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Equine musculoskeletal development and performance: impact of the production system and early training

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Abstract. The welfare debate around horse racing appears to be focussed on musculoskeletal injury and the racing of 2-year-olds. Much of this debate appears contrary to the evolutionary history of the horse as a cursorial animal and the capability of the equine musculoskeletal system to respond to the demands of race training. Epidemiological studies have reported that 2-year-old racehorses have a longer time period from entering training to the first race and a greater number of lost training days than older horses. However, this is, in part, due to the time taken to learn to train and the impact of dorsal metacarpal disease, which is due to loading of naïve as opposed to immature tissue. Across several racing jurisdictions and codes, it has been demonstrated that horses that train and race as 2-year-olds have longer, more successful, careers than those that start racing later in life. This positive trend has also been observed with horses starting in equestrian sport at an early age. The literature on the growth and development of the horse indicates that the musculoskeletal system is primed for activity and loading from an early age. Additional exercise for the young horse has a positive rather the negative effect, with many tissues having a sensitive period for 'priming' when the horse is a juvenile. This implies that under many modern management systems, the challenge to horse welfare is not 'too much exercise too soon' but 'too little too late'. The current limitation in our understanding is the lack of knowledge of what is the correct exercise dose to optimise the musculoskeletal system. Modern management systems invariably provide too little exercise, but is the exercise data from feral horses the 'gold standard', or more a reflection of what the horse is capable of if resources such as food and water are limited? Further research is required to refine our understanding of the optimal exercise levels required and development of greater precision in identifying the sensitive periods for priming the musculoskeletal system.

Additional keywords: horse, lameness, racehorse, racing, welfare.

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Introduction

The racehorse occupies a unique niche somewhere between that of a production animal (and, thus, marginal utility based on production capability) and that of a companion animal (marginal utility disproportionate to economic worth). As such, welfare issues within the racing industry are rarely associated with a lack of financial consideration or abject neglect. Therefore, any potential compromises to welfare relate either directly or indirectly to the integral parts of the production process.

Televised coverage of racing has increased the potential audience for the sport, but also exposure when unfortunate events occur. The large negative reaction to the events around the injuries and euthanasia of horses in the 2008 Kentucky Derby and the 2014 and 2018 Melbourne Cup highlighted this. Social media has also increased the ability to rapidly and widely disseminate both positive and negative images of events during racing, and has been widely used by several lobby groups (Graham and McManus 2016). An interesting by-product of the increasing use of social media by society has been the opportunity to collect data on the metrics of social media-post topics and the subsequent reach and dissemination of these posts. These readily available data provide the opportunity to quantify not only what are the issues of the wider public-welfare concerns relating to racing, but also the magnitude or level of concern with the differing issues (Graham and McManus 2016).

A quick review of the scientific literature indicates that the public concern for welfare of racehorses appears to be largely focussed on racing itself, rather than issues involved in the management of racehorses and intensive management systems (McIlwraith 2015). The focus from lobby groups and issues highlighted in public press and social media have tended to focus on emotive statements about immature horses, whipped to perform, catastrophic injuries and the number of horses sent to slaughter post-racing (PETA 2017).

The welfare lobby presents several emotive arguments about how the production process within the racing industry compromises the welfare of the horse. Much of the literature and information provided via social-media platforms have failed to utilise the peer-reviewed literature, or current statistics, to demonstrate the robustness of the argument. At present, there is some significant discourse between the information provided by welfare lobby groups and the scientific literature on the evolutionary adaptations of the horse as a precocious cursorial animal (Rogers *et al*. 2012). The present review examines the current welfare issues in racing and focuses on the scientific literature examining the role of early exercise and training on the musculoskeletal system and the impact of these on the career length.

Wastage in the racing industry

Within the racing industry, and other equine industries or sports such as show jumping, dressage or eventing, the rule of one-third appears to apply. Within any given year cohort, about one-third of horses born will not enter sport. Of the remaining two-thirds of the foal crop, one-third will retire or withdraw from training due to voluntary reasons (often lack of ability), one-third will withdraw due to involuntary reasons (often musculoskeletal injury) and one-third will remain within the production system (Ricard and Fournethanocq 1997; O'Brien *et al*. 2005; Friedrich *et al*. 2011). These production constraints (voluntary and involuntary retirements) are reflected in the short median competition career of racehorses (2–3 years; Bolwell *et al*. 2016) and competition sport horses of 3–4 years (Friedrich *et al*. 2011).

Across racing jurisdictions, there are some subtle differences in the ranking of the minor reasons for involuntary retirement or withdrawal from training, but the major reason for retirement or lost training days is musculoskeletal injury, which accounts for ~66% of all involuntary retirements (Perkins *et al*. 2005*a*; Bolwell *et al*. 2013). Thus, much of the research attention over the past several decades has been on the aetiology and epidemiology of musculoskeletal injury (Verheyen 2013).

