 9 shows a microradiograph of Horse 6 of the Exercised Group and Horse 8 of the Rested Group. The segmentation is shown in Figure 10. Resorption canal densities in the dorsal region of the cortex were different to that of the palmar region in horses of the Rested Group ($P < 0.005$). Horse 6 had the lowest resorption canal densities in the Exercised Group (8.85 RC/cm^2) with Horse 8 having the greatest resorption canal densities (202.63 RC/cm^2). For Horse 10, a roughened periosteal surface was noted and several resorption canals formed a porous furrow progressing into the cortex (Figure 11).

Medial condyle of the third metacarpal bone (MCC), and the lateral condyle of the third metatarsal bone (MT)

Significant differences in the resorption canal densities were detected in the MCC between Exercised and Rested Groups. Horse 9 had a focal region of resorption surrounding the articular surface of the palmar margin of the condyle, while the section from Horse 7 had a large palmar ulcerated region extending into the subchondral bone (Figure 12). Similarly, the MT section of Horse 7 showed a focal region of resorption surrounded by sclerotic subchondral bone (Figure 13).

Tibia

Figure 14 shows a microradiograph of Horse 2 of the Exercised Group and Horse 8 of the Rested Group. Differences between Tibial sections in horses of the Exercised Group had reduced resorption when compared with the Rested Group ($P < 0.005$). Resorption canals were evenly distributed throughout the cranial and caudal cortices with the lowest resorption canal densities seen in Horse 2 (3.75 RC/cm2). In Horse 11 the entire tibial section was damaged and therefore excluded from analysis. There were more resorption canals in the periosteal regions compared to endosteal regions ($P < 0.005$) in the Rested Group.

Tenth rib

A microradiograph of Horse 2 of the Exercised Group and Horse 12 of the Rested Group are shown in Figure 15. Rib sections in horses of the Exercised and Rested Group had no difference in resorption canal densities ($P = 0.69$; Table 15).

Humerus

Microradiographs of the lateral aspect of the humerus section were not statistically analysed as there was considerable variation in shape and size of the bone. There was clear demarcation between cortical and trabecular bone in all sections with the thinnest cortex being located laterally at the deltoid tuberosity. In Horse 5, extensive resorption was present in this region of the lateral cortex and it was difficult to differentiate cortical bone from trabecular bone (Figure 16). In Horse 3 of the Exercised Group, a wide furrow was seen extending perpendicular into the cortex unaccompanied by resorption canals (Figure 17).

Medial proximal sesamoid bone

One section of the mid-body of the proximal sesamoid bone of Horse 12 was imaged with SEM. The dorsal surface of the section showed densely compacted subchondral bone extending from the articular surface towards the abaxial fossa. There was no distinct border between subchondral and trabecular bone and resorption canals were not present in this section. In one SEM image, a large trabeculae was seen extending deep into the bone (Figure 18).

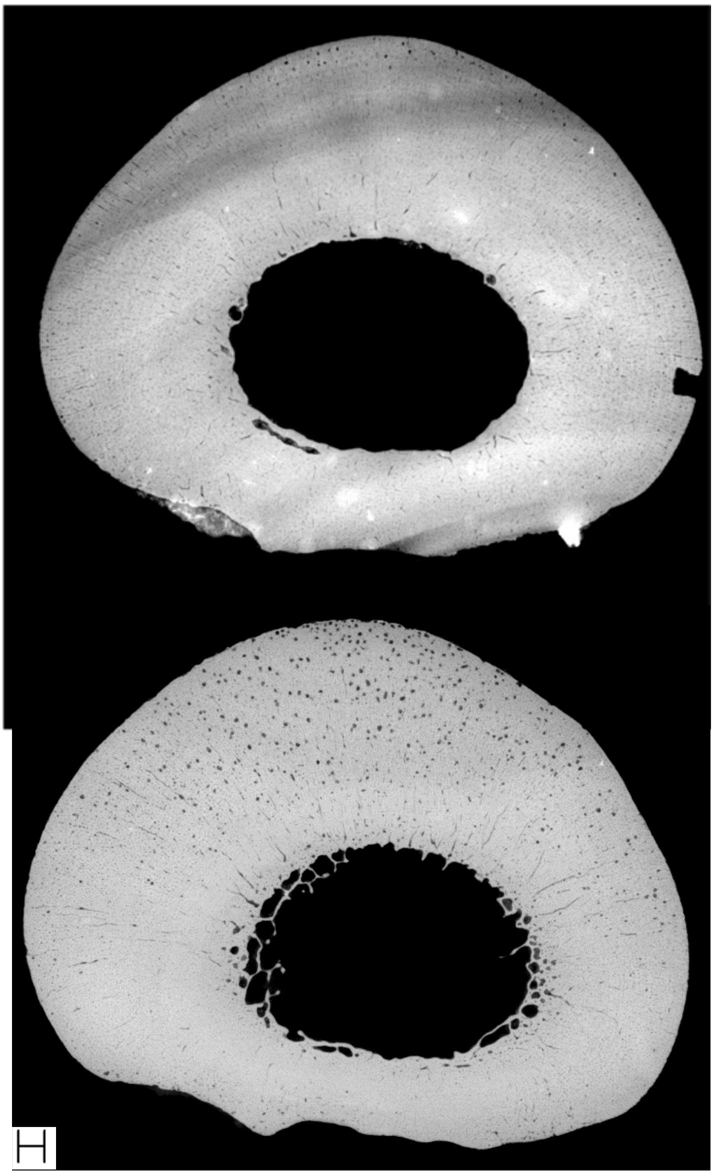


Figure 6: Microradiographs (26 kV, 25 µm per pixel, 2x magnification) of 250 µm thick transverse sections of the mid-diaphysis of the right third metacarpal bone. Horse 4 of the Exercised Group (top) and Horse 8 of the Rested Group (bottom). Note the difference in resorption canal numbers and distribution between the two horses. Medial = left, bar = 2000 µm.

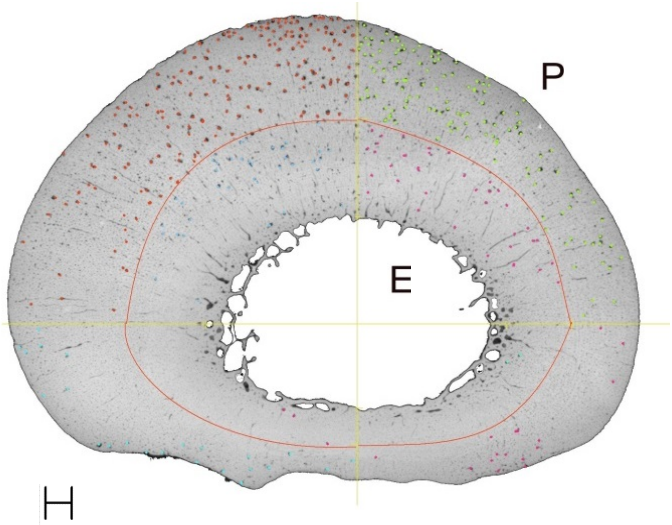


Figure 7: Reconstructed microradiograph of the mid-diaphysis of the right third metacarpal bone from Horse 12 of the Rested Group. The bone is segmented (red line) for comparison of the resorption canal densities in the periosteal (P) and endosteal (E) regions. Medial = left, bar = 2000 µm.

