Comparison of limb kinematics between collected and lengthened (medium/extended) trot in two groups of dressage horses on two different surfaces.

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Keywords: Equine, suspensory ligament, metacarpophalangeal joint, metatarsophalangeal joint

Ethical Considerations: The study was approved by the Clinical Ethical Review Committee of the Animal Health Trust (Project Number: AHT19-2013). There was informed owners' consent.

Competing Interests: None to declare

Sources of Funding: Elise Pilkington Charitable Trust, Dr W. Bechtolscheimer and British Dressage.

Acknowledgements: We would like to thank study participants and students from the College of West Anglia for their assistance during data collection.

Authorship: Walker, Tranquille, Dyson & Murray contributed to study design, data analysis and interpretation and preparation of the manuscript. Walker, Tranquille, Brandham and Northrop acquired the data. Northrop carried out surface analysis. Newton performed statistical analysis and contributed to the manuscript. All authors approved the final version of the manuscript.

Word count: 4236

SUMMARY

Background: Dressage horses are often asked to work in lengthened paces during training and competition, but to date there is limited information about the biomechanics of dressage-specific paces. Preliminary work has shown increased fetlock extension in extended compared with collected paces, but further investigation of the kinematic differences between collected, medium and extended trot in dressage horses is warranted. Objectives: Investigation of the effect of collected versus medium/extended trot on limb kinematics of dressage horses. Study design: Prospective kinematic evaluation. Methods: Twenty clinically sound horses in active dressage training were used: Group 1) ten young horses (≤ 6 years) were assessed at collected and medium trot; Group 2) ten mature horses (≥9 years) were assessed at collected and extended trot. All horses were evaluated on two different surfaces. High-speed motion-capture (240Hz) was used to determine kinematic variables. Forelimb and hindlimb angles were measured at midstance. Descriptive statistics and mixed-effect multilevel-regression analyses were performed. Results: Speed and stride length were reduced and stride duration increased at collected compared with medium/extended trot. Lengthened trot (medium/extended trot) was associated with increased fetlock extension in both the forelimbs and hindlimbs in both groups of horses. Changes were greater in Group 2 compared with Group 1. Shoulder and carpus angles were associated with forelimb fetlock angle. Hock angle was not significantly influenced by pace. Surface had no effect on fetlock or hock angles. Main limitations: Only 2D motion analysis was carried out. Results may have been different in horses with more extreme gait characteristics. Conclusions: Medium/extended trot increases extension of the forelimb and the hindlimb fetlock joints compared with collected trot in both young and mature dressage horses, respectively.

INTRODUCTION

Dressage horses are often asked to work in lengthened paces during training and competition, but to date there is limited information about the biomechanics of dressage-specific paces [1-7]. The current literature highlights the high prevalence of injuries of the suspensory apparatus and the metacarpophalangeal or metatarsophalangeal (fetlock) joints in dressage horses [8-11]. Dressage-specific movements may be implicated in causation or sub-clinical injuries may be exacerbated by the highly repetitive nature of dressage training [12]. However to determine this we need to first understand the biomechanics of dressage-specific paces, therefore investigation of the kinematic differences between collected, medium and extended trot in dressage horses is warranted.

During the stance phase the limbs are progressively loaded until peak load at midstance. In the forelimbs this results in shoulder and elbow flexion and carpus and fetlock extension; in the hindlimbs there is hip, stifle, and hock flexion and fetlock extension [13,14]. In all limbs, the role of the suspensory apparatus is to limit fetlock extension; consequently any variable which increases fetlock extension is likely to increase load on the joint and the suspensory apparatus, [15,16] and therefore may increase injury risk to these structures. Increased speed and stride length and reduced stride duration in medium and extended trots compared with collected trot have been described [3]. More recently it was shown that changes in temporal variables can influence extension in trot [17-18]. These findings were supported by a pilot study of four mature advanced dressage horses in which greater fetlock extension and hock flexion were found in extended trot compared with collected trot [7].