The racing process or production system is consistent across countries and jurisdictions (Bolwell *et al*. 2017*b*; Gee *et al*. 2017; Rogers *et al*. 2017). The majority of the prise money (~60%) is targeted towards age-specific races for 2-year-olds and 3-year-olds. However, while the majority of thoroughbreds will begin early education and race training as 2-year-olds, most will have their first official race start as a 3-year-old (Bolwell *et al*. 2016). Across age categories, 2-year-olds are responsible for the largest number of days lost to training and have the longest time period from start of training until the first trial start (Perkins *et al*. 2005*b*). This is, in part, due to the horses learning to train and the imposition of training load on naïve tissue. In contrast to older horses, most lost training days with 2-year-olds are reported to be due to dorsal metacarpal disease (DMD). The cumulative incidence of DMD varies among racing jurisdictions and countries, with rates between 16% and 42% being generally reported in Australasia (Bailey *et al*. 1998; Perkins *et al*. 2005*a*), but cumulative incidence as high as 70% has been previously reported in some USA-based studies (Norwood 1978).

Dorsal metacarpal disease is localised remodelling and bone growth on the dorsal surface of the third metacarpal bone (the cannon bone), which causes acute localised pain in response to palpation, short striding and sometimes lameness. A major risk for developing DMD is a rapid increase in gallop work and insufficient exposure to high-speed work early in race training (Verheyen *et al*. 2005). The condition is temporary and often resolves rapidly with rest or reduced workload.

In contrast, injuries in older horses are less frequent, but the implications in relation to continuation of racing career are greater, in part due to the nature of the injuries and in part due to reducing opportunities for racing (with an increasing horse age). Injuries in older horses relate to cyclic overload and the interaction of this with a tissue that has a reduced capacity to tolerate load (Martig *et al*. 2014). The most susceptible tissues with flat racing are tendons and ligaments (soft tissue), with the superficial digital flexor tendons being most often affected (Perkins *et al*. 2005*a*).

Too young to race

A consistent theme with the welfare lobby groups, and even within the non-racing sector of the equestrian community, has been the statement that *2-year-old racehorses are too young to race*. The irony with this assertion is that, as a by-product of its evolutionary history, the horse is primed for early exercise. The emerging welfare concern with most modern management systems is the negative effect on welfare that restriction of exercise has on the development and health of the horse (Rogers *et al*. 2012).

Growth and development

Evolutionarily, the horse is a precocious cursorial animal. The evolutionary niche occupied by the horse has shaped an animal that can efficiently cover considerable distances (up to 28 km/day) in search of food and water (Hampson *et al*. 2010*b*). The precocious foal is capable of standing and locomotion within 1 h postpartum and, at a few weeks of age, is capable of covering up to 15 km per day with its dam (Hampson *et al*. 2010*b*; Dicken *et al*. 2012). Within modern management systems and breeds, these evolutionary pressures are reflected in the rapid growth and development of the foal, and a drive for exercise and social contact (Kurvers *et al*. 2006; Cameron *et al*. 2008).

Epigenetics and plasticity

There is an increasing body of evidence documenting not just the ability of the early neonatal phenotype to respond to its environment, but also the plasticity of the expression of the genotype to the intrauterine environment. This plasticity in the genotype has led to the recognition of the developmental origin of health and disease, or Barker hypothesis (Barker 2007). In brief, this hypothesis recognises that alterations in the maternal environment have a direct effect on the developmental pathways of the embryo and fetus that has both short-term and long-term health and developmental implications.

In line with other mammalian species, restricted maternal nutrition has been associated with increased pancreatic beta-cell sensitivity to glucose in the subsequent offspring (foal; Ousey *et al*. 2008). However, within the racing industries, over-nutrition rather than under-nutrition may be a greater risk. It has been proposed that the feeding of (high levels of) concentrates to the dam, may lead to lower insulin sensitivity and predispose the foal to osteochondrosis (Henson *et al*. 1997; George *et al*. 2009). Maternal exercise has also been implicated as important for programming the fetus for optimal orthopaedic and metabolic development (Laker *et al*. 2014; Eclarinal *et al*. 2016). For the racing and breeding industries, the major limitation with many of these findings is direct translation of these to the horse and pragmatic application within commercial equine-production systems.