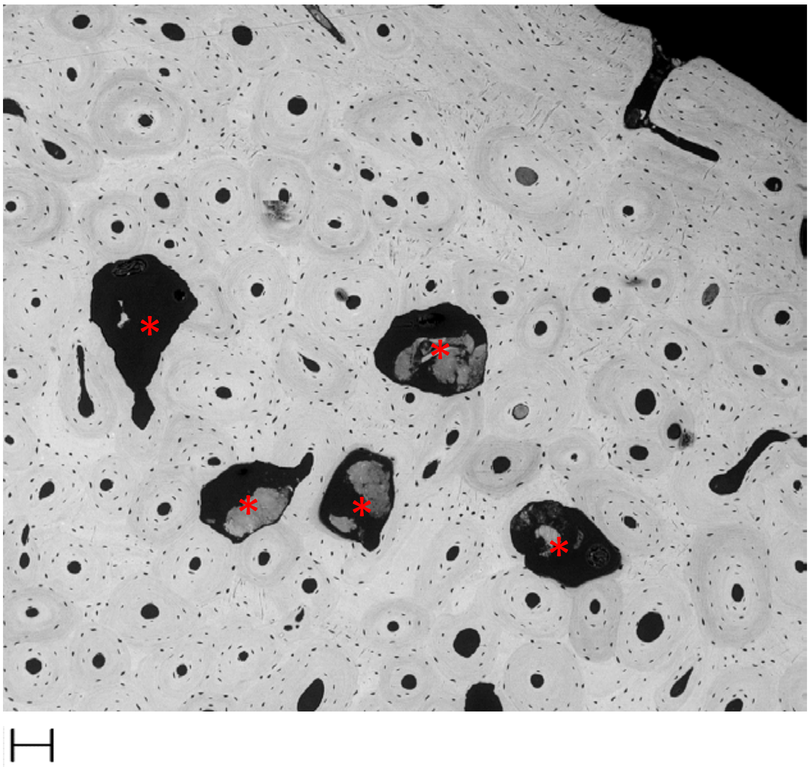


Figure 8: Five resorption canals (*) imaged within the cortex of the mid-diaphysis of the right third metacarpal bone from Horse 12 (20 kV, 52x magnification) using backscattered electron scanning electron microscopy. Medial = left, bar = 100 µm.

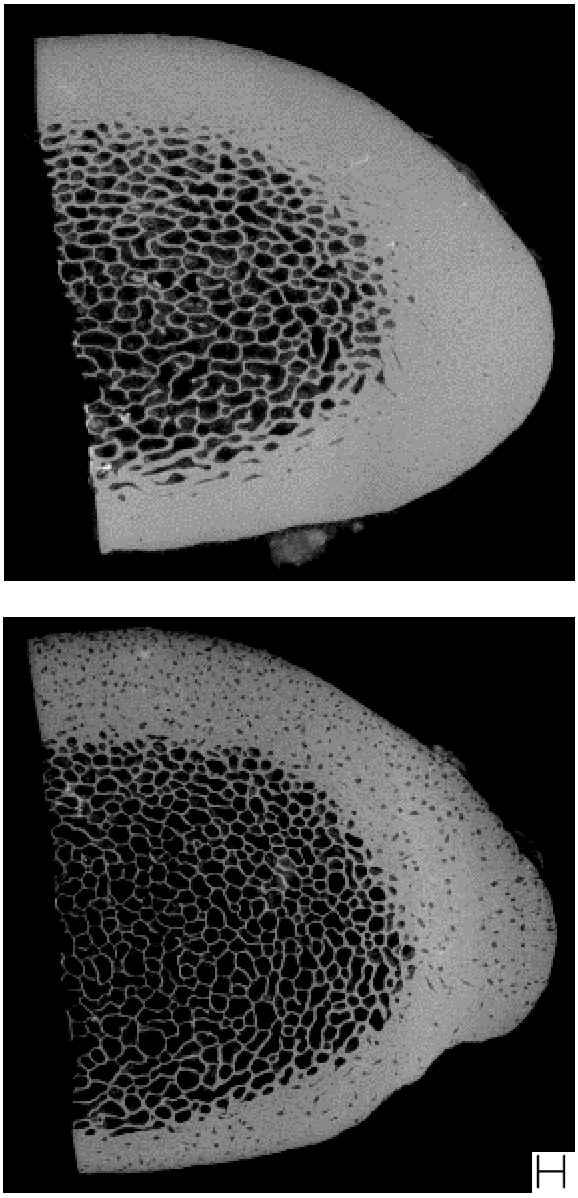


Figure 9: Microradiographs (26 kV, 25 µm per pixel, 2x magnification) of 250 µm thick transverse sections of the lateral metaphysis of the right third metacarpal bone. Horse 6 from the Exercised Group (top) and Horse 8 from the Rested Group (bottom). Note the difference in resorption canal densities between the two horses. Medial = left, bar = 2000 µm.

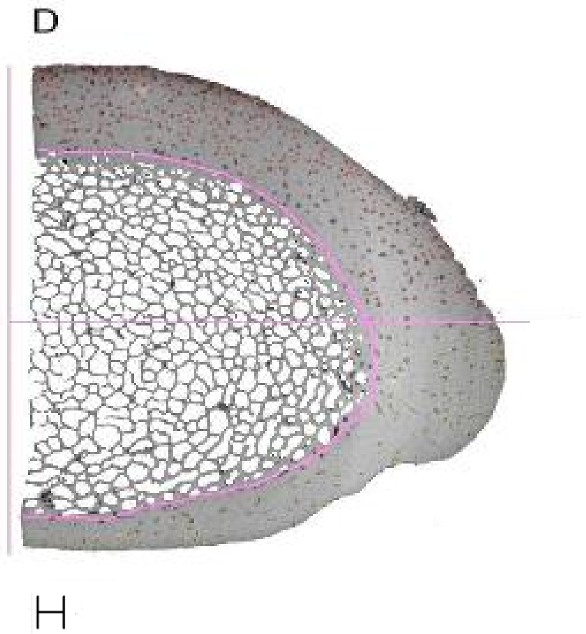


Figure 10: Reconstructed microradiograph of the transverse section of the lateral metaphysis of the right third metacarpal bone from Horse 8. The bone is segmented (purple line) for comparison of the resorption canal densities in the dorsal (D) and palmar cortices. Medial = left, bar = 2000 µm.

