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Variation in GPS and accelerometer recorded velocity and stride parameters of galloping Thoroughbred horses

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Running title: Speed and stride characteristics of racing Thoroughbreds

Summary

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

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

Study design: Retrospective cross-sectional analysis of archived data.

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

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

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

Conclusions: There was substantial inter-horse variation in stride parameters, with speed predicting half or less of this variation. Speed alone does not fully explain stride

characteristics in horses. Future studies aimed at investigating the impact of gait on bone biology and pathology would benefit from accounting for stride characteristics (e.g. length and duration).

Introduction

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

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

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

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

Materials and methods

Data sources:

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

The dataset was sorted by date within horse identification number and then each race-start was assigned a race-start number for each horse (n = 33,459 individual race starts). Erroneous values were identified and excluded from statistical analysis according to Fig. 1. Biologically plausible speed and stride parameters were defined based on published data for galloping horses under non-race conditions [13], and manual assessment of detailed records of second-by-second GPS recordings provided by the manufacturer. The resulting exclusion criteria for the GPS and accelerometer derived data were: speeds below 12.57 m/s or above 21 m/s, stride lengths below 5.3 m or greater than 9.2 m, and stride durations below 0.37 seconds or greater than 0.49 seconds. As the present study aimed to describe characteristics of healthy horses only, we excluded horses that pulled up, lost a rider, fell, or were injured or disqualified. The official race result dataset was merged with the StrideMaster dataset using a one-to-one match on race date, race track, race number, and horse name. The final merged dataset for analysis consisted of 25,259 starts. This included 153,315 observations (200 m sectional recordings within race-starts) for 2,678 individual horses (Fig. 2).

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

Data analysis

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

Associations between stride parameters were quantified using pairwise Pearson correlation coefficients and presented as R-squared values. To assess whether a linear equation appropriately described the nature of the relationship between stride length and duration (independent variables) with speed (dependent variable), the Stata 'curve fit' package was employed which implements 34 alternative non-linear transformations. Model fit was assessed by correlation coefficients and minimisation of Akaike's information criterion (AIC) as well as graphically [24]. We generated a variable for the maximal sectional velocity for each horse over the entire data-set. We defined elite horses based on (1) the top ten percent of horses according to maximal sectional speed (vs. the remaining 90% of horses), and (2) horses that won or placed in each race start (vs. the other starters in that race start). We used scatterplots to assess for an observable plateauing of either stride variable (length or duration), and then stratified our analysis by horse categorised as elite vs. non-elite. In both stratifications no evidence of plateauing was detected. The relationship between speed and the number and duration of strides are presented as Sunflower plots (a density-based scatter plot) due to the large numbers of observations with overlapping speed-to-stride measure pairs observed [25]. Using the outcome of speed, three-way-interactions between the number of strides per 200 m, stride duration (s) and a series of race-level factors were analysed and assessed graphically to understand the strategies horses use to change speed during a race. The race-level variables assessed included race distance, track rating, stage of race, finishing position (win vs. lose, place vs. lose, place vs. finishing in the bottom three), as well as elite horses vs. the remaining cohort. Plots for each variable consisted of the linear prediction of the slope of each stride variable based on changes in the corresponding stride variable and the race-variable.

Two separate regression analyses were carried out to identify factors associated with each of the stride variables [number of strides per 200 m and stride duration (s)]. In the first, for 200 m sectionals from the early, middle and late stages of the race, the univariable association between the explanatory variables trainer, track surface type and condition, distance and class of race was assessed by fitting univariable mixed-effects linear regression models. Here, a zero-mean, Gaussian distributed random intercept term was included in the model to account for lack of independence in the data arising from repeated observations on individual horses over time. Explanatory variables from the univariable analyses described above that were associated with the study outcome with $P<0.2$ were then selected for inclusion in the multivariable analysis for which we used a backwards stepwise variable selection procedure. All explanatory variables that were unconditionally associated with the outcome with $P<0.2$ were entered into the model and then removed one at a time, beginning with the least significant, until only those at $P<0.05$ remained. Explanatory variables were then re-entered into the model and retained if there was more than a 10% change in the magnitude of the regression coefficients of the other variables. Variables retained were screened for biologically plausible interaction effects. Diagnostics conducted included evaluation of model residuals, linearity, heteroscedasticity, and goodness of fit. Descriptive statistics, univariable and multivariable analysis at 200 m sectionals for the early, middle and late race were analysed using Stata version 15.0.[a]