On the basis of the scientific literature, the conceptual representation of plasticity presented in Fig. 1 represents

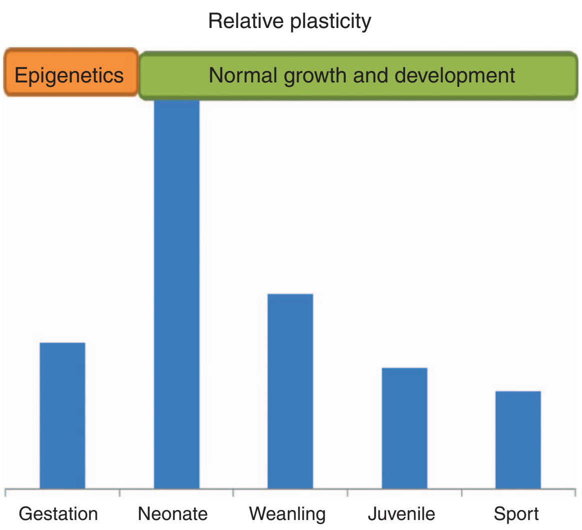

Fig. 1. Schematic representation of the relative plasticity of tissue (and the developmental pathway) to environmental stimuli at differing life stages for a racehorse.

our current understanding of the opportunity to prime the horse for a future athletic career. At birth, irrespective of breed, birthweight is ~10% of mature weight. During the initial weeks of life, up to 4 months of age, the thoroughbred foal is growing at ~1.5 kg/day and, from weaning up to yearling sales, will continue to grow at ~0.7 kg/day. At the time of yearling sales (~14 months old), a thoroughbred will be ~90% of mature height and ~85% of mature weight (Brown-Douglas *et al.* 2005; Fig. 2). This period of rapid grow appears to be when the equine musculoskeletal system is most sensitive to priming. As the horse ages, growth rate decreases and so does the receptivity of several tissues, particularly tendon and cartilage.

Observational and intervention trials have started to provide an understanding of the different stages of tissue receptivity for the major components of the equine musculoskeletal system (Fig. 3). It appears that some tissues, such as tendon, are relatively inert and resistant to stimuli. The addition of a 30% increase in canter exercise to foals failed to provoke changes in cross-sectional area of the superficial digital flexor tendon (SDFT) in young thoroughbreds (Moffat *et al.* 2008). Data from other species (pigs) have indicated that the window for plasticity may be as short as the first few days of life, after which the developmental pathway of this tissue appears heavily constrained (Woo *et al.* 1980).

Cartilage in mature mammals has a low turnover rate, with most estimates placing turnover time for cartilage in the horse at ~150 years (van Weeren *et al.* 2008). This low turnover rate and accumulated wear and load cycles contribute to the association of osteoarthritis in older horses. The equine neonate is born with a 'blank joint' and heterogeneity of the cartilage across the joint occurs in response to the magnitude and number of load cycles it is exposed to (Brama *et al.* 2000). Early work with differing housing systems identified that in warmblood foals, there was a greater biochemical heterogeneity of the cartilage in pasture-kept foals than in foals reared in open stall systems. The variation in the cartilage of the pasture-reared foals reflected the loading pattern from *in vivo* studies, whereas the stall-reared foals more closely resembled the neonatal blank joint (Brama *et al.* 2002). At 11 months of age, when all foals had been at pasture, there was some compensatory change with the previously stall-reared foals having an increase in biochemical heterogeneity. The addition of 30% more cumulative workload in pasture-reared thoroughbred foals also provided a positive response, indicating that canter and gallop exercise between 2 weeks of age and 6 months of age was able to positively prime the cartilage (increased chondrocyte viability; Dykgraaf *et al.* 2008; Rogers *et al.* 2008*b*).

Equine skeletal muscle is highly responsive to exercise stimuli. The rapid rate of growth and development in the horse is reflected in the chemical composition of 160-day-old thoroughbred foals being similar to that reported for mature ponies (Gee *et al.* 2003). Exercise trials in young horses have indicated that the response to early exercise is more closely aligned with a tissue-specific response to exercise load rather than a reprogramming of the developmental capacity of the tissue (Dingboom *et al.* 1999; Suwannachot *et al.* 1999).

Bone, particularly the bones of the distal limb are capable of a dynamic response to loading throughout life (Firth *et al.* 2012; Bogers *et al.* 2014). During growth and development in the foal, maturation occurs earliest in the most-distal long bones. Despite this rapid period of growth and maturation, it appears that the imposition of additional exercise (on top of normal pasture exercise) early in life may stimulate bone responses. In young thoroughbred foals, additional exercise stimulates an increase in the cross-sectional area of the distal epiphysis of the third metacarpal bone (Mc3) and, increases in the cross-sectional area of the mid-diaphysis of both the Mc3 and the proximal phalanx (Firth *et al.* 2011, 2012). These data imply that even though initial bone growth is dynamic and rapid, and maintains a capability to respond to load later in life, early exercise can stimulate the pre-programmed developmental process.

