

# Turf track surface interaction with speed and musculoskeletal injury risk in Thoroughbred racehorses

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## Funding information

New Zealand Equine Trust, Grant/Award Number: ET 2/2019

## Abstract

**Background:** Injury modelling based on changes in speed and stride characteristics of racehorses has become a primary industry focus for the Thoroughbred racing industry. However, speed and stride characteristics are strongly associated with track condition; therefore, reliable quantification of surface variables for use in future models is imperative.

**Objectives:** This study aimed to understand the interaction of objective turf track condition score (TCS) measurement with racing speed and injury in flat racing Thoroughbred horses.

**Study Design:** Retrospective time series analysis.

**Methods:** Race-day data from 16 flat racing seasons (2008/9–2023/24,  $n = 40,824$  races) were used to compare monthly TCS (based on penetrometer measurements), the coefficient of variability (CV) for TCS, race speed (over the final 600 m) and the number of race starts. Injury data from 7 seasons (2015–17, 2019–24) were used to calculate the monthly incidence rate (IR per 1000 race starts) of musculoskeletal injury (MSI). A mixed effects linear model was used to assess the relationship between speed, TCS, race distance and horse rating.

**Results:** Race starts ( $n = 437,506$ ), TCS and speed showed strong seasonal fluctuations, with more starts, lower and more variable TCS (4, IQR 3–5,  $CV = 0.44$ ) and higher race speed (16.7 m/s, IQR 16.1–17.2) in summer compared with winter (TCS 10, IQR 8–10,  $CV = 0.22$ ,  $p < 0.001$  and speed 15.1 m/s, IQR 14.3–15.8,  $p < 0.001$ ). Race speed had a strong negative quadratic relationship with TCS ( $\beta_2 = -0.03$ ,  $p < 0.001$ ), a negative linear correlation with race distance and was positively correlated with horse rating. There were 433 MSI (IR = 2.22, 95% CI 2.20–2.44), with an immediate (0 lag time) positive association with seasonal changes in TCS ( $r = -0.28$ ).

**Main Limitations:** Low monthly numbers of MSI constrained analysis of interaction with track variables.

**Conclusions:** TCS provides a reliable quantitative measure of track condition which could be used to refine future models of injury risk in racing Thoroughbreds.

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**KEYWORDS**

biomechanics, hoof–surface interaction, horse, penetrometer, turf track condition

## 1 | INTRODUCTION

Musculoskeletal injury (MSI) is the most common reason for involuntary loss of horses in the Thoroughbred racing industry. A primary industry focus at present is the use of biometric sensors to capture data characterising racing and training movement patterns of racehorses.<sup>1</sup> These devices enable large scale data collection for use in risk models, providing early identification of increased MSI risk, with reductions in stride length of 0.10 m associated with MSI.<sup>2</sup> However, surface type and condition can also influence horse stride variables and movement patterns, with reported changes in stride length of 0.18 m due to different track surface preparations and ‘firmness’.<sup>3</sup>

There are various measures of track surface which quantify the firmness, grip, shear and consistency of surface. The penetrometer consists of a 1 kg weight dropped 1 m onto a probe with a cross-sectional area of 1 cm<sup>2</sup>, providing reliable and repeatable measurements of the racetrack firmness.<sup>4</sup> In New Zealand, it is a requirement for penetrometer readings to be reported to the National Racing Board at multiple set times prior to and on the morning of every race meeting.<sup>5</sup> New Zealand is currently the only racing jurisdiction that uses the quantitative values from a measurement device to set the definition of going on turf tracks.<sup>6</sup>

Penetrometer values have a strong relationship with the material properties of the turf track as well as race speed.<sup>7,8</sup> The speed of the horse depends on the stride length and stride frequency, both of which are easily measurable parameters using biometric sensors. Greater speed on firmer tracks is thought to be due to the greater traction available when a horse is galloping. However, increased track firmness is also associated with more rapid deceleration of the horse's limb and a reduced and abrupt slide and stop, increasing the concussive forces on the limb.<sup>9</sup> Combined with an increase in stride length on firmer tracks,<sup>2</sup> this rapid deceleration of the limb is one of the explanations for the greater odds of distal limb fracture being associated with ‘fast tracks’.<sup>10</sup>

Due to the association between track surface type and condition which influences both speed and stride characteristics, it is increasingly important to refine future injury prediction models to include a quantitative measure of surface condition. Therefore, the aim of this study was to understand the implications and interaction of turf track condition score with speed and MSI in Thoroughbred racehorses.