In the second analysis for all 200 m sectionals over the entire race, explanatory variables found to be significant in the final multivariable models described above were included in a cross-classified multi-level multivariable model for each stride measure using the lmer function in R (R Core Team 2017).[b] The hierarchal levels in this data set comprised sectional observations nested within horse start, horse starts nested within individual horses and horses nested within trainer. In addition, there was a cross-classified hierarchy with horse starts nested within races within meetings (Fig. 2). Zero-mean, Gaussian distributed random effect terms were included in the model to account for these unmeasured influences on stride variables. As for the approach taken for the first analysis, backwards stepwise variable selection was used. Variance estimates of each of the random effect terms are reported as standard deviations, in addition to the intraclass correlation coefficient (ICC). The ICC quantifies the proportion of unexplained variation in the data attributable to each hierarchal level. Assessment of model fit was made on the basis of minimising the Bayesian information criterion (BIC) and visual assessment of scatter plots of observed versus predicted model outcomes. Model diagnostics were performed as per analysis (1).

Results

Speed and stride characteristics are presented in Table 1 and Fig. 3. R-squared correlations between speed and stride parameters are presented in Table 2. Speed correlated more strongly with the number of strides than with stride duration, but both stride variables had the greatest correlation in the final 200 m of each race ($P<0.001$; Table 3, Fig 3). The number of strides per 200 m and stride duration increased, and stride length and speed decreased with race progression ($P<0.001$). Mean (±SD) stride length, number of strides, stride duration and speed were 7.08±0.39m, 28.32±1.56 strides/200 m, 0.43±0.02 s/stride and 16.63±1.04m/s across all sectionals and starts. Linear models, compared to the non-linear transformations implemented in 'curve fit' best described the relationship between stride length and speed and stride duration and speed. There was no observable deviation from linearity for all stride characteristics between the elite horses and the general cohort, nor with race distance or finishing position based on scatter plots and density scatter plots. Using three-way interactions, all stride variables responded similarly to increasing speed under differing conditions.

Univariable associations between stride variables and horse- and race-level factors for early, mid and late race stages are presented in Table S1. In the multivariable staged models for the first set of analyses accounting for speed as a fixed effect, male sex, greater race distances, and firmer track surfaces were associated with fewer strides per sectional and longer duration of strides (Fig. 4). Male sex (geldings and intact males) was associated with fewer strides per sectional and longer stride durations, with geldings having the lowest number and longest duration and mares and fillies having the greatest number of strides of the shortest duration ($P<0.001$). Horses competing in longer distance races took fewer strides and strides of longer duration per 200 m sectional, an effect which was strongest mid race ($P<0.001$). Horses' stride characteristics on the synthetic track surface were similar to harder turf tracks (Fig. 4). On turf tracks the number of strides per sectional increased and stride duration decreased with increasing track rating, where firm tracks had the lowest number of strides per sectional and heavy tracks the greatest number of strides ($P<0.001$). Horses racing in Maiden and Class 1 races (lower class races) had a greater number of strides in the early race stages, with Listed and Group races (high class races) associated with the least number of strides per sectional ($P=0.02$). Horses that finished in a better position took less strides per sectional of longer stride durations early and mid-race, with more strides of shorter duration in the final sectional ($P<0.01$). Horses with a greater number of career starts took more strides per sectional in the mid and final sectionals ($P<0.01$). Weight carried was influential in the early and mid-race stages, with higher weights associated with fewer strides and longer stride durations ($P<0.001$). In the early race stage, older horse age was associated with longer stride durations ($P=0.04$) and shorter stride durations mid race ($P<0.001$).

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

In the cross-classified multi-level models across all 200 m sectionals race characteristics and horse sex influenced both the number of strides taken and the duration of strides (Table 3). Model fits were improved by the addition of a quadratic term for the percentage of the race complete interacting with the mean speed of each sectional recording, where speed gradually increased during each race start and then reduced as horses approached race completion. The cross-hierarchal multivariable models were improved by the addition of the interaction between class to weight carried described.

The majority of the unexplained variance in stride parameters was at the individual horse-level, with less variation at the start, race, meeting or trainer level (Table 3). The horse-level ICC for the number of strides taken and the duration of strides was 0.658 and 0.655, respectively. That is, sixty-six percent of the total unexplained variation in each stride variable was attributable to unmeasured horse-level effects.