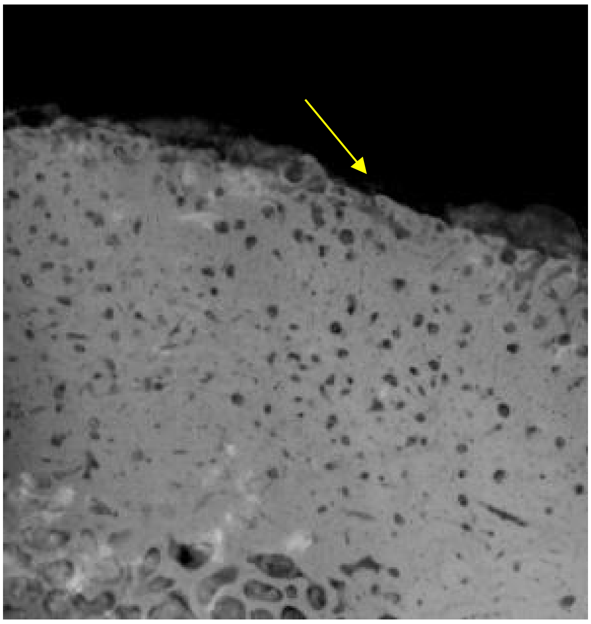


Figure 11: Enlarged microradiograph of the transverse section of lateral metaphysis of the right third metacarpal bone from Horse 10 of the Rested Group. The periosteum is roughened with several resorption canals joining to form a resorption furrow (arrow), which extends into the interior.

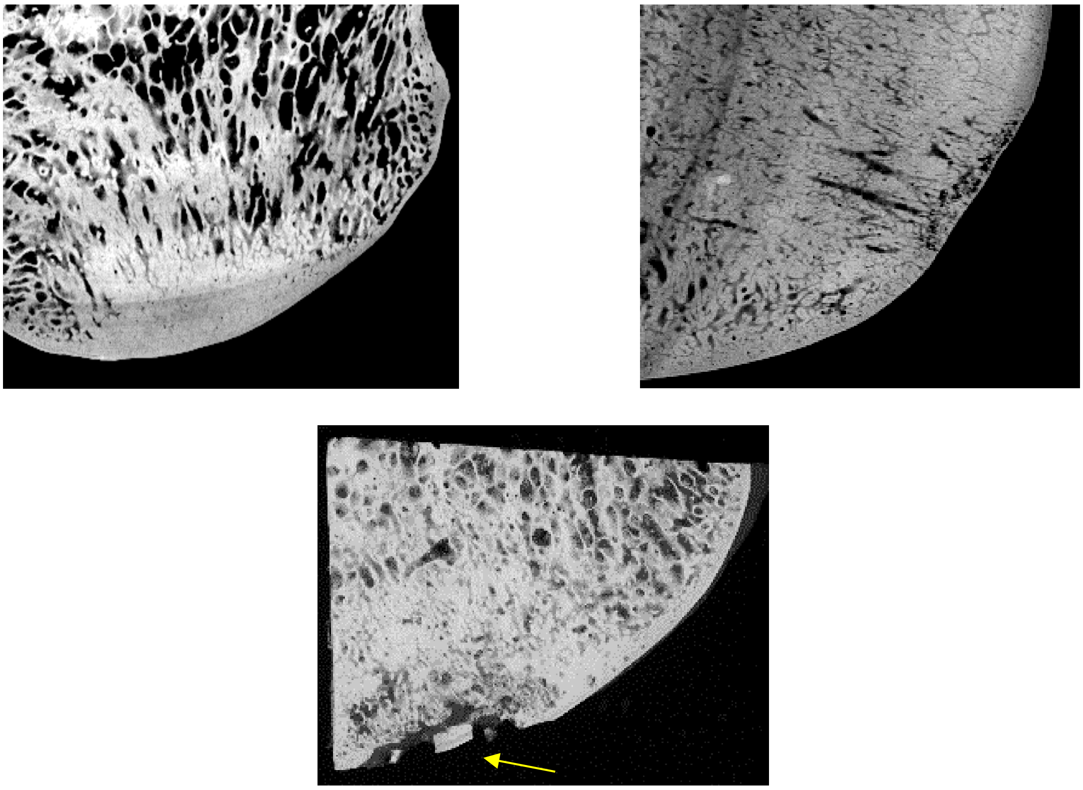


Figure 12: Microradiographs (26 kV, 16.7µm per pixel, 3x magnification) of 250 µm thick parasagittal sections of the medial condyle of the right third metacarpal bone palmar wedge. Note the difference in subchondral bone resorption between Horse 2 of the Exercised Group (top left) and Horse 9 of the Rested Group (top right). A microradiograph (bottom; 12.75µm, 4x magnification) of the same region as the two top images but from Horse 7 of the Rested Group shows fragmentation and ulceration of the articular surface (arrow).