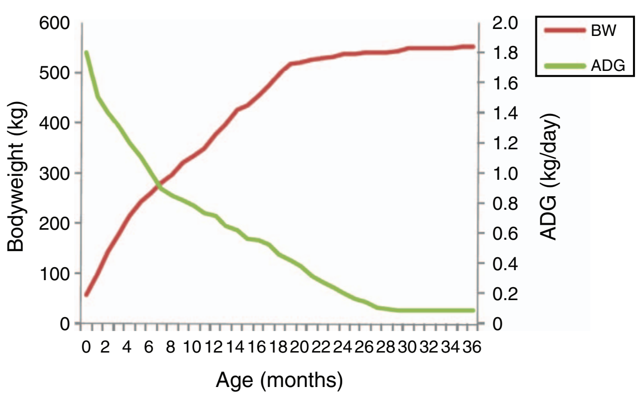

Fig. 2. Typical bodyweight (BW) and average daily gain (ADG) in bodyweight for a New Zealand thoroughbred from birth to 3 years old (adapted from Brown-Douglas *et al.* 2005).

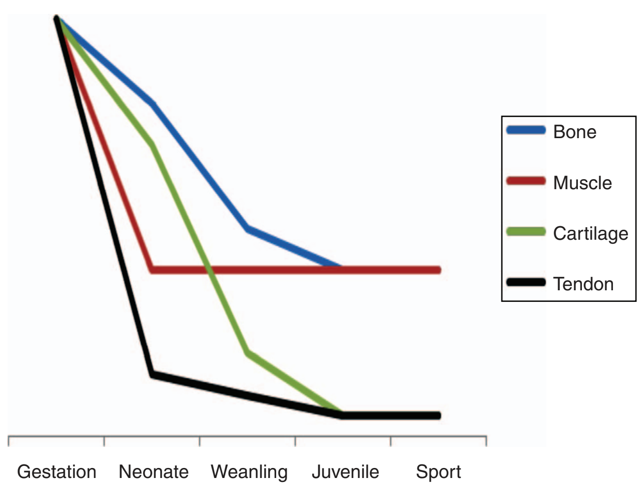

Fig. 3. Diagrammatic representation of the capability of different musculoskeletal tissues (phenotype) to respond positively to environmental stimuli at differing developmental stages.

How much exercise?

At present, we lack robust data on the optimal level of exercise to promote or maintain musculoskeletal health in the horse. Several studies have identified that increases in the volume of exercise available for young foals have a positive effect on several body systems and no detrimental effect on subsequent racing career (Rogers *et al*. 2008*a*, 2008*b*). The difficulty with provision of a recipe for early exercise is the limited data available on exercise and exercise load in horses kept in domestic management situations and those in a natural environment (Hampson *et al*. 2010*a*, 2010*b*). Data from GPS tracking imply that daily distance travelled by mare and foal units has a curvilinear relationship with paddock size, with the relationship reaching a plateau at ~15 ha and 7 km/day (Hampson *et al*. 2010*b*). Data on the distance covered by feral horses may not provide an ideal measure of optimal exercise, as the scarcity of food and water resources appears to have a large influence on the daily distance covered; however, these data do provide some indication of the distances that can be covered by foals that are only a few weeks old (Hampson *et al*. 2010*a*).

Data from cohorts of foals managed at pasture, compared with a more restrictive open stall and, open stall and sprint exercise system, highlighted the benefit of free pasture exercise and a possible detrimental effect of superimposing sprint exercise on a base of limited exercise (Barneveld and van Weeren 1999). In association with this is the importance of exercise load in relation to the sensitive or receptive window for the different tissues in the musculoskeletal system, some of which may have a very limited window early in life (tendon and cartilage) and others, such as bone, may be capable of response well into maturity (Moffat *et al*. 2008; Firth *et al*. 2011).

Perfect practices: foal activity

Within the sport literature, there is a saying 'perfect practice makes perfect'. Examination of foal activity when at pasture implies that this may be the purpose of much neonatal foal activity. When pre-weaning foal activity at pasture was calculated as an exercise volume (cumulative work index = distance × velocity), foals provided the greatest high-strain rate loads (canter and gallop) when the cartilage appears most receptive to stimuli (Brama *et al*. 2002; Kurvers *et al*. 2006; Fig. 4).

Thus, modern commercial thoroughbred-management systems may provide a pasture-based environment that could facilitate optimal priming of the cartilage in to response to the training and racing loads applied later in life (Brama *et al*. 2001; Brommer *et al*. 2003; Rogers *et al*. 2007*a*).

Yearling exercise

During the preparation of yearlings for the annual sale series in New Zealand, stud managers provide controlled exercise to yearlings in addition to free exercise at pasture (Bolwell *et al*. 2012*b*). Most farms provide walking in-hand for their yearlings on an average of 3–5 days per week, with ~20% of farms using mechanical horse walkers (Bolwell *et al*. 2012*b*). Although, in most cases, this controlled exercise is given as part of their education for the final auction-sale presentation (Bolwell *et al*. 2012*b*), increased hand-walking exercise during yearling preparation has been associated with a decreased risk of voluntary breaks in training as a 2-year-old (Bolwell *et al*. 2012*a*).