Discussion

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

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

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

Over the course of a race start, horse speed and stride length reduced and stride count and stride duration increased. Leach and Sprigings [33] assessed the speed of 17 horses at the beginning and end of their races (1200-1400 m) and, similar to our findings, all horses reduced speed and increased stride duration over the course of the race. Investigations of speed and racing position across a large number of race-starts in the UK identified a similar reduction in speed with race progression [34]. In that study, speed was influenced by racing strategy, race distance and positioning within the field to reduce wind resistance [34]. Our finding of reducing speed and stride length during a race is comparable to data in human triathletes which the authors suggested was in response to fatigue [35]. Similarly, changes in stride length and frequency of horses at the end of a race were termed "gait fatigue" by Leach and Sprigings [33]. That study showed a consistent relationship between stride duration and speed but divergent responses between stride length and speed; approximately half of the horses reduced, a third maintained, and the remainder increased their stride length despite reduced speed [33]. The authors described the latter category as "over-striding" indicative of poor running technique compared to the more energy efficient pattern of a shorter stride length at a higher stride frequency. As a cohort, our horses demonstrated both reduced stride length and increased duration (reduced frequency) in association with the reduction in speed.

Individual horse-level factors were associated with stride characteristics. Female horses took the greatest number of strides per sectional with the shortest stride duration. Differing stride characteristics based on horse-level factors were previously recorded in non-race galloping sessions, with fillies having shorter strides compared to colts, and 2-year-olds having shorter strides than older horses [13]. We postulate that this is in part due to the smaller body size and shorter limb length of female and younger horses [36-38]. Comparatively, age had a more variable effect on duration of stride by race stage in the present study and was not statistically significantly associated with the number of strides taken. Total race time decreases (i.e. horses run faster) for 3-year-olds compared with 2-year-olds [39]. Higher weight carried was associated with reduced number of strides of greater duration in the early and mid-race stages. Across all 200 m race sectionals this effect was more prominent in lower class races, with horses in high class races maintaining their stride characteristics as weight carried increased. There was no effect on stride duration of increasing weight carried in Warmbloods at walk, trot or canter, although carrying 10% additional bodyweight in Standardbreds was associated with an increased stride rate [29,40]. The effect of weight on stride length for galloping horses has not been analysed to the best of our knowledge. Finally, in the present study, for the late stages of a race better finishing positions were associated with greater stride counts (shorter stride lengths). The final 200 m sectional corresponds with the most competitive environment, and therefore it could have been expected that stride lengths would be longer for better performing horses, however, in this part of the race the shorter stride durations were associated with improved performance. In humans stride length is positively correlated with performance, which agrees with the association between finishing position and stride length we observed over whole race starts [35].

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

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

Equine limbs need to withstand large forces when galloping at racing speeds and the magnitude and duration of loading is associated with injury [1,3,4,47,48]. Therefore, variation in stride characteristics could be an important contributor to an individual's risk of injury. Of the horse- and race-level factors associated with stride characteristics in the present study, in particular older age, male sex, and firmer turf track surfaces are demonstrated risk factors for race day catastrophic musculoskeletal injuries [49]. The largest degree of variation in stride characteristics found was between individual horses; therefore, comparing horses in determining injury-risk may not be as important as longitudinal monitoring individual horses to recognise changes in stride parameters over time.

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

Conclusions

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

Authors' declaration of interests

The authors have no competing interests to declare.

Ethic animal research

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

Owner informed consent

Data collection is required by the racing authority. Representatives of Tasracing gave consent for this study.

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Data accessibility statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Authorship

A. Morrice-West, P. Hitchens, E. Walmsley and R.C. Whitton contributed to the study design. A. Morrice-West contributed to the study execution. A. Morrice-West, P. Hitchens, M. Stevenson and R.C. Whitton contributed to the data analysis and interpretation. All authors contributed to the preparation and approval of the manuscript.

Manufacturers' addresses

[a]Stata Version 15.0 StataCorp, College Station, Texas, USA.

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

Figure legends

Fig 1: Flowchart illustrating the size of the database used and sequential data exclusion.

Fig 2: Data structure showing the cross-classified hierarchy of 200 m race sectional stride and speed data of individual starts within individual horse and within race and meeting for GPS recorded Thoroughbred races in Tasmania, Australia.

Fig 3: Sunflower density plot showing the relationship of speed with sectional (200 m) averages for the number of strides per 200 m (top row) and stride frequency (bottom row) in Thoroughbred racing for *n*=25,259 race starts in Tasmania, Australia derived from GPS recordings. From low density (peripheral) to high density (central areas): blue areas represent one-two observations, followed by moderate density, where each brown segment of the region represents one observation. The high-density region is shown in orange, with each black segment representing 25 observations. The darkest middle region therefore represents the highest density of overlapping observations.