Epidemiological data has highlighted surface as a risk factor for injury in dressage horses [8, 9]. Surface properties have been found to influence limb kinematics in horses competing in other disciplines such as racing [19-20] and trotting [21-24], but there has been minimal investigation on the effect of surface in collected or extended trot. Greater fetlock extension at extended trot has been reported in dressage horses on a synthetic surface compared with dirt [21], which suggests that surface may influence kinematics at this pace.

The study aimed to investigate forelimb and hindlimb kinematics in: 1) young dressage horses at collected and medium trot and 2) mature dressage horses at collected and extended trot. It was hypothesised that 1) increased forelimb and hindlimb fetlock extension and hock flexion would be seen at medium/extended trot compared with collected trot; 2) medium/extended trot would have greater speed, stride length and reduced stride duration compared with collected trot; 3) speed, stride length and stride duration and forelimb joint angles would be correlated with forelimb fetlock extension and speed, stride length and stride duration and hindlimb joint angles would be correlated with hock angle and hindlimb fetlock extension; 4) hindlimb fetlock extension and hock flexion would be related to maximal hindlimb protraction and retraction angles; 5) forelimb and hindlimb fetlock extension and hock flexion would be affected by surface.

MATERIALS AND METHODS

Horses

A power calculation indicated that a sample size of 19 horses was required to detect a difference at a significance level $P<0.05$ for distal metatarsal coronary band vertical ratio (MTCR) which represents hind fetlock extension, and hock angles based on pilot data [7].

Twenty clinically sound horses, with no history of suspensory ligament injury, in active dressage training were used: Group 1) ten young (≤ 6 years) horses working at novice to elementary level dressage [25]; Group 2) ten mature (≥9 years) horses working at Prix St Georges and above [25]. Horses were conventionally shod or barefoot. Horses did not wear boots or bandages. All horses were assessed on two different outdoor surfaces (Surfaces A and B, Table 1). Surface composition was analysed by taking a sample from each arena and carrying out simple material tests to quantify percentage moisture, sand, fibre and wax as described in previous work [26]. The arena conditions were chosen because they simulated surface composition and preparation routinely used for training and competing dressage horses.

All horse were evaluated by an experienced veterinarian (RM-Diplomate of the American College of Veterinary Surgeons) in-hand at walk and trot in straight lines and in-hand at walk in 5m diameter circles on a firm surface to ensure that they were free from lameness or graded <1/8 lame [27]. Domed 30mm markers were placed at predetermined anatomical sites (Figure 1A) on the left and right sides by a single experienced technician (blinded for review), verified by a veterinarian, according to palpable surface landmarks [28]. Marker placement repeatability has been previously validated [7]. Horses were warmed-up by their normal rider, as they would be at a competition, for up to 30 minutes before testing.

Testing took place at a single venue, on both surfaces consecutively in a randomised order, using a cross-over design. When the horses moved from the first surface to the second, 10 minutes were available for acclimatisation (duration used was rider-determined). Each horse was ridden at collected trot sitting (the degree of collection depended upon the stage of training) and at medium (Group 1) or extended (Group 2) trot sitting in a straight line marked out with cones (Figure 1B).

Data Collection

High-speed motion-capture (240Hz, 1280 x 720 pixels) was used to assess each horse from the left side. The camera (Casio EX-FH250[1]) was placed 6m from the middle of the trot pathway and the field of view was 5m wide and 3m high (Figure 1A). The camera was calibrated using a known object in the field of view and also using a known measurement on the horse. These were both compared to ensure that the calibration was accurate to 0.5 mm. A minimum of four strides for each type of trot on each surface were collected. Strides were recorded when the horse passed the camera. A single complete stride was selected per pass, because the field of view prohibited recording of consecutive strides. Recordings were retained for analysis if the stride was correct according to the Fédération Equestre International Rules for Dressage [29], contained the entire stance phase, and was in the centre third of the field of view (directly in front of the camera) to reduce the camera/marker angle in order to maximise accuracy. This was judged by 3 authors (RM, VW, JB). Speed was calculated from the time it took for each horse to get from the cone at the start of the runway to the cone at the end of the runway and was verified from normal-speed video camera footage.