## 2 | MATERIALS AND METHODS

Race-day data, including every Thoroughbred race start between 1 August 2008 and 31 July 2024 (16 racing seasons) were provided by New Zealand Thoroughbred Racing (NZTR), the governing body for Thoroughbred racing in New Zealand. These data included track-related

data for every race (track condition score and penetrometer readings for races run on turf tracks) as well as race-specific data, including race distance and individual race times and horse-specific data including horse rating (domestic rating). Rating is a dynamic measure of performance and is recalculated within 2 days of a horse's most recent race start, with higher-rated horses having more racing success.<sup>11</sup> Maiden horses have a domestic rating of 45–55, horses that have 1–2 wins are rated at 55–65, and open grade horses are  $\geq 75$ . The official racing season in New Zealand runs from 1 August to 31 July. Summer racing in the southern hemisphere occurs during the months of December to January and winter racing is from June to August. Only flat races run on turf tracks were used for analyses in this study.

Penetrometer measurements are converted to a numeric track condition score (TCS, from 1 to 11) relating to historic descriptive track conditions according to Table 1. The TCS was revised to a 1–10 scale in 2022, with the top category of 11 removed.<sup>12</sup>

Injury and fatality data for every race-day veterinary examination of a horse between 15 March 2019 and 31 July 2024 were provided by the Racing Integrity Board (RIB), an independent regulatory body which oversees racing integrity within New Zealand. Veterinary examinations of horses may be requested due to a racing event or accident, or if the horse performed below expectation. These data included race and horse details, as well as the reasons for and main findings from each veterinary examination. These data were combined with injury data retrieved manually from stipendiary stewards reports in the 2015/16–2016/17 racing seasons as documented by Gibson et al.<sup>14</sup> Musculoskeletal injuries (MSI) included fatalities from MSI and were defined as any clinical finding of lameness, fracture or musculoskeletal soft tissue injury that occurred during or post-race. Horses that did not start or were injured pre-race were removed from the dataset.

### 2.1 | Data analysis

Data were tested for normality with the Kolmogorov–Smirnov test ( $p < 0.05$ ). Descriptive statistics were used to summarise, describe and screen the combined data sets, with differences between variables tested with the Wilcoxon rank sum test for non-normally distributed data. The incidence rate (IR) and 95% confidence intervals (95% CI) of MSI were calculated per month based on the number of MSI or fatalities per 1000 racing starts. Race speed was calculated using the official recorded time over the final 600 m for every horse completing a race. Data were grouped by month and year to determine monthly means for each variable of interest. The coefficient of variability (CV) of the TCS was calculated monthly. These monthly means were used to create time series variables for TCS, race speed, CV and IR.

Time series analyses were used to decompose the variables of interest into long-term trend, seasonal and residual components (using

loess), to describe trends and cyclical patterns. Missing values in the series (due to Covid19 interruptions when all racing in New Zealand was halted) were visually inspected and automatically computed using univariate time-series imputation to fit the data based on the available data and checked to determine biological plausibility. Line plots were used to describe the variables with respect to time. Monthly boxplots of each variable were generated to identify cyclical trends. Autocorrelation function (ACF) plots were used to assess the seasonality of variables. Pearson's correlation, cross-correlation and covariance of the decomposed series were used to assess interactions between variables and determine differences in lag times.

**TABLE 1** Reference values for track condition descriptors based on penetrometer readings for the track, measured on the morning of race day.

Historical track condition	Track condition (since 2022)	Track condition scale	Penetrometer
Fast	Firm	1	0.5–1.9
Good	Good	2	2.0–2.2
		3	2.3–2.5
Dead	Soft	4	2.6–2.8
		5	2.9–3.2
		6	3.3–3.5
Slow	Heavy	7	3.6–3.8
		8	3.9–4.2
Heavy	N/A	9	4.3–4.5
		10	4.6–5.5/4.6+
		11	5.6+

Source: Based on data from reference <sup>13</sup>.