Fig 4: Coefficient plot from multivariable linear regression modelling of speed of each of the 25,259 race starts to the number of strides taken in 200 m sectionals (left pane) and the duration of strides (right pane), showing the proportional change of horse and race-level factors on the respective stride parameters in the early, middle and late stages of Thoroughbred racing by 2,678 horses in Tasmania, Australia, plotted as coefficients and their 95% confidence intervals.

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

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

Missing points for weight carried, age and race class variables imply non significance in multivariable models.

Supplementary Information

Table S1: Univariable regression results for stride parameters early, mid and late race.

Table S2: Multivariable regression results for stride parameters early, mid and late race.

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705 **Table 1:** *Descriptive analysis of speed and stride characteristics (mean ± SD.) determined by StrideMaster GPS and accelerometer derived data for n=25,259 Thoroughbred race starts, by 2,678 horses [totalling 153,315 sectionals observations (200 m race segments)] in Tasmania, Australia. Results are stratified by the distance (m) and the class of each race start.*

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

Class 2-5	3,808	17.01±1.07	27.98±1.58	7.17±0.41	0.42±0.02
HCP/BM	16,428	16.68±0.99	27.96±1.50	7.17±0.39	0.43±0.02
Open	40	16.64±0.46	27.36±1.40	7.33±0.37	0.44±0.02

⁺Handicap/Benchmark races

Table 2: *Pearson correlation coefficients as R-squared values and their associated 95% confidence intervals (95%CI) for speed (m/s), number of strides per 200 m and stride duration (s) of n=25,259 Thoroughbred race starts in Tasmania, Australia using GPS and accelerometer derived data and stratified by three stages of each race.*

Outcome	Early⁺	Middle⁺	Late⁺	All race sectionals⁺
	R^2 (95% CI)	R^2 (95% CI)	R^2 (95% CI)	R^2 (95% CI)
Number of strides to speed	0.423 (0.412 ,0.432)	0.375 (0.365 ,0.383)	0.536 (0.527 ,0.543)	0.510 (0.506, 0.513)
Stride duration to speed	0.203 (0.195 ,0.213)	0.166 (0.158 ,0.174)	0.269 (0.260 ,0.279)	0.270 (0.266 ,0.274)
Number of strides to stride duration	0.145 (0.137 ,0.154)	0.221 (0.213 ,0.230)	0.040 (0.035 ,0.44)	0.049 (0.048 ,0.051)

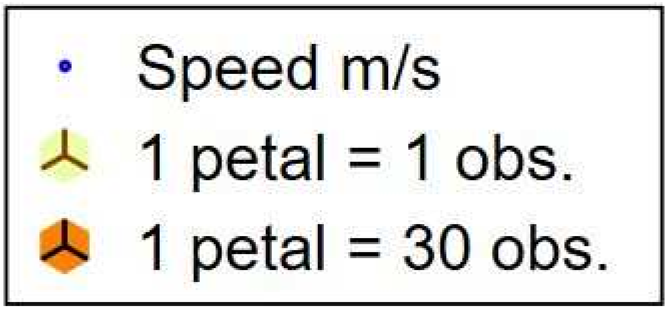
⁺All correlations $p<0.001$

Table 3: *Multivariable models of number of strides per 200 m sectional and stride duration of n=25,259 Thoroughbred race starts (totalling 153,315 sectional observations) in Tasmania, Australia using GPS and accelerometer derived data. Model results are presented as regression coefficients, with associated standard errors of the mean (s.e.m.), t-values, p-values and 95% confidence intervals. Variation at each hierarchal level (random effect terms) is displayed as the standard deviation (intraclass correlation coefficients [ICC]).*