Data Analysis

Images were analysed by an experienced analyst (blinded for review) using previously validated techniques [7]. Data was tracked through the entire stance phase and a low-pass Butterworth filter with a cut off of 15Hz was used. Shoulder, elbow, carpal, forelimb fetlock, hip, stifle and tarsal angles (Figure 2) were determined at midstance, when the fetlock joint was maximally extended and mid swing when the carpus/hock joint was maximally extended/flexed. Fetlock extension angle throughout the stance phase was plotted graphically and the frame of peak fetlock extension was determined. Repeatability of this frame selection was carried out 5 times for 5 horses (Coefficient of variation $< 3\%$). Hindlimb fetlock extension was measured as MTCR at midstance, which was defined as the distance between the fetlock and the coronary band marker. This was calculated as the difference between the vertical location of markers 12 and 13 (Figure 3) on the Y axis at maximal extension of the MTPJ, as previously described [7]. The MTCR measurement was used to determine the presence of fetlock hyperextension (defined as marker 12 located below marker 13 at midstance). Using this technique, it was less labour intensive to compare the degree of hyperextension/extension among horses and between groups than measuring static fetlock angles and then making a comparison with midstance angles. This was only performed in the hindlimbs because it is commonly accepted that forelimb fetlock extension occurs during normal locomotion [30,31]. We aimed to determine metatarsophalangeal joint extension compared with the coronary band, using a method which has been successfully applied previously [7]. The measurements of $\geq$ 1mm were accurate. Data from the left side only were analysed.

The angle of the dorsal coronary band (marker 11) to a vertical line drawn from the tuber ischii (marker 19) was used to represent hindlimb retraction (Figure 4A). Relative protraction of the hindlimb was calculated as the angle between the dorsal coronary band marker relative to the vertical line drawn from the proximal end of the tuber coxae (marker 15) (Figure 4B). Forelimb protraction was defined as the angle between a vertical line drawn from the cranial eminence of the greater tubercle of the humerus (marker 4) and the dorsal hoof wall marker (marker 10), when the forelimb was in its foremost position just before hoof impact (Figure 4C). Forelimb retraction was defined as the angle between a vertical line drawn from the cranial eminence of the greater tubercle of the humerus (marker 4) and the dorsal hoof wall marker (marker 10) when the forelimb was maximally retracted, but with the toe still in contact with the ground (Figure 4D). These markers were chosen in preference to the spinous process of the 6th thoracic vertebra (marker 24) and the tubera sacrale (marker 22) because they were easier to see and also to minimise any effect of trunk rotation on the measurements.

Statistical Analysis

Descriptive statistics and mixed effect multilevel regression analyses were performed using Stata^{TM} 12.0 software[2] with statistical significance taken at $P \leq 0.05$. All continuous data were considered normally distributed after evaluation graphically using kernel density and normal quantile plots. Outcome variables examined in separate analyses were i) midstance forelimb fetlock angle (°), ii) midstance hock angle (°) and iii) MTCR (cm), which were each considered continuous variables. Kinematic predictor variables of the forelimbs and hindlimbs (Table 2), along with trot pace (collected, medium and extended) and surface (A and B), were assessed. Following preliminary univariable linear regression analyses to examine the relationship between outcome variables and each predictor variable separately, multivariable linear regression was then used to investigate the relationship between outcomes and simultaneous multiple predictor variables. Each capture was one observation (fetlock angle and MTCR n=308, hock angle n= 320), because data comprised repeated measures with 16 separate observations made on each of 20 individual horses. Mixed effect multiple linear regression models were developed to evaluate continuous and categorical fixed effects variables as multiple simultaneous predictors of midstance fetlock and hock joint angles and MTCR, each separately, with horse set as a random effect (intercept) variable in all three models. Model building was by forward stepwise selection of variables, with the final model retaining variables that were significantly associated with the outcome and/or that significantly improved the overall fit of the model, based on likelihood ratio testing. The distribution and outlier values of the standardised residuals (difference between the model predicted and actual outcome values) from each model were also assessed.