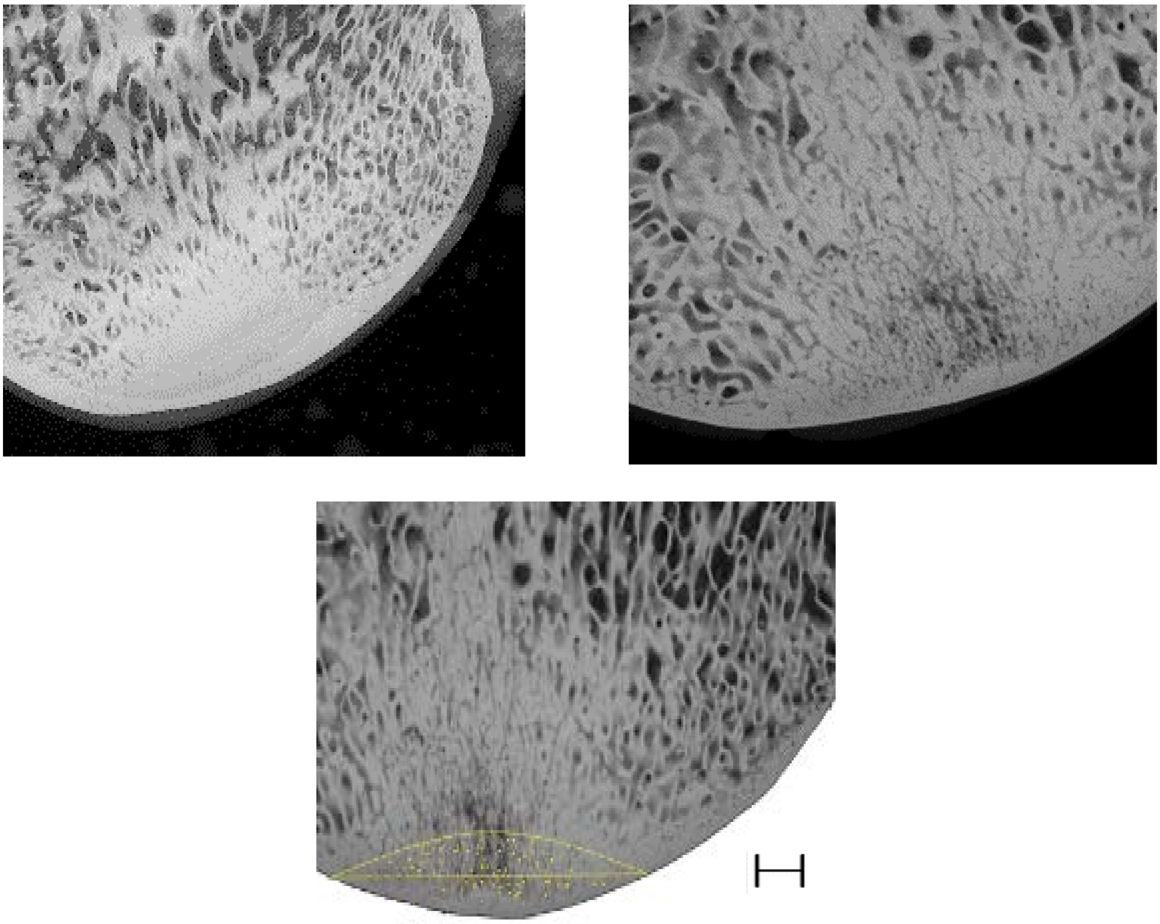


Figure 13: Microradiographs (26 kV, 16.7µm per pixel, 3x magnification) of 250 µm thick transverse sections of the lateral condyle of the right third metatarsal bone plantar wedge. Note the difference in subchondral bone resorption between Horse 5 of the Exercise Group (top left) and Horse 7 of the Rested Group (top right). The bottom image is a reconstructed microradiograph of the lateral condyle of the right third metatarsal bone of Horse 7 illustrating the selected standardised area (demarcated in yellow) used for counting resorption canals. Bar = 1700 µm.

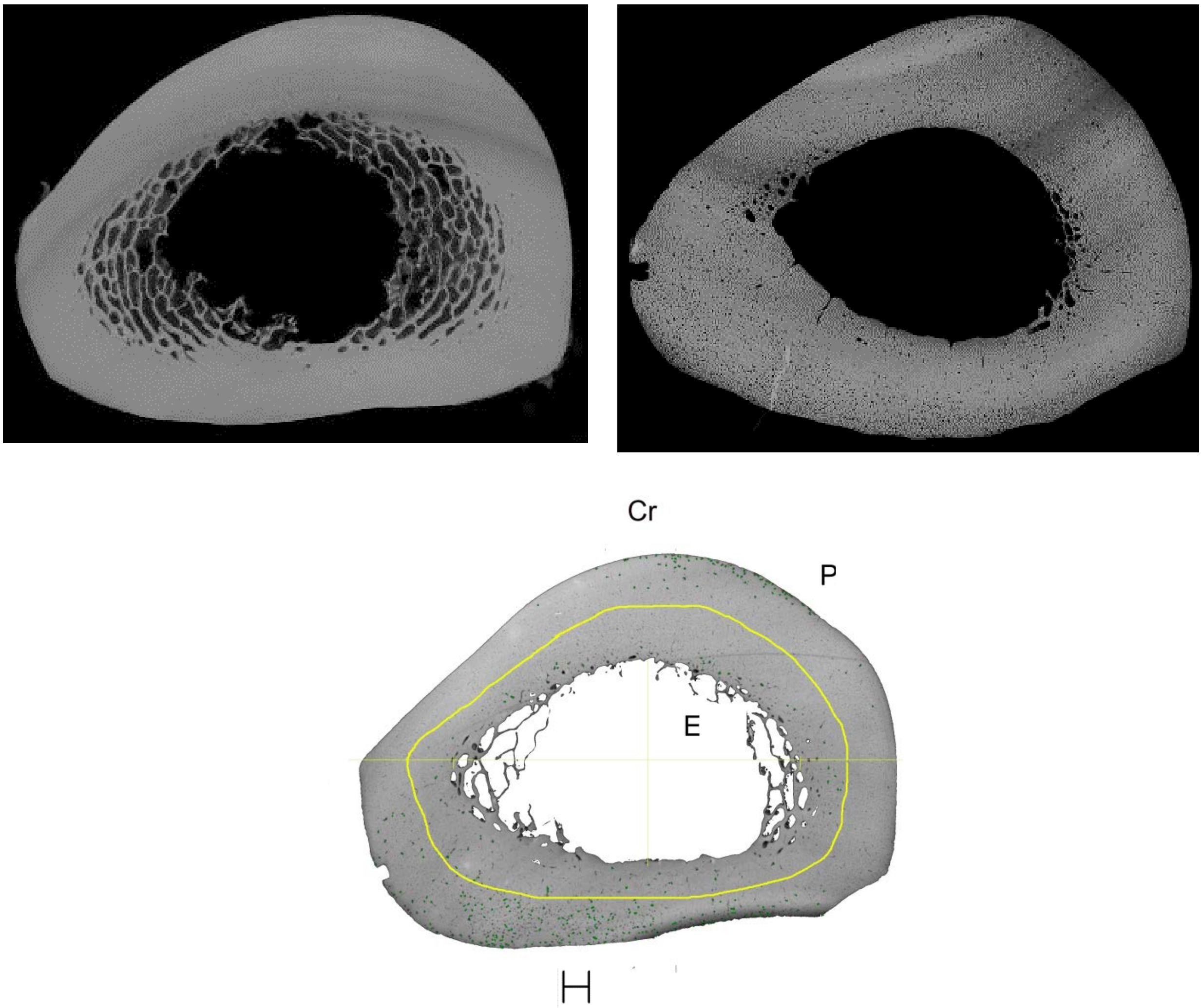


Figure 14: Microradiographs (26 kV at 25 µm per pixel, 2 x magnification) of 250 µm thick transverse sections of right distal tibia. Note the difference in resorption canal density between Horse 2 of the Exercised Group (top left) and Horse 8 of the Rested Group (top right). The bottom image is a reconstructed microradiograph of the distal tibia in Horse 9 of the Rested Group. The bone is segmented (yellow line) to facilitate comparison of the resorption canal densities in the periosteal (P) and endosteal (E) regions. Cr = cranial, medial = right, bar = 2100 µm.