Racehorse distances in training

In a race-training environment, most horses are housed in loose boxes with turnout in yards less than 5 m × 5 m (Williamson *et al*. 2007), which, on the basis of GPS data, would facilitate total activity of less than 1 km per day (Hampson *et al*. 2010*b*). The majority of the exercise load for a racehorse is provided by the race-training program, which translates to a daily total of between 1.6 and 3.6 km depending on the training environment and the daily schedule (Rogers and Firth 2004; Verheyen *et al*. 2006). The regularity and robustness of the race-training data provide a nice model to investigate the effect of early exercise (as a 2-year-old) in race training on career length and racing success, which are proxy measures for musculoskeletal health (Bolwell *et al*. 2013). However, currently, training data are not routinely collected in most racing jurisdictions, nor are musculoskeletal injury rates during training, leading to a gap in knowledge and reliance on proxy measures.

Racing industry

Milestones

The large capital investment in the individual horses and the small margin between winning and losing have greatly restricted the ability to perform large prospective intervention trials within the racing industry. However, the tight regulatory environment within racing and the collection of performance data for the gambling industry provide a unique and robust dataset for epidemiological examination. Within these datasets, key performance milestones provide a measure of success and a proxy measure for musculoskeletal health (Bolwell *et al*. 2012*c*). These regularly recorded milestones, such as age first registered with a trainer, age of the first trial or race and total number of race starts, are common across several racing jurisdictions (Tanner *et al*. 2012).

The racing industry in New Zealand is focussed on the production of horses that are best suited for racing as 3-year-olds and older (Fennessy 2010; Waldron *et al*. 2011). This

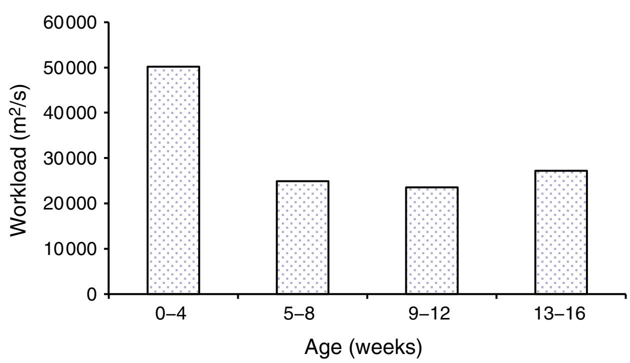

Fig. 4. The accumulated daily workload (m^2/s) in a cohort of foals at pasture up to 16 weeks old (adapted from Kurvers *et al*. 2006).

production trend is reflected within the demographic structure of the horses that have race starts (Fig. 5). Despite only a few horses having starts as 2-year-olds, most racehorses will start their early education as a 2-year-old or younger (Bolwell *et al.* 2010). In line with other racing jurisdictions, many horses will start their early education (breaking-in) as long yearlings, generally in the time period immediately after the yearling sales.

Quantification of load and quantification of loss

Within the literature, the primary reason for loss of training days and horses from the industry is related to musculoskeletal injury (Parkin 2008). The site and the nature of the musculoskeletal injury have been attributed to several parameters, including the age of the horse, the environment (track surface), training load and the trainer effect. These risk factors are often not discrete, but have an inter-relationship in the magnitude of the risk for the different musculoskeletal injuries.

Training-load response

The art of training is the balance between the imposition of load, recovery and application of the stimulatory load (Rogers *et al.* 2007*b*). Insufficient load, or too long a recovery period between loads, will result in no lasting tissue response (Fig. 6*a*). Too large a load, or insufficient recovery, will result in overload and loss of functionality (Fig. 6*c*). The magnitude of the load depends not only on environmental conditions, but also on the capability of the tissue to respond, which may vary depending on the previous training exposure (i.e. previous training or age).

Two-year-old training

Two-year-old racehorses take longer to reach their first race trial of a preparation than do the older horses (≥3-year-olds). The reason for this is, in part, due to young horses needing to learn how to train and a higher incidence rate (IR) of lost training days 2.92 (95% CI 2.56–3.22)/1000 training days (Perkins *et al.* 2004). The major reason for the lost training days is musculoskeletal injury and primarily DMD (shin soreness), which accounts for ~50% of cases. The prevalence reported for DMD varies among locations and trainers and ranges from 16% to 70% (Norwood 1978; Bailey *et al.* 1999; Perkins *et al.* 2005*a*).

The localised remodelling and bone growth on the dorsal surface of the third metacarpal bone associated with DMD is the response of naive bone to load rather than that of immature bone (Fig. 7). The imposition of the same training load on naïve 3- and 4-year-old horses also results in an increase in the incidence of DMD (Nunamaker *et al.* 1990).

The bone in the mid-diaphysis of Mc3 responds dynamically to load and the magnitude and nature of the response vary with the gait. The imposition of canter or pace-work stimulates an increase in bone density; however, to resist the greater strain associated rates associated with gallop work, there must also be an associated increase in bone size (periosteal circumference; Firth *et al.* 2005). The horse may require only a few gallop-load cycles to stimulate the appropriate bone response and DMD represents either a delay in the introduction of gallop work or an imbalance in the volume of canter and gallop work in the training program (Verheyen *et al.* 2005). The introduction of a few gallop strides early in the training preparation is a simple and pragmatic technique to reduce the incidence of DMD.