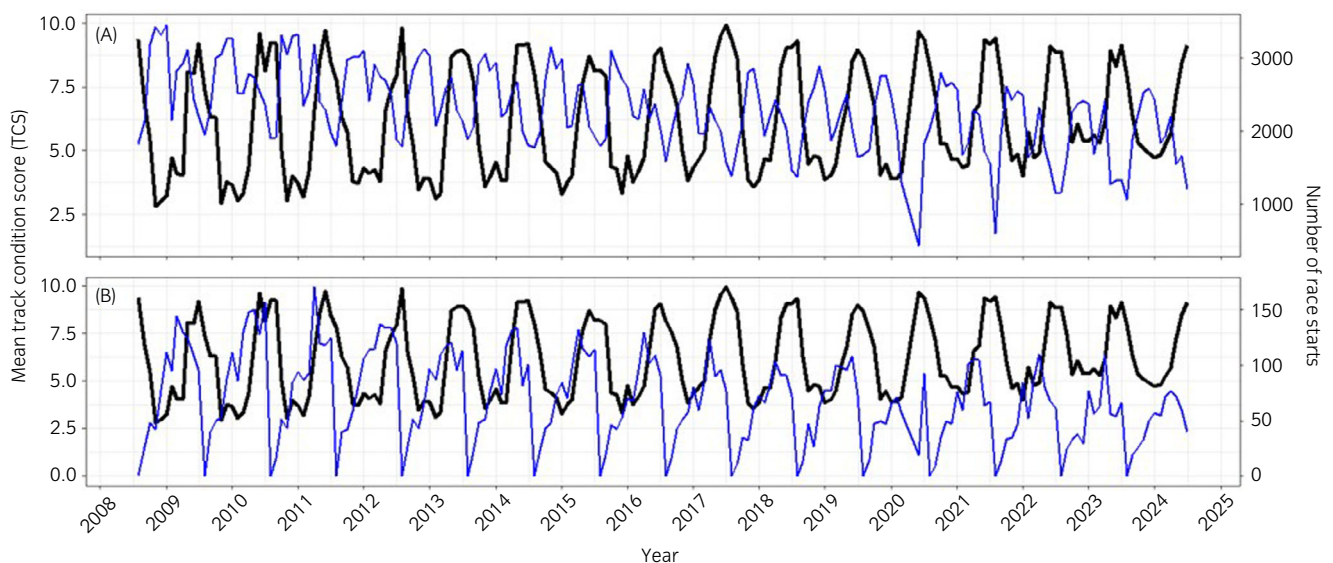
Univariable analysis was used to screen relevant predictor variables for speed over the final 600 m (Table S1). Track condition score, race distance and domestic rating were considered as fixed effects. Domestic rating is a dynamic measure of a horse's performance, with higher rated horses able to compete in the higher stakes races. These variables were then modelled using a mixed effect linear regression model with horse as a random effect. Variables which improved model fit ( $p < 0.05$ ) were selected using a forwards selection procedure in the multivariable model. Raw data were visually examined and TCS was included as a quadratic function ( $TCS + TCS^2$ ) to account for the observed nonlinear relationship between TCS and speed. Models were compared using the ANOVA function, and residual plots were examined for goodness of fit.

All statistical analyses were conducted using R 4.4.3 (R Core Team, 2025) with the level of significance set at  $p < 0.05$ .