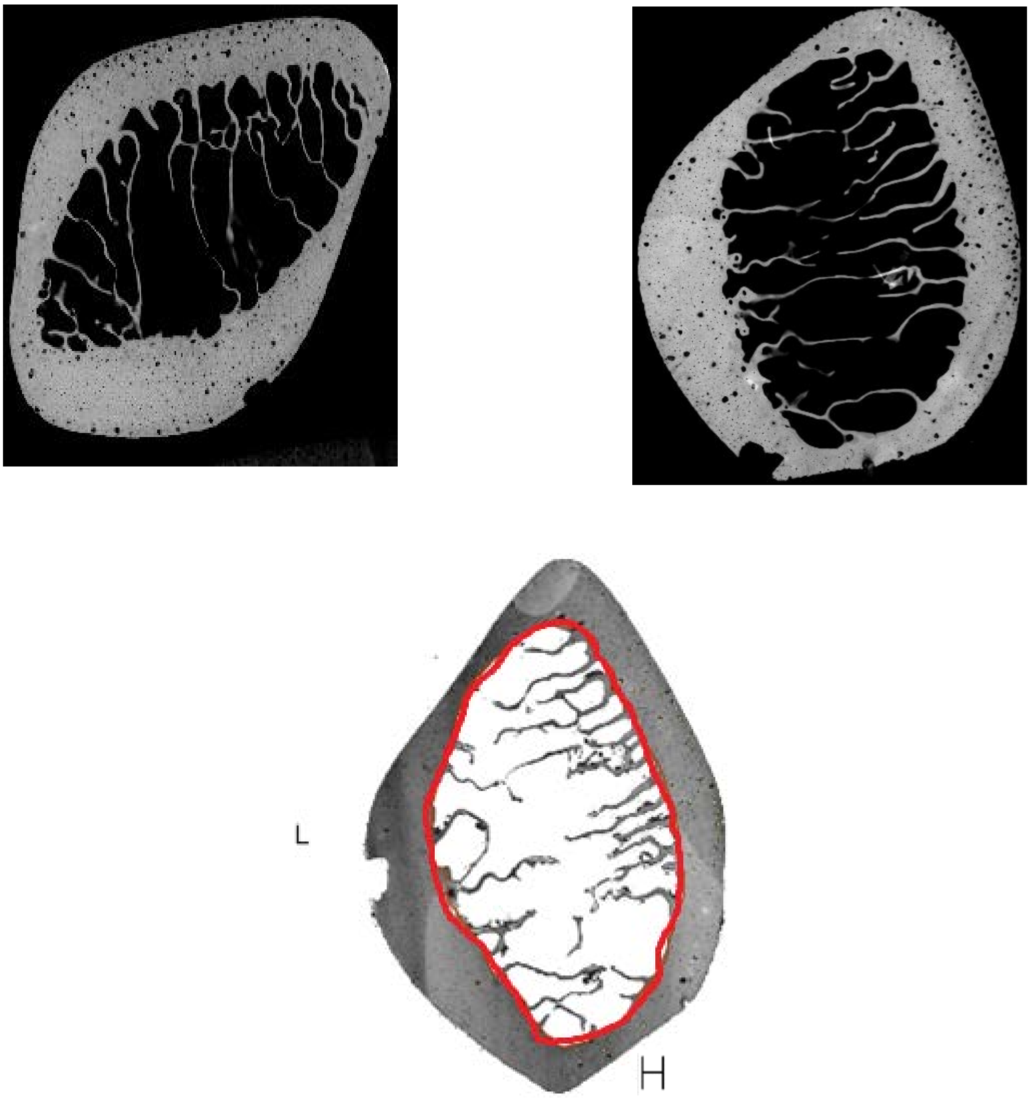


Figure 15: Microradiographs (26 kV at 10µm per pixel, 5x magnification) of 250 µm thick transverse sections of left tenth rib. Note the equal resorption canal densities between Horse 2 of the Exercised Group (top left) and Horse 12 of the Rested Group (top right). The bottom image is a microradiograph of the tenth rib of Horse 8 (Rested Group) illustrating the border (in red) between the cortex and medulla drawn to facilitate the counting or resorption canals in the cortex of the bone. L = lateral, bar = 800 µm.

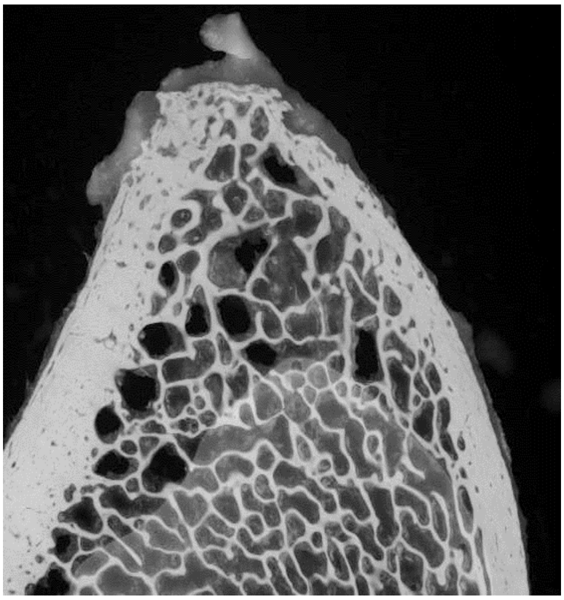


Figure 16: Microradiographs (26 kV, 10µm per pixel, 5x magnification) of 250 µm thick transverse section of the lateral aspect of the proximal left humerus. Note the large numbers of resorption canals on the periosteal region of the bone of Horse 5 of the Exercised Group.