	Number of strides per 200 m				**Stride duration (s)**			
	Regression coefficient (s.e.m)	**t value**	**p value**	**95%CI**	**Regression coefficient (s.e.m)**	**t value**	**p value**	**95%CI**
Fixed effects								
Speed (m/s)	-1.134 (0.002)	-609.97	<0.001	-1.138, -1.130	-0.009 (0.000)	-318.52	<0.001	-0.009, -0.009
Horse Sex								
Filly/Mare	(reference)				(reference)			
Gelding	-0.658 (0.032)	-20.25	<0.001	-0.722, -0.594	0.010 (0.001)	20.38	<0.001	0.009, 0.011
Colt/Stallion	-0.429 (0.103)	-4.15	<0.001	-0.632, -0.227	0.007 (0.002)	4.26	<0.001	0.004, 0.010
Race Distance (per 100 m)	-0.077 (0.001)	-63.82	<0.001	-0.079, -0.075	0.001 (0.000)	68.98	<0.001	0.001, 0.001
Track type & Rating								
Synthetic	(reference)				(reference)			
Firm 2	-0.005 (0.128)	-0.04	0.97	-0.257, 0.246	-0.0001 (0.002)	-0.06	0.96	-0.004, 0.004
Good 3	0.028 (0.025)	1.13	0.26	-0.021, 0.077	-0.0002 (0.0004)	-0.63	0.53	-0.001, 0.0005
Good 4	0.047 (0.017)	2.72	0.01	0.013, 0.081	-0.001 (0.0003)	-2.23	0.03	-0.001, -0.0001
Soft 5	0.081 (0.019)	4.36	<0.001	0.045, 0.117	-0.001 (0.0003)	-4.62	<0.001	-0.002, -0.001
Soft 6	0.179 (0.028)	6.47	<0.001	0.124, 0.233	-0.003 (0.0004)	-6.85	<0.001	-0.004, -0.002

Soft 7	0.293 (0.029)	10.15	<0.001	0.236, 0.349	-0.004 (0.0004)	-10.32	<0.001	-0.005, -0.004
Heavy 8	0.442 (0.027)	16.51	<0.001	0.389, 0.494	-0.006 (0.0004)	-15.91	<0.001	-0.007, -0.006
Heavy 9	0.508 (0.047)	10.76	<0.001	0.415, 0.601	-0.007 (0.0007)	-9.32	<0.001	-0.008, -0.005
Heavy 10	0.642 (0.067)	9.53	<0.001	0.510, 0.774	-0.008 (0.001)	-8.32	<0.001	-0.010, -0.006
Finishing position (per 10 places)	0.111 (0.007)	16.17	<0.001	0.097, 0.124	-0.002 (0.0001)	-15.61	<0.001	-0.002, -0.001
Percentage race complete (x)	104.874 (10.63)	9.87	<0.001	84.049, 125.699	10.194 (0.159)	48.61	<0.001	9.918, 10.470
Percentage race complete (x^2)	642.709 (9.376)	-68.55	<0.001	-661.086, -624.332	0.552 (0.141)	72.42	<0.001	0.548, 0.555
Weight carried (per 10kg)	-0.017 (0.019)	-0.91	0.36	-0.053, 0.019	0.0002 (0.0003)	0.87	0.39	-0.0003, 0.001
Race class								
Maiden/Class 1	(reference)				(reference)			
Class 2-5	0.067 (0.192)	-1.39	0.16	-0.221, 0.087	0.004 (0.003)	1.55	0.12	-0.001, 0.010
Restricted (HCP/BM)	-0.255 (0.134)	-1.91	0.06	-0.518, 0.007	0.004 (0.002)	2.05	0.04	0.0002, 0.008
Listed /Group	0.071 (0.659)	-0.56	0.58	-0.158, 0.299	0.009 (0.01)	0.97	0.33	-0.010, 0.029
Open	0.479 (0.444)	1.08	0.28	-0.391, 1.349	-0.006 (0.007)	-0.9	0.37	-0.019, 0.007
Intercept	48.592 (0.114)	427.63	<0.001	48.369, 48.814	0.552 (0.002)	324.71	<0.001	0.548, 0.555
Interaction terms								
Speed:Percentage race complete (x)	-3.782 (0.641)	-5.9	<0.001	-5.037, -2.526	-0.510 (0.010)	-53.1	<0.001	-0.529, -0.491
Speed:Percentage race complete (x^2)	39.435 (0.566)	69.74	<0.001	38.327, 40.544	-0.634 (0.008)	-74.72	<0.001	-0.651, -0.618

