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Article

Hoof Impact and Foot-off Accelerations in Galloping Thoroughbred Racehorses Trialling Eight Shoe-surface Combinations

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Simple Summary: To achieve optimal performance and low injury occurrence in horse racing it is important to understand hoof-surface interactions. This study measured hoof accelerations in retired Thoroughbred racehorses as they galloped over turf and artificial surfaces in four shoeing conditions (aluminium, barefoot, steel and GluShu), using hoof-mounted accelerometers. During hoof landing, accelerations were increased for hindlimbs and leading limbs and on turf compared to the artificial surface. Barefoot hooves experienced the lowest impact accelerations and contrasted most with steel. During the propulsive stage of the stride, accelerations at 'foot-off' were increased for low stride times, particularly in hindlimbs, and on the artificial track. Increased impact accelerations on turf and in shod conditions could be detrimental to health and have implications for musculoskeletal injuries, whereas increased foot-off accelerations on the artificial surface may reflect this surface returning energy to the hoof and aiding propulsion, which could confer a performance benefit. Further work is needed to relate these findings to injury risk and racing outcomes specifically, particularly in racehorses galloping at top speeds.

Abstract: The athletic performance and safety of racehorses is influenced by hoof-surface interactions. This intervention study assessed the effect of eight horseshoe-surface combinations on hoof acceleration patterns at impact and foot-off in 14 galloping Thoroughbred racehorses retired from racing. Aluminium, barefoot, GluShu (aluminium-rubber composite) and steel shoeing conditions were trialled on turf and artificial (Martin Collins Activ-Track) surfaces. Shod conditions were applied across all four hooves. Tri-axial accelerometers (SlamStickX, range ±500 g, sampling rate 5000 Hz) were attached to the dorsal hoof wall (x: medio-lateral, medial=positive; y: along dorsal hoof wall, proximal=positive; z: perpendicular to hoof wall, dorsal=positive). Linear mixed models assessed whether surface, shoeing condition or stride time influenced maximum (most positive) or minimum (most negative) accelerations in x, y and z directions, using ≥40,691 strides (significance at $p<0.05$). Day and horse-rider pair were included as random factors and stride time as a covariate. Collective mean accelerations across x, y and z axes were 22–98 g at impact and 17–89 g at foot-off. Mean stride time was 0.48 ± 0.07 s (mean ± 2 s.d.). Impact accelerations were larger on turf in all directions for forelimbs and hindlimbs ($p \le 0.015$), with the exception of forelimb z-minimum, and in absolute terms maximum values were typically double minimum values. Surface-type affected all foot-off accelerations ($p \le 0.022$), with the exception of hindlimb x-maximum; for example, there was an average increase of 17% in z-maximum across limbs on the artificial track. Shoe-type influenced all impact and foot-off accelerations in forelimb and hindlimb datasets ($p \le 0.024$), with the exception of hindlimb impact y-maximum. Barefoot hooves generally experienced the lowest accelerations.

Stride time affected all impact and foot-off accelerations (p<0.001). Identifying factors influencing hoof vibrations on landing and hoof motion during propulsion bears implication for injury risk and racing outcomes.

Keywords: racehorse; hoof; acceleration; gallop; shoeing; surface; stride time

1. Introduction

Whole horse kinematics and injury mechanics are influenced by hoof-surface interactions. Establishing factors that control the timing and patterns of equine hoof motion throughout a stride cycle is necessary for optimising equine biomechanical function and performance, lessening the risk of injuries and enhancing economic gains. Thoroughbred racehorses galloping at high speeds during training and racing are particularly vulnerable to injuries [1–5]. As a result, the racing industry are placing increasing emphasis on understanding intrinsic and extrinsic factors that modulate a horse's output on the track. This study focuses on the latter, and in particular seeks to better understand how the hoof kinematics of Thoroughbred racehorses relates to their shoeing condition and the ground surface they are travelling over, at a range of gallop speeds.

Horses move asymmetrically over the course of a gallop stride cycle, so the sequence of footfalls influences the accelerations and loads experienced [6,7]. Hooves experience high deceleration and impact shock vibrations as they collide with the ground surface during galloping [8]. These vibrations are transmitted through the distal limbs [9,10] and may be quantified by accelerometers mounted to the hooves and/or the distal limbs [11–16]. Hoof impact-related shock is damped by the musculoskeletal structures of the limbs and hooves [10,17]. The accelerations just before the impact can be attributed to variability in hoof position in preparation for hoof contact with the ground surface [15]. The larger magnitude peaks are usually caused by the impact and hoof sliding and decelerating on the surface [18]. The hoof is also is highly efficient at energy absorption [19], with approximately 70% of impact vibrations being damped in this structure [9]. The primary impact, or landing phase, for each hoof is followed by the secondary impact, during which time the hoof becomes largely fixed to the ground surface. The mass of the horse and jockey move forwards in the secondary impact and although forces experienced by the limb in question are high, the hoof experiences minimum deceleration [8,12,20]. It may slide and/or sink into the surface at this stage. This lowers the forces during deceleration [21,22] and reduces bending moments on the cannon bone [18]. However, excessive hoof slide can predispose to injury, such as tears to the digital flexor muscles [23]. Each limb experiences peak vertical load as the horse transitions from braking to propulsion and its centre of mass is accelerated forwards [24]. This stage is termed 'mid-stance' and is a period of greater hoof stability [25]. Vertical ground reaction force peaks at 50–60% of the way through stance [6,26], but can vary with speed and whether the leg is the lead or non-lead leg; although at fast gallop this distinction disappears [8]. During propulsion, the heels of a hoof lift away from the surface and rotate about the toe, and the associated limb is gradually unloaded [8,27]. The solear surface is rotated through approximately 90 degrees during 'hoof breakover' [28]. Finally, a limb will enter the swing phase, and hoof accelerations are once again high due to rapid hoof rotation as the joints of the digit flex and the limbs catch up with and overtake the position of the upper body while travelling at high speed.

To understand what enables horses to perform well and how injuries occur, it is important to consider all aspects of the hoof-surface interaction and the factors that may control this. Early proactive interventions may preserve the health of racing equine athletes as well as improve performance both in the short and longer term. Micro-fractures in subchondral bone, cartilage breakdown and joint degeneration have been documented in response to the natural landing of the hoof during locomotion [9,18,29,30]. In trotting horses, the acceleration power and frequency of hoof wall vibrations increase with increasing substrate hardness [31,32]. Lameness and injuries have been linked to the magnitude of impact forces and surface hardness [33,34], including injuries to the superficial digital flexor tendons in trotters through altered loading and joint kinematics [35,36]. The detrimental effect of high-frequency vibrations on the musculoskeletal system is also apparent through osseous changes, which can ultimately result in lameness [37–39]. The influence of surface type on racing injuries, specifically, has been documented previously, but with conflicting results. A pooled analysis of multiple studies suggested that there were no differences in catastrophic musculoskeletal injuries between turf and all-weather or synthetic tracks, or turf and dirt tracks [1]. However, the nuances of individual racing settings may be an important consideration. For example, the competitive nature of the track varies across racing settings. In Florida, turf races are more competitive than dirt races and are run with larger fields, over longer distances and for more prize money [40]. It may also be important to consider front and hind limbs and lead versus non-lead limbs separately: for example, when turf, synthetic and dirt tracks are compared, forelimb injuries are more common on dirt whereas fatal hindlimb fractures are most likely on turf; although regardless of surface, forelimbs are more likely to fracture [41]. Furthermore, the exact nature of each surface should be considered, as the broad categories of turf, synthetic and dirt may not well represent individual tracks; there is considerable variation in the composition of synthetic surfaces. Track conditions are also critical, as temperature and moisture content influence properties such as firmness and cushioning [42–44]. Saturated dirt tracks are more risky than turf [1] and muddy and/or sloppy dirt tracks are associated with more catastrophic musculoskeletal injuries compared to faster dirt tracks [40,45,46]. Some research also suggests turf tracks that are faster increase the risk of fatal and non-fatal fractures and musculoskeletal injuries [2,45,47,48], catastrophic musculoskeletal injuries and fatality [49–51], fatal distal limb fracture [52,53], and fatal lateral condylar fracture [54]. The nature of the injury is also a relevant consideration; for example, all-weather tracks may increase the risk of biaxial proximal sesamoid bone fracture [55], fatal distal limb fracture [52,53], lateral condylar fracture [56] and lower limb injuries [2] compared to turf. However, more generally speaking, fatal and non-fatal fractures may be at a lower risk on synthetic tracks compared to turf and dirt [57]. Relatively low hoof accelerations, vibrations and peak ground reaction forces have been associated with some synthetic surfaces relative to turf and dirt, which may explain the reduction in some injuries [15,58]. This may be related to their damping capacities: ex-vivo synthetic surfaces have been shown to have a greater damping capacity than dirt [58] and in-vivo studies indicate synthetic surfaces also have a greater damping capacity and lead to reduced hoof vibrations on landing, compared to turf and dirt [15] and crushed sand [16]. Furthermore, in terms of racing performance, a smoother transition from stance to propulsion has been linked to a faster track rebound rate, which has an inverse relationship with vertical hoof deceleration on impact [59]. This track property was investigated on turf overlying sandy loam soil, with artificially altered moisture content.

Epidemiological evidence suggests that, in addition to surface conditions, certain types of horseshoes are associated with a higher risk of injury in racehorses, and hence they are a further key component of the hoof-surface interaction. Rim shoes similar to natural hoof shape may decrease injury risk [60]. However, toe grabs may increase the incidence of fatal musculoskeletal injury, suspensory apparatus failure and cannon bone condylar fracture [60–62], possibly because toe grabs can be associated with an increase in hoof accelerations on impact and at breakover [63] and increased breaking forces [64]. Nevertheless, it seems important to take a holistic approach to understanding horse and race specific risk factors. For example, the association between injuries and toe grabs may not hold for other breeds, such as racing Quarter horses [65] and not all studies associate toe grabs with an increased risk of injury, such as suspensory apparatus failure in Thoroughbreds either [66]. In addition, racing Thoroughbreds commonly have a flat-foot, low heel hoof conformation (Dabareiner et al 2003, Peel et al., 2006), which may be lowered further by gallop training [67]. This hoof conformation has been linked to injury [68–70], perhaps because these horses experience different foot mechanics to other horses [71,72].

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In equestrian disciplines other than racing, and at lower speeds, the influence of shoe type on equine gait kinematics has received greater attention. For example, at walk and trot, horseshoe shape and material have been reported to change slip during the secondary impact [73] and shoe mass may influence the flight arc of the hoof in the swing phase [74,75]. The influence of shoeing on horse upper body motion has also been reported, including the effect lateral hindlimb road nails and orthotic lifts have on increasing pelvic motion in trotting horses [76,77]. The nature of the hoof trim can also be influential to gait kinematics, including breakover duration [78–81], although this finding is not universal [82]. However, data collected from horses used in other equestrian disciplines and at slower gaits are not directly relatable to the racehorse. Limited data are available to understand the effect of shoes on the racehorse gait kinematics, and these have so far tended to rely upon simulated conditions, such as treadmill work [83] or mechanical shoe testing devices [84], with unclear representation to a horse racing on a track. Our recent work assessing galloping racehorses in the field has alluded to the influence of shoe-surface conditions on hoof kinematics; hoof breakover appears to be accelerated on an artificial surface compared to turf for all limbs and additionally influenced by shoeing condition in the non-leading hindlimb [28]. Further work is needed to establish the collective impact of shoes and surfaces on racehorse gait kinematics and kinetics, including the accelerations and loads experienced. In particular, it is worth noting that alterations to hoof motion appear to be reflected in the upper body movements of horses and their jockeys [85]. Hence, understanding the controls on the hoof-surface interaction in greater detail is likely to have implications for the likelihood of jockey injury and falls.

The aim of this study was to investigate the response of Thoroughbred hoof accelerations to different shoeing conditions trialled at gallop on turf and artificial surfaces. Both the magnitude of the hoof accelerations associated with the impact shock on landing, plus the accelerations associated with foot-off during the propulsive phase of stride cycles were of interest. We focussed on quantifying the magnitude and duration of vibrations experienced at the dorsal hoof wall, because of the equine hoof's strong ability to damp vibrations [9,10] and hence its sensitivity to variations in shoeing and surfaces should be greater than more proximal structures. The surfaces and shoeing conditions tested in this study were selected on the basis that they would develop a better understanding of widely used shoe-surface options, reflecting current racing guidelines in the UK. In addition, this study sought to investigate easily accessible yet novel shoeing options, which could be adopted by racehorse farriers, trainers and owners in the future.

In the UK, most horse races take place on turf, and there are currently only six racetracks with an artificial surface. However, artificial surfaces are more commonly used for training rather than for racing on. At present, UK farriers typically shoe Thoroughbred racehorses in steel shoes for training, and aluminium shoes for racing. This is because aluminium has the assumed benefit of being light, but it is more expensive than steel for farriers (and hence trainers) and it wears down quicker. During UK racing, it is a currently mandatory requirement that all horses competing in flat turf races enter fully shod, unless permission is otherwise granted by the British Horseracing Authority prior to the 48 hour declaration time to race, or for National Hunt flat races. This rule was implemented by the British Horseracing Authority in 2016 following an analysis of 12 months of race data; the data indicated an increased risk of a horse slipping if it was partially shod when racing under flat turf conditions. In addition, the following shoe-types are banned in the UK: shoes with protrusions on the ground surface other than calkins or studs on the hind, limited to 3/8" in height; American type toe-grab plates; and shoes with a sharp flange [86]. The latter rules appear to be a reflection of the epidemiological data discussed above. Toe grabs will also be banned in the USA from July 2022. From July, the rules in the USA will be as follows: horseshoes with full rims 2 mm or less from the ground surface of the horseshoe will not be allowed; traction devices will be prohibited on forelimb and hindlimb horseshoes during racing and training on dirt or synthetic racing tracks; and traction devices will be prohibited on forelimb and hindlimb horseshoes during training and racing on turf [87]. Here, traction devices include but are not limited to rims, toe grabs, bends, jar calks and stickers. Through this study, it is hoped that by developing a better understanding of the effect of various kinds of shoe-surface combinations on hoof motion at gallop, we will facilitate more informed selections of shoe-surface combinations to optimise Thoroughbred racing performance and lessen injury risk moving forward.

2. Materials and Methods

2.1. Ethics

Ethical approval for this study was received from the RVC Clinical Research Ethical Review Board (URN 2018 1841-2). Informed consent was given by the jockeys, farriers and owners of the horses participating in this study.

2.2. Horse and jockey participants

Fourteen retired Thoroughbred horses in regular work and utilised for jockey education at the British Racing School (BRS) in Newmarket, UK, provided a convenience sample. All horses were considered sound by the jockey, farriers and BRS management prior to data collection. They ranged in age from 6–20 years old, had heights between 15.3 and 16.3 hh (1.6–1.7 m) and their masses, quantified using a weigh tape, ranged from 421 to 555 kg. Additional body dimensions, hoof morphometrics and shoe masses for the horses are reported in [88]. Four jockeys participated in this study. One horse was ridden by two jockeys, giving rise to 15 horse-rider pairs. The same horse and jockey pairings were used throughout this study so 'horse-jockey combination' was fixed, while shoe-surface condition varied.

2.3. Trial conditions

Horses underwent trials on an artificial (Martin Collins Activ-Track) and turf surface at the BRS in four shoeing conditions: aluminium raceplates (Kerkhaert Aluminium Kings Super Sound horseshoes), barefoot, GluShus (aluminium-rubber composite shoes) and steel shoes (Kerkhaert Steel Kings horseshoes). The artificial track was a mixture of well-sorted quartz sand and CLOPFF fibre and it was wax coated. The turf track was well-drained owing to the predominantly chalk lithology beneath. Weather data on and preceding data collection days are available in [88]. Horses' hooves were trimmed prior to data collection and/or the application of shoes by the farriery team (JC, HC, LB or DH). All farriers followed the same trimming procedure set out by the lead farrier (JC). The order of trials for the eight possible shoe-surface combinations was randomized. The horses underwent a warm-up period in walk, trot, canter and gallop prior to data collection. Each data trial consisted of a minimum of two runs, to generate data for the horses galloping on both leads. However, some horses participated in additional runs if they struggled to achieve the desired lead, behaved unusually in a trial (such as bucking) or if equipment fell-off and needed to be reaffixed.

2.4. Equipment

Tri-axial accelerometers (SlamStick X) recording at a sample rate of 5000 Hz and with a measurement range of ±500 g were mounted to the dorsal hoof wall of each hoof in custom-made aluminium brackets (Figure 1). The brackets were glued to the hoof using Superfast hoof adhesive (Vettec). The accelerometers had in-built data loggers capable of recording continuously for up to 30 hours and their mass was 70 g. The x-axis of the accelerometers had a medio-lateral orientation (medial = positive), the y-axis was aligned along the hoof wall (proximal = positive) and the z-axis was in the dorso-palmar orientation (dorsal hoof wall = positive). Figure 1 illustrates the bracket design and sensor mounted to the hoof.

(A) **(B)** **(C)**

Figure 1. A) Aluminium bracket. **B)** Slamstick accelerometer. **C)** Sensor and bracket system mounted to hoof.

2.5. Data processing

Approximate timings of individual gallop runs were noted during data collection. These were used to identify relevant blocks of accelerometry data and a custom-written Matlab script was used to extract these data. A second custom-written Matlab script associated with a GUI was then used to identify key features of interest at hoof impact and push-off. In summary, strides were selected manually from blocks of accelerometry data and then visually enlarged. The approximate positions of impact and foot-off for the strides were then clicked on manually. The impact was taken to encompass accelerations immediately before heel strike, through to early stance. These positions were used in combination with a specified search window to identify the precise 'minimum' (most negative) and 'maximum' (most positive) values for the three acceleration axes at impact and push-off. A second impact peak was used to define stride time. The size of the search window was adjusted manually to cover the same features of interest regardless of stride duration, shoeing condition or surface. Data in the medio-lateral axis were inverted for the right fore and right hind to achieve a configuration with the medial direction as positive. The area under the acceleration traces at set points forwards and backwards from the timing of the minimum and maximum were also quantified; these were defined both in time (±5 ms, ±10 ms, ±15 ms and ±20 ms) and by percentage through stride (±1%, ±2%, ±3%, ±4%, ±5%). The areas reflected the change in velocity of the hoof in the period immediately prior to and post impact and push-off. The data were grouped by horse, jockey, limb, shoeing condition, surface, gallop lead and gallop run. All data were processed by the same person (KH).

A total of 41,183 strides were included in the analysis. Table 1 summarises the number available per shoe-surface combination for each limb.

Table 1. Number of strides per shoe-surface combination and the mean stride time over which the acceleration data were collected.

Limb	Shoe-Surface	n	Mean stride time
Leading Forelimb	Aluminium-Artificial	1420	0.472
Leading Forelimb	Aluminium-Turf	1030	0.490
Leading Forelimb	Barefoot-Artificial	1484	0.473
Leading Forelimb	Barefoot-Turf	599	0.486
Leading Forelimb	GluShu-Artificial	1032	0.492
Leading Forelimb	GluShu-Turf	1000	0.487
Leading Forelimb	Steel-Artificial	1337	0.482
Leading Forelimb	Steel-Turf	879	0.486
Non-leading Forelimb	Aluminium-Artificial	1357	0.471
Non-leading Forelimb	Aluminium-Turf	1060	0.491
Non-leading Forelimb	Barefoot-Artificial	1416	0.473
Non-leading Forelimb	Barefoot-Turf	700	0.484
Non-leading Forelimb	GluShu-Artificial	945	0.486
Non-leading Forelimb	GluShu-Turf	1063	0.484
Non-leading Forelimb	Steel-Artificial	1213	0.483
Non-leading Forelimb	Steel-Turf	887	0.485
Mixed-lead Forelimb	Aluminium-Artificial	771	0.479
Mixed-lead Forelimb	Aluminium-Turf	104	0.474
Mixed-lead Forelimb	Barefoot-Artificial	682	0.477
Mixed-lead Forelimb	Barefoot-Turf	606	0.464
Mixed-lead Forelimb	GluShu-Artificial	377	0.481
Mixed-lead Forelimb	GluShu-Turf	108	0.484
Mixed-lead Forelimb	Steel-Artificial	233	0.480
Mixed-lead Forelimb	Steel-Turf	579	0.477
Leading Hindlimb	Aluminium-Artificial	1235	0.469
Leading Hindlimb	Aluminium-Turf	972	0.491
Leading Hindlimb	Barefoot-Artificial	1452	0.470
Leading Hindlimb	Barefoot-Turf	753	0.483
Leading Hindlimb	GluShu-Artificial	997	0.491
Leading Hindlimb	GluShu-Turf	1088	0.489
Leading Hindlimb	Steel-Artificial	1286	0.483
Leading Hindlimb	Steel-Turf	936	0.481
Non-leading Hindlimb	Aluminium-Artificial	1180	0.470
Non-leading Hindlimb	Aluminium-Turf	972	0.489
Non-leading Hindlimb	Barefoot-Artificial	1581	0.471
Non-leading Hindlimb	Barefoot-Turf	594	0.479
Non-leading Hindlimb	GluShu-Artificial	1054	0.491
Non-leading Hindlimb	GluShu-Turf	982	0.487
Non-leading Hindlimb	Steel-Artificial	1035	0.483
Non-leading Hindlimb	Steel-Turf	986	0.478
Mixed-lead Hindlimb	Aluminium-Artificial	660	0.480
Mixed-lead Hindlimb	Aluminium-Turf	90	0.468
Mixed-lead Hindlimb	Barefoot-Artificial	523	0.470
Mixed-lead Hindlimb	Barefoot-Turf	751	0.455
Mixed-lead Hindlimb	GluShu-Artificial	353	0.481
Mixed-lead Hindlimb	GluShu-Turf	96	0.482
Mixed-lead Hindlimb	Steel-Artificial	112	0.479
Mixed-lead Hindlimb	Steel-Turf	613	0.466

2.6. Statistics

Mixed models were implemented in SPSS to test for significant differences in tri-axial acceleration peaks and areas under peaks at both impact and push over, under the different shoe and surface conditions. Shoe, surface and 'shoe-surface interaction' were defined as fixed factors and horse-rider pair and day as random factors. Stride time was included as a covariate. Histograms of models' residuals were plotted and normality confirmed. The significance threshold in all statistical tests was set at $p<0.05$. Models included data from all strides and a sub-set of the data for stride frequencies ≥2 Hz; 2 Hz is approximately equivalent to 9 ms^{-1} [89], which is a speed consistent with slow galloping speeds [90] and should exceed canter speeds of Thoroughbreds [83,91,92].