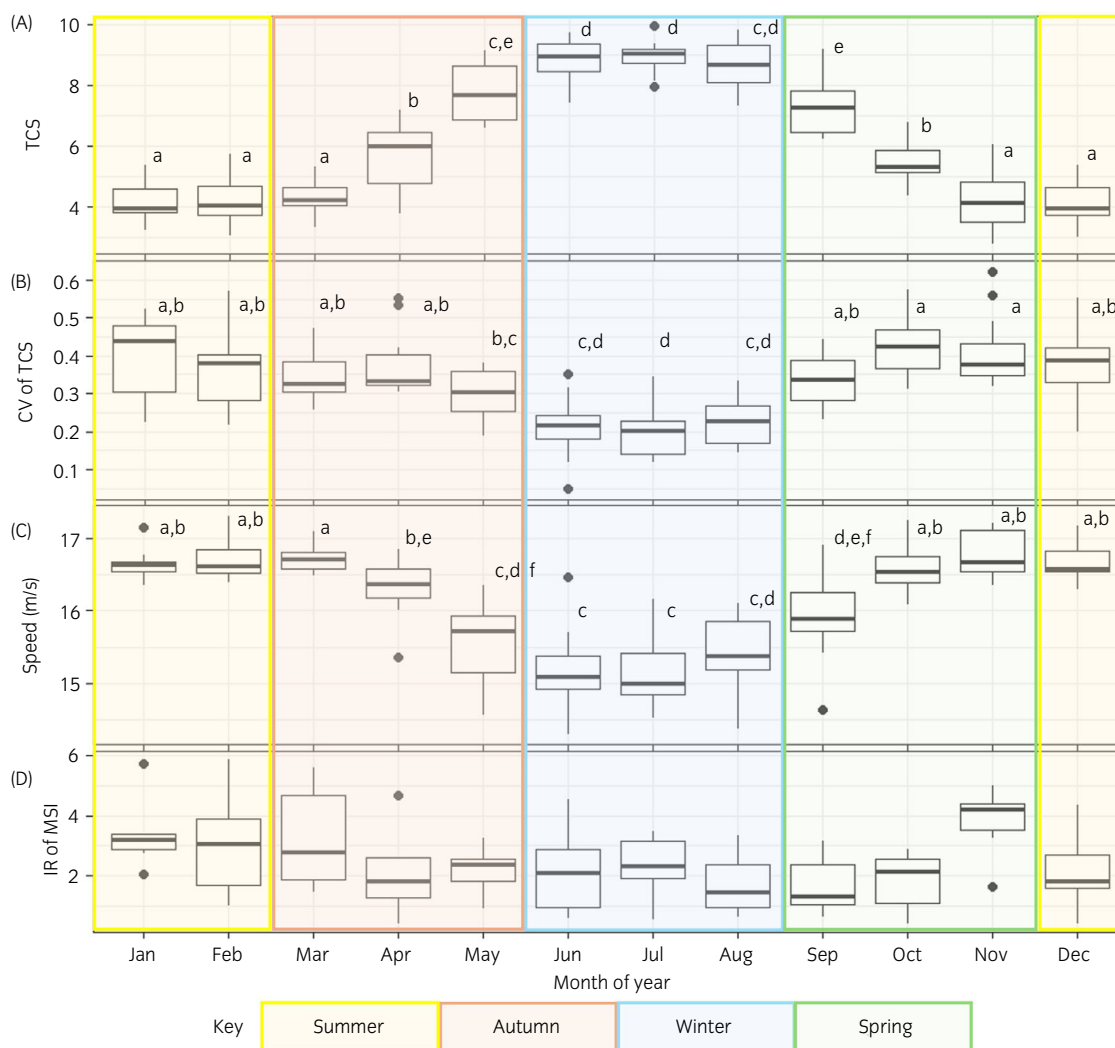
### 3 | RESULTS

Over 16 racing seasons (2008/09–2023/24) in New Zealand, there were 437,506 flat racing starts, of which, 3% ( $n = 13,119$ ) were by 2-year-old racehorses. The number of racing starts fluctuated seasonally (Figure 1), with more racing starts in summer (median 2573, IQR 2214–2933), and fewer starts in winter (median of 1822, IQR 1545–2037,  $p < 0.001$ ). Most starts by 2-year-old horses were in autumn (median 107, IQR 92–129), with the lowest median number of 2-year-old starts in spring (39, IQR 26–47,  $p < 0.001$ ).

Over the same period, there were 40,824 flat turf races. Half of these races (19,223, 47.1%) had a published penetrometer reading, and 40,792 (99.9%) had a reported TCS. The median TCS for all years was 5.0 (IQR 3.0–8.0), TCS showed a clear annual seasonal variation (Figures 1 and 2). Racetrack surfaces were firmer in January (summer),



**FIGURE 1** Time-series line plot of track condition score (TCS, black) and number of (A) total race starts (blue) and (B) 2-year-old horses race starts (blue) for all flat races on turf tracks between 2008/09–2023/24 racing seasons in New Zealand.