Weight carried:Maiden/Class 1	(reference)				(reference)			
Weight carried:Class 2-5	0.056 (0.034)	1.64	0.10	-0.011, 0.124	-0.001 (0.001)	-1.79	0.07	-0.002, 0.0001
Weight carried:Restricted (HCP/BM)	0.062 (0.566)	2.6	<0.001	0.015, 0.109	-0.001 (0.0004)	-2.74	0.01	-0.002, -0.0003
Listed /Group	0.071 (0.071)	0.61	0.54	-0.158, 0.299	-0.002 (0.002)	-1	0.32	-0.005, 0.002
Weight carried:Open	-0.067 (0.079)	-0.854	0.39	-0.221, 0.087	0.001 (0.001)	0.71	0.48	-0.001, 0.003
Random effects	SD. (ICC)				SD. (ICC)			
Horse start	0.178 (0.032)				0.003 (0.032)			
Horse	0.808 (0.658)				0.012 (0.655)			
Race	0.122 (0.015)				0.002 (0.013)			
Meeting	0.110 (0.012)				0.002 (0.013)			
Trainer	0.119 (0.014)				0.002 (0.015)			



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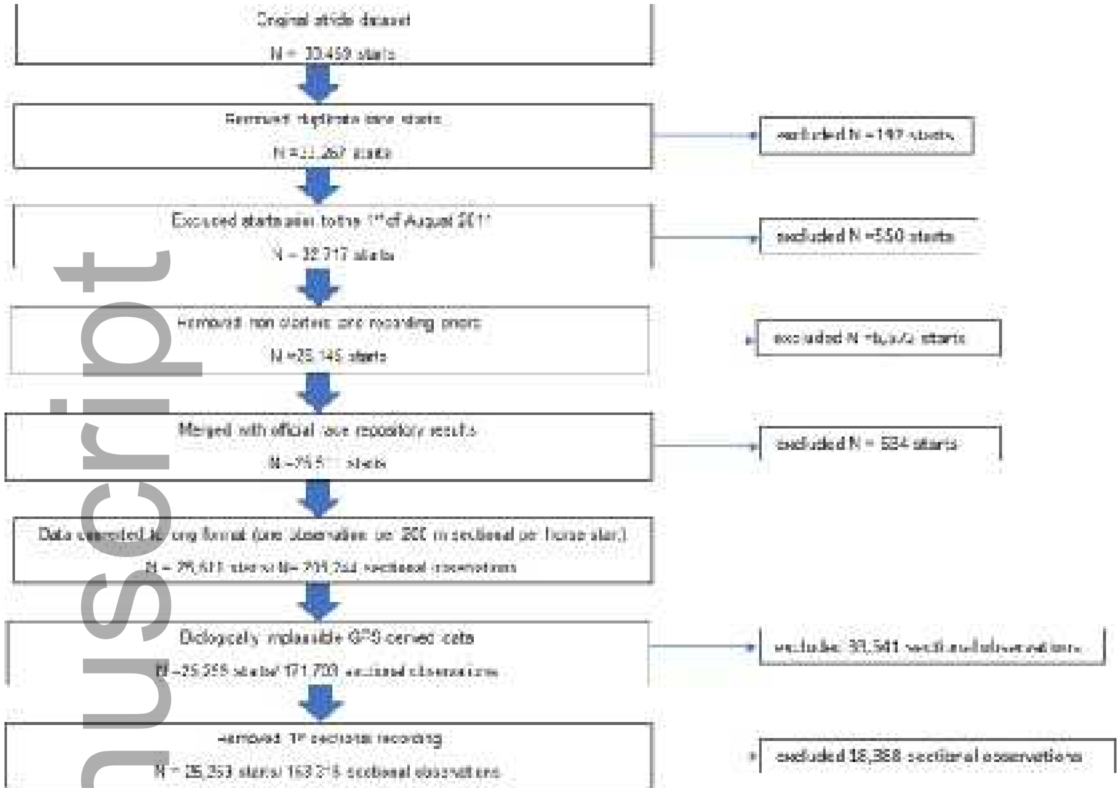