3. Results

3.1. Overview

We first present combined data for all limbs to assess the general patterns in the acceleration magnitudes per axis at impact and foot-off, independent of shoe or surface type. We then assess variability as a function of shoe and surface type for forelimbs versus hindlimbs, in which we incorporate data from all gallop runs, irrespective of whether the limb was leading or non-leading; this allows us to include data from mixed-lead gallop runs. There were 3460 forelimb and 3198 hindlimb data entries belonging to gallop runs in which a lead switch was noted at the time of data collection or apparent from the hoof accelerometry data (the regularity in impact and foot-off peak timings changed at the point of a lead switch). Alongside the leading and non-leading limb data, these 'mixed lead' runs were included in the linear mixed models for the forelimb and hindlimb data outputs listed as 'combined'. In addition, we assess leading and non-leading forelimbs and hindlimbs separately using only gallop runs in which the horse maintained a consistent gallop lead. Figure 2 illustrates example extracts of gallop strides per shoe-surface combination. The full raw data set is available in the Supplementary Data File.

It was apparent from the statistical models and a visual analysis of the minimum and maximum data using boxplots that differences between the entire dataset and the sub-set of data for stride frequencies ≥2 Hz were slight. Therefore, we focus on presenting and discussing the data from the entire data set in the main manuscript but make all results available in the Supplementary Data File.

To tackle the high volume of area data, a visual inspection using boxplots was helpful in identifying consistent trends amongst parameters. It was apparent that areas calculated for time windows extending further from the peaks had trends amongst shoe-surface conditions that were similar to those closer to the peaks. Therefore, we decided to focus on a small time window (5 ms) as this would best represent the nature of the main peak (sharp or broad) immediately following impact or foot-off. In addition, although the data representing areas under minimum and maximum peaks were similar, it was decided that the areas under maximum peaks depicted clearer trends and were likely to be more informative because they are associated with the accelerations transferred into the hoof in the distal to proximal direction. We also considered area data after the main peaks to be of more relevance than those that preceded the main peaks. As such, we present results for area data at impact and foot-off in the 5 ms time window after the maximum (Appendix 1); these data are available in the Supplementary Data File.

3.2. Combined limb overview

Considering all limbs together, on impact maximum accelerations were 44 ± 68 g (n = 41183) in the x direction (mean ±2 s.d., unless otherwise stated), 98 ± 128 g (n = 40844) in the y direction and 89 ± 128 g (n = 40691) in the z direction. Minimum accelerations at impact were -22 ± 35 g in the x direction, -34 ± 54 g in the y direction and -38 ± 49 g in the z direction. At foot-off, maximum accelerations were 17 ± 21 g in the x direction, 89 ± 72 g in the y direction and 50 ± 41 g in the z direction, while minimum accelerations were -17 ± 18 g in the x direction, -38 ± 44 g in the y direction and -30 ± 39 g in the z direction. The mean stride time was used as a proxy for speed, and this ranged from 0.32–0.66 s, with a mean value of 0.48 ± 0.07 s (mean stride frequency = 2.09 ± 0.3 Hz).

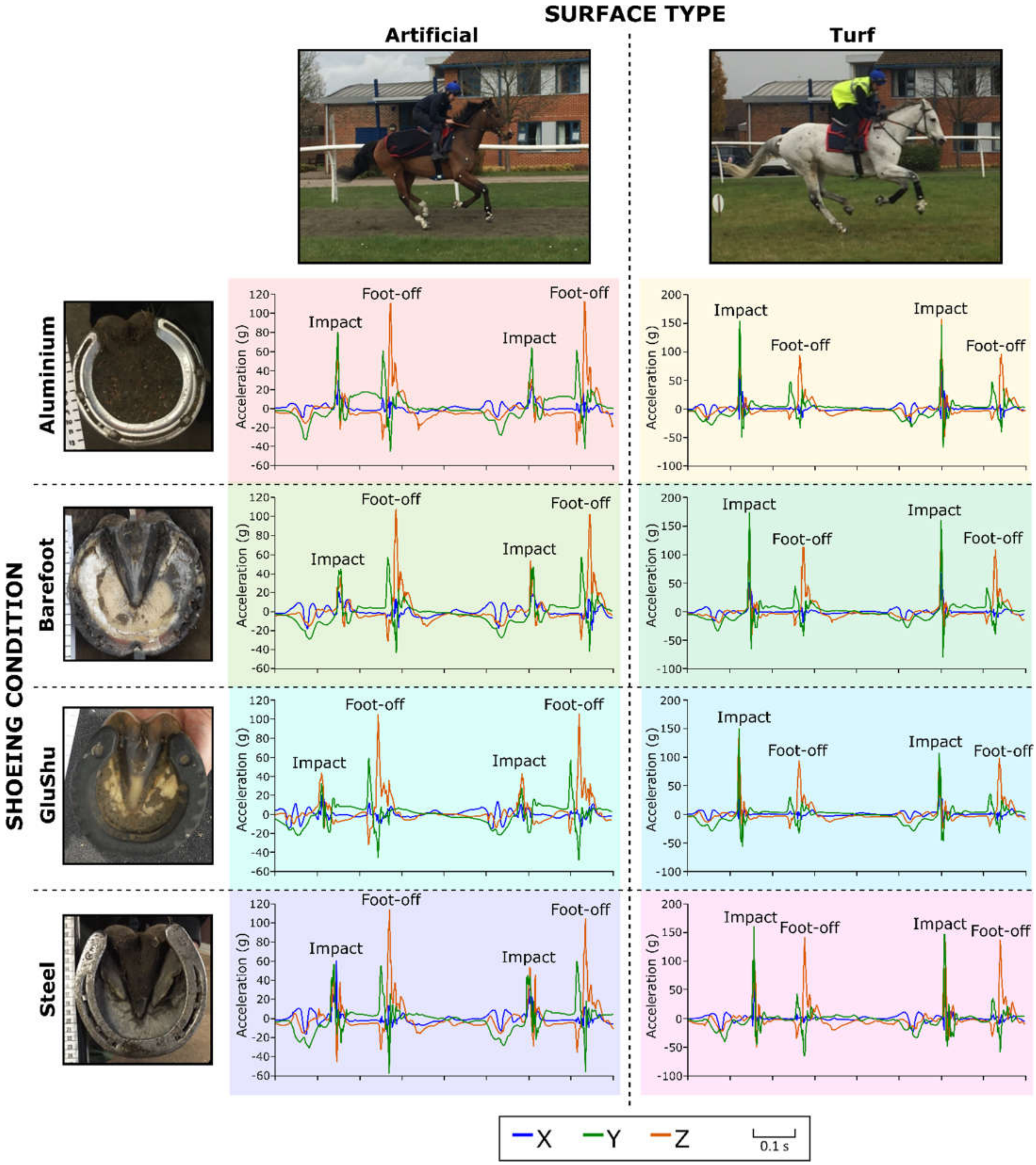

Figure 2. Examples of tri-axial accelerometry data collected from the hooves of the horse from horse-jockey combination 8 under the eight different shoe surface combinations: x is medio-lateral, y is along the hoof wall proximo-distal, and z is dorso-palmar.

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3.3. Forelimbs

3.3.1. Impact

All significance values that were output from the Linear Mixed Models are available in the Supplementary Data File (Table S1). In summary, minimum and maximum impact accelerations for forelimbs were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time ($p \leq 0.003$). The exceptions were y-maximum, which was unaffected by a shoe*surface interaction ($p=0.125$); and z-minimum, which was unaffected by surface type ($p=0.106$).

On impact, maximum accelerations in the leading forelimb were 42.4 ± 49.4 g (n = 8781) in the x direction, 94.4 ± 97.2 g (n = 8633) in the y direction and 102.2 ± 123.7 g (n = 8781) in the z direction. Minimum accelerations at impact were -20.7 ± 31.8 g in the x direction, -36.6 ± 51.4 g in the y direction and -35.4 ± 38.4 g in the z direction. Minimum and maximum accelerations for the leading forelimb were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time ($p \leq 0.027$). The exceptions were: x-maximum, which was unaffected by a surface*stride time interaction ($p=0.122$); and z-minimum, which was unaffected by either surface ($p=0.083$) or a surface*stride time interaction ($p=0.704$).

Maximum accelerations at impact in the non-leading forelimb were 30.7 ± 37.1 g (n = 8641) in the x direction, 78.0 ± 83.8 g (n = 8450) in the y direction and 67.9 ± 85.4 g (n = 8641) in the z direction. Minimum accelerations at impact were -17.4 ± 22.8 g in the x direction, -27.7 ± 38.7 g in the y direction and -36.6 ± 48.6 g in the z direction. Minimum and maximum accelerations for the non-leading forelimb were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time ($p \leq 0.035$). The exceptions were: x-maximum, which was unaffected by a shoe*stride time interaction ($p=0.052$) or a surface*stride time interaction ($p=0.831$); x-minimum, which was unaffected by surface*stride time ($p=0.799$); y-minimum, which was unaffected by shoe ($p=0.114$) and shoe*surface ($p=0.094$); and z-minimum, which was unaffected by surface ($p=0.530$).

Further details and comparisons amongst the shoe and surface conditions at impact are provided in sections 3.5–3.7.

3.3.2. Foot-off

Minimum and maximum foot-off accelerations for forelimbs were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time ($p \leq 0.024$). The exceptions were: x-maximum, which was unaffected by shoe*stride time ($p=0.082$); and y-minimum, which was unaffected by surface*stride time ($p=0.102$).

At foot-off, maximum accelerations in the leading forelimb were 14.6 ± 20.1 g (n = 8781) in the x direction, 95.7 ± 64.9 g (n = 8633) in the y direction and 46.8 ± 45.0 g (n = 8781) in the z direction. Minimum accelerations at impact were -16.7 ± 16.9 g in the x direction, -34.5 ± 34.3 g in the y direction and -29.9 ± 43.1 g in the z direction. Minimum and maximum accelerations for the leading forelimb were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time ($p \leq 0.037$). The exceptions were: x-maximum, which was unaffected by surface ($p=0.602$) or a surface*stride time interaction ($p=0.424$); y-minimum, which was unaffected by surface ($p=0.170$); and z-maximum, which was unaffected by either shoe ($p=0.072$) or a shoe*stride time interaction ($p=0.243$).

Maximum accelerations at foot-off in the non-leading forelimb were 13.3 ± 14.5 g (n = 8641) in the x direction, 91.6 ± 63.0 g (n = 8450) in the y direction and 43.8 ± 36.6 g (n = 8641) in the z direction. Minimum accelerations at impact were -17.3 ± 19.6 g in the x direction, -32.8 ± 31.6 g in the y direction and -27.9 ± 41.8 g in the z direction. Minimum and maximum accelerations for the non-leading forelimb were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time ($p \leq 0.017$). This was true for all axis directions.

Further details and comparisons amongst the shoe and surface conditions at foot-off are provided in sections 3.5–3.7.

3.4. Hindlimbs

3.4.1. Impact

Minimum and maximum impact accelerations for hindlimbs were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time (p≤0.048). The exceptions were x-maximum, which was unaffected by a shoe*stride time interaction (p=0.053); y-maximum, which was unaffected by shoe (p=0.053) or a shoe*stride interaction (p=0.184).

At impact, maximum accelerations in the leading hindlimb were 59.4 ± 85.9 g (n = 8719) in the x direction, 123.4 ± 150.6 g (n = 8719) in the y direction and 98.5 ± 120.4 g (n = 8606) in the z direction. Minimum accelerations at impact were -27.1 ± 42.2 g in the x direction, -37.5 ± 55.6 g in the y direction and -41.4 ± 62.9 g in the z direction. Minimum and maximum accelerations for the leading hindlimb were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time (p≤0.029). The exceptions were: y-maximum, which was unaffected by a surface*stride time interaction (p=0.755); y-minimum, which was unaffected by surface (p=0.916); z-maximum, which was unaffected by a surface*stride time interaction (p=0.962); and z-minimum, which was unaffected by either shoe (p=0.145) or a shoe*stride time interaction (p=0.067).

Maximum accelerations in the non-leading hindlimb were 39.5 ± 57.2 g (n = 8384) in the x direction, 87.1 ± 120.0 g (n = 8384) in the y direction and 65.6 ± 89.3 g (n = 8223) in the z direction. Minimum accelerations at impact were -19.1 ± 32.5 g in the x direction, -30.8 ± 52.3 g in the y direction and -39.2 ± 39.2 g in the z direction. Minimum and maximum accelerations for the non-leading hindlimb were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time (p≤0.028). The exception was x-minimum, which was unaffected by a shoe (p=0.267) or a shoe*stride time interaction (p=0.431). At impact there also tended to be a reduced spread in data for the non-leading hindlimb; this was also true for the non-leading forelimb (Figure 2).

Further details and comparisons amongst the shoe and surface conditions at impact are provided in sections 3.5–3.7.

3.4.2. Foot-off

Minimum and maximum foot-off accelerations for hindlimbs were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time (p<0.001). The exception was x-maximum, which was unaffected by surface (p=0.144) or a surface*stride time interaction (p=0.288).

At foot-off, maximum accelerations in the leading hindlimb were 19.8 ± 22.6 g (n = 8719) in the x direction, 77.8 ± 72.5 g (n = 8719) in the y direction and 51.7 ± 36.9 g (n = 8606) in the z direction. Minimum accelerations at impact were -16.3 ± 17.2 g in the x direction, -39.8 ± 46.9 g in the y direction and -30.2 ± 35.7 g in the z direction. Minimum and maximum accelerations for the leading hindlimb were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time (p≤0.044). The exception was x-maximum, which was unaffected by a shoe*stride time interaction (p=0.090).

Maximum accelerations in the non-leading hindlimb at foot-off were 16.3 ± 19.1 g (n = 8384) in the x direction, 83.8 ± 67.2 g (n = 8384) in the y direction and 56.0 ± 40.3 g (n = 8223) in the z direction. Minimum accelerations at impact were -17.2 ± 14.8 g in the x direction, -40.4 ± 45.9 g in the y direction and -33.5 ± 32.4 g in the z direction. Minimum and maximum accelerations for the non-leading hindlimb were significantly affected by shoe, surface, stride time, and interactions between shoe and surface, shoe and stride time and surface and stride time (all p≤0.047).

Further details and comparisons amongst the shoe and surface conditions at foot-off are provided in sections 3.5–3.7.

3.5. Summary of shoe effect

3.5.1. Impact

The estimated marginal means (EMMs) for shoe effects on impact are presented in Table 2 and all post-hoc pairwise comparisons (with Bonferroni correction) are provided in Table S2. Shoe-type significantly influenced all impact accelerations in the forelimbs (p≤0.026), with the exception of y-minimum in the non-leading forelimb (p=0.114). In the hindlimbs, shoe-type significantly influenced all impact accelerations (p≤0.010), with the exception of y-maximum for the combined dataset (p=0.053); z-minimum in the leading hindlimb (p=0.145) and x-minimum in the non-leading hindlimb (p=0.267). The EMM impact accelerations were largest in terms of absolute magnitude for y-maximum in the leading hindlimb (mean of EMMs across shoeing conditions was 128.1 g), with the individual largest EMM acceleration of 142.7±21.9 g (mean ± 2.s.e. in this section unless otherwise stated) being recorded for the y-maximum in the steel shoeing condition. For the y-maximum parameter, steel was most different to the barefoot condition particularly in the leading hindlimb (EMM difference = 33.1±4.1 g) increase in steel shoes compared to barefoot for the leading forelimb and the leading hindlimb, respectively (Supplementary Data Table S2). Mean impact maximum accelerations were 1.8–3.1 times larger than mean impact minimum accelerations, per axis direction. Y-maximum and z-maximum accelerations were of comparable magnitude and approximately double the magnitude of the x-maximum. The smallest accelerations, in terms of absolute magnitude, were recorded for the x-minimum in the non-leading forelimb (EMM average across shoeing conditions was 19.2 g), with the individual smallest absolute EMM acceleration of 16.2±5.0 g being recorded for the x-minimum in the barefoot condition.

Considering all six acceleration axes together in the individual limb datasets (non-leading forelimb, leading forelimb, non-leading hindlimb, leading hindlimb), the barefoot condition generated the lowest absolute means for EMM accelerations for all limbs: these ranged from 43.7±20.8 g (n=6) in the non-leading forelimb to 64.1±30.8 g in the leading hindlimb. In contrast, the steel condition generated the highest absolute means for EMM accelerations for all limbs: these ranged from 53.1±23.9 g in the non-leading forelimb to 74.2±35.5 g in the leading hindlimb.

3.5.2. Foot-off

Shoe-type significantly influenced all foot-off accelerations in the forelimbs (p≤0.024), with the exception of z-maximum in the leading forelimb (p=0.072). In the hindlimbs, shoe-type significantly influenced all impact accelerations (p≤0.044). The estimated marginal means (EMMs) for shoe effects on foot-off are presented in Table 2. The mean impact accelerations were largest in terms of absolute magnitude for y-maximum in the combined forelimb dataset (mean of EMMs across shoeing conditions was 95.6 g), with the individual largest EMM acceleration of 98.5±11.2 g being recorded for the y-maximum in the GluShu shoeing condition for the leading forelimb; the subsequent three largest acceleration magnitudes were for the y-maximum in the steel condition (97.2±11.2 g, 98.4±9.8 g and 97.6±10.7 g for the leading, non-leading and combined forelimb data, respectively) The smallest accelerations, in terms of absolute magnitude, were recorded for the x-maximum in the non-leading forelimb (mean across shoeing conditions was 13.7 g), with the individual smallest absolute EMM acceleration of 13.6±2.3 g being recorded for the x-maximum in the GluShu condition for the non-leading forelimb. Noticeably, the y-maximum accelerations were considerably larger than accelerations in the other axis directions: y-maximum were on average 5.4 times larger than x-axis accelerations, and 2.3 times larger than the y-minimum and z-axis accelerations. Nevertheless, pairwise comparisons between shoeing conditions only indicated a maximum difference of 13.1±1.2 g, which

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occurred between steel versus barefoot for the y-minimum parameter. The mean absolute difference between EMMs for pairwise shoe comparisons across all limbs was 3.2±0.3 g.

Considering all six acceleration axes together in the individual limb datasets (non-leading forelimb, leading forelimb, non-leading hindlimb, leading hindlimb), differences between conditions were small. The barefoot condition generated the lowest absolute means for EMM accelerations for all limbs: these ranged from 37.1±23.9 and 37.1±19.5 g (n=6) and in the non-leading forelimb and the leading hindlimb, respectively, to 39.1±21.6 g in the leading hindlimb. In contrast, the steel condition generated the highest absolute means for EMM accelerations for all limbs: these ranged from 40.2±25.2 g in the non-leading forelimb to 43.8±23.2 g in the non-leading hindlimb.

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Table 2 Estimated Marginal Means for shoe effects.