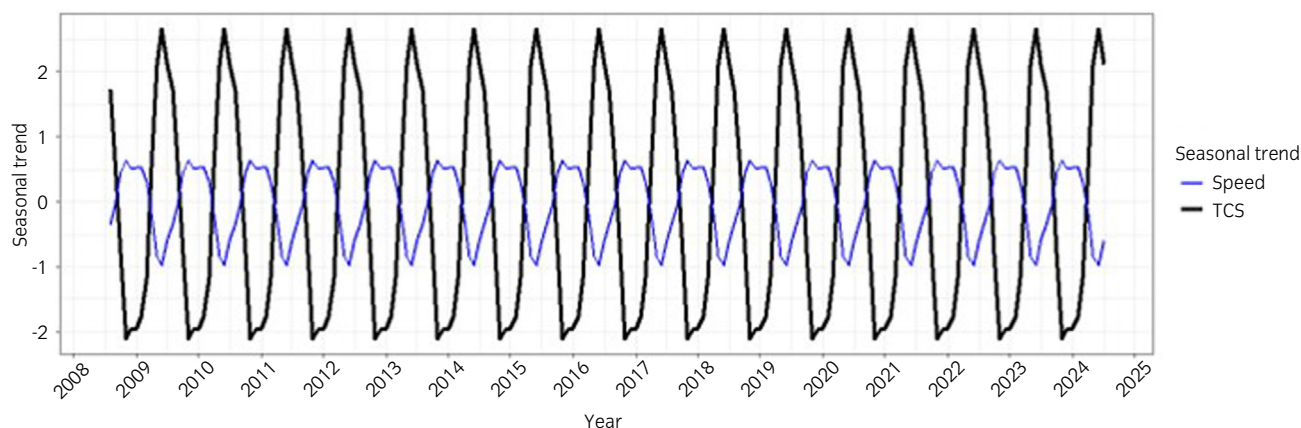
**FIGURE 2** Monthly boxplots for flat races on turf in New Zealand of (A) track condition score (TCS), (B) coefficient of variability (CV) of TCS, (C) race speed over the final 600 m (m/s) during the 2008/09–2023/24 racing seasons and (D) musculoskeletal injury (MSI) incidence rate (IR) per 1000 racing starts during the 2015/16–2016/17 and 2018/19–2023/24 racing seasons (southern hemisphere). Superscripts denote differences between months ( $p < 0.05$ ).

with a median TCS of 4 (IQR 3–5), a median penetrometer reading of 2.5 (IQR 2.3–2.8) and had a CV of 0.44. July (winter) recorded the highest median TCS of 10 (IQR 8–10), corresponding to a median penetrometer reading of 4.5 (IQR 3.9–5.2) with a CV of 0.22, indicating a lower variability in track surface rating during winter compared with summer (Figure 2).

Median speed over the final 600 m was 16.4 m/s (IQR 15.6–16.9 m/s) for all racing seasons. Race speed over the final 600 m also varied seasonally from 16.7 m/s (IQR 16.1–17.2 m/s) in January (summer) to 15.1 m/s (IQR 14.3–15.8 m/s) in July (winter) (Figure 2), showing an inverse seasonal relationship with TCS (Pearson's  $r = -0.94$ ). The decomposed seasonal trend for speed showed a plateau at the higher speeds of the speed oscillation, corresponding to a lower TCS (Figure 3). A mixed effect linear regression model which contained horse as a random effect (accounting for 15% of model variance) was fitted to the data (Table S2). There was a quadratic

relationship between speed and TCS ( $TCS^2$ ), with speed reaching a plateau at TCS 3–4. Speed was negatively associated with race distance and positively associated with horse domestic rating (Table 2; Figure 4).

There were 433 MSI (including fatalities) over seven flat racing seasons 2015/16–2016/17 and 2018/19–2023/24, resulting in an overall IR of 2.22 per 1000 race starts (95% CI 2.20–2.44). Monthly IR of MSI was variable but showed a weak seasonal trend (Figure 2). Autocorrelation functions showed strong seasonal correlations for TCS, CV and speed, but not for IR of MSI. When annual trends were removed from the data, IR of MSI showed seasonal similarity corresponding to peaks in CV of the TCS ( $r = 0.25$ ) (Figure 5) and peaks in speed ( $r = 0.23$ ). There was an inverse association of MSI with seasonal changes in TCS ( $r = -0.28$ ). Cross-correlation of TCS and MSI IR showed an immediate relationship with 0 lag time between variables.



**FIGURE 3** Decomposed seasonal trends of track condition score (TCS, black) and speed over the final 600 m (blue) over the 2008/9–2023/24 turf flat racing seasons in New Zealand. The seasonal component represents deviations from the long-term trend, scaled to highlight recurring seasonal patterns. A value of +1 or –1 indicates that the variable (e.g., TCS or speed) is one unit above or below its expected value for that time of year, relative to the long-term trend.

**TABLE 2** Mixed effect multivariable linear regression model of the association of speed (m/s) in the final 600 m of a race with predictor variables: track condition score (TCS + TCS<sup>2</sup>), race distance (m) and domestic rating of the horse, with the random effect of horse included in the model.