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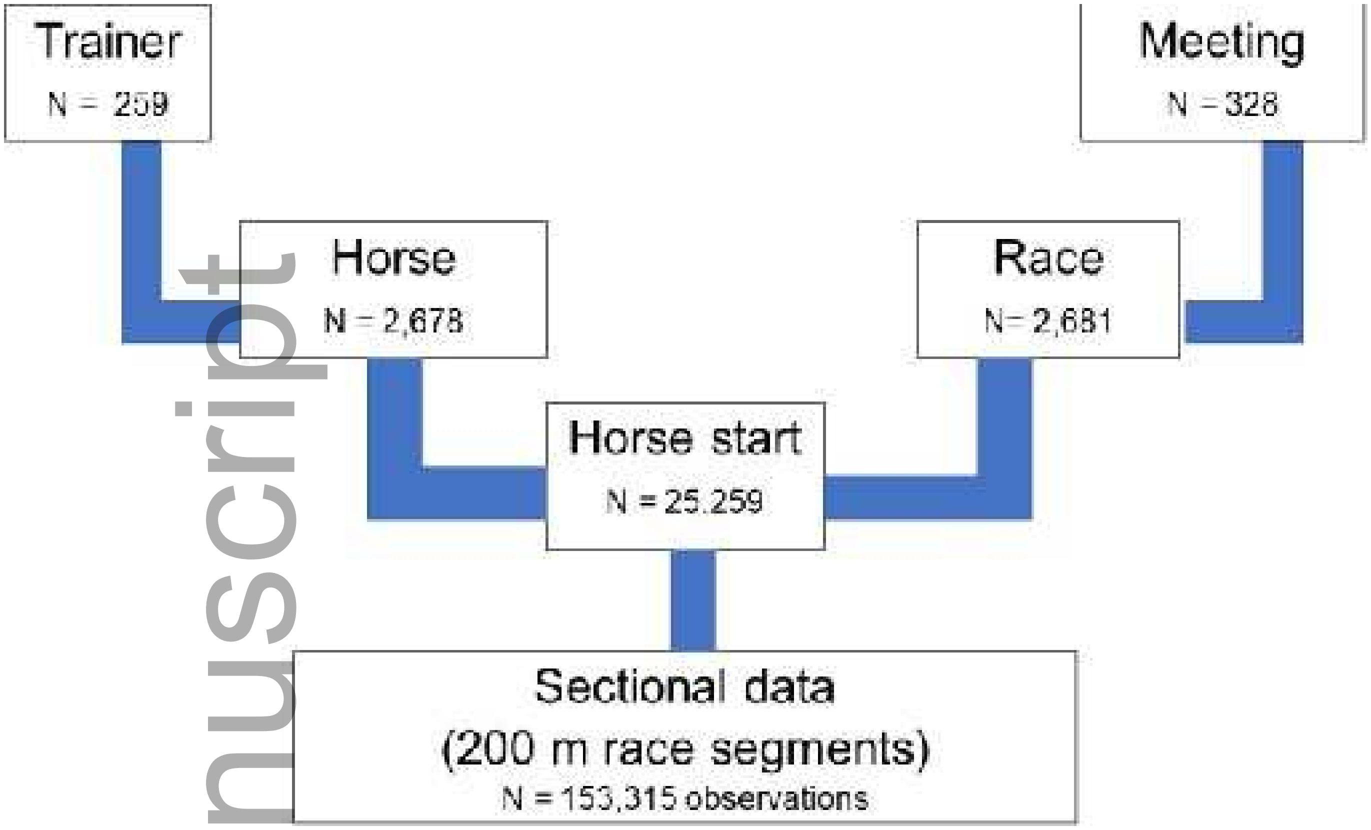

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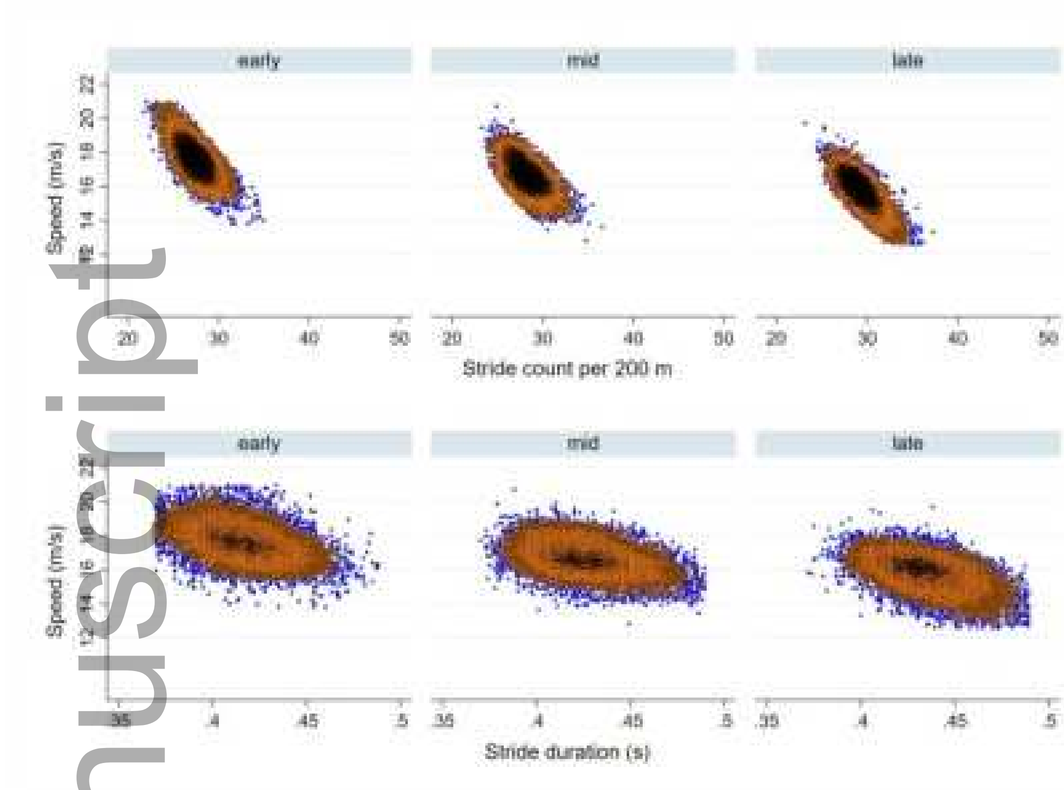