Limb	Parameter	Shoe	Impact Mean	Impact Std. Error	Impact df	Impact 95% Confidence Interval (lower bound)	Impact 95% Confidence Interval (upper bound)	Foot-off Mean	Foot-off Std. Error	Foot-off df	Foot-off 95% Confidence Interval (lower bound)	Foot-off 95% Confidence Interval (upper bound)
Forelimb (combined)	X-maximum	Aluminium	41.38	2.77	27.65	35.70	47.06	14.44	1.84	24.82	10.66	18.22
		Barefoot	37.26	2.77	27.66	31.58	42.94	14.80	1.84	24.83	11.02	18.58
		GluShu	40.60	2.78	28.09	34.90	46.30	13.67	1.84	24.99	9.88	17.45
		Steel	41.44	2.78	28.01	35.74	47.13	15.01	1.84	24.98	11.23	18.80
	X-minimum	Aluminium	-21.33	2.57	25.13	-26.63	-16.03	-17.49	2.16	23.93	-21.95	-13.02
		Barefoot	-16.96	2.57	25.13	-22.26	-11.66	-17.93	2.16	23.93	-22.39	-13.46
		GluShu	-21.30	2.58	25.31	-26.61	-15.99	-18.88	2.17	24.04	-23.35	-14.41
		Steel	-24.17	2.58	25.30	-29.47	-18.86	-18.19	2.17	24.04	-22.66	-13.72
	Y-maximum	Aluminium	93.60	7.90	23.77	77.30	109.91	93.47	5.36	23.59	82.41	104.54
		Barefoot	85.66	7.90	23.76	69.36	101.97	95.34	5.36	23.58	84.28	106.40
		GluShu	94.36	7.91	23.96	78.03	110.70	95.78	5.36	23.69	84.71	106.86
		Steel	102.49	7.91	23.93	86.16	118.82	97.60	5.36	23.68	86.53	108.68
	Y-minimum	Aluminium	-37.19	4.12	25.82	-45.66	-28.72	-35.04	3.85	19.47	-43.09	-26.99
		Barefoot	-30.39	4.12	25.81	-38.86	-21.93	-31.83	3.85	19.47	-39.89	-23.78
		GluShu	-35.26	4.13	26.05	-43.74	-26.78	-34.96	3.86	19.55	-43.01	-26.90
		Steel	-42.00	4.13	26.01	-50.48	-33.51	-34.99	3.86	19.54	-43.05	-26.93
	Z-maximum	Aluminium	102.57	9.07	21.50	83.73	121.41	46.94	2.85	23.52	41.06	52.83
		Barefoot	96.72	9.07	21.50	77.87	115.56	40.04	2.85	23.53	34.15	45.93
		GluShu	92.75	9.09	21.67	73.87	111.62	44.31	2.86	23.75	38.41	50.21
		Steel	97.89	9.09	21.65	79.02	116.76	47.87	2.86	23.73	41.97	53.77
	Z-minimum	Aluminium	-43.13	3.68	24.13	-50.72	-35.54	-31.25	7.12	23.91	-45.96	-16.55
		Barefoot	-33.67	3.68	24.13	-41.26	-26.08	-24.65	7.12	23.91	-39.36	-9.94
		GluShu	-37.48	3.69	24.32	-45.08	-29.88	-28.83	7.13	23.95	-43.54	-14.12
		Steel	-41.24	3.69	24.30	-48.84	-33.64	-33.02	7.13	23.95	-47.73	-18.31
Leading forelimb	X-maximum	Aluminium	47.50	3.65	25.04	39.99	55.01	15.17	2.82	24.41	9.35	20.99
		Barefoot	40.31	3.65	25.23	32.79	47.83	15.12	2.82	24.47	9.30	20.94
		GluShu	46.32	3.67	25.52	38.78	53.86	14.10	2.83	24.58	8.27	19.93
		Steel	46.88	3.67	25.47	39.34	54.42	15.41	2.83	24.59	9.58	21.23
	X-minimum	Aluminium	-22.06	2.70	21.68	-27.67	-16.45	-16.93	2.00	24.11	-21.05	-12.80
		Barefoot	-17.44	2.71	21.81	-23.05	-11.83	-17.87	2.00	24.17	-21.99	-13.75
		GluShu	-22.83	2.71	22.03	-28.45	-17.20	-18.25	2.00	24.29	-22.38	-14.12
		Steel	-24.73	2.71	22.00	-30.35	-19.10	-18.76	2.00	24.30	-22.89	-14.64
	Y-	Aluminium	102.03	8.79	21.46	83.78	120.28	92.72	5.60	22.57	81.13	104.30

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	maximum	Barefoot	91.63	8.79	21.54	73.37	109.89	93.74	5.60	22.61	82.14	105.33
		GluShu	97.22	8.82	21.74	78.92	115.51	98.48	5.61	22.74	86.88	110.09
		Steel	108.79	8.81	21.70	90.49	127.08	97.23	5.61	22.73	85.62	108.83
	Y-minimum	Aluminium	-40.08	3.77	22.19	-47.89	-32.27	-35.00	4.16	18.19	-43.73	-26.27
		Barefoot	-33.86	3.77	22.34	-41.68	-26.05	-31.33	4.16	18.22	-40.07	-22.59
		GluShu	-37.22	3.79	22.67	-45.06	-29.38	-35.98	4.17	18.30	-44.72	-27.23
		Steel	-47.09	3.79	22.56	-54.93	-39.25	-37.10	4.17	18.30	-45.84	-28.35
	Z-maximum	Aluminium	118.42	14.33	22.88	88.76	148.07	46.59	3.34	22.79	39.67	53.51
		Barefoot	109.48	14.34	22.93	79.81	139.15	39.17	3.35	22.95	32.23	46.09
		GluShu	105.67	14.35	23.02	75.98	135.36	42.57	3.36	23.21	35.62	49.52
		Steel	109.19	14.36	23.03	79.50	138.89	50.92	3.36	23.17	43.97	57.86
	Z-minimum	Aluminium	-39.65	3.20	23.67	-46.26	-33.04	-30.29	8.04	19.86	-47.07	-13.51
		Barefoot	-33.77	3.21	23.81	-40.39	-27.15	-26.41	8.04	19.88	-43.20	-9.63
		GluShu	-35.61	3.21	24.04	-42.24	-28.97	-28.95	8.05	19.91	-45.74	-12.16
		Steel	-42.36	3.21	24.01	-49.00	-35.73	-33.84	8.05	19.92	-50.63	-17.05
Non-leading forelimb	X-maximum	Aluminium	33.15	2.65	26.13	27.71	38.59	13.72	1.13	27.16	11.41	16.04
		Barefoot	33.24	2.65	26.25	27.79	38.69	14.01	1.13	27.27	11.70	16.33
		GluShu	33.37	2.66	26.62	27.91	38.84	13.59	1.13	27.61	11.27	15.91
		Steel	36.35	2.66	26.64	30.88	41.82	13.60	1.13	27.63	11.27	15.92
	X-minimum	Aluminium	-18.89	2.50	24.82	-24.04	-13.74	-17.86	2.71	23.53	-23.46	-12.26
		Barefoot	-16.15	2.50	24.86	-21.30	-10.99	-19.28	2.71	23.56	-24.89	-13.68
		GluShu	-19.17	2.51	25.02	-24.33	-14.01	-19.82	2.72	23.67	-25.43	-14.21
		Steel	-22.44	2.51	25.06	-27.60	-17.27	-16.55	2.72	23.71	-22.16	-10.94
	Y-maximum	Aluminium	81.08	8.65	24.25	63.24	98.91	91.36	4.90	24.12	81.24	101.47
		Barefoot	74.13	8.65	24.27	56.30	91.97	93.78	4.90	24.14	83.67	103.90
		GluShu	89.05	8.66	24.46	71.18	106.92	93.06	4.91	24.33	82.93	103.20
		Steel	94.86	8.67	24.48	76.99	112.73	98.36	4.91	24.34	88.22	108.49
	Y-minimum	Aluminium	-30.70	4.18	24.78	-39.31	-22.09	-35.44	3.97	18.69	-43.76	-27.11
		Barefoot	-27.07	4.18	24.81	-35.68	-18.45	-32.76	3.98	18.70	-41.09	-24.43
		GluShu	-31.18	4.19	25.00	-39.80	-22.55	-34.63	3.98	18.80	-42.97	-26.30
		Steel	-37.99	4.19	25.01	-46.62	-29.35	-32.31	3.98	18.81	-40.65	-23.97
	Z-maximum	Aluminium	79.49	6.63	27.91	65.91	93.07	46.68	3.13	24.28	40.23	53.13
		Barefoot	76.95	6.63	27.99	63.36	90.54	39.88	3.13	24.34	33.42	46.33
		GluShu	74.21	6.65	28.24	60.60	87.83	45.14	3.14	24.56	38.67	51.60
		Steel	84.50	6.65	28.28	70.87	98.12	45.64	3.14	24.60	39.17	52.11
	Z-	Aluminium	-43.68	4.55	21.28	-53.13	-34.22	-27.15	5.86	25.65	-39.21	-15.09

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	minimum	Barefoot	-34.83	4.55	21.32	-44.28	-25.37	-23.03	5.86	25.68	-35.08	-10.97
		GluShu	-38.98	4.56	21.48	-48.45	-29.51	-28.22	5.87	25.77	-40.29	-16.15
		Steel	-42.46	4.56	21.50	-51.93	-32.98	-34.56	5.87	25.80	-46.63	-22.49
Hindlimb (combined)	X-maximum	Aluminium	58.21	4.72	21.97	48.42	67.99	18.93	1.29	23.55	16.26	21.60
		Barefoot	48.57	4.72	21.95	38.78	58.35	18.14	1.29	23.52	15.48	20.81
		GluShu	50.71	4.74	22.34	40.89	60.52	16.85	1.30	24.00	14.17	19.53
		Steel	56.17	4.73	22.21	46.36	65.98	18.44	1.30	23.83	15.77	21.12
	X-minimum	Aluminium	-27.02	2.30	27.13	-31.73	-22.31	-16.86	1.45	19.54	-19.89	-13.83
		Barefoot	-25.66	2.29	27.09	-30.37	-20.95	-17.69	1.45	19.53	-20.72	-14.65
		GluShu	-25.83	2.31	27.63	-30.56	-21.10	-16.27	1.46	19.73	-19.31	-13.23
		Steel	-28.41	2.30	27.43	-33.13	-23.69	-16.37	1.45	19.67	-19.40	-13.33
	Y-maximum	Aluminium	116.56	10.35	21.23	95.06	138.07	81.79	6.65	24.08	68.06	95.52
		Barefoot	103.61	10.35	21.22	82.11	125.11	85.74	6.65	24.08	72.01	99.47
		GluShu	117.05	10.38	21.48	95.50	138.61	79.74	6.66	24.17	66.00	93.48
		Steel	120.07	10.37	21.40	98.52	141.61	86.59	6.66	24.15	72.85	100.33
	Y-minimum	Aluminium	-36.32	3.20	24.54	-42.92	-29.71	-44.23	3.68	23.75	-51.82	-36.64
		Barefoot	-34.61	3.20	24.51	-41.21	-28.01	-35.74	3.68	23.73	-43.33	-28.15
		GluShu	-41.65	3.22	24.99	-48.28	-35.02	-44.90	3.68	23.94	-52.50	-37.29
		Steel	-41.31	3.22	24.82	-47.93	-34.68	-46.10	3.68	23.89	-53.70	-38.49
	Z-maximum	Aluminium	96.18	13.77	19.52	67.42	124.94	55.98	2.66	20.59	50.44	61.52
		Barefoot	109.47	13.76	19.51	80.71	138.23	46.72	2.66	20.56	41.18	52.26
		GluShu	85.57	13.78	19.61	56.78	114.35	58.54	2.67	20.81	52.99	64.09
		Steel	93.95	13.78	19.59	65.17	122.73	57.20	2.67	20.75	51.65	62.75
	Z-minimum	Aluminium	-47.00	4.55	25.99	-56.35	-37.64	-33.89	3.31	24.04	-40.71	-27.07
		Barefoot	-45.81	4.55	25.97	-55.16	-36.46	-29.97	3.31	24.02	-36.79	-23.15
		GluShu	-38.41	4.56	26.21	-47.78	-29.03	-28.84	3.31	24.17	-35.67	-22.01
		Steel	-42.67	4.56	26.15	-52.04	-33.30	-32.67	3.31	24.14	-39.50	-25.84
Leading Hindlimb	X-maximum	Aluminium	67.08	6.00	23.08	54.67	79.48	19.54	2.13	18.82	15.07	24.01
		Barefoot	51.41	6.00	23.11	39.00	63.82	18.28	2.13	18.84	13.81	22.75
		GluShu	59.54	6.03	23.53	47.08	71.99	17.49	2.14	19.06	13.01	21.97
		Steel	67.05	6.02	23.37	54.61	79.50	20.80	2.14	18.98	16.32	25.28
	X-minimum	Aluminium	-30.52	2.51	21.40	-35.73	-25.29	-14.83	1.51	19.12	-17.99	-11.67
		Barefoot	-28.73	2.51	21.46	-33.95	-23.51	-16.33	1.51	19.13	-19.49	-13.17
		GluShu	-28.90	2.53	22.09	-34.15	-23.64	-13.90	1.51	19.39	-17.07	-10.73
		Steel	-33.19	2.53	21.77	-38.44	-27.95	-16.05	1.51	19.30	-19.21	-12.89
	Y-	Aluminium	126.62	10.90	23.84	104.12	149.12	76.62	6.62	20.77	62.84	90.39

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	maximum	Barefoot	109.63	10.90	23.88	87.12	132.13	80.86	6.62	20.77	67.08	94.63
		GluShu	133.41	10.95	24.29	110.82	156.00	75.29	6.63	20.90	61.50	89.08
		Steel	142.69	10.94	24.13	120.12	165.26	83.66	6.63	20.87	69.87	97.45
	Y-minimum	Aluminium	-39.60	4.27	23.06	-48.42	-30.77	-42.58	4.06	25.58	-50.93	-34.24
		Barefoot	-36.00	4.27	23.09	-44.83	-27.17	-36.17	4.06	25.59	-44.52	-27.83
		GluShu	-43.77	4.29	23.49	-52.63	-34.91	-44.36	4.07	25.86	-52.72	-35.99
		Steel	-47.27	4.28	23.34	-56.12	-38.42	-44.27	4.07	25.78	-52.63	-35.91
	Z-maximum	Aluminium	104.04	11.42	18.78	80.12	127.97	53.05	2.83	18.43	47.11	58.98
		Barefoot	113.85	11.42	18.79	89.92	137.78	44.26	2.83	18.45	38.33	50.20
		GluShu	97.14	11.45	18.97	73.16	121.11	56.39	2.84	18.67	50.45	62.34
		Steel	111.18	11.44	18.92	87.22	135.14	55.42	2.84	18.59	49.48	61.37
	Z-minimum	Aluminium	-46.84	4.83	26.76	-56.74	-36.93	-31.43	3.77	19.60	-39.30	-23.56
		Barefoot	-44.78	4.83	26.79	-54.69	-34.88	-26.58	3.77	19.60	-34.45	-18.71
		GluShu	-38.43	4.85	27.25	-48.37	-28.48	-26.87	3.78	19.75	-34.75	-18.99
		Steel	-43.81	4.84	27.05	-53.74	-33.87	-32.19	3.77	19.71	-40.07	-24.31
Non-leading hindlimb	X-maximum	Aluminium	47.14	3.92	23.35	39.05	55.24	17.07	1.63	19.93	13.66	20.47
		Barefoot	37.53	3.93	23.61	29.42	45.64	16.54	1.63	20.08	13.13	19.95
		GluShu	39.92	3.94	23.87	31.79	48.05	15.53	1.64	20.24	12.12	18.95
		Steel	46.97	3.94	23.73	38.84	55.09	15.90	1.64	20.17	12.48	19.31
	X-minimum	Aluminium	-22.71	2.98	24.90	-28.85	-16.56	-17.69	1.65	21.70	-21.11	-14.28
		Barefoot	-21.53	2.99	25.04	-27.69	-15.38	-17.56	1.65	21.81	-20.98	-14.14
		GluShu	-21.75	2.99	25.19	-27.92	-15.59	-17.52	1.65	21.94	-20.95	-14.10
		Steel	-24.28	2.99	25.13	-30.44	-18.12	-16.08	1.65	21.90	-19.50	-12.66
	Y-maximum	Aluminium	99.82	7.79	20.48	83.59	116.05	81.07	5.96	22.93	68.72	93.41
		Barefoot	83.96	7.82	20.75	67.69	100.23	87.88	5.97	23.01	75.53	100.23
		GluShu	100.63	7.85	21.01	84.31	116.94	81.80	5.98	23.10	69.44	94.15
		Steel	99.11	7.84	20.83	82.81	115.41	90.58	5.98	23.08	78.22	102.94
	Y-minimum	Aluminium	-31.07	2.51	26.83	-36.23	-25.92	-39.71	3.96	20.83	-47.93	-31.48
		Barefoot	-28.51	2.53	27.48	-33.69	-23.33	-34.16	3.96	20.94	-42.40	-25.92
		GluShu	-38.31	2.54	27.97	-43.52	-33.10	-44.92	3.97	21.07	-53.17	-36.68
		Steel	-38.23	2.53	27.42	-43.42	-33.03	-47.26	3.97	21.03	-55.51	-39.01
	Z-maximum	Aluminium	79.33	11.34	20.21	55.69	102.96	55.99	3.07	21.49	49.61	62.36
		Barefoot	85.79	11.35	20.26	62.13	109.44	47.06	3.07	21.63	40.68	53.44
		GluShu	70.51	11.36	20.32	46.85	94.18	58.34	3.08	21.76	51.95	64.73
		Steel	82.81	11.35	20.30	59.15	106.47	58.41	3.08	21.69	52.02	64.79
	Z-	Aluminium	-43.43	4.06	22.77	-51.83	-35.02	-32.77	2.65	22.22	-38.25	-27.28

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	minimum	Barefoot	-43.53	4.07	22.89	-51.94	-35.11	-31.17	2.65	22.37	-36.66	-25.68
		GluShu	-36.81	4.07	23.00	-45.24	-28.39	-30.55	2.65	22.50	-36.05	-25.06
		Steel	-43.67	4.07	22.95	-52.09	-35.25	-34.72	2.65	22.43	-40.22	-29.23

3.6. Summary of surface effect

3.6.1. Impact

Surface-type significantly influenced all impact accelerations in the forelimbs ($p \leq 0.013$), with the exception of z-minimum ($p=0.106$ for combined forelimb data, $p=0.083$ for the leading forelimb, $p=0.530$ for the non-leading forelimb). In the hindlimbs, surface significantly affected all impact accelerations ($p \leq 0.015$), with the exception of y-minimum ($p=0.916$) in the leading hindlimb. The EMMs for surface effects on impact are presented in Table 3. These effects were clearly apparently across all acceleration axes (Figure 2). Impact accelerations were always larger on turf in all directions for forelimbs and hindlimbs. Of note, the z-maximum and y-maximum provoked the highest accelerations. The highest EMM acceleration was recorded on turf for y-maximum in the leading hindlimb (167.1±21.8 g; mean ± 2 s.e. in this section, unless otherwise stated)), while the lowest was observed for the x-minimum on the artificial the non-leading forelimb (15.0±5.0 g). The y-maximum and z-maximum indicated the greatest absolute differences in accelerations between turf and artificial surfaces (Supplementary Data Table S3), with the greatest contrast being present for the y-maximum in the leading hindlimb; accelerations were 78.1±3.6 g larger on turf.

Considering all six acceleration axes together in the individual limb datasets (non-leading forelimb, leading forelimb, non-leading hindlimb, leading hindlimb), the absolute means of EMM accelerations on the artificial surface ranged from 36.4±15.7 g (n=6) in the non-leading forelimb, to 49.5±23.8 g in the leading hindlimb. In contrast, absolute means for EMM accelerations on turf ranged from 59.8±28.6 g in the non-leading forelimb to 87.7±41.5 g in the leading hindlimb.

3.6.2. Foot-off

Surface-type significantly influenced all foot-off accelerations in the forelimbs ($p \leq 0.022$), with the exception of x-maximum ($p=0.602$) in the leading forelimb and y-minimum ($p=0.170$) in the leading forelimb. In the hindlimbs, surface significantly affected all foot-off accelerations ($p \leq 0.047$), with the exception of x-maximum ($p=0.144$) in combined hindlimb data. The EMMs for surface effects on foot-off are presented in Table 3. Foot-off accelerations were nearly always greater on the artificial surface: the exceptions being: x-minimum and y-minimum in the non-leading forelimb; x-minimum in the leading hindlimb, x-maximum and y-minimum in the non-leading hindlimb. As observed amongst the shoe effects, the y-maximum were noticeably larger than accelerations in the other axis directions: here, y-maximum were on average 5.0 times larger than x-axis accelerations, and 2.3 times larger than the y-minimum and z-axis accelerations. However, it was again the z-maximum, in this case for the leading forelimb, which displayed the greatest contrast (12.6±1.2 g) between turf and artificial surfaces. On average for forelimbs the z-maximum accelerations were 25% higher on turf, and this compared to an increase of 9% on turf for hindlimbs

Considering all six acceleration axes together in the individual limb datasets (non-leading forelimb, leading forelimb, non-leading hindlimb, leading hindlimb), the absolute means of EMM accelerations on the artificial surface ranged from 40.3±25.3 g for the non-leading forelimb to 42.2±25.7 g in the leading forelimb. Absolute means for EMM accelerations on turf ranged from 37.2±22.6 g and 37.2±22.5 g in the leading forelimb and in the non-leading forelimb, respectively to 40.8±21.0 g in the non-leading hindlimb. These data therefore indicate that the accelerations on turf at foot-off were reduced relative to the artificial surface, which is in contrast to the impact data, where the reverse was true. Specifically, accelerations were up to 33% greater on the artificial surface compared to the turf for forelimbs and up to 20% greater in the hindlimbs. The maximum absolute differences between turf and artificial were observed in the leading forelimb; 12.6 ± 1.2 g for the z-maximum parameter and 10.4 ± 1.2 g for the y-maximum parameter (Table S3).