Tendon and ligament injuries are rarely seen in 2-year-olds (incidence rate 0.09; 95% CI 0.04–0.018)/1000 days training), but appear to increase almost linearly with age, with much higher IR rates being reported in older horses (≥5 years; IR 0.55; 95% CI 0.39–0.76)/1000 training days; Perkins *et al.* 2004). In the study by Perkins *et al.* (2004), the older horse-age group (≥5 years) had a 6.3 (95% CI 2.8–14.2) greater relative risk of tendon or ligament injury than did 2-year-old horses. The incidence rate for all ages during training is similar to that reported for SDFT injury during flat racing in the UK (0.55 per 1000 starts; Parkin 2008; and 0.61 per 1000 starts; Rosanowski *et al.* 2017). The greater relative risk in older horses has been attributed to the increased number of load cycles, particularly on the SDFT and the age-related changes occurring in this tendon, with the loss of crimp and structural integrity being associated with the ageing process (Patterson-Kane *et al.* 1997, 1998).

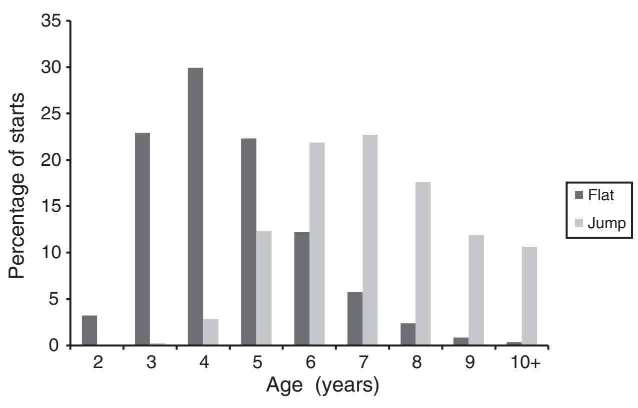

Fig. 5. Distribution of race starts and age of thoroughbreds competing in flat and jump racing in New Zealand (adapted from Bolwell *et al.* 2016).

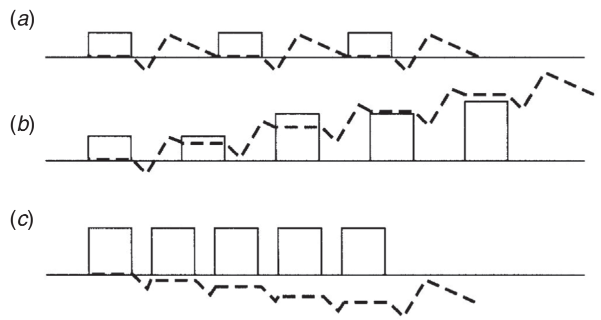

Fig. 6. Diagrammatic representation of load (boxes) and tissue response (dotted line) for (*a*) lack of tissue response due to sufficient load but too long a recovery period, (*b*) increasing response in relation to an increasing training load and correct recovery period and (*c*) overload of tissue due to insufficient recovery period (adapted from Rogers *et al.* 2007*b*).