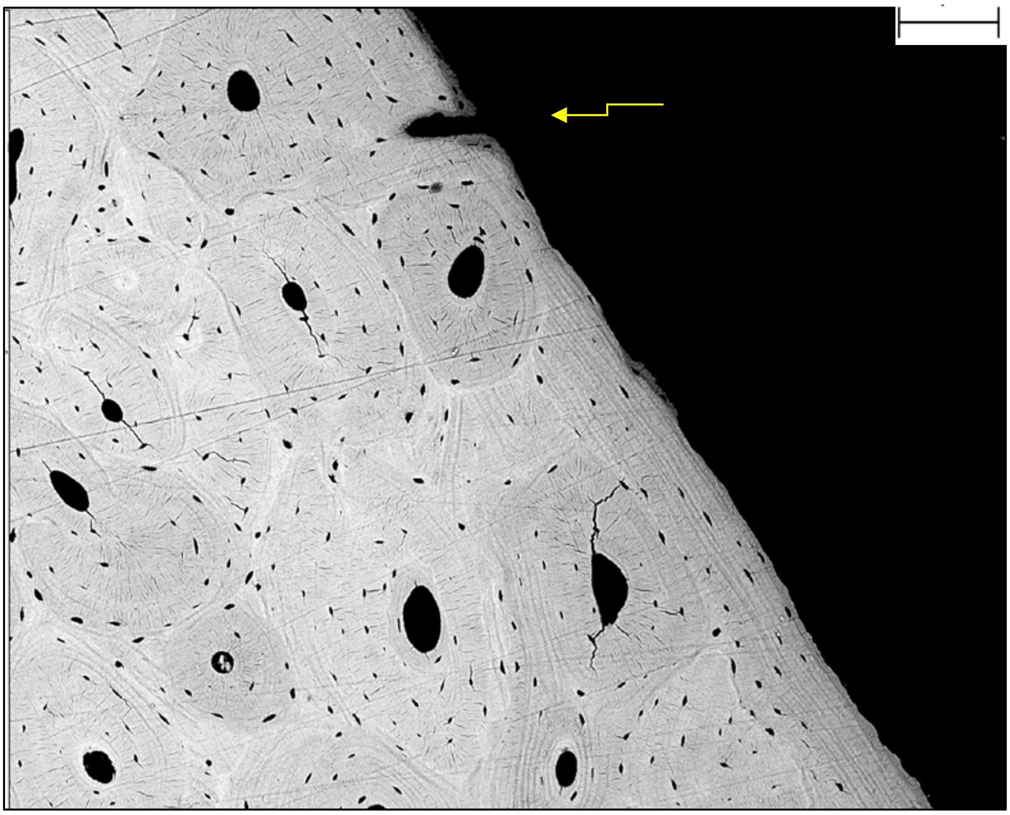


Figure 17: Transverse section imaged using back scattered electron scanning electron microscopy (20 kV, 100x magnification) of the lateral aspect of the proximal left humerus of Horse 3 of the Exercised Group. A wide furrow (arrow) bordered by poorly mineralised bone and extending perpendicularly into the cortex unaccompanied by resorption canals. Bar = 100 µm.

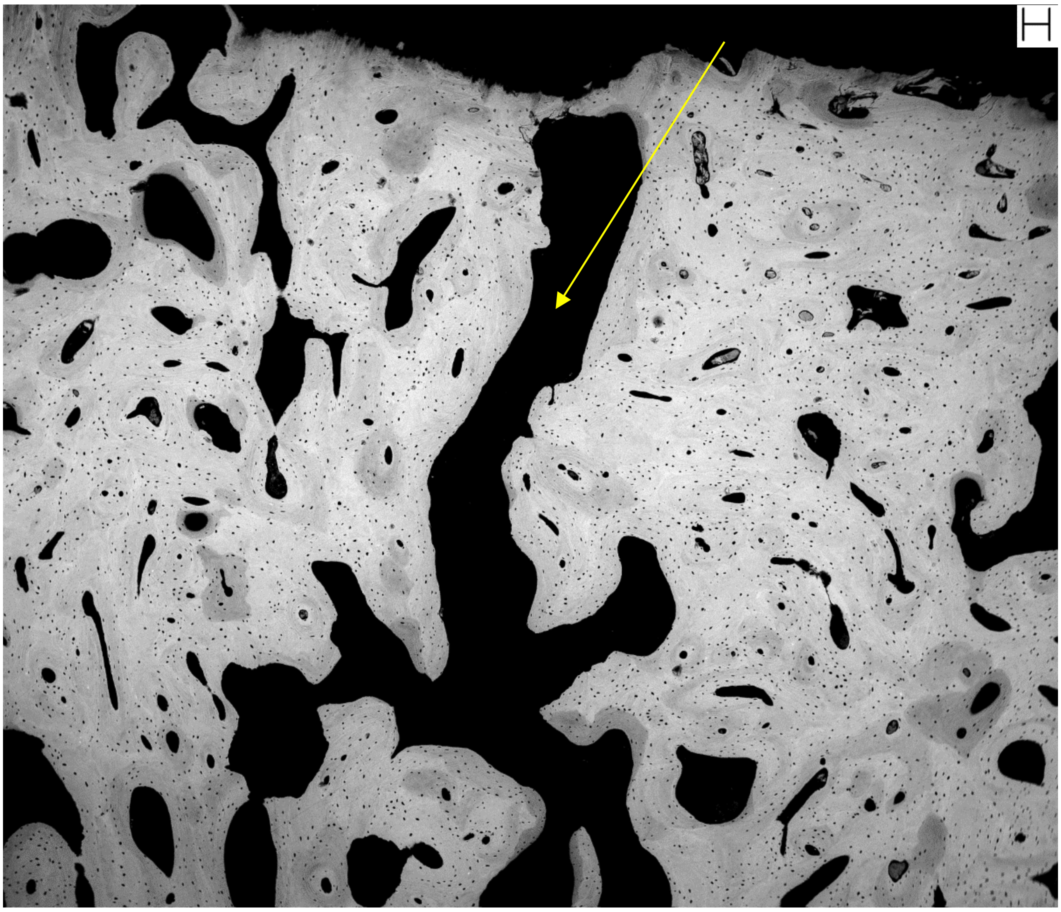


Figure 18: Parasagittal section imaged using back scattered electron scanning electron microscopy (20 kV, 26x magnification) of the right fore medial proximal sesamoid bone of Horse 12 of the Rested Group showing a large trabecula (arrow) extending proximally from the basilar surface of the bone. Basilar surface = top, bar = 100 µm.

5.4 Discussion

In the present study, extensive areas of resorption were seen in horses of the Rested Group in the dorsal cortical bone of the mid-diaphysis of the third metacarpal bone, the lateral cortical bone of the metaphysis of the third metacarpal bone and in the tibia, while the palmar region of the medial condyle of the third metacarpal bone showed extensive subchondral bone erosion. Resorption was identified based on two dimensional resorption canals as defined by Frost (1969) and Parfitt (2002), who proposed that resorption was an accurate histological measurement of bone remodelling. It is hypothesised that resorption canals are indicative of activated bone multicellular units that form the cutting cone for the dynamic remodelling process (Schaffler and Jepsen 2000, Parfitt 2002). The finding that resorption canal densities were greater in horses in the Rested Group than the Exercised Group further supports the proposal that the stimulus for remodelling is the removal of damaged bone matrix produced in response to fatigue, and its replacement with new healthy bone.

This has important implications for racehorse management, in particular the re-introduction process of high speed training after returning from a prolonged rest period. While traditional diagnostic imaging methods such as digital radiography, nuclear scintigraphy and magnetic resonance imaging may assist in detecting macroscopic pre-fracture pathology (Trope, Anderson et al. 2011, Tranquille, Parkin et al. 2012), the ability to detect microscopic bone resorption canals *in vivo* are inadequate. More research is required in the technology to detect real-time bone resorption to allow further understanding of the effect of dynamic bone remodelling process.

Resorption creates a temporary state of porosity, which undesirably reduces bone yield stress and stiffness (Schaffler and Burr 1988, McCalden, McGeough et al. 1997, Wachter, Krischak et al. 2002). Focal areas of resorption may also create stress risers allowing propagation of fracture along the path of least resistance (Hernandez, Gupta et al. 2006). In the study by Holmes, Mirams et al. (2014), horses rested from training had variably eroded articular surfaces of the lateral and medial condyles of the third metacarpal bone, with the most extensive changes identified in horses that had been rested between 21 days to 70 days. Horses in the Rested Group in the current study had rest durations of 35 to 94 days.