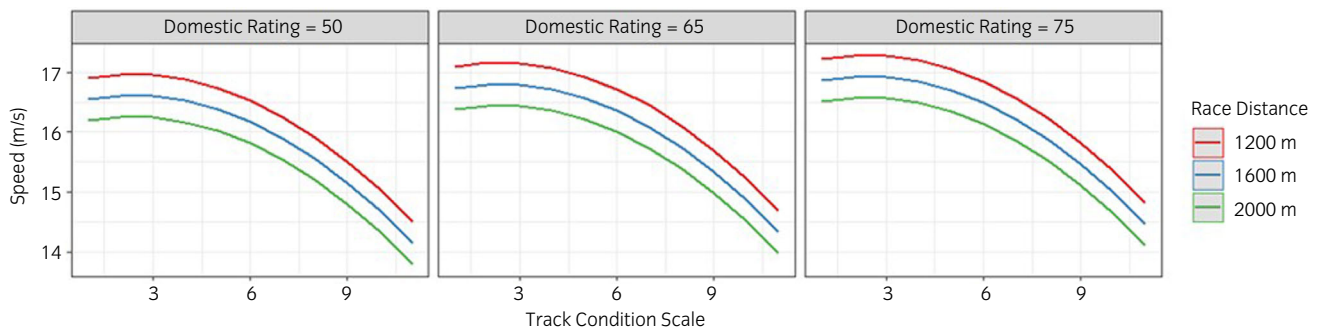
	Estimates	95% confidence interval	Standard error	t-value	p value
<b>Fixed effects</b>					
(Intercept)	17.21	17.17–17.24	0.016	1058	<0.001
TCS	0.16	0.15–0.16	0.004	40	<0.001
TCS <sup>2</sup>	–0.031	–0.034 to –0.033	0.0003	–113	<0.001
Race distance (per 100 m)	–0.089	–0.090 to –0.088	5.4e–3	–164	<0.001
Domestic rating	0.0129	0.0125–0.0132	0.0002	76	<0.001
<b>Random effects</b>					
$\sigma^2$ (residual variance)	0.43				
$\tau_{00}$ (horse)	0.08				
Between subjects variance					
ICC	0.15				
N (horse)	19,442				
Observations	207,507				
Marginal R <sup>2</sup>	0.58				
Conditional R <sup>2</sup>	0.64				

## 4 | DISCUSSION

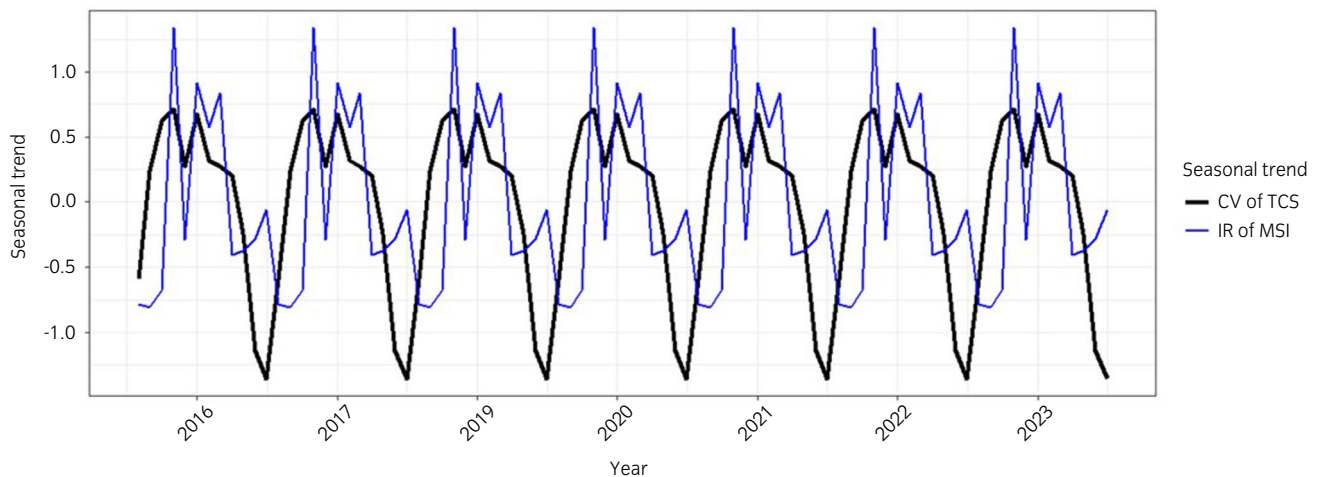
Track condition score is based on quantitative penetrometer readings, which have been validated as an effective measure of track surface properties (yield and material properties) since 1996.<sup>7</sup> The strong seasonality and association between TCS with speed (moderated by horse domestic rating or quality, and race distance) found in the current study, provide further support that penetrometer assessment is a repeatable measure with which to determine the properties of a race-track surface.