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Table 3 Estimated Marginal Means for surface effects.

Limb	Parameter	Surface	Impact					Foot-off				
			Mean	Std. Error	df	95% Confidence Interval (lower bound)	95% Confidence Interval (upper bound)	Mean	Std. Error	df	95% Confidence Interval (lower bound)	95% Confidence Interval (upper bound)
Forelimb (combined)	X-	Artificial	29.21	2.77	27.48	23.54	34.89	14.74	1.83	24.77	10.96	18.51
	maximum	Turf	51.13	2.77	27.61	45.45	56.81	14.23	1.83	24.82	10.44	18.01
	X-	Artificial	-15.65	2.57	25.08	-20.95	-10.35	-18.17	2.16	23.90	-22.63	-13.71
	minimum	Turf	-26.23	2.57	25.12	-31.53	-20.93	-18.07	2.16	23.93	-22.54	-13.61
	Y-	Artificial	66.59	7.89	23.70	50.29	82.89	98.90	5.35	23.55	87.84	109.96
	maximum	Turf	121.47	7.90	23.75	105.17	137.78	92.20	5.36	23.58	81.14	103.26
	Y-	Artificial	-27.29	4.11	25.73	-35.75	-18.82	-35.16	3.85	19.45	-43.21	-27.11
	minimum	Turf	-45.13	4.12	25.79	-53.60	-36.67	-33.25	3.85	19.47	-41.30	-25.20
	Z-	Artificial	68.44	9.07	21.44	49.61	87.28	49.28	2.85	23.45	43.39	55.16
	maximum	Turf	126.52	9.07	21.49	107.68	145.36	40.30	2.85	23.51	34.41	46.19
	Z-	Artificial	-31.87	3.68	24.07	-39.46	-24.29	-30.35	7.12	23.90	-45.06	-15.65
	minimum	Turf	-45.89	3.68	24.12	-53.48	-38.30	-28.53	7.12	23.91	-43.23	-13.82
Leading forelimb	X-	Artificial	32.62	3.64	24.83	25.12	40.12	15.37	2.82	24.36	9.55	21.19
	maximum	Turf	57.89	3.65	25.04	50.38	65.40	14.53	2.82	24.42	8.71	20.35
	X-	Artificial	-15.91	2.70	21.53	-21.51	-10.30	-18.27	2.00	24.05	-22.39	-14.15
	minimum	Turf	-27.62	2.70	21.68	-33.23	-22.02	-17.63	2.00	24.12	-21.75	-13.51
	Y-	Artificial	71.06	8.77	21.34	52.83	89.29	100.72	5.59	22.50	89.13	112.30
	maximum	Turf	128.78	8.79	21.45	110.53	147.02	90.37	5.60	22.56	78.78	101.95
	Y-	Artificial	-30.71	3.76	21.97	-38.51	-22.92	-36.38	4.16	18.15	-45.11	-27.65
	minimum	Turf	-48.41	3.77	22.17	-56.22	-40.61	-33.32	4.16	18.19	-42.06	-24.59
	Z-	Artificial	80.34	14.32	22.83	50.70	109.99	51.11	3.34	22.62	44.19	58.02
	maximum	Turf	141.04	14.33	22.89	111.38	170.70	38.52	3.34	22.80	31.59	45.44
	Z-	Artificial	-32.09	3.20	23.52	-38.69	-25.48	-31.24	8.04	19.84	-48.02	-14.46
	minimum	Turf	-43.61	3.20	23.67	-50.22	-37.00	-28.51	8.04	19.86	-45.29	-11.73
Non-leading forelimb	X-	Artificial	25.56	2.64	25.88	20.13	30.99	14.11	1.13	26.94	11.80	16.42
	maximum	Turf	42.49	2.65	26.07	37.05	47.94	13.35	1.13	27.11	11.04	15.67
	X-	Artificial	-15.03	2.50	24.73	-20.18	-9.88	-17.84	2.71	23.47	-23.44	-12.24
	minimum	Turf	-23.29	2.50	24.80	-28.44	-18.14	-18.92	2.71	23.52	-24.52	-13.31
	Y-	Artificial	62.47	8.64	24.14	44.65	80.29	98.42	4.90	24.00	88.32	108.53
	maximum	Turf	107.09	8.64	24.21	89.26	124.92	89.86	4.90	24.07	79.75	99.97
	Y-	Artificial	-24.77	4.18	24.67	-33.37	-16.16	-33.68	3.97	18.64	-42.00	-25.35
	minimum	Turf	-38.70	4.18	24.74	-47.30	-30.08	-33.89	3.97	18.67	-42.22	-25.56

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	Z-maximum	Artificial Turf	57.33	6.62	27.77	43.77	70.90	48.46	3.12	24.15	42.02	54.91
			100.24	6.63	27.88	86.66	113.82	40.20	3.13	24.25	33.75	46.65
	Z-minimum	Artificial Turf	-33.26	4.54	21.18	-42.71	-23.82	-29.43	5.86	25.61	-41.48	-17.37
			-46.71	4.55	21.25	-56.16	-37.26	-27.05	5.86	25.65	-39.11	-14.99
Hindlimb (combined)	X-maximum	Artificial Turf	35.47	4.71	21.83	25.70	45.25	18.54	1.29	23.36	15.88	21.21
			71.35	4.71	21.87	61.57	81.13	17.64	1.29	23.42	14.97	20.31
	X-minimum	Artificial Turf	-17.94	2.29	26.91	-22.64	-13.24	-16.88	1.45	19.47	-19.91	-13.85
			-35.52	2.29	26.98	-40.23	-30.82	-16.71	1.45	19.49	-19.74	-13.68
	Y-maximum	Artificial Turf	78.44	10.34	21.14	56.96	99.93	84.36	6.65	24.05	70.63	98.09
			150.20	10.34	21.17	128.71	171.69	82.57	6.65	24.06	68.84	96.30
	Y-minimum	Artificial Turf	-23.00	3.20	24.35	-29.60	-16.41	-43.07	3.67	23.68	-50.66	-35.48
			-53.94	3.20	24.41	-60.54	-47.34	-42.41	3.67	23.70	-50.00	-34.82
	Z-maximum	Artificial Turf	71.01	13.76	19.49	42.26	99.77	56.84	2.66	20.51	51.30	62.37
			121.57	13.76	19.50	92.82	150.33	52.38	2.66	20.53	46.84	57.92
	Z-minimum	Artificial Turf	-38.43	4.55	25.91	-47.78	-29.08	-32.25	3.30	23.99	-39.07	-25.43
			-48.51	4.55	25.94	-57.86	-39.16	-30.43	3.30	24.01	-37.25	-23.61
Leading Hindlimb	X-maximum	Artificial Turf	41.32	5.98	22.82	28.94	53.70	20.75	2.13	18.69	16.28	25.21
			81.22	5.99	22.95	68.83	93.61	17.31	2.13	18.76	12.84	21.77
	X-minimum	Artificial Turf	-19.81	2.50	20.95	-25.01	-14.61	-14.92	1.51	18.97	-18.07	-11.76
			-40.86	2.51	21.17	-46.07	-35.65	-15.64	1.51	19.04	-18.79	-12.48
	Y-maximum	Artificial Turf	89.04	10.87	23.59	66.58	111.50	81.65	6.62	20.70	67.89	95.42
			167.13	10.89	23.72	144.65	189.61	76.56	6.62	20.74	62.78	90.33
	Y-minimum	Artificial Turf	-26.07	4.26	22.82	-34.88	-17.26	-43.03	4.05	25.43	-51.37	-34.69
			-57.25	4.26	22.94	-66.07	-48.43	-40.66	4.05	25.51	-49.00	-32.32
	Z-maximum	Artificial Turf	81.98	11.41	18.69	58.07	105.88	54.62	2.82	18.31	48.70	60.55
			131.13	11.42	18.74	107.21	155.05	49.94	2.83	18.38	44.01	55.87
	Z-minimum	Artificial Turf	-38.58	4.81	26.49	-48.46	-28.69	-31.01	3.76	19.53	-38.88	-23.15
			-48.35	4.82	26.63	-58.25	-38.45	-27.52	3.77	19.56	-35.39	-19.65
Non-leading hindlimb	X-maximum	Artificial Turf	28.95	3.91	23.07	20.87	37.03	15.52	1.63	19.78	12.12	18.92
			56.83	3.91	23.18	48.74	64.91	17.00	1.63	19.83	13.60	20.40
	X-minimum	Artificial Turf	-15.70	2.98	24.76	-21.84	-9.56	-18.07	1.64	21.59	-21.49	-14.66
			-29.44	2.98	24.81	-35.58	-23.29	-16.35	1.64	21.63	-19.77	-12.94
	Y-maximum	Artificial Turf	68.13	7.77	20.18	51.94	84.32	85.90	5.96	22.86	73.57	98.24
			123.63	7.78	20.29	107.42	139.83	84.76	5.96	22.89	72.42	97.09
	Y-minimum	Artificial Turf	-20.27	2.49	25.99	-25.40	-15.14	-40.22	3.95	20.73	-48.44	-32.00
			-47.79	2.50	26.32	-52.93	-42.65	-42.81	3.95	20.77	-51.03	-34.58

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	Z-maximum	Artificial	62.23	11.33	20.16	38.60	85.86	57.64	3.06	21.36	51.27	64.00
		Turf	96.99	11.33	20.17	73.36	120.62	52.26	3.06	21.38	45.89	58.62
	Z-minimum	Artificial	-38.01	4.06	22.66	-46.41	-29.61	-32.99	2.64	22.09	-38.46	-27.51
		Turf	-45.70	4.06	22.67	-54.10	-37.30	-31.62	2.64	22.11	-37.10	-26.14

3.7. Shoe-surface interactions

The EMMs for shoe-surface combinations are presented in Table 4. Post-hoc tests were run on acceleration parameters that indicated a significant shoe-surface interaction. In the post-hoc linear mixed models, a new combined 'shoe-surface' term was introduced as a fixed factor (in place of shoe and surface). Stride time was included as a covariate and fixed-factor. Day and horse-rider pair were kept as random factors. As the y-maximum parameter seemed to be particularly sensitive to shoe and surface effects (sections 3.5 and 3.6) and often recorded the highest peak accelerations, we focus on outlining the results of shoe-surface combination from this parameter. This is also the parameter most strongly correlated to stride time at foot-off (Supplementary Figure 1). However, the full output of this post-hoc analysis for all acceleration parameters is provided in the Supplementary Data File (Table S4). In each case, where EMM differences are reported below for pairwise comparisons, the first condition mentioned has the larger EMM value resulting in a positive difference. Please note that values reported below in the shoe-surfaces comparisons are from the post-hoc models (Table S4) and hence differ slightly from those from the initial models (Table 4).

3.7.1. Impact

The y-maximum data for the leading forelimb indicated that the greatest EMM difference of 72.8 ± 3.8 g was observed between the Aluminium-Turf and Barefoot-Artificial conditions. However, this was closely followed by the comparison between the Steel-Turf and Barefoot-Artificial conditions, which had an EMM difference of 71.4±3.9 g. The only pairwise comparisons that were not significant were Aluminium-Artificial versus GluShu-Artificial, Aluminium-Turf versus Steel-Turf and Barefoot-Turf versus GluShu-Turf (p=1.0 in each case). For the non-leading forelimb, the magnitudes of EMM differences were reduced. Specifically, the largest EMM difference between the Steel-Turf and Barefoot-Artificial was 64.3±3.3 g (mean ±2 s.e. in this section), which was followed by the comparison between the Steel-Turf versus Aluminium-Artificial (EMM difference = 58.6±3.5 g) and GluShu-Turf versus Barefoot-Artificial (EMM difference = 58.4±3.4 g). Only the Aluminium-Artificial and GluShu-Artificial combinations were not significantly different (p=0.166). Please note the combined forelimb data were not significantly affected by a shoe-surface interaction (Table S1), so the offsets amongst shoe-surface conditions are not reported here.

The y-maximum data for the hindlimbs indicated larger acceleration differences were at play amongst the shoe-surface combinations, relative to the forelimb data. For the combined hindlimb data, the EMM differences between the Aluminium-Turf versus Barefoot-Artificial and GluShu-Turf versus Barefoot-Artificial, each of 89.0 g, were the largest; followed by Steel-Turf versus Barefoot-Artificial, which had an EMM difference of 87.1 ± 3.8 g. There were four pairwise comparisons that were not significantly different: Aluminium-Artificial versus GluShu-Artificial; Aluminium-Turf versus GluShu-Turf; Aluminium-Turf versus Steel-Turf; and GluShu-Turf versus Steel-Turf (all p=1.0). All other comparisons for the combined hindlimb data were significant (p≤0.006).

For the leading hindlimb, peak EMM acceleration differences reached 110.0 ± 5.7 g for the Steel-Turf versus Barefoot-Artificial condition, closely followed by GluShu-Turf versus Barefoot-Artificial (EMM difference = 99.6±6.0 g) and Steel-Turf versus Aluminium-Artificial (EMM difference = 99.4±6.1 g). In contrast, the Aluminium-Turf versus GluShu-Turf comparison indicated no significant difference (p=1.0), and the GluShu-Artificial and Steel-Artificial were also not significantly different (p=0.104); all other comparisons were different (p≤0.007).

The non-leading hindlimb data indicated that GluShu-Turf versus Barefoot-Artificial was most different (EMM difference of 75.8±5.2 g), followed by Aluminium-Turf versus Barefoot-Artificial (72.8±4.8 g) and Steel-Turf versus Barefoot-Artificial (68.3±4.8 g). The data therefore show differences amongst shoe-surface conditions were greater in the leading limbs, for both hind and forelimbs. For the non-leading hindlimb, there were four non-significantly different conditions: Aluminium-Artificial versus GluShu-Artificial;

Aluminium-Turf versus GluShu-Turf; Aluminium-Turf versus Steel-Turf; and GluShu-Artificial versus Steel-Artificial (all p=1.0).

3.7.2. Foot-off

Accelerations at foot-off had smaller absolute magnitudes for EMM differences amongst shoe-surface combinations. For the combined forelimbs, the largest EMM difference of 11.1±1.5 g was observed between the GluShu-Artificial versus Aluminium-Turf, closely followed by the GluShu Artificial versus GluShu-Turf (EMM difference = 10.7±1.3 g) and the Steel-Artificial versus Aluminium-Turf (EMM difference = 10.2±1.4 g). Only the Aluminium-Artificial versus Barefoot-Artificial, Aluminium-Turf versus GluShu-Turf, Barefoot-Turf versus Steel-Turf and GluShu-Artificial versus Steel-Artificial conditions were not significantly different (each with p=1.00); all other pairwise comparisons were significant, with p values <0.001.

For the leading forelimb, there were eight EMM differences with magnitudes exceeding 10 g. The largest differences were between GluShu-Artificial and Aluminium-Turf (17.3 ± 2.0 g), followed by GluShu-Artificial versus Barefoot-Turf (15.4±2.2 g) and Steel-Artificial versus Aluminium-Turf (14.4±2.0 g). The following pairwise comparisons were not statistically different: Aluminium-Artificial versus Barefoot-Artificial (p=1.00), Aluminium-Turf versus Barefoot-Turf (p=1.00), Barefoot-Turf versus Steel-Turf (p=0.375) and GluShu-Turf versus Steel-Turf (p=1.00); all other comparisons had p values ≤0.049.

For the non-leading forelimb, the GluShu-Artificial versus GluShu-Turf and Steel-Artificial versus GluShu-Turf comparisons, each had differences of 13.9 g. They were followed in magnitude by the Barefoot-Artificial versus GluShu-Artificial EMM difference (12.4±2.0 g). For this limb, there were seven pairwise shoe-surface comparisons that were not significantly different (p≥0.084).

Amongst the combined hindlimb data, differences amongst conditions were comparable to the forelimb data. The largest EMM difference was for the Barefoot-Turf versus GluShu-Turf (12.5±1.5 g), followed by the Steel-Artificial versus GluShu-Turf (11.6±1.5 g). All other EMM differences were less than 10 g, and eight of these were non-significant (p=1.00).

EMM differences in the leading hindlimb were largest between the Steel-Artificial and GluShu-Turf conditions at 16.9±2.1 g. This was followed by the EMM differences between Steel-Artificial and Aluminium-Turf (13.9±2.1 g) and Steel-Artificial versus Steel Turf (13.8±2.0 g). Here there were more comparisons that were not significantly different; p values for 11 comparisons were ≥0.95.

In the non-leading hindlimb, the largest differences were observed between Steel-Artificial versus GluShu-Turf (13.6±2.1 g), closely followed by Barefoot-Turf versus GluShu-Turf (13.5±2.3 g). There were eight non-significant pairwise comparisons (p≥0.077).

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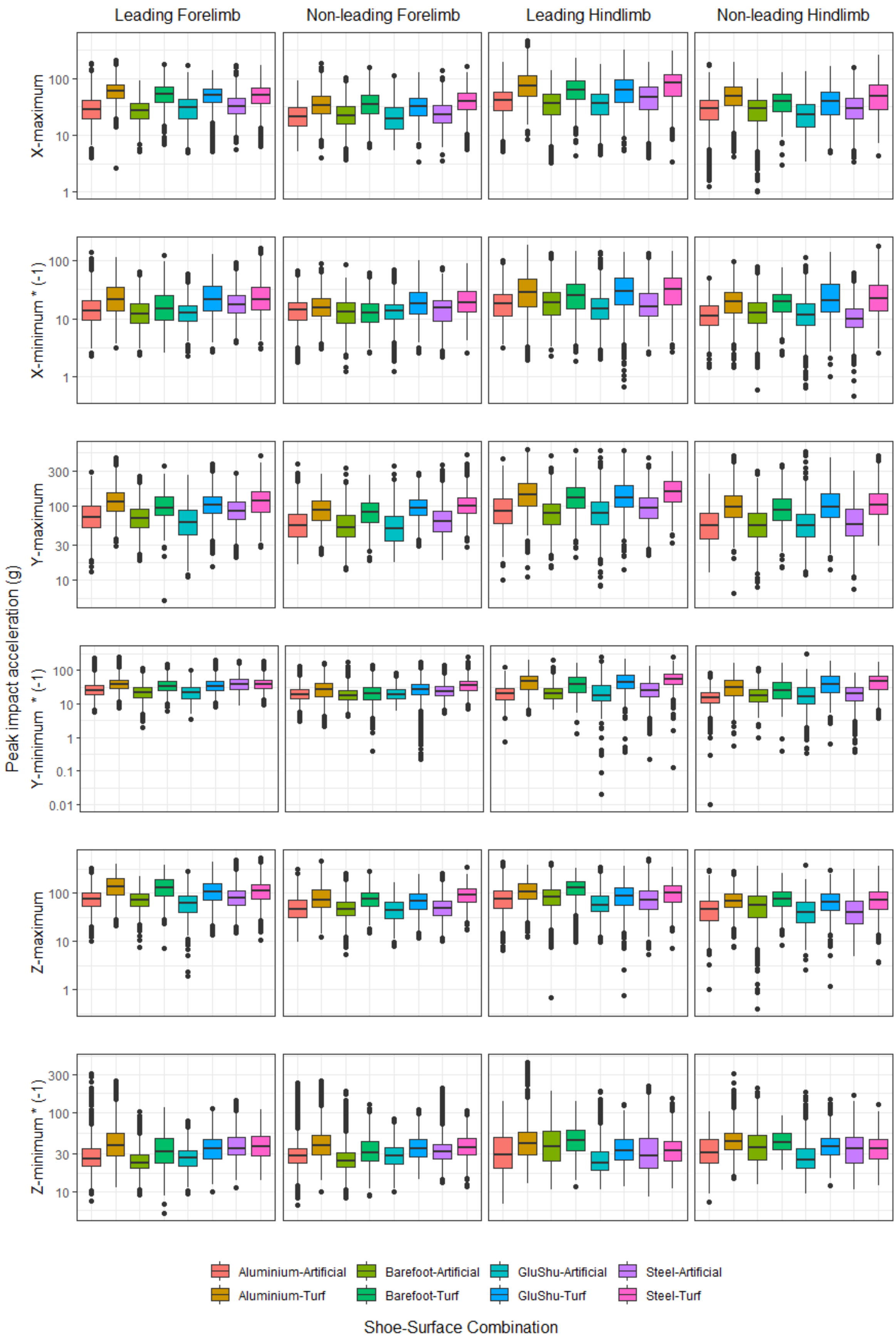

Figure 2. Boxplots illustrating minimum and maximum impact accelerations per shoe-surface combination. P-values for pairwise comparison (with Bonferroni correction) are provided in Table S4.