A rest period of one to four months was selected based on results presented in a study on two year old horses in ascending race training (McCarthy and Jeffcott 1988), and a beagle dog experimental model (Burr, Schaffler et al. 1989a, Burr, Schaffler et al. 1989b), in which bone resorption was detected between one to four months. There is also some epidemiological evidence that racehorses returning after a two month rest period are at greater risk to sustaining catastrophic humeral fractures (Carrier, Estberg et al. 1998). However, the time taken for completion of bone remodelling in

Thoroughbred racehorses is unknown and is likely to be complicated by individual variations in bone loading, training and resting patterns. It may therefore not be practical or safe for racehorses to rest the entire four month period given that bone resorption is profound in highly loaded bones as seen in the present study. Future studies should focus on identifying the risk factors in horses returning to work after the one to four month rest period.

The tenth rib was the only bone that did not demonstrate any trend or difference in resorption canal densities in either group. This suggests that while loading of bones of the appendicular skeleton increases proportionally with faster exercise (Nunamaker, Butterweck et al. 1990, Davies 2006, Rubin, Seeherman et al. 2013), loads on the rib bones may be the same regardless of whether the horse is exercising or resting. This would explain why fatigue fractures are rare in rib bones compared to limb bones as microdamage is resorbed unhindered. In contrast, bones which experience increasing loads have greater accumulation of microdamage and are at greater risk of sustaining fatigue fractures. While the current study was not designed to show the association between microdamage and bone resorption, there is support from experimental studies demonstrating the close spatial relationship between microdamage and bone resorption in bone that is dynamically loaded (Lanyon and Rubin 1984, Rubin 1984, Bentolila, Boyce et al. 1998, Lee, Staines et al. 2002).

Identification of resorption canals at specific fatigue fracture sites is unsurprising. Disruptions of the articular bone surface, and disruption of deeper subchondral and trabecular bone structure in both the lateral condyle of the third metatarsal bone and medial condyle of the third metacarpal bone correlate closely with clinical outcomes as fatigue fractures occur commonly at these sites. The resorption seen in both Exercised and Rested Groups highlights the complex relationship between fatigue and exercise, and that resorption may still occur in loaded bone, which has previously been demonstrated by Whitton, Mirams et al. (2013). Furthermore, repair of bone through resorption was not always evident. In the humeral section, the furrow showed a poorly mineralised border, while the proximal sesamoid section displayed microcracks surrounded by areas of hypermineralisation with no prior resorption being evident. This suggests that osteoclastic resorption may not be obligatory for bone repair, and healing may occur *in situ* in the absence of microcracks (Boyde 2003, Da Costa Gómez, Barrett et al. 2005) and that focal bone modelling may occur in areas of bone that have been overloaded (Whitton, Trope et al. 2010, Whitton, Mirams et al. 2013). The preference for bone to be repaired with or without resorption is unknown, although the obvious advantage in repair without resorption is the reduction in time for repair to occur, which warrants further research.

The median age of horses in the two groups was marginally different (P = 0.05). While the most plausible biological explanation for greater resorption canal densities is associated with the remodelling process that occurs with rest, the association between age, longer careers and bone remodelling response is unknown. In the study by Holmes, Mirams et al. (2014), horses in the exercised group with a longer training history had greater bone resorption of the lateral condyle compared to horses which were sampled earlier in their training life, but there was no association between the duration of the rest period and bone resorption in the rested horses. Exercised horses in the study by Holmes, Mirams et al. (2014) were older than horses in the rested group and bone resorption was unaffected after adjusting for age. It is likely that age and bone resorption display collinearity, but older horses that have been in training for longer periods may accumulate greater microdamage and subsequent bone resorption, which may potentially exacerbate the remodelling response. Older horses returning from a long period of rest may therefore be at higher risk and benefit most from fracture prevention strategies.

To the author's knowledge, no previous studies have reported on the differences in fracture-free bone resorption between exercised and rested racehorses. Choosing non-fractured horses was paramount as horses with diagnosed catastrophic or non-catastrophic fractures may have had altered normal bone loading patterns and would not be truly representative of bone loading and resorption, although it was possible that other non-fracture related reasons may also have caused significant lameness which, may have reduced the intensity of bone loading during high intensity exercise. Furthermore, this selection criterion resulted in a small sample size, which could have limited the power of the study to detect small differences between groups and increased the possibility of random error. Matching for age was not considered practical and would have further reduced case numbers. Therefore, restricting the selection criterion to high intensity exercise was considered to be appropriate and additionally, to have the advantage of reducing the confounding influence of training variation between horses. Various other studies have adopted the same design (Whitton, Trope et al. 2010, Whitton, Mirams et al. 2013, Holmes, Mirams et al. 2014).

Variation in bone geometry was minimised by cutting bone blocks in pre-determined standardised locations. The relationship between bone remodelling and bone geometry was not within the scope of this study but is likely to be affected by differences in mechanical loading (Piotrowski, Sullivan et al. 1983, Nunamaker, Butterweck et al. 1989, Davies 2006), and changes to the second moment of inertia (Nunamaker, Butterweck et al. 1990, Merritt and Davies 2010) to minimise peak bone strains. It is therefore not unreasonable to assume that different training regimens may have influenced the geometry of some of the bone sections, and the relationship between bone resorption and bone geometry should be explored in future studies. The counting of resorption canals was conducted manually and it was possible that non-randomisation may have created some bias, but the radiolucent appearance of the resorption canal was clearly visible and was performed by a single observer. Given the aim of the study, microradiography was considered a suitable imaging technique to identify bone resorption, however future studies should be aimed at identifying other markers of bone remodelling, for example calcein labelling, to evaluate bone formation rate (Boyde and Firth 2005).

5.5 Conclusion

The densities of resorption canals in the mid-diaphysis and medial condyle of the right third metacarpal bone and in the left distal tibia differed between Rested and Exercised Group horses. Bone remodelling significantly occurs after removal from a high strain environment, particularly in bones of the appendicular skeleton. Resorption occurs preferentially at sites predisposed to fatigue fracture suggesting that inappropriate re-introduction to high speed exercise may be catastrophic. Horses in the Rested Group (rested for one to four months after high intensity exercise) have considerably greater bone resorption, and future studies should be directed at determining the appropriate training regimen when horses are reintroduced to exercise following an extended period of rest.