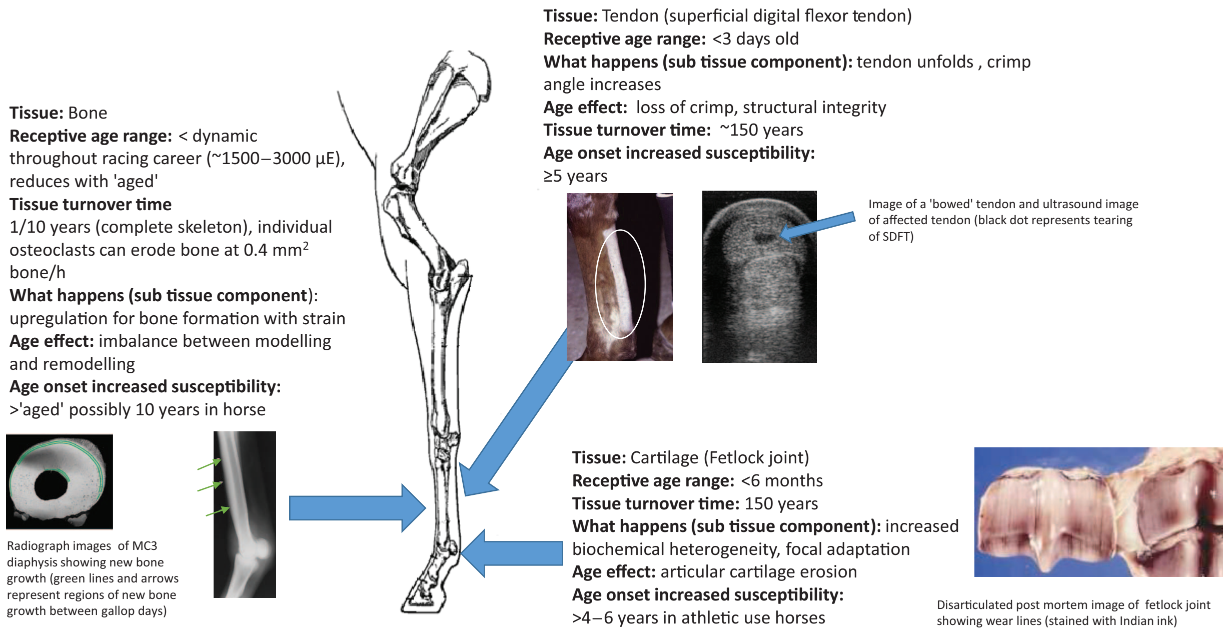

Fig. 7. Representation of the horses forelimb and the anatomical location and tissue affected by age and training.

Fracture in the racehorse is a cyclic overload injury and age does not appear to feature as a major risk factor. Older horses will often present with greater evidence of micro damage, but these and the observed changes in the material properties of the bone, particularly the distal limb, are related to accumulated training load. The primary culprits for fracture during training and racing relate to the rapid accumulation of high-speed training work and higher speed during racing on hard racetracks (Martig *et al*. 2014).

Dose response of early exercise

Data from retrospective examination of an entire foal crop indicate that, in both the thoroughbred and standardbred racing populations, there appears to be a positive dose response in relation to the provision of early exercise (Tanner *et al*. 2011, 2013; Velie *et al*. 2013). Within the New Zealand 2001–2002 thoroughbred foal crop, 67% (3152/4683) of the foals were registered as in training with a trainer, 57% (2661/4683) had a race trial, and 45% (2109/4683) had at least one race start. These proportions are very similar across the different racing nations, despite subtle differences in racing production systems (Wilsher *et al*. 2006; Velie *et al*. 2013). Examination of career length identified that horses registered with a trainer as a 2-year-old, rather than as a 3-year-old or older were more successful, placed or won more (odds ratio 2.71; 95%CI 0.22–3.22; P = 0.001), had more race starts (hazzard ratio 0.75; 95%CI 0.65–0.83; P = 0.002) and raced for more years (HR 0.75; 95%CI 0.65–0.83; P = 0.002). This positive effect increased as the level of activity as a 2-year-old increased, from just entering race training as a 2-year-old through to having a race start as a 2-year-old. Similar results have also been reported for the Australian thoroughbred, with horses having a race start as a 2-year-old having longer and more successful racing careers (Velie *et al*. 2013).

Track

The training and racing surface has a large influence of the magnitude and the duration of the loading of the distal limb (Peterson *et al*. 2012) and, as such, it is not surprising that there is a clustering of injury aetiology and risk associated with different track surfaces (dirt vs all-weather vs turf). In the USA, the general observation has been that the lowest rate of catastrophic musculoskeletal injury is on synthetic, followed by turf and, then, dirt tracks (Georgopoulos and Parkin 2016). In contrast, in the United Kingdom, the incidence of injury was reported to be lower on turf than on all-weather surfaces (Rosanowski *et al*. 2017). In Australasia, racing is generally conducted on turf tracks and some synthetic all-weather tracks and, because of this, limited data will be presented for dirt tracks. There are two additional considerations for injury risk with regards to surface; first, within each surface is the ground condition, or going (Rosanowski *et al*. 2017); and, second, the similarity or difference between the racing and training surface (Verheyen *et al*. 2003).

Grass versus all-weather tracks

Within Australasia, there are limited data on the differences in injury rate between grass and all-weather tracks, as the majority of racing takes place on turf tracks. However, in spite of much of the racing taking place on turf, the majority of the non-galloping pace work takes place on the plough and the sand training tracks (Rogers *et al*. 2008*a*).

Tracks rated as fast (penetrometer of <2) have been implicated as an increased risk of fracture and musculoskeletal injury (Parkin *et al*. 2004; Rosanowski *et al*. 2017). The biomechanical reason for this is the greater rate of deceleration of the hoof (limb) and greater peak loads of the less compliant race surface (fast tracks have less moisture and are less compliant; Peterson *et al*. 2012). If these forces exceed the critical strain and strain rate for the bones in the distal limb, then microcracks can propagate. Subsequent similar loading of the limb at too great a frequency (short duration between training and racing episodes) can, subsequently, result in a catastrophic failure (Martig *et al*. 2014). The fracture rate during racing ranges from 0.69 to 4.4 per 1000 starts, depending on the surface and racing jurisdiction (Cohen *et al*. 1999; Williams *et al*. 2001; Rosanowski *et al*. 2018).