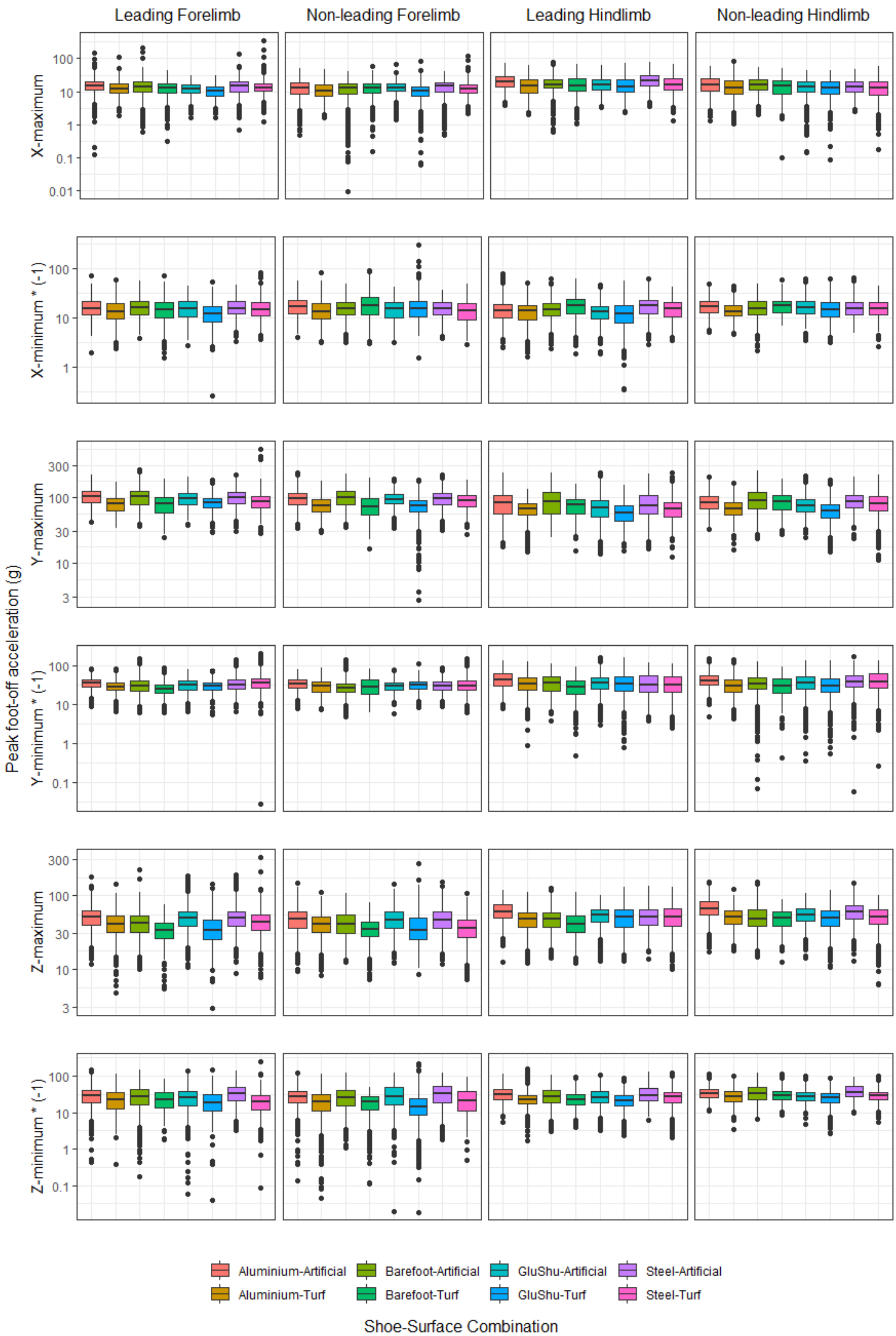

Figure 3. Boxplots illustrating minimum and maximum foot-off accelerations per shoe-surface combination. P-values for pairwise comparison (with Bonferroni correction) are provided in Table S4.

Table 4 Estimated Marginal Means for shoe and surface effects.

Limb	Parameter	Shoe	Surface	Impact					Foot-off				
				Mean	Std. Error	df	95% Confidence Interval (lower bound)	95% Confidence Interval (upper bound)	Mean	Std. Error	df	95% Confidence Interval (lower bound)	95% Confidence Interval (upper bound)
Forelimb (combined)	X-maximum	Aluminium	Artificial	29.97	2.79	28.23	24.26	35.67	14.99	1.84	25.03	11.21	18.78
			Turf	52.79	2.80	28.70	47.06	58.51	13.89	1.84	25.19	10.10	17.68
		Barefoot	Artificial	24.50	2.78	28.09	18.80	30.20	14.34	1.84	24.98	10.55	18.12
			Turf	50.03	2.80	28.90	44.29	55.76	15.26	1.84	25.26	11.47	19.05
		GluShu	Artificial	31.85	2.80	28.88	26.12	37.59	14.74	1.84	25.27	10.95	18.53
			Turf	49.35	2.80	28.88	43.62	55.09	12.59	1.84	25.26	8.80	16.39
		Steel	Artificial	30.53	2.80	28.74	24.80	36.26	14.88	1.84	25.25	11.08	18.67
			Turf	52.34	2.80	28.79	46.61	58.07	15.15	1.84	25.25	11.36	18.95
	X-minimum	Aluminium	Artificial	-16.21	2.58	25.35	-21.52	-10.90	-18.09	2.17	24.07	-22.56	-13.62
			Turf	-26.45	2.58	25.53	-31.76	-21.13	-16.88	2.17	24.17	-21.35	-12.40
		Barefoot	Artificial	-12.28	2.58	25.29	-17.58	-6.97	-17.31	2.16	24.03	-21.78	-12.84
			Turf	-21.64	2.59	25.60	-26.96	-16.32	-18.55	2.17	24.22	-23.02	-14.07
		GluShu	Artificial	-15.08	2.59	25.61	-20.40	-9.76	-18.81	2.17	24.22	-23.29	-14.34
			Turf	-27.52	2.59	25.60	-32.84	-22.20	-18.95	2.17	24.22	-23.42	-14.47
		Steel	Artificial	-19.03	2.59	25.59	-24.35	-13.71	-18.46	2.17	24.22	-22.94	-13.99
			Turf	-29.30	2.59	25.59	-34.62	-23.98	-17.91	2.17	24.21	-22.39	-13.44
	Y-maximum	Aluminium	Artificial	65.77	7.92	23.99	49.43	82.11	97.36	5.36	23.71	86.29	108.44
			Turf	121.44	7.93	24.22	105.07	137.80	89.58	5.37	23.83	78.49	100.67
		Barefoot	Artificial	57.27	7.91	23.93	40.94	73.60	96.42	5.36	23.67	85.35	107.49
			Turf	114.05	7.94	24.26	97.68	130.42	94.26	5.37	23.85	83.17	105.35
		GluShu	Artificial	67.78	7.94	24.26	51.41	84.15	101.13	5.37	23.86	90.04	112.22
			Turf	120.94	7.94	24.30	104.57	137.32	90.43	5.37	23.88	79.34	101.53
		Steel	Artificial	75.53	7.94	24.23	59.16	91.90	100.68	5.37	23.85	89.59	111.77
			Turf	129.46	7.94	24.23	113.09	145.83	94.53	5.37	23.85	83.44	105.62
	Y-minimum	Aluminium	Artificial	-28.46	4.13	26.08	-36.94	-19.97	-36.52	3.86	19.56	-44.58	-28.46
			Turf	-45.92	4.14	26.36	-54.42	-37.42	-33.56	3.86	19.65	-41.62	-25.49
		Barefoot	Artificial	-18.81	4.13	26.01	-27.29	-10.33	-32.15	3.86	19.53	-40.21	-24.10
			Turf	-41.97	4.14	26.40	-50.48	-33.47	-31.51	3.86	19.67	-39.58	-23.44
		GluShu	Artificial	-26.79	4.14	26.41	-35.30	-18.29	-35.86	3.86	19.67	-43.93	-27.80

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			Turf	-43.72	4.14	26.45	-52.23	-35.21	-34.05	3.86	19.68	-42.12	-25.98
		Steel	Artificial	-35.08	4.14	26.36	-43.58	-26.57	-36.10	3.86	19.66	-44.16	-28.03
			Turf	-48.92	4.14	26.37	-57.42	-40.41	-33.88	3.86	19.66	-41.95	-25.82
	Z-maximum	Aluminium	Artificial	71.03	9.10	21.71	52.16	89.91	50.82	2.86	23.81	44.91	56.72
			Turf	134.10	9.11	21.87	115.20	153.01	43.07	2.87	24.04	37.16	48.99
		Barefoot	Artificial	59.98	9.09	21.65	41.11	78.84	41.65	2.86	23.74	35.75	47.55
			Turf	133.46	9.12	21.95	114.54	152.37	38.43	2.87	24.14	32.51	44.35
		GluShu	Artificial	68.87	9.12	21.95	49.95	87.79	50.75	2.87	24.14	44.83	56.66
			Turf	116.62	9.12	21.94	97.70	135.54	37.87	2.87	24.13	31.95	43.79
		Steel	Artificial	73.89	9.12	21.93	54.97	92.81	53.89	2.87	24.10	47.98	59.81
			Turf	121.89	9.12	21.93	102.97	140.80	41.84	2.87	24.10	35.92	47.76
	Z-minimum	Aluminium	Artificial	-34.69	3.69	24.37	-42.29	-27.08	-33.11	7.13	23.96	-47.82	-18.39
			Turf	-51.57	3.69	24.56	-59.19	-43.96	-29.40	7.13	24.00	-44.11	-14.68
		Barefoot	Artificial	-23.13	3.69	24.31	-30.73	-15.53	-23.28	7.13	23.95	-37.99	-8.57
			Turf	-44.21	3.70	24.64	-51.83	-36.59	-26.02	7.13	24.02	-40.74	-11.30
		GluShu	Artificial	-31.85	3.70	24.65	-39.47	-24.23	-29.49	7.13	24.02	-44.21	-14.77
			Turf	-43.11	3.70	24.64	-50.73	-35.49	-28.17	7.13	24.02	-42.89	-13.45
		Steel	Artificial	-37.82	3.70	24.61	-45.44	-30.20	-35.52	7.13	24.02	-50.24	-20.80
			Turf	-44.67	3.70	24.62	-52.29	-37.04	-30.52	7.13	24.02	-45.24	-15.80
Leading forelimb	X-maximum	Aluminium	Artificial	32.93	3.67	25.80	25.37	40.48	15.97	2.83	24.66	10.14	21.80
			Turf	62.08	3.69	26.16	54.50	69.65	14.37	2.83	24.78	8.53	20.21
		Barefoot	Artificial	26.33	3.67	25.63	18.78	33.87	15.57	2.83	24.60	9.74	21.40
			Turf	54.30	3.72	27.21	46.66	61.94	14.67	2.84	25.10	8.82	20.53
		GluShu	Artificial	35.10	3.70	26.42	27.51	42.70	15.10	2.84	24.87	9.26	20.94
			Turf	57.55	3.70	26.38	49.96	65.14	13.11	2.83	24.85	7.26	18.95
		Steel	Artificial	36.12	3.69	26.25	28.53	43.71	14.85	2.84	24.85	9.01	20.69
			Turf	57.65	3.71	26.61	50.04	65.25	15.96	2.84	24.94	10.12	21.81
	X-minimum	Aluminium	Artificial	-15.95	2.72	22.22	-21.59	-10.32	-17.19	2.00	24.38	-21.32	-13.06
			Turf	-28.17	2.73	22.48	-33.82	-22.52	-16.66	2.01	24.51	-20.80	-12.53
		Barefoot	Artificial	-12.08	2.71	22.10	-17.71	-6.45	-17.94	2.00	24.32	-22.07	-13.81
			Turf	-22.80	2.75	23.23	-28.48	-17.12	-17.80	2.01	24.87	-21.94	-13.65
		GluShu	Artificial	-15.65	2.73	22.68	-21.31	-9.99	-19.39	2.01	24.61	-23.53	-15.25
			Turf	-30.01	2.73	22.64	-35.66	-24.35	-17.11	2.01	24.59	-21.25	-12.98
		Steel	Artificial	-19.94	2.73	22.58	-25.59	-14.28	-18.57	2.01	24.59	-22.71	-14.43
			Turf	-29.52	2.74	22.82	-35.19	-23.86	-18.96	2.01	24.69	-23.10	-14.82
	Y-	Aluminium	Artificial	69.46	8.83	21.85	51.15	87.77	98.31	5.61	22.80	86.69	109.92

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	maximum		Turf	134.60	8.85	22.09	116.25	152.95	87.13	5.62	22.94	75.50	98.75
		Barefoot	Artificial	60.61	8.82	21.75	42.31	78.91	97.76	5.61	22.74	86.15	109.36
			Turf	122.65	8.90	22.60	104.22	141.08	89.72	5.64	23.23	78.07	101.37
		GluShu	Artificial	69.93	8.86	22.20	51.56	88.30	104.44	5.62	23.01	92.81	116.07
			Turf	124.51	8.87	22.23	106.13	142.88	92.53	5.62	23.02	80.89	104.16
		Steel	Artificial	84.23	8.86	22.13	65.87	102.59	102.36	5.62	22.99	90.73	113.99
			Turf	133.34	8.87	22.30	114.96	151.73	92.09	5.63	23.07	80.45	103.73
	Y-minimum	Aluminium	Artificial	-30.01	3.80	22.88	-37.86	-22.15	-36.42	4.17	18.34	-45.17	-27.68
			Turf	-50.16	3.81	23.30	-58.04	-42.28	-33.58	4.17	18.43	-42.33	-24.82
		Barefoot	Artificial	-21.59	3.79	22.71	-29.44	-13.75	-34.27	4.17	18.30	-43.01	-25.52
			Turf	-46.14	3.85	24.20	-54.08	-38.19	-28.39	4.18	18.62	-37.16	-19.62
		GluShu	Artificial	-27.07	3.82	23.48	-34.97	-19.18	-38.04	4.18	18.48	-46.80	-29.28
			Turf	-47.36	3.82	23.54	-55.26	-39.46	-33.91	4.18	18.48	-42.67	-25.15
		Steel	Artificial	-44.18	3.82	23.29	-52.07	-36.29	-36.78	4.18	18.47	-45.54	-28.02
			Turf	-50.00	3.83	23.63	-57.90	-42.09	-37.41	4.18	18.52	-46.18	-28.65
	Z-maximum	Aluminium	Artificial	80.71	14.36	23.09	51.00	110.41	52.44	3.37	23.44	45.48	59.40
			Turf	156.13	14.38	23.18	126.40	185.86	40.74	3.38	23.75	33.76	47.72
		Barefoot	Artificial	70.93	14.36	23.04	41.23	100.62	43.54	3.36	23.30	36.59	50.49
			Turf	148.03	14.42	23.45	118.23	177.83	34.79	3.41	24.63	27.76	41.82
		GluShu	Artificial	76.03	14.39	23.26	46.28	105.78	51.18	3.39	23.97	44.18	58.17
			Turf	135.32	14.39	23.24	105.58	165.07	33.97	3.39	23.94	26.98	40.95
		Steel	Artificial	93.71	14.39	23.25	63.96	123.46	57.26	3.38	23.85	50.27	64.25
			Turf	124.68	14.40	23.32	94.91	154.45	44.57	3.39	24.14	37.57	51.57
	Z-minimum	Aluminium	Artificial	-31.33	3.22	24.24	-37.97	-24.68	-31.43	8.05	19.94	-48.23	-14.64
			Turf	-47.97	3.23	24.51	-54.63	-41.31	-29.15	8.05	19.97	-45.95	-12.35
		Barefoot	Artificial	-25.98	3.22	24.11	-32.62	-19.35	-26.23	8.05	19.92	-43.02	-9.44
			Turf	-41.56	3.26	25.29	-48.26	-34.86	-26.60	8.06	20.08	-43.41	-9.78
		GluShu	Artificial	-30.36	3.24	24.71	-37.03	-23.69	-28.68	8.06	20.01	-45.49	-11.88
			Turf	-40.86	3.24	24.68	-47.52	-34.19	-29.22	8.06	20.00	-46.02	-12.42
		Steel	Artificial	-40.67	3.24	24.61	-47.34	-34.00	-38.61	8.06	20.01	-55.42	-21.81
			Turf	-44.05	3.24	24.86	-50.73	-37.37	-29.07	8.06	20.03	-45.88	-12.26
Non-leading forelimb	X-maximum	Aluminium	Artificial	24.51	2.67	27.01	19.03	29.99	14.00	1.14	27.96	11.67	16.32
			Turf	41.79	2.68	27.30	36.29	47.28	13.45	1.14	28.21	11.12	15.78
		Barefoot	Artificial	23.38	2.67	26.78	17.91	28.85	13.16	1.13	27.75	10.84	15.49
			Turf	43.10	2.70	28.10	37.58	48.63	14.86	1.15	28.93	12.52	17.20
		GluShu	Artificial	26.55	2.69	27.75	21.04	32.06	15.10	1.14	28.62	12.77	17.44

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		Turf	40.19	2.68	27.45	34.69	45.69	12.08	1.14	28.35	9.75	14.42
	Steel	Artificial	27.80	2.69	27.58	22.29	33.31	14.17	1.14	28.48	11.83	16.51
		Turf	44.90	2.69	27.83	39.38	50.41	13.02	1.14	28.70	10.68	15.36
X-minimum	Aluminium	Artificial	-15.01	2.51	25.16	-20.17	-9.84	-18.10	2.72	23.77	-23.72	-12.49
		Turf	-22.78	2.51	25.27	-27.95	-17.61	-17.62	2.72	23.84	-23.23	-12.00
	Barefoot	Artificial	-13.19	2.51	25.07	-18.35	-8.02	-17.19	2.72	23.70	-22.80	-11.58
		Turf	-19.11	2.52	25.57	-24.29	-13.92	-21.37	2.73	24.05	-27.00	-15.75
	GluShu	Artificial	-14.16	2.52	25.45	-19.34	-8.98	-18.40	2.72	23.97	-24.02	-12.78
		Turf	-24.17	2.51	25.33	-29.35	-19.00	-21.24	2.72	23.89	-26.85	-15.62
	Steel	Artificial	-17.77	2.52	25.43	-22.95	-12.59	-17.66	2.72	23.97	-23.29	-12.04
		Turf	-27.11	2.52	25.50	-32.29	-21.93	-15.43	2.73	24.01	-21.06	-9.81
Y-maximum	Aluminium	Artificial	59.67	8.68	24.59	41.78	77.55	95.21	4.92	24.45	85.07	105.36
		Turf	102.48	8.69	24.76	84.57	120.39	87.50	4.93	24.63	77.35	97.66
	Barefoot	Artificial	54.65	8.67	24.48	36.78	72.52	97.88	4.91	24.35	87.74	108.01
		Turf	93.62	8.71	25.03	75.67	111.56	89.69	4.94	24.89	79.51	99.86
	GluShu	Artificial	64.84	8.70	24.90	46.91	82.77	99.91	4.93	24.76	89.75	110.08
		Turf	113.26	8.70	24.82	95.34	131.17	86.22	4.93	24.68	76.05	96.38
	Steel	Artificial	70.73	8.70	24.87	52.80	88.66	100.69	4.93	24.74	90.53	110.86
		Turf	119.00	8.71	24.94	101.06	136.93	96.03	4.94	24.80	85.85	106.20
Y-minimum	Aluminium	Artificial	-23.63	4.19	25.13	-32.26	-14.99	-36.54	3.98	18.86	-44.88	-28.20
		Turf	-37.78	4.20	25.31	-46.42	-29.13	-34.33	3.99	18.94	-42.68	-25.98
	Barefoot	Artificial	-20.66	4.19	25.02	-29.29	-12.04	-31.18	3.98	18.80	-39.52	-22.84
		Turf	-33.47	4.21	25.58	-42.14	-24.80	-34.34	3.99	19.07	-42.69	-25.98
	GluShu	Artificial	-24.43	4.21	25.45	-33.09	-15.77	-34.61	3.99	19.01	-42.96	-26.26
		Turf	-37.92	4.20	25.37	-46.57	-29.27	-34.66	3.99	18.97	-43.01	-26.31
	Steel	Artificial	-30.36	4.21	25.41	-39.02	-21.70	-32.39	3.99	19.01	-40.74	-24.03
		Turf	-45.61	4.21	25.49	-54.28	-36.95	-32.24	3.99	19.03	-40.60	-23.88
Z-maximum	Aluminium	Artificial	57.15	6.66	28.49	43.51	70.79	50.39	3.14	24.77	43.91	56.86
		Turf	101.82	6.67	28.67	88.17	115.48	42.97	3.15	24.92	36.48	49.45
	Barefoot	Artificial	53.24	6.65	28.33	39.62	66.86	41.79	3.14	24.64	35.32	48.26
		Turf	100.66	6.70	29.18	86.95	114.36	37.96	3.16	25.36	31.46	44.47
	GluShu	Artificial	58.10	6.69	28.97	44.42	71.79	50.61	3.16	25.18	44.11	57.11
		Turf	90.32	6.68	28.77	76.66	103.99	39.67	3.15	25.01	33.18	46.16
	Steel	Artificial	60.84	6.69	28.90	47.15	74.53	51.07	3.16	25.13	44.57	57.57
		Turf	108.15	6.70	29.04	94.46	121.85	40.21	3.16	25.24	33.70	46.71
Z-	Aluminium	Artificial	-35.60	4.57	21.64	-45.08	-26.12	-28.23	5.87	25.84	-40.31	-16.16