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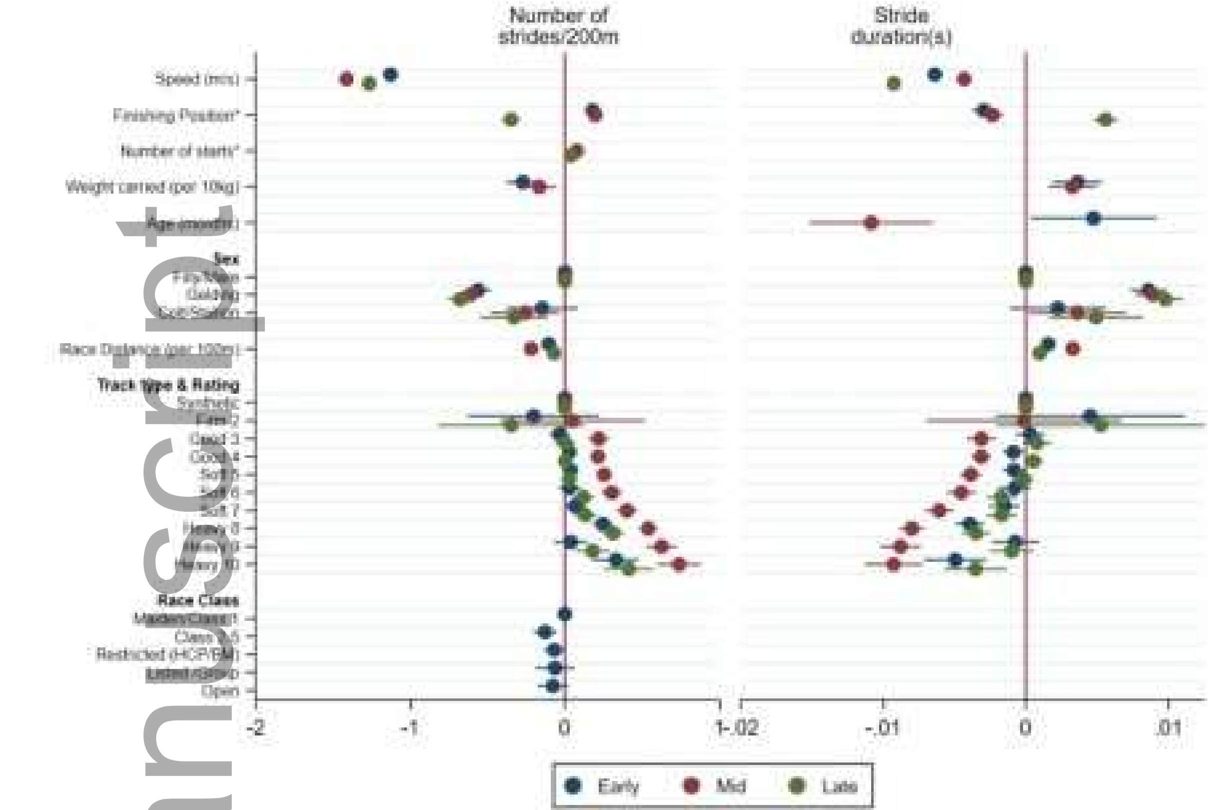

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