Firm ground and increasing age have been identified as risk factors for SDFT injury during racing (Reardon *et al*. 2012, 2013). This association may be due to age-associated changes in the integrity of the SDFT (Thorpe *et al*. 2010) and fatigue of the associated muscle body that helps attenuate the loading of the SDFT (Butcher *et al*. 2007). The injury rate during racing for soft tissue and SDFT injury is commonly reported to be 0.55–0.78 per 1000 starts (Parkin 2008). SDFT strain has been identified as being responsible for 14% of all racehorse retirements from Hong Kong and, thus, represented the largest single musculoskeletal reason for retirement in this population of horses (Lam *et al*. 2007).

Internationally, New Zealand appears to have a low rate of racetrack musculoskeletal injury (Tanner *et al*. 2016; Bolwell *et al*. 2017*a*). It is highly probable that this may be associated with the reported high predictability of the racetrack environment (clockwise racing direction, and 1800-m circumference on turf) and the absence of race-day tracks classified with fast going (less than 2% of all flat races; Rogers *et al*. 2014).

Training load

As previously described, the application of high-speed training events can be protective for DMD and fracture. However, the protective effect of accumulated high-speed work appears to be quadratic and, thus, too much high-speed work will prevent the appropriate remodelling of bone and, thus, lead to an increase in risk (Verheyen *et al*. 2006; Martig *et al*. 2014).

Given the limited low-cost imaging modalities, or precise biomarkers currently available to quantify bone response to training, the trainer is faced with challenge as how to best interpret the balance of work and recovery (Bogers *et al*. 2014). However, epidemiological studies have provided insight into where the greatest periods of risk are, and the number of load cycles (strides) accumulated in a 30-day period that increase the pre-disposition to fracture risk. Early studies identified the increased risk for catastrophic musculoskeletal injury with a rapid accumulation of high-speed exercise, and a rapid accumulation of high-speed work after a break from training (spell; Estberg *et al*. 1996). More recent examination of training records has identified an increased risk of fracture when 7700 loading cycles at canter and 880 cycles at gallop in a 30-day period are exceeded (Verheyen *et al*. 2006). Thus, the trainer needs to not only consider the number of high-speed load cycles (strides) but also the balance of these with the canter (pacework), because the differing strain rates between the gaits promote subtly different responses of the bone to load (Firth *et al*. 2005).

Trainer effect

A consistent variable identified in epidemiological studies has been a trainer effect associated with both soft-tissue injury and fracture in racehorses (Perkins *et al*. 2005*b*; Rosanowski *et al*. 2017). In some cases, there is significant between-trainer variation in injury rates, which implies that some trainers are highly skilled in providing the appropriate balance between load and recovery.

The training practises of racehorse trainers are generally consistent among trainers within a racing jurisdiction or region (Bolwell *et al*. 2010), and differences in injury rates within models are often driven by one or two trainers. Data from riding-school owners and managers have indicated that some schools have significantly lower injury rates than do others on the basis of insurance data. Lower injury rates are associated with higher industry qualifications and it has been proposed that this may be associated with a greater ability to detect and prevent injury at an earlier stage (Lönnell *et al*. 2012). A growing body of research is increasing our understanding of the training-related risk factors for injury and musculoskeletal injury, and mechanisms to reduce risk (Verheyen *et al*. 2005, 2006; Martig *et al*. 2014), but this research is hampered by the lack of training data in most jurisdictions.

Optimising racing systems and the way forward

Several epidemiological studies have highlighted key risk factors for different types of injury and reasons for retirement from racing. However, an overarching theme has been the observation that the risks for injury and retirement are multifactorial and, in some cases, non-linear (Parkin 2008; Rosanowski *et al*. 2017). The early exposure to exercise had been clearly demonstrated to have some protective effect and to moderate some of the risk factors for injury and retirement. This supports the need to consider the evolutionary origins of the horse when considering how to optimise welfare. Recent work from our group has highlighted how holistic measures of the performance of a racing jurisdiction, such as failure to finish, may provide auditing tools for interventions, but also the need to consider the racing production process as a complex system (Tanner *et al*. 2016). Further work is required to understand the complexity of the interaction or the early rearing environment, early education, pre-training and training, through to the opportunity to race and recovery periods (spells) between races. This holistic or complex systems approach may help us understand the differences in injury rate and catastrophic breakdown rate between racing jurisdictions which superficially look to have a similar structure.

It is conceivable that, in the future, the voice of protest by animal-rights groups regarding the welfare of racehorses will grow only louder. As such, the challenge for the racing industry is how to disseminate information that will improve the welfare of racing horses. In the first instance, this must be undertaken in a pragmatic and effective manner to the racehorse trainers, so as to continue to improve training practices and, subsequently, improve welfare. The second challenge is to dissemination of research findings to the general public and welfare lobby groups.

Conflicts of interest

The authors declare no conflicts of interest.

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