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	minimum		Turf	-51.75	4.57	21.75	-61.25	-42.26	-26.07	5.88	25.90	-38.15	-13.99
		Barefoot	Artificial	-26.09	4.56	21.54	-35.56	-16.61	-23.46	5.87	25.79	-35.53	-11.39
			Turf	-43.57	4.59	22.07	-53.09	-34.05	-22.59	5.89	26.06	-34.68	-10.49
		GluShu	Artificial	-33.59	4.58	21.93	-43.09	-24.08	-30.25	5.88	26.00	-42.34	-18.16
			Turf	-44.37	4.58	21.81	-53.87	-34.88	-26.19	5.88	25.93	-38.28	-14.11
		Steel	Artificial	-37.77	4.58	21.88	-47.28	-28.27	-35.76	5.88	26.01	-47.85	-23.67
			Turf	-47.14	4.59	21.98	-56.65	-37.63	-33.36	5.88	26.03	-45.45	-21.27
Hindlimb (combined)	X-maximum	Aluminium	Artificial	37.47	4.74	22.46	27.65	47.30	19.46	1.30	24.15	16.78	22.14
			Turf	78.94	4.76	22.78	69.09	88.79	18.40	1.31	24.56	15.71	21.09
		Barefoot	Artificial	29.90	4.73	22.25	20.09	39.71	17.20	1.30	23.90	14.52	19.87
			Turf	67.23	4.76	22.76	57.38	77.08	19.09	1.30	24.52	16.40	21.78
		GluShu	Artificial	34.09	4.77	22.89	24.22	43.95	17.35	1.31	24.68	14.65	20.04
			Turf	67.33	4.77	22.90	57.46	77.19	16.35	1.31	24.70	13.65	19.04
		Steel	Artificial	40.44	4.77	22.88	30.57	50.30	20.17	1.31	24.64	17.47	22.86
			Turf	71.90	4.76	22.70	62.05	81.75	16.72	1.30	24.44	14.03	19.41
	X-minimum	Aluminium	Artificial	-18.40	2.31	27.80	-23.13	-13.67	-17.16	1.46	19.78	-20.20	-14.12
			Turf	-35.63	2.32	28.26	-40.38	-30.89	-16.55	1.46	19.94	-19.60	-13.51
		Barefoot	Artificial	-18.71	2.30	27.52	-23.43	-13.98	-15.71	1.45	19.68	-18.74	-12.67
			Turf	-32.61	2.32	28.22	-37.36	-27.86	-19.66	1.46	19.93	-22.71	-16.62
		GluShu	Artificial	-15.20	2.32	28.40	-19.96	-10.45	-16.99	1.46	20.00	-20.04	-13.94
			Turf	-36.46	2.32	28.42	-41.21	-31.71	-15.55	1.46	20.01	-18.59	-12.50
		Steel	Artificial	-19.44	2.32	28.35	-24.20	-14.68	-17.65	1.46	20.01	-20.70	-14.60
			Turf	-37.38	2.32	28.13	-42.13	-32.63	-15.08	1.46	19.91	-18.13	-12.04
	Y-maximum	Aluminium	Artificial	79.71	10.39	21.56	58.15	101.28	83.69	6.66	24.19	69.95	97.43
			Turf	153.42	10.41	21.77	131.81	175.02	79.89	6.67	24.27	66.14	93.64
		Barefoot	Artificial	65.08	10.37	21.42	43.53	86.61	80.65	6.66	24.15	66.91	94.39
			Turf	142.14	10.41	21.76	120.53	163.74	90.83	6.67	24.26	77.08	104.58
		GluShu	Artificial	80.42	10.42	21.85	58.79	102.04	82.36	6.67	24.30	68.60	96.11
			Turf	153.69	10.42	21.85	132.06	175.31	77.12	6.67	24.30	63.37	90.88
		Steel	Artificial	88.57	10.43	21.85	66.94	110.20	90.75	6.67	24.31	76.99	104.50
			Turf	151.56	10.41	21.73	129.96	173.17	82.43	6.67	24.26	68.68	96.18
	Y-minimum	Aluminium	Artificial	-20.28	3.22	25.14	-26.92	-13.64	-46.14	3.69	23.99	-53.74	-38.53
			Turf	-52.35	3.24	25.56	-59.01	-45.69	-42.32	3.69	24.16	-49.94	-34.71
		Barefoot	Artificial	-19.01	3.22	24.89	-25.64	-12.39	-34.60	3.68	23.89	-42.20	-27.00
			Turf	-50.21	3.24	25.52	-56.87	-43.55	-36.88	3.69	24.14	-44.50	-29.26
		GluShu	Artificial	-26.09	3.24	25.68	-32.75	-19.42	-45.19	3.69	24.22	-52.81	-37.57

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			Turf	-57.21	3.24	25.70	-63.88	-50.54	-44.60	3.69	24.22	-52.22	-36.98
		Steel	Artificial	-26.63	3.24	25.65	-33.30	-19.96	-46.36	3.70	24.23	-53.98	-38.74
			Turf	-55.98	3.24	25.45	-62.64	-49.32	-45.83	3.69	24.13	-53.45	-38.21
	Z-maximum	Aluminium	Artificial	70.84	13.79	19.64	42.05	99.64	59.77	2.67	20.88	54.21	65.33
			Turf	121.51	13.80	19.70	92.70	150.32	52.19	2.68	21.06	46.62	57.75
		Barefoot	Artificial	69.12	13.78	19.58	40.34	97.89	48.08	2.67	20.74	42.53	53.63
			Turf	149.83	13.80	19.70	121.02	178.64	45.37	2.68	21.04	39.80	50.93
		GluShu	Artificial	62.65	13.81	19.74	33.83	91.47	60.17	2.68	21.15	54.60	65.74
			Turf	108.48	13.80	19.74	79.66	137.30	56.91	2.68	21.15	51.34	62.48
		Steel	Artificial	81.44	13.81	19.75	52.61	110.26	59.33	2.68	21.16	53.76	64.90
			Turf	106.47	13.80	19.69	77.66	135.28	55.06	2.68	21.02	49.50	60.63
	Z-minimum	Aluminium	Artificial	-38.02	4.56	26.28	-47.40	-28.64	-34.49	3.31	24.21	-41.33	-27.66
			Turf	-55.97	4.57	26.45	-65.36	-46.58	-33.29	3.32	24.32	-40.12	-26.45
		Barefoot	Artificial	-39.58	4.56	26.14	-48.95	-30.22	-27.98	3.31	24.13	-34.81	-21.15
			Turf	-52.03	4.57	26.43	-61.42	-42.65	-31.96	3.32	24.30	-38.79	-25.12
		GluShu	Artificial	-33.02	4.58	26.54	-42.42	-23.63	-30.10	3.32	24.37	-36.94	-23.26
			Turf	-43.79	4.57	26.54	-53.18	-34.39	-27.57	3.32	24.37	-34.41	-20.73
		Steel	Artificial	-43.09	4.58	26.55	-52.49	-33.70	-36.44	3.32	24.39	-43.29	-29.60
			Turf	-42.25	4.57	26.42	-51.63	-32.86	-28.90	3.32	24.30	-35.74	-22.06
Leading hindlimb	X-maximum	Aluminium	Artificial	42.72	6.05	23.88	30.23	55.20	21.87	2.15	19.23	17.38	26.36
			Turf	91.44	6.06	24.11	78.93	103.95	17.22	2.15	19.35	12.72	21.71
		Barefoot	Artificial	33.67	6.03	23.60	21.22	46.13	18.60	2.14	19.08	14.12	23.08
			Turf	69.15	6.09	24.50	56.59	81.70	17.96	2.15	19.54	13.46	22.46
		GluShu	Artificial	39.96	6.08	24.37	27.42	52.50	18.57	2.15	19.49	14.07	23.07
			Turf	79.11	6.07	24.22	66.59	91.64	16.41	2.15	19.41	11.91	20.90
		Steel	Artificial	48.93	6.07	24.08	36.41	61.45	23.96	2.15	19.35	19.46	28.45
			Turf	85.18	6.08	24.28	72.64	97.71	17.64	2.15	19.44	13.14	22.14
	X-minimum	Aluminium	Artificial	-19.42	2.55	22.69	-24.70	-14.14	-14.21	1.52	19.58	-17.38	-11.03
			Turf	-41.61	2.56	23.09	-46.91	-36.31	-15.45	1.52	19.72	-18.63	-12.27
		Barefoot	Artificial	-20.04	2.54	22.24	-25.30	-14.78	-14.01	1.52	19.42	-17.18	-10.85
			Turf	-37.42	2.58	23.75	-42.74	-32.09	-18.65	1.53	19.95	-21.83	-15.46
		GluShu	Artificial	-16.46	2.57	23.46	-21.78	-11.14	-14.54	1.52	19.88	-17.72	-11.35
			Turf	-41.33	2.57	23.23	-46.63	-36.02	-13.27	1.52	19.79	-16.44	-10.09
		Steel	Artificial	-23.32	2.56	22.90	-28.61	-18.02	-16.92	1.52	19.72	-20.10	-13.74
			Turf	-43.07	2.57	23.30	-48.39	-37.76	-15.18	1.52	19.83	-18.36	-12.00
	Y-	Aluminium	Artificial	84.49	10.99	24.63	61.84	107.14	77.72	6.64	20.99	63.92	91.53

	maximum		Turf	168.75	11.01	24.87	146.06	191.44	75.51	6.64	21.05	61.69	89.32
		Barefoot	Artificial	72.78	10.96	24.36	50.19	95.38	79.24	6.63	20.90	65.45	93.03
			Turf	146.47	11.06	25.25	123.71	169.23	82.47	6.65	21.15	68.65	96.29
		GluShu	Artificial	95.28	11.05	25.13	72.53	118.02	78.99	6.65	21.13	65.17	92.81
			Turf	171.55	11.03	24.98	148.83	194.26	71.59	6.64	21.08	57.78	85.41
		Steel	Artificial	103.62	11.02	24.84	80.91	126.32	90.67	6.64	21.07	76.85	104.48
			Turf	181.77	11.04	25.04	159.03	204.50	76.66	6.65	21.11	62.84	90.48
	Y-minimum	Aluminium	Artificial	-21.51	4.30	23.81	-30.39	-12.63	-43.28	4.08	26.05	-51.65	-34.90
			Turf	-57.68	4.31	24.04	-66.58	-48.78	-41.89	4.08	26.19	-50.27	-33.50
		Barefoot	Artificial	-21.11	4.29	23.55	-29.97	-12.24	-36.51	4.07	25.88	-44.88	-28.15
			Turf	-50.90	4.33	24.41	-59.82	-41.97	-35.83	4.09	26.41	-44.23	-27.43
		GluShu	Artificial	-29.34	4.32	24.28	-38.26	-20.42	-45.75	4.09	26.35	-54.15	-37.35
			Turf	-58.20	4.32	24.14	-67.10	-49.29	-42.96	4.08	26.25	-51.35	-34.57
		Steel	Artificial	-32.32	4.31	24.01	-41.23	-23.42	-46.58	4.08	26.20	-54.97	-38.19
			Turf	-62.22	4.32	24.20	-71.14	-53.31	-41.97	4.09	26.30	-50.36	-33.57
	Z-maximum	Aluminium	Artificial	75.77	11.47	19.09	51.77	99.77	56.72	2.84	18.83	50.76	62.67
			Turf	132.32	11.48	19.18	108.30	156.34	49.38	2.85	18.95	43.41	55.34
		Barefoot	Artificial	80.32	11.45	18.98	56.35	104.30	46.68	2.84	18.69	40.73	52.63
			Turf	147.38	11.51	19.33	123.33	171.44	41.85	2.86	19.14	35.88	47.82
		GluShu	Artificial	73.80	11.50	19.32	49.75	97.85	58.63	2.85	19.12	52.66	64.60
			Turf	120.47	11.49	19.25	96.44	144.51	54.16	2.85	19.03	48.19	60.12
		Steel	Artificial	98.02	11.49	19.20	73.99	122.05	56.46	2.85	18.95	50.50	62.43
			Turf	124.34	11.50	19.26	100.30	148.38	54.38	2.85	19.04	48.41	60.35
	Z-minimum	Aluminium	Artificial	-34.10	4.86	27.61	-44.07	-24.13	-31.52	3.78	19.85	-39.41	-23.64
			Turf	-59.58	4.88	27.86	-69.57	-49.59	-31.34	3.78	19.92	-39.23	-23.45
		Barefoot	Artificial	-39.86	4.85	27.31	-49.81	-29.92	-26.46	3.78	19.75	-34.34	-18.58
			Turf	-49.70	4.89	28.27	-59.72	-39.68	-26.69	3.79	20.03	-34.60	-18.79
		GluShu	Artificial	-34.84	4.89	28.21	-44.85	-24.82	-30.40	3.79	20.03	-38.30	-22.50
			Turf	-42.01	4.88	28.03	-52.02	-32.01	-23.34	3.79	19.97	-31.24	-15.45
		Steel	Artificial	-45.51	4.88	27.81	-55.50	-35.51	-35.67	3.78	19.94	-43.57	-27.78
			Turf	-42.10	4.88	28.03	-52.11	-32.10	-28.70	3.79	19.98	-36.60	-20.80
Non-leading hindlimb	X-maximum	Aluminium	Artificial	30.34	3.96	24.35	22.17	38.50	15.68	1.64	20.51	12.26	19.10
			Turf	63.95	3.97	24.55	55.78	72.13	18.45	1.65	20.62	15.03	21.88
		Barefoot	Artificial	25.97	3.94	23.89	17.84	34.10	15.65	1.64	20.24	12.24	19.07
			Turf	49.09	4.01	25.75	40.83	57.34	17.43	1.66	21.30	13.98	20.87
		GluShu	Artificial	26.59	3.98	24.82	18.39	34.79	15.69	1.65	20.78	12.26	19.12

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		Turf	53.25	3.97	24.73	45.06	61.44	15.38	1.65	20.73	11.95	18.81
	Steel	Artificial	32.91	3.99	24.90	24.70	41.12	15.04	1.65	20.86	11.60	18.47
		Turf	61.02	3.98	24.74	52.83	69.21	16.75	1.65	20.74	13.32	20.18
X-minimum	Aluminium	Artificial	-15.84	3.00	25.44	-22.02	-9.67	-18.84	1.65	22.13	-22.26	-15.41
		Turf	-29.57	3.00	25.54	-35.74	-23.39	-16.55	1.66	22.21	-19.98	-13.12
	Barefoot	Artificial	-16.85	2.99	25.20	-23.01	-10.69	-17.03	1.65	21.94	-20.45	-13.61
		Turf	-26.22	3.02	26.18	-32.43	-20.01	-18.08	1.66	22.72	-21.53	-14.64
	GluShu	Artificial	-14.01	3.01	25.70	-20.19	-7.82	-18.37	1.66	22.35	-21.80	-14.93
		Turf	-29.50	3.01	25.65	-35.68	-23.32	-16.68	1.66	22.30	-20.11	-13.24
	Steel	Artificial	-16.09	3.01	25.77	-22.28	-9.90	-18.06	1.66	22.42	-21.50	-14.62
		Turf	-32.47	3.01	25.67	-38.65	-26.28	-14.10	1.66	22.32	-17.53	-10.66
Y-maximum	Aluminium	Artificial	69.03	7.89	21.51	52.64	85.41	81.64	5.98	23.23	69.27	94.01
		Turf	130.61	7.91	21.72	114.20	147.02	80.49	5.99	23.28	68.11	92.87
	Barefoot	Artificial	59.75	7.85	21.04	43.44	76.07	83.11	5.98	23.09	70.75	95.47
		Turf	108.17	8.02	22.97	91.58	124.76	92.65	6.01	23.62	80.24	105.06
	GluShu	Artificial	69.18	7.94	21.98	52.72	85.64	85.68	5.99	23.37	73.29	98.07
		Turf	132.07	7.93	21.90	115.63	148.52	77.91	5.99	23.34	65.53	90.30
	Steel	Artificial	74.56	7.95	22.03	58.07	91.05	93.18	6.00	23.44	80.78	105.58
		Turf	123.66	7.93	21.88	107.21	140.11	87.98	5.99	23.36	75.59	100.36
Y-minimum	Aluminium	Artificial	-17.47	2.57	29.32	-22.72	-12.22	-38.87	3.98	21.25	-47.13	-30.61
		Turf	-44.68	2.58	29.87	-49.95	-39.41	-40.54	3.98	21.34	-48.81	-32.27
	Barefoot	Artificial	-18.71	2.54	28.14	-23.92	-13.50	-31.62	3.97	21.06	-39.86	-23.37
		Turf	-38.30	2.65	33.04	-43.69	-32.92	-36.71	4.00	21.83	-45.01	-28.40
	GluShu	Artificial	-21.88	2.60	30.34	-27.18	-16.58	-44.31	3.99	21.46	-52.59	-36.03
		Turf	-54.74	2.59	30.20	-60.02	-49.45	-45.54	3.98	21.42	-53.81	-37.26
	Steel	Artificial	-23.02	2.60	30.18	-28.33	-17.71	-46.08	3.99	21.54	-54.37	-37.80
		Turf	-53.44	2.59	30.09	-58.73	-48.15	-48.44	3.98	21.44	-56.71	-40.16
Z-maximum	Aluminium	Artificial	60.12	11.37	20.41	36.43	83.80	60.44	3.09	22.02	54.04	66.84
		Turf	98.53	11.37	20.45	74.84	122.22	51.53	3.09	22.10	45.13	57.94
	Barefoot	Artificial	65.61	11.36	20.33	41.95	89.27	47.91	3.08	21.79	41.52	54.30
		Turf	105.96	11.41	20.68	82.22	129.70	46.21	3.11	22.72	39.77	52.65
	GluShu	Artificial	52.40	11.38	20.52	28.69	76.10	60.92	3.10	22.29	54.50	67.33
		Turf	88.63	11.38	20.49	64.93	112.33	55.77	3.09	22.21	49.35	62.18
	Steel	Artificial	70.80	11.39	20.56	47.08	94.52	61.29	3.10	22.36	54.86	67.71
		Turf	94.82	11.38	20.47	71.12	118.51	55.52	3.09	22.16	49.11	61.93
	Aluminium	Artificial	-37.23	4.08	23.22	-45.67	-28.79	-32.02	2.66	22.77	-37.53	-26.51

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Z-mini-mum		Turf	-49.63	4.08	23.29	-58.07	-41.18	-33.52	2.66	22.86	-39.03	-28.00
	Barefoot	Artificial	-40.72	4.07	23.03	-49.15	-32.30	-30.54	2.65	22.53	-36.04	-25.04
		Turf	-46.33	4.11	23.82	-54.81	-37.85	-31.80	2.68	23.49	-37.34	-26.26
	GluShu	Artificial	-30.57	4.09	23.45	-39.02	-22.11	-30.74	2.67	23.04	-36.26	-25.21
		Turf	-43.06	4.09	23.38	-51.51	-34.61	-30.37	2.67	22.97	-35.89	-24.85
	Steel	Artificial	-43.54	4.10	23.53	-52.00	-35.07	-38.65	2.67	23.12	-44.17	-33.12
		Turf	-43.80	4.09	23.34	-52.24	-35.35	-30.80	2.67	22.91	-36.32	-25.28

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3.8. Stride time

Impact accelerations for all axes showed only weak negative correlations with stride time. There were moderate correlations between stride time and foot-off accelerations, in particular for the y-maximum and z-maximum parameters. These trends are illustrated in Figure 4, where the strength of the correlations and significance values are also indicated per limb type. Sub-dividing the foot-off data for the y-maximum acceleration parameter, which showed the strongest correlation with stride time (Figure 4), according to shoe-surface combination (using the full dataset for forelimbs and hindlimbs) revealed that the barefoot condition had the strongest relationship with stride time (Figure 5).