The TCS of New Zealand racetracks showed clear cyclical variation, corresponding to the seasons of the year. This was expected due

to New Zealand's temperate climate and the pragmatic structure of the racing calendar to optimise racetrack locations for the best surface conditions during the different seasons.<sup>13</sup> Moisture content is one of the most important factors in the dynamic properties of all equestrian surfaces<sup>15</sup> and winter in New Zealand has the highest rainfall, which was reflected in the higher TCS during the winter months (June–August). There was also less variation in TCS during the winter months, indicating that all racetracks were relatively saturated with moisture. The opposite was true during the summer months (December–February); racetracks had a lower TCS but more variability in TCS, highlighting the effect seasonal rain or irrigation strategies had on racetrack surface properties. Therefore, seasonal changes in



**FIGURE 4** Predicted values of speed (m/s) for Thoroughbred horses in flat races with respect to track condition score (TCS), race distance (m) and domestic (maiden horses rated 50, horses with 1–2 wins rated 65 and open rated horses rated 75) in a mixed effect linear regression model with random effect of horse.



**FIGURE 5** Decomposed seasonal trends of the coefficient of variation (CV) of track condition score (TCS, black) and Incidence rate (IR per 1000 starts) of musculoskeletal injury (MSI, blue) over the 2015/16–2016/17 and 2018/19–2023/24 turf flat racing seasons in New Zealand. The seasonal component represents deviations from the long-term trend, scaled to highlight recurring seasonal patterns.

rainfall, as well as temperature (affecting evaporation and dew fall) and adverse weather events have a large effect on track properties, and effective management during these time periods is paramount.

Racing in New Zealand occurs year-round, with seasonal fluctuations in the quality and quantity of horses racing, with a focus on higher stakes (listed and group) racing in summer (December–February). Correspondingly, there were more horse starts during spring and summer carnival racing, and a smaller peak in autumn when there is also a crossover with ‘winter’ horses commencing racing, and ‘summer’ horses finishing their season. Most horses in New Zealand begin their careers at 3 years old. However, of the 18% that begin racing at 2 years of age,<sup>16</sup> the majority start during autumn (September–November), at the end of their 2-year-old year. The differences in horse quality and numbers racing during the different seasons provide confounding variables to the relationship between TCS, speed and MSI, with higher rated horses more likely to race on the firmer summer tracks, when higher stakes are on offer and speeds are higher. In Australia, better performing horses were also associated with higher speeds and longer stride

lengths,<sup>2</sup> and as these factors are known to be associated with MSI, they should be included in injury risk models.

The relationship between horse speed and TCS, moderated by horse rating (as a proxy for quality of race) and race distance was highly correlated. It is well documented that higher speeds are associated with increased track firmness, which is due to the greater traction possible at breakover and the ability to optimise elastic rebound.<sup>9,17</sup> Race speed plateaued between a TCS of 1–4, before steeply decreasing in a linear relationship after a TCS of 6. These data indicate that firmer tracks (TCS <3–4) provide limited benefits to horse performance but instead increase the risk of injury. This is due to the increased impact shock and higher ground reaction force over a shorter period of time resulting in a greater rate of deceleration of the limb associated with a firmer surface.<sup>9,18</sup> Track firmness modifies the speed-stride frequency relationship with greater speeds on firm surfaces attained by increases in stride frequency rather than length.<sup>2,3,19</sup> Given the relationship between stride frequency and stride length is often used in models with biometric sensors, it is important to quantify track surface as a known effect modifier.<sup>3</sup> The

quantifiable relationship between TCS and speed established in the current paper could be a valuable addition to future predictive MSI risk modelling.

New Zealand actively aims to reduce the exposure risk of racehorses by maintaining a minimum TCS of 3,<sup>5</sup> thus removing most of the hard and fast track conditions which are associated with a higher risk of MSI.<sup>20–22</sup> Only 3% of all race starts between 2011/2012 and 2021/2022 were run on a TCS of less than three.<sup>23</sup> This may provide an explanation for the lack of a clear time-series association between MSI and TCS, contradicting findings from previous studies.<sup>10,21</sup> Restricting races to a TCS of 3 and above appears to be an effective safety strategy, as evidenced by the overall low incidence rate of MSI, which constrained analysis. However, there are multiple other factors including training variables (surface changes, length of preparations and spells, accumulated distance and speed) which also influence race day MSI risk.<sup>10,21,24–27</sup> Exploration of these risk factors for MSI may be an important avenue for future research.