Chapter 6:

General discussion and conclusions

Fractures in Thoroughbred racehorses are welfare issues of great importance to the racing industry. Racing jurisdictions worldwide attempt to capture data that enables them to quantify the risk of fractures in the industry to compare with similar jurisdictions. Such comparison could trigger detailed investigations if risk factors are greater than that observed for similar jurisdictions. This thesis describes in detail the number and incidence rates of non-catastrophic and catastrophic fractures at the Hong Kong Jockey Club from 2004 to 2011. Although descriptive studies are not designed to examine cause and effect relationships, they are vital in directing future analytical studies in the investigation of fracture specific risk factors. We have endeavoured to investigate a specific factor with a case series study using microradiography.

To address these objectives the incidence risk/rate of fractures were investigated in racing and in training. The focus of Chapter Three has largely been in relation to race related fatalities. Chapter Three used near census data detailing count of catastrophic and non-catastrophic fractures in racing between 2003 to 2011 racing seasons. A descriptive analysis of the data was conducted to document incidence rates for catastrophic and non-catastrophic fracture in racing. The key finding here were that the catastrophic fracture incidence rate in racing at the Hong Kong Jockey Club was 0.6 per 1000 racing starts. The incidence rate of non-catastrophic fracture increased significantly from 2004 to 2011 (IRR 4.66, 95% CI 1.93 - 11.21, $P < 0.001$) while the catastrophic incidence rate trended to decrease (IRR 0.42, 95% CI 0.11 - 1.08, $P = 0.4$).

The reported incidence rate for racing at the HKJC sits above that of that for Victoria, Australia (Boden, Anderson et al. 2006) and United Kingdom (Parkin, Clegg et al. 2004a, Reardon, Boden et al. 2014), but lower than North American studies (Peloso, Mundy et al. 1994, Estberg, Stover et al. 1996b, Hernandez, Hawkins et al. 2001, Cruz, Poljak et al. 2007, Beisser, McClure et al. 2011). Direct comparisons are difficult given the differences in case definition of catastrophic fracture. However, the catastrophic incidence rate reported in this chapter represents the number of catastrophic fractures related to racing on and off the racetrack, and only includes first fracture events. It is likely that the incidence rate reported from other studies are an underestimation of the true rate in their respective jurisdiction as in the Victorian study, the authors identified that the incidence rate was due to underreporting from country racetracks (Boden, Anderson et al. 2006). Reporting an accurate incidence rate of catastrophic fractures will have positive flow on effects for future analytical studies and assist in the comparison of fracture trends in the future. Our study highlighted the great proportion of catastrophic proximal sesamoid bone fractures sustained in racing (and training). Seventy one percent of catastrophic fractures involving one bone were due to proximal sesamoid bone fractures which is of particular concern and warrants further research.

Non-catastrophic fractures in racing have previously received little attention compared to catastrophic fractures, however, Chapter Three also highlights the importance on the monitoring of these fractures. During the 2005 to 2006 racing season, a new ‘To Watch’ injury detection system was implemented aiming to identify horses which may have transient or low risk conditions. This increased level of monitoring may have improved the detection of non-catastrophic fractures post-race and prevented the development of catastrophic fractures in later seasons. Furthermore, the ratio of non-catastrophic fractures to catastrophic fractures in racing is alarming: 3.6 to 1, and to our knowledge this has previously been unreported. While non-catastrophic fractures may not result in fatality, they cause significant morbidity to the horse and the consequences for performance and longevity may best be examined in the future using a prospective cohort design.

The rigorous monitoring environment at the HKJC also enabled the accurate collection of non-catastrophic fracture data particularly in training, which has notoriously been the fallacy of epidemiological research in racehorses in the past three decades (Parkin 2008). The difficulty surrounds the lack of detection systems in place due to the logistics in racehorse training. The HKJC is one of the few racing jurisdictions in the world which governs and monitors the activity of Thoroughbreds in training and thus, in Chapter Four we were able to determine the rate at which both catastrophic and non-catastrophic fractures occur. In this chapter the overall incidence rate (combined catastrophic and non-catastrophic) was 0.93 per 10,000 horse training days at risk. This estimate compare favourably to a study conducted in the United Kingdom (IR 0.94 per 100 horse months (equates to 3.1 per 10,000 horse training days; Verheyen and Wood (2004)), and New Zealand (IR 0.14 per 1,000 horse training days (equates to 1.4 per 10,000 training days (Perkins, Reid et al. 2005a)).

Specifically, the catastrophic fracture and non-catastrophic incidence rates were 0.08 and 0.85 per 10,000 training days respectively, suggesting that in a population of 1,000 horses in training, we would see three catastrophic fractures and 31 non-catastrophic fractures every 365 training days. Initially, this might suggest that the training environment in Hong Kong is relatively innocuous, however our data only included first event fractures, and it is likely that the true number of training related catastrophic and non-catastrophic fractures in other populations are much greater. In a prospective cohort study, the risk of sustaining a second musculoskeletal injury after the initial injury was significantly greater than in horses sustaining the first injury (RR 1.45, 95% CI 1.23 - 1.72, $P < 0.001$, Perkins, Reid et al. 2005a). It is likely that horses which sustain non catastrophic fractures may be rested and be at greater risk of sustaining a catastrophic fracture in the future. It is therefore pertinent for an accurate first fracture incidence rate to be determined as the effects of rest periods on bone, altered bone loading and rehabilitation training for future events are unknown. Therefore, the emphasis on the prevention and detection of the first fracture event should be a priority.

Chapter Five aimed at describing the effect of rest on highly trained racehorse by utilising post mortem material from horses which have been retired from racing for one to four months (Rested group), and horses which perished recently from high intensity race training (Exercised group). Special emphasis was placed on the third metacarpal bone as it was a common site of non-catastrophic dorsometacarpal fracture, and catastrophic condylar fracture (Riggs 2002). Resorption canals were imaged using microradiography which was seen as an efficient method in identifying resorption canals as a proxy for active bone remodelling. In the third metacarpal, third metatarsal and tibial sections, the lowest two resorption canal densities were consistently associated with the exercise group, and the top two resorption canal densities were consistently associated with the rested group. Resorption canals in the rested group were also seen concentrated at the dorsal mid-diaphysis of the third metacarpal bone, outer margin of the tibia, and the palmar/plantar condyles of the third metacarpal/tarsal bone. Concurrently, resorption canals were also seen in several horses in the exercise group and in particularly one humeral section, resorption canals had almost obliterated the lateral cortex. High powered SEM images also showed an alternate aspect of bone repair without resorption which may be associated with compensatory bone modelling and warrants further investigation. The finding in this study that bone remodelling is increased in horses after a period of one to four months has important implications in the re-introduction to high speed exercise given that they occur in fatigue fracture predilection sites.

The overall outcome of the research in this thesis provides increased knowledge on the true number and incidence rate of fractures associated with the Thoroughbred racehorse. These results represent a valuable contribution to our capacity to highlight issues which should be a priority for the international Thoroughbred industry.

Chapter 7:

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