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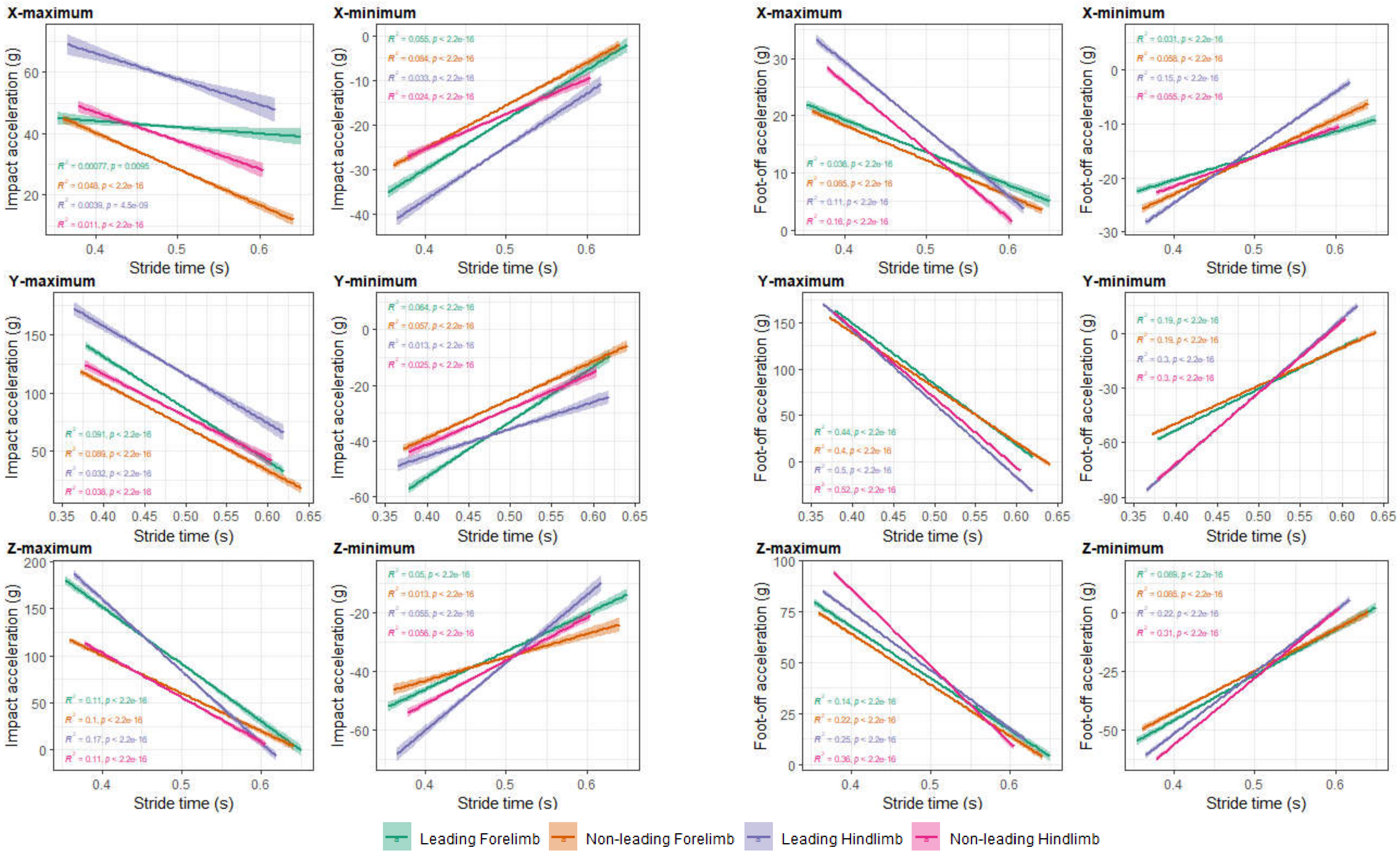

Figure 4. Relationship between stride time and the impact and foot-off accelerations. Data are sub-divided according to acceleration parameter for each limb. The r² and p values for the linear regressions are indicated on the sub-plots. The shaded areas represent the 95% confidence intervals for predictions from a linear model.

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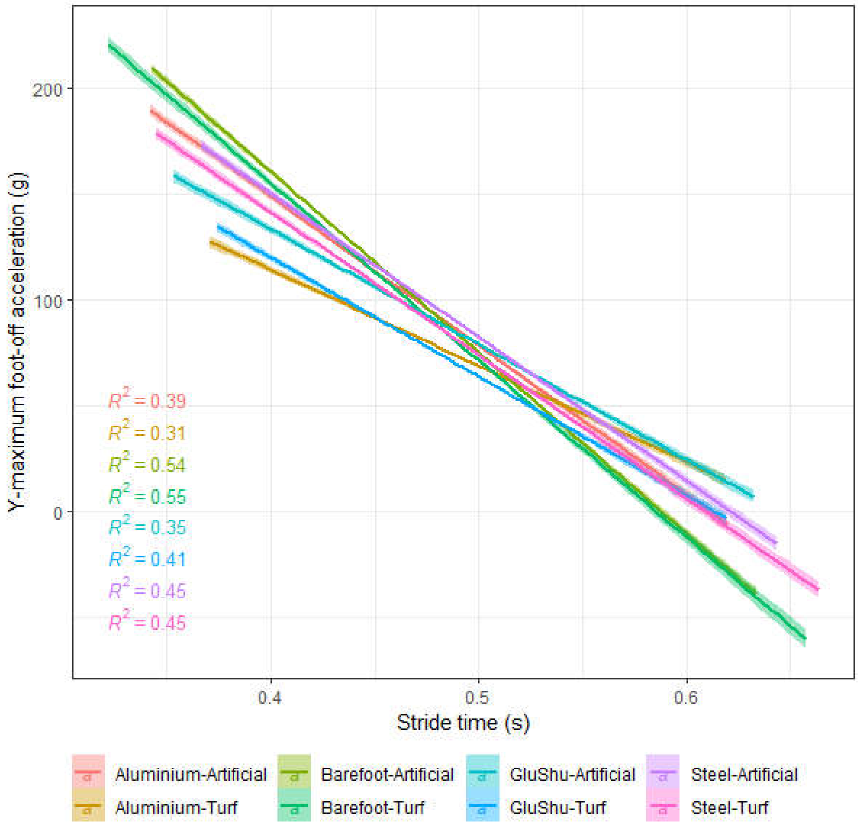

Figure 5. Relationship between foot-off acceleration and stride time for the y-maximum parameter, sub-divided by shoe-surface combination for the entire dataset. The r^2 values for the linear regressions are indicated. All $p<2.2 \times 10^{-16}$.

4. Discussion

Identifying factors that influence the accelerations experienced by a horse's hoof during landing and take-off bears implication for the injury risk and performance of racehorses and jockeys on the racetrack. Although epidemiological evidence indicates that multiple factors are associated with injury risk, including horse characteristics (age, sex, performance quality), training and racing history, pre-existing injuries and race characteristics (e.g. geometry, class), the ground surface conditions and hoof shoeing conditions are factors that may be managed relatively easily and offer practical solutions to improve racing outcomes. This study emphasised the important influence that ground surface type and shoeing condition have on tri-axial accelerations experienced at the dorsal hoof wall. Not only does this have implications for hoof health, but it also impacts on the health and biomechanics of more proximal structures of the limb and upper body in the horse and jockey.

4.1. Impact

The data presented indicated that the hoof accelerations experienced on impact were 1.4–1.9 times and 1.2–2.4 times greater on turf compared to the artificial track, for the forelimbs and hindlimbs, respectively. This trend toward higher accelerations on turf than synthetic surfaces is consistent with previous studies comparing hoof impact variations on turf versus synthetic surfaces at the trot and canter [15,93]. The acceleration power and frequency of hoof wall vibrations have previously been linked to surface hardness [12,15,22,32,59,94]. It likely that the results here reflect the greater hardness of the turf compared to the artificial surface. The artificial surface was probably better at damping impact accelerations and provided greater cushioning to the hoof on landing; although this was not perceivable by the jockeys [88]. The smallest relative difference between surfaces was observed in the z-minimum for all limbs, although the z-minimum parameter was the most difficult to target consistently during data processing. For the forelimbs, the y-maximum and z-maximum showed the largest relative differences between surfaces (all 1.7–1.9 times larger on turf). The largest difference in absolute terms occurred for the leading forelimb (60.7 g) for the z-maximum parameter. In the hindlimbs, the greatest relative difference between surfaces was apparent for the y-minimum (2.2–2.4 times greater on turf), although as noted in the *Results*, the largest absolute difference between surfaces was 78.1 g for the y-maximum parameter in the leading hindlimb.

The differing sensitivity of the six acceleration axes to surface type between forelimbs and hindlimbs may indicate that the hoof orientation on and immediately after landing is consistently different between the fore and hindlimbs. For example, it would make sense for the accelerations represented by z-maximum (in the dorsal direction of the hoof) to be most closely associated with horizontal braking. Forelimbs are responsible for decelerating the horse in each stride cycle [20,95,96] and it is therefore logical that the z-maximum parameter would have greater sensitivity to surface-type in forelimbs. In addition, the forelimb hooves may have a greater tendency to land obliquely, while it is possible that the hindlimb hooves adopt an orientation on landing whereby the solar surface is closer to a parallel orientation to the ground surface. This would be consistent with observations that hindlimbs have higher horizontal hoof velocities than forelimbs, and forelimbs contact the ground with more acute velocity vector angles than hindlimbs [97]. It is important to note that when hooves land flatter, the timing of events following primary impact are shorter, which results in a shorter period of horizontal hoof braking and higher vertical and horizontal loading rates [10]. Rapid rotation of the hoof and fetlock joint during the horizontal braking of the hoof is an important factor in the initial attenuation of the impact, and may be related to injury of the distal joints [98,99]. A shorter braking period is associated with higher amplitudes in the longitudinal retardation of third metacarpal bone and more rapid oscillation of segments, which has relevance for orthopaedic health [10].

Increased speed also results in a rise of the vertical force and the rate of angular displacement in the hoof segment and fetlock joint [100], and vertical and horizontal decelerations also increase. Although the strength of the correlation coefficients is low, the general trend of increasing magnitude in the y-minimum and z-minimum impact peaks with increasing speed (or lower stride times, Figure 4) observed here is consistent with previous studies, which have reported an elevated magnitude in a negative acceleration peak perpendicular to the solear surface (e.g. Ratzlaff et al., 2005). As the time between hoof contact on the ground and full support is reduced at high speeds, this results in a faster translation and rotation of the distal bone segments [10]. Comparing the impact data across all stride times, it is suggested from our data that at low stride times (i.e. higher speeds) the accelerations in the dorso-palmar (especially z-maximum) direction are proportionally larger for the leading limbs (Figure 4). This could suggest that the hoof landing patterns are dependent on speed and may also reflect the reduced overlap between individual limb stance phases at upper gallop speeds [89]. During impact, the y-axis data (along the hoof wall) is probably most closely related to the ground reaction force, which may explain why the accelerations were often large along this axis, and why the y-maximum parameter appeared particularly sensitive to shoe-surface conditions. Also, at upper gallop speeds it is plausible that there is proportionally greater hindlimb loading [28] and this may help to explain why the y-minimum EMMs showed the largest proportional differences between surfaces for hindlimbs, when assessing the data as a whole.

Previous studies have indicated that the right hindlimb on a counter-clockwise track (this would be the non-leading hindlimb) has an overall higher incidence of fracture than the left hindlimb, but shows no difference in risk ratio due to surface type [41]. In addition, previous comparisons between contralateral and ipsilateral pairs of limbs found that the leading forelimb and non-leading hindlimb were at greater risk [41]. Data from this study suggest the leading limbs experience the largest accelerations on the tracks used here, which had only a very slight anticlockwise bend [85]. Based on EMMs for surface effects (Table 3) averaged across all acceleration axes, the leading limbs had accelerations that were 1.5 times larger than the non-leading limbs. This could place them more vulnerable to injury, as high accelerations reflect more rapid loading during the secondary impact phase of the stride cycle, and previous work has found a relationship between impact forces and lameness [33], and track hardness appears related to racing injuries [34,101]. This study also highlighted that accelerations on turf at impact are considerably higher than those on the artificial surface, under the ground conditions studied ("soft" to "good to firm"), which suggests that risks associated with turf versus artificial surface types still deserves consideration.

The largest impact acceleration offsets amongst shoeing conditions, in absolute terms, were most commonly observed between the steel and barefoot conditions (Table S2): 11/18 comparisons in the forelimbs (combined forelimb data, leading forelimb and non-leading forelimb) and 6/18 hindlimbs (combined hindlimb data, leading hindlimb and non-leading hindlimb); for the six acceleration directions. Barefoot was amongst the pairwise comparisons with the largest offsets in 29/36 instances. Considering all acceleration axes together, data indicated that impact acceleration peaks were 7–12 % higher in aluminium, 2–8% higher in GluShu and 10–18% higher in steel, when compared to the barefoot condition (comparisons made in the individual limbs). This compares to a previously reported difference of 15% between shod and unshod horses during simulated impact loading at trot in an in-vitro model [9]. However, accelerations were up to 25–30% higher in steel compared to barefoot for the y-minimum and x-minimum parameters. The higher accelerations typically associated with the steel shoeing condition at impact may reflect the high rigidity and relative hardness of this material [102], which initiated rapid energy loss through hoof and limb vibrations. Shoeing with steel shoes has also been found to increase the maximal vertical force compared to barefoot in trotting Warmblood horses [103]. In contrast, the greater similarity in accelerations for GluShu relative to barefoot probably reflects greater damping in this condition due to the rubber coating on the shoe. Some previous work has also found synthetic polyurethane shoes and pads made of synthetic rubber can help in reducing peak impact vibrations in trotting horses [11,104], although no differences amongst shoeing conditions with and without a pad and packing material were found in an in-vitro model [80].

The hoof was perhaps most efficient at energy absorption on landing when barefoot because the tubules embedded in the inter-tubular matrix were better able to resist high-speed impacts without catastrophic structural failure under compression and loading. Specifically, cracking and deformation of tubules dissipates energy while protecting the matrix from fracture or damage; this occurs even after 60% compressive strain under quasi-static loading and avoids whole structural failure [19]. Unshod feet are known to undergo a greater degree of heel expansion, and this movement could help to dissipate the impact vibrations [105]. In addition, because the barefoot sole is closer to the ground surface compared to a shod foot, the frog and solear surface participate in the impact sooner than in the shod conditions, and the load is perhaps more readily distributed over the full area of the solear surface [106]; an effect which is also likely to reduce the frequency of the vibrations measured at the dorsal hoof wall. When combined with the artificial surface, which appeared to be springy and deformable on impact in high-speed video footage [28], it is therefore unsurprising that the barefoot hooves usually experienced the lowest impact accelerations and typically contrasted most with steel shod hooves on turf. However, although the accelerations were commonly lower when barefoot, it is worth noting that when galloping barefoot on turf a greater proportion of the runs involved the horses swapping leads (Table 1); 18% of mixed-lead forelimb runs and 23% of mixed-lead hindlimb runs were from the barefoot-turf condition compared to just 7–9% of the data from the individual limbs. This could signify the horses were more unbalanced in the barefoot-turf condition, and may explain why the jockeys perceived gallop runs to be less smooth in this condition [88]. However, it is worth noting that there was also a tendency towards lower mean stride times (faster speeds) in the mixed-lead forelimb and mixed-lead hindlimb data when barefoot on turf, compared to the other shoe-surface combinations (Table 1).

Although contrasts in vibrations may be apparent at the level of the hoof between shod and unshod conditions, an in-vitro model simulating trot indicated that minimal differences existed at the level of the phalanx and metacarpus [80]. Nevertheless, at gallop when the accelerations and loads are amplified, even small differences could be relevant for injuries and safety. In fact, the findings here tie in with the horse and jockey centre of mass displacements, which indicated that the largest vertical displacement differences were present between barefoot-artificial and steel-turf [85]. This suggests that hoof kinematic patterns are translated into upper body kinematics. Further work is needed though to establish the relative risk of damage to the hoof and more proximal limb structures in association with the observed variability in accelerations amongst barefoot and shod conditions at gallop. It will be important to establish whether there are certain thresholds for impact vibrations that may be conducive to the development of injury or pathologies, such as osteoarthritis. Performance implications are also key. Previous work has suggested that a reduction in the decelerative peak may signify an increased stride efficiency, by permitting a smoother transition from retardation to propulsion [59]. Hoof acceleration signals at different stages of the trimming/shoeing cycle will also be important to understand. For example, a gradual dorsal shift in the centre of pressure with respect to the distal interphalangeal joint due to hoof growth and backwards tilting of the foot in unshod hooves [103] may influence the depth of penetration of the heel into a compliant surface during loading. Indeed, hoof pitch rotation during early stance due to heels sinking into the surface has been reported in walk [107]. This effect may be linked to the magnitude of impact accelerations being recorded at the hoof wall. In addition, it would be beneficial moving forward to assess hoof impact accelerations in different shoe-surface combinations during jump races, as show jumpers show elevated peak vertical hoof accelerations at take-off when jumping at the canter, especially in hindlimbs [108].

4.2. Foot-off

At foot-off, the large acceleration spikes are caused by the hoof accelerating to the forward speed of the horse. Accelerations were more similar between turf and artificial surfaces when compared to the impact data but were almost always larger on the artificial surface. The maximum absolute differences occurred in the leading forelimb between surfaces for z-maximum and y-maximum (difference of 12.6 g and 10.4 g, respectively), which may reflect the fact that in this limb the braking and vertical impulses must decelerate the centre of mass and provide it with sufficient upward vertical velocity for the flight phase of the stride [95]. Vertical centre of mass displacements are indeed larger by around 5.7 mm downwards and 2.5 mm upwards on the artificial surface as a result of this action [85]. The general trend toward higher hoof accelerations on the artificial surface (Table 3) is also consistent with a faster breakover on this surface [28]. Larger acceleration peaks at foot-off have previously been related to greater rebound rates and reduced hardness of the track [59]. Here, the more deformable artificial track may return greater energy to the hoof during the propulsive phase, explaining these higher accelerations also. It is possible that higher accelerations at foot-off may lend themselves towards a more energy-efficient gait. A smoother transition from retardation to propulsion may be important in determining the safety of racing surfaces [59]. Nevertheless, even if an artificial surface is deemed favourable, as the majority of UK racing currently takes place on turf tracks there may logistical constraints in the immediate future.

Consistent with the impact data, we found that the barefoot hoof had the lowest hoof accelerations overall. Considering all acceleration axes together, our data indicate that foot-off accelerations were 4–7% higher in aluminium, 5–6% higher in GluShu and 8–12% higher in steel, when compared to the barefoot condition (comparisons made in the individual limbs). The pairwise comparisons with the largest offsets included barefoot in 18/36 cases, although in two of these instances (for the x-minimum) the barefoot condition actually had the larger accelerations of the two shoeing conditions. In some ways, these observations are surprising because a barefoot hoof would be expected to deform more on impact and then return more energy to the hoof, which might be expected to lead to more rapid accelerations. Indeed, at the higher gallop speeds barefoot hooves do appear to experience proportionally higher foot-off accelerations relative to the shod conditions (Figure 5). This is consistent with breakover becoming relatively faster for barefoot hooves at upper gallop speeds in the non-leading hindlimb; the only limb in which breakover duration was sensitive to shoeing condition [28]. This previous work also indicated that at low gallop speeds barefoot hooves have a longer breakover duration relative to the shod conditions (in the non-leading hindlimb), and proposed that shoe shape, and in particular the bevelled toe of the shoes, might be important in increasing breakover rate [28] and by extrapolation hoof accelerations also for the shod conditions at low-moderate speeds. As the retired ex-racehorses used in this study tended to gallop at average speeds of around 40 km h^{-1}, this may explain why accelerations associated with the barefoot condition tended to be reduced. In addition, given it was the mixed lead data that represented more of the faster barefoot runs (Table 1), it is consistent that an analysis of the barefoot condition in the individual limb data sets (for lower stride times) would tend towards lower values. Interestingly, it was the non-leading hindlimb that experienced slightly higher accelerations overall at foot-off compared to the other limbs (up to 6% higher on average across all acceleration axes), which may explain its sensitivity to shoeing condition in terms of breakover duration [28].

At the upper range of gallop speeds assessed here, the foot-off accelerations were increased across all acceleration axes proportionally more in the hindlimbs compared to the forelimbs, with the exception of x-minimum in the non-leading hindlimb (Figure 4). This trend also mirrors the observations in the breakover duration data [28]. It likely relates to a difference in landing orientation and subsequent hoof trajectory in forelimbs versus hindlimbs as speeds increase; including greater hindlimb loading and more rapid push-off from the hind end. Further work is needed to establish the effect of turns on hoof acceleration patterns, as turning imposes additional asymmetrical forces on the limbs on the inside and outside of the turn [109]. The effect of hoof growth on foot-off accelerations is also potentially important. Long toes may lead to longer breakover durations and due to an increase in the length of the resistance arm, there will be an increase in tension on the deep digital flexor tendon to initiate breakover [110] and toe penetration depth is likely to increase. Extending the duration of breakover would plausibly reduce the magnitude of accelerations in the foot-off window.