There was little association between MSI and TCS or speed when considered as time-series variables. However, the decomposed seasonal trends of MSI and CV of TCS followed a similar pattern. There was a tendency for a higher MSI incidence to coincide with a greater variability in TCS, which occurred in the spring and autumn months. These months tend to be at the beginning and end of most horses' summer campaigns (December–February), both of which have previously been identified as risk factors for MSI.<sup>28</sup> Additionally, horses adjust to different surfaces by fine-tuning how the tendons dampen the loading of the limb,<sup>29</sup> and tend to habituate to the surface they train and race on with limited capacity to adapt quickly to surface changes.<sup>30–32</sup> Therefore, this lack of adaptability may, in part, account for the weak association between MSI and times when there is greater variability between racing surfaces. It is clear that there is a threshold TCS (3–4) below which there is no increase in speed, but biomechanically the risk of MSI is likely to increase. Therefore, pre-race measurement of TCS using a penetrometer can provide guidelines for balancing optimal performance and minimising injury risk in Thoroughbred racehorses. Additionally, the use of penetrometer readings (or TCS) may add refinement to predictive models of MSI based on biometric sensors capturing large-scale data measuring individual stride characteristics.

## 4.1 | Limitations

This study used the TCS calculated from penetrometer recordings, rather than the penetrometer recordings themselves. This increased the statistical power of the data, as TCS were more consistently reported in the industry dataset, despite potentially losing some accuracy by grouping the penetrometer recordings within the reported ranges. However, the published TCS were calculated from the original penetrometer readings and had a significant collinearity ( $R^2 = 0.9$ ,  $p < 0.001$ ), so it was unlikely to affect the results. Additionally, TCS is a more easily understood metric, as it relates well to the traditional descriptions of going in racing. Only one TCS was available to assess the going of each race, which was an average of ~20 penetrometer

readings on the track, so within racetrack variation was not assessed in this study, only variation between race days.

Speed over the final 600 m of the race was used to provide a consistent metric for all races. The advantage of using this metric minimised the potential for racing tactics (which would occur in the earlier stages of the race) to affect the measurement. The final stages of a race have also been identified as the section of the race where injury or accidents to horse or jockey are most likely to occur.<sup>33,34</sup> Therefore, the final portion of the race was also most relatable to the MSI metric, and was similar to the final 200 m used to calculate stride characteristics to assess MSI risk in racing horses.<sup>2</sup>

## 5 | CONCLUSION

This study provides further evidence of the effectiveness of the penetrometer in assessing track surface conditions and its usefulness as a simple predictor of racehorse speed or injury. Track condition score and race speed of New Zealand racetracks show strong seasonality, with less variation during winter. Race speed had a strong negative quadratic relationship with TCS, a negative linear correlation with race distance and was positively correlated with horse rating. The nonlinear relationship between TCS and race speed provides a threshold value (TCS of 3–4) after which the speed of the horse does not increase, but injury risk is likely to increase. This value may optimise the appropriate balance between surface yield and functionality for the horse. The seasonality in horse types (age and rating) and numbers racing also provides insight into the differences in speed and MSI rate interaction with TCS.

## FUNDING INFORMATION

This study was supported by the New Zealand Equine Trust (ET 2/2019).

## ACKNOWLEDGEMENTS

We thank New Zealand Thoroughbred Racing for provision of the data. Open access publishing facilitated by Massey University, as part of the Wiley - Massey University agreement via the Council of Australian University Librarians.

## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## AUTHOR CONTRIBUTIONS

**K. A. Legg:** Conceptualization; investigation; writing – original draft; methodology; writing – review and editing; formal analysis. **M. J. Gibson:** Writing – review and editing. **E. K. Gee:** Writing – review and editing. **C. W. Rogers:** Conceptualization; investigation; methodology; writing – review and editing; funding acquisition.

## DATA INTEGRITY STATEMENT

K. A. Legg had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

## ETHICAL ANIMAL RESEARCH

Research ethics committee oversight not currently required by this journal: data sources are in the public domain.

## INFORMED CONSENT

Representatives from New Zealand's Racing Integrity Board gave consent for use of injury data.

## PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/evj.70003>.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from New Zealand's Racing Integrity Board. Restrictions apply to the availability of these data, which were used under licence for this study.

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### SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Legg KA, Gibson MJ, Gee EK, Rogers CW. Turf track surface interaction with speed and musculoskeletal injury risk in Thoroughbred racehorses. *Equine Vet J*. 2025. <https://doi.org/10.1111/evj.70003>