5. Conclusions

Tri-axial hoof accelerations at impact and foot-off in galloping Thoroughbreds were influenced by shoeing condition and surface type. Accelerations were elevated at impact on the turf surface compared to the artificial track by 1.2–2.4 times, depending on the acceleration axis considered; acceleration magnitudes were largest and offsets between surfaces greatest along the hoof wall and in the dorso-palmar direction. Accelerations were on average 2–18% higher at impact in the shod conditions compared to barefoot, when considering all acceleration axis directions together, but rose up to 30% more in steel. Preventing excessive shock loading and related muculo-skeletal injuries in racehorses is of critical relevance to the racing industry. This work suggests that the combination of an artificial surface and barefoot hooves may be beneficial for minimising the exposure of the hoof and distal limb to large accelerations during hoof landing. At foot-off, it was most commonly observed that accelerations were amplified on the artificial surface compared to the turf; average accelerations per individual limb were 2–12% greater for the former. We inferred that the artificial surface deformed, at least to some extent, more elastically under load and subsequently recovered and returned a higher proportion of energy to the hoof. This will have aided propulsion, leading to more rapid hoof breakover, and could confer a performance benefit. Overall, barefoot hooves typically experienced the lowest accelerations at foot-off, although at top gallop speeds accelerations for barefoot hooves appeared to increase at relatively higher rate than for shod conditions. Further work is needed to relate these findings to injury risk and racing outcomes specifically, particularly in racehorses galloping at top speeds.

Supplementary Materials:

Supplementary Data File containing the following:

- Full raw data spreadsheet with data dictionary;
- Table S1: Significance values for the entire data set and a sub-set of the data with stride frequencies of 2 Hz and above.
- Table S2: Post-hoc pairwise comparisons (with Bonferroni correction) for shoeing conditions using peak impact and foot-off accelerations. The entire data set was used here (i.e. across all stride times).
- Table S3: Post-hoc pairwise comparisons (with Bonferroni correction) for surfaces using peak impact and foot-off accelerations. The entire data set was used here (i.e. across all stride times).
- Table S4: Post-hoc pairwise comparisons (with Bonferroni correction) for shoe-surface combinations using peak impact and foot-off accelerations. The entire data set was used here (i.e. across all stride times).
- Table S5: Significance values for area values within 5 ms of the maximum acceleration (entire data set).
- Table S6: Estimated Marginal Means for shoeing conditions using area data. The entire data set was used here (i.e. across all stride times).
- Table S7: Estimated Marginal Means for surface conditions using area data. The entire data set was used here (i.e. across all stride times).
- Table S8. Estimated Marginal Means for shoe-surface conditions using area data. The entire data set was used here (i.e. across all stride times).

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Institutional Review Board Statement: Ethical review was performed and approval granted for this study by the Royal Veterinary College Clinical Research Ethical Review Board (URN 2018 1841-2, 19 November 2018).

Data Availability Statement: Data supporting the results are presented in the 'Results' section of this manuscript and the 'Supplementary Data File'

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Conflicts of Interest: We have the following interests: J.C. owns the company James Coburn AWCF Farriers Ltd., which employed D.H., L.B. and H.C. at the time of the study; J.C., P.D., H.C., D.H. and L.B. are now registered farriers; M.P. is the director of the Racetrack Safety Program and Principal of the company Biologically Applied Testing LLC; T.P. is the owner of Equigait, a provider of gait analysis products and services. This does not alter our adherence to all polices on sharing data and

materials. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A: Supplementary Information

A.1 Peak impact and foot-off correlations

To assess which impact and foot-off parameters were most closely related, Pearson Product Moment Correlation Coefficients were calculated for comparisons between each of the impact parameters and foot-off parameters and stride time. The results are presented in Figure S1. The amplitude of the minimum and maximums were inversely correlated with stride time, with the strongest correlation occurring between stride time and y maximum at foot-off (correlation coefficient = -0.67). X-maximum at impact was most closely strongly correlated with the y and z impact maximums (correlation coefficients of 0.71 and 0.57, respectively), but also showed a moderate correlation with the x-minimum at impact (correlation coefficient = -0.51). The x-minimum at impact was moderately correlated with the y maximum at impact (correlation coefficient = -0.53). The impact y-maximum showed moderate correlations with y minimum and z maximum at impact (correlation coefficients of -0.64 and 0.64, respectively), whereas the impact y-minimum was weakly correlated with the impact z-maximum. At foot-off, the y maximum additionally showed a moderate correlation with both the y-minimum and the z-minimum (correlation coefficients of -0.54 and -0.57, respectively). All other correlation coefficients were ≤ 0.5.

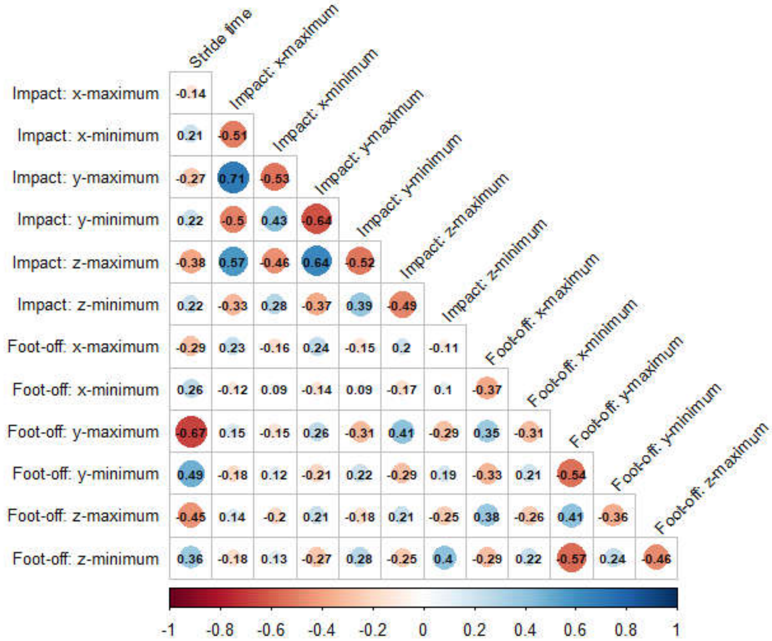

Figure A1 Correlation matrix comparing the Pearson Product correlation coefficient amongst minimum and maximum acceleration parameters. All data are included here for all limbs.

A.2 Peak accelerations versus areas

We considered trends in area data to be more meaningful than absolute values because we arbitrarily selected a given time-frame away from minimum and maximum peaks to study. The justification for the time-window chosen was provided in section 3.1. Figure S2A illustrates the trends amongst shoe-surface conditions for the summed (positive) acceleration data in the 5 ms window ahead of the maximum, for comparison to the plots in Figures 2 and 3. For the impact phase, the area data indicated that accelerations were larger for the leading compared to the non-leading limbs and it was clearly apparent that the areas for the turf were larger than those for the artificial surface. The inter-quartile ranges for the turf data were also typically larger than for the artificial surface. Shoe effects were subtler but when looking at the y-maximum parameter (the focus of section 3.7) the

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Steel-Turf condition once again had the largest accelerations. At foot-off accelerations were larger on the artificial surface compared to the turf, with the exception of the x-axis data when the horse was barefoot.

Therefore, the area results appeared to largely mimic those of the minimum and maximum. To investigate this relationship in more detail, the area data were plotted against the peak acceleration data and the modelled by a linear regression for each limb at impact and foot-off (Figure S2B). There was a significant positive correlation between peak values and area data in all cases, but the correlation was most strong for the area versus y-maximum acceleration datasets at foot-off (mean r2 = 0.76).

All of the raw area data are available in the Supplementary Data File. Linear Mixed Models were also run on the summed (positive) acceleration data in the 5 ms window ahead of the maximum and the significance values and Estimated Marginal Means output from these statistical analyses are provided in the Supplementary Data File (Tables S5-S8).

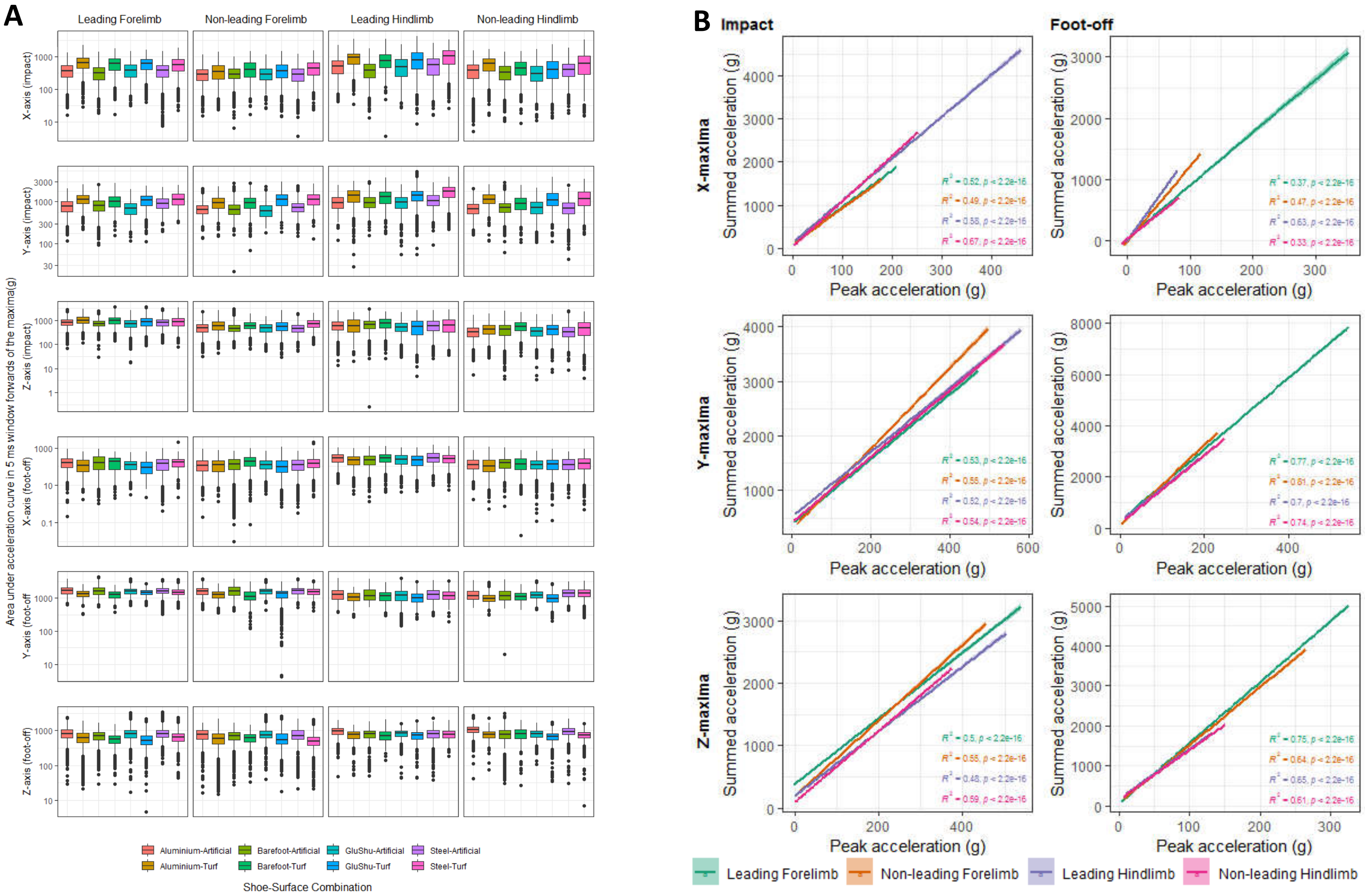

Figure A2. A) Boxplots illustrating the summed (positive) acceleration data in the 5 ms window ahead of the maximum, sub-divided according to shoe-surface condition. B) Positive linear relationship between peak accelerations and summed accelerations (positive) within 5 ms forward in time of the maximum peak. Data are sub-divided according to acceleration parameter for each limb.

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A.3 Relationship between hoof accelerometry data and centre of mass displacements

Scatter plots were used to investigate whether the hoof acceleration patterns were correlated with the tri-axial centre of mass displacements of the horses reported previously [85] and these are included as supplementary information in Figure S3. In summary, weak to moderate correlations were found between the tri-axial hoof impact acceleration parameters and the tri-axial centre of mass displacements. The dorso-ventral COM minima was most closely related to the hoof data, with correlation coefficients of $r^2 = 0.76$ and $r^2 = 0.72$ for the hoof y-minimum and y-maximum, respectively. The foot-off accelerations were not closely correlated with the COM data (Figure S4).

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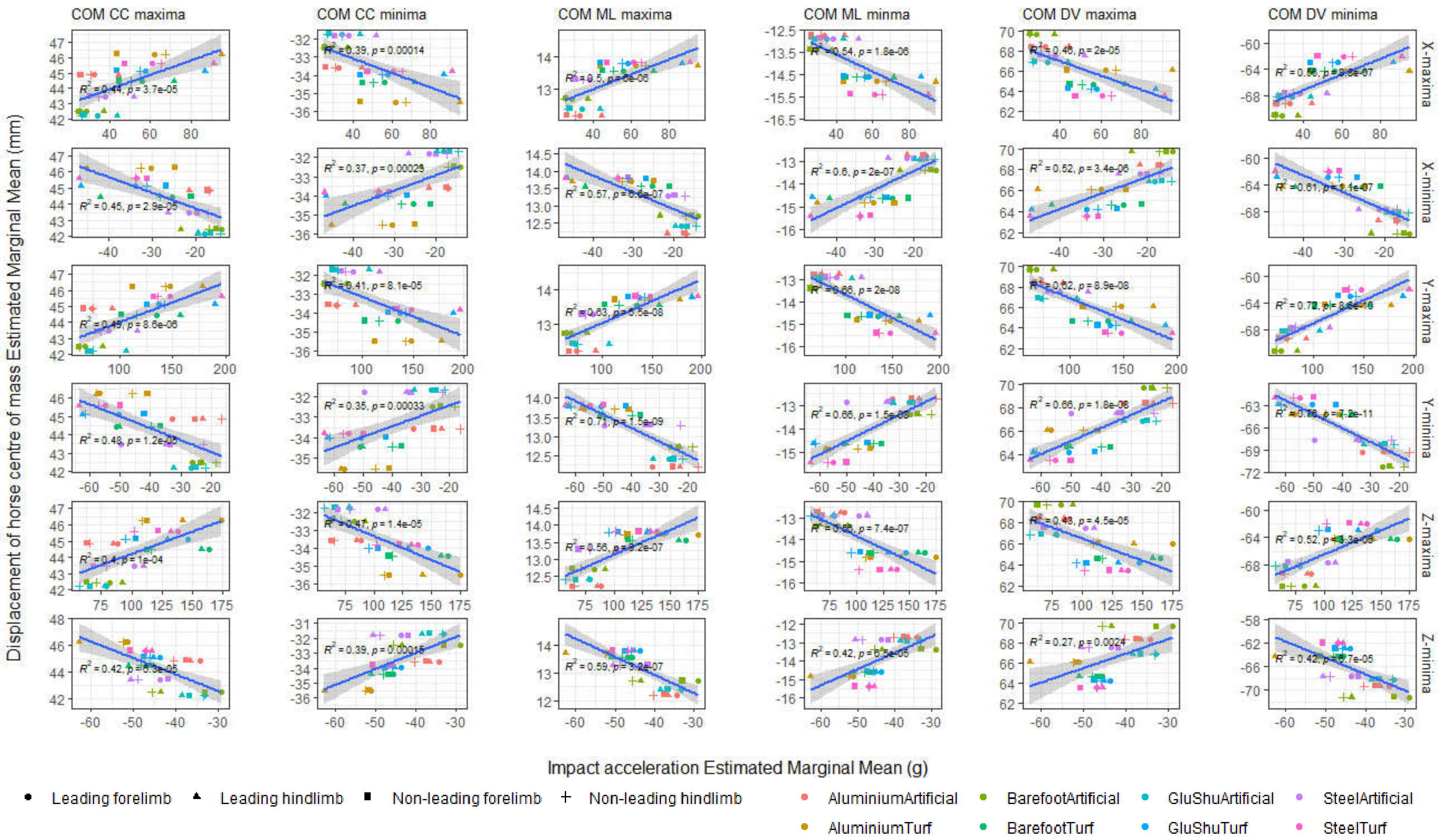

Figure A3. Relationship between impact acceleration data and centre of mass (COM) displacements. Data are sub-divided horizontally by the hoof acceleration parameters (X-maximum, X-minimum, Y-maximum, Y-minimum, Z-maximum and Z-minimum) and vertically by the COM parameters (CC-maximum, CC-minimum, ML-maximum, ML-minimum, DV-maximum, DV-minimum); as indicated by the labels on the right side of the plot. The comparison centre of mass displacement is indicated by the headers along the top of the plot. Within each subplot, the data are further sub-divided according to both shoe-surface combination and limb.

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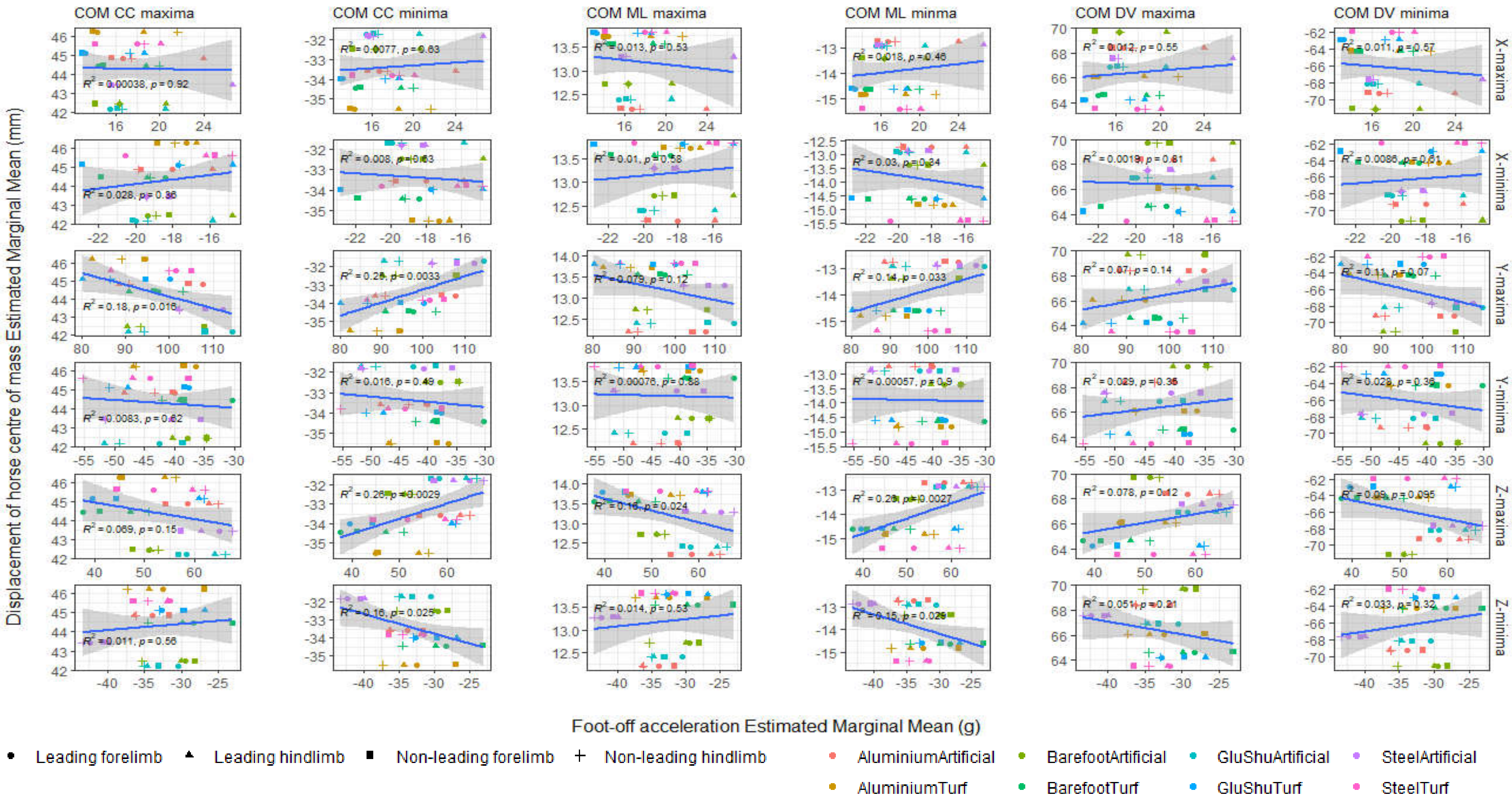

Figure A4. Relationship between foot-off acceleration data and centre of mass (COM) displacements. Data are sub-divided horizontally by the hoof acceleration parameters (X-maximum, X-minimum, Y-maximum, Y-minimum, Z-maximum and Z-minimum) and vertically by the COM parameters (CC-maximum, CC-minimum, ML-maximum, ML-minimum, DV-maximum, DV-minimum); as indicated by the labels on the right side of the plot. The comparison centre of mass displacement is indicated by the headers along the top of the plot. Within each subplot, the data are further sub-divided according to both shoe-surface combination and limb.

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