RESULTS

For Group 1 mean age was 5.5±0.7 years and mean height was 167±7 cm. For Group 2 mean age was 12.3±2.3 years and mean height was 169±6cm. Warm-up duration ranged from 12-29 minutes (mean 18 minutes). Means and standard deviations for all kinematic variables are shown in Table 2.

Table 3 summarises final models from mixed effect multiple linear regression analyses with only statistically significant variables retained for predicting i) midstance forelimb fetlock angle, ii) midstance hock angle and iii) MTCR with horse included as a statistically significant ($P<0.0001$) random effect variable in each model. Results can be considered as representing biologically plausible statistical models to predict values of each of the three continuous outcome measures. Outcome values are derived as the sum of a baseline (intercept) value with addition (positive regression coefficient values) or subtraction (negative regression coefficient values) of estimated parameter values, comprising the product of each predictor variable measurement and its corresponding regression coefficient. Surface was not retained as a statistically significant predictor variable in any of the final models.

Speed and stride length were significantly increased and stride duration was significantly decreased at medium trot compared with collected trot in Group 1 and at extended trot compared with collected trot in Group 2 (P<0.0001 for all).

Forelimb fetlock angle

The final model predicted that forelimb fetlock extension angle was significantly increased (positive regression coefficient values) at medium and extended trots compared with collected trot (P<0.001 for both). It also predicted that forelimb fetlock extension angle was significantly decreased (negative regression coefficient value, indicating reduced fetlock extension) when stride length was increased (P=0.05). The final model predicted that forelimb fetlock extension angle significantly decreased (negative regression coefficient values) when shoulder angle was increased (indicating decreased shoulder flexion) (P=0.042). Forelimb fetlock extension angle significantly increased (positive regression coefficient values) when carpus angle was increased (P<0.001).

Hock angle

Hock angle was not affected by pace. Hock angle significantly decreased, indicating greater hock flexion, when stride duration (P<0.001) and speed (P=0.002) were increased. Hock angle significantly increased when hip angle increased (P=0.005). Hock angle significantly decreased, indicating greater hock flexion, when hindlimb protraction and retraction angles were increased (P<0.001 for both).

MTCR

MTCR significantly decreased, indicating greater hindlimb fetlock extension, at medium and extended trots, both compared with collected trot (P<0.001 for both). MTCR significantly increased, indicating reduced fetlock extension, when speed increased (P=0.001). The final model predicted that MTCR significantly decreased, indicating greater hindlimb fetlock extension, when hindlimb retraction angle was increased (P=0.032).

DISCUSSION

This study successfully investigated forelimb and hindlimb kinematics in young and mature dressage horses at collected and lengthened trots. In both groups, lengthened (medium and extended) trot was associated with forelimb and hindlimb fetlock extension, supporting our first hypothesis, and had greater speed, stride length and reduced stride duration compared with collected trot, supporting our second hypothesis. However, hock angle was not affected by pace. The third hypothesis that speed, stride length, stride duration and forelimb joint angles would be correlated with forelimb fetlock extension was partially supported. Forelimb fetlock extension angle was positively correlated with carpus angle, and negatively correlated with shoulder angle and stride length. No correlations between forelimb fetlock angle and speed, stride duration or elbow angle were detected. For the hindlimb, our hypothesis that speed, stride length, stride duration and hindlimb joint angles would be correlated with hock angle and hindlimb fetlock extension was also partially proven. Hock angle significantly decreased when stride duration and speed were increased, and was positively correlated with hip angle but not stifle, MTCR or stride length, MTCR increased with speed (i.e. hindlimb fetlock extension was reduced), but was not related to any of the measured hindlimb joint angles, stride length or duration. The fourth hypothesis that hindlimb fetlock extension and hock flexion would be related to maximal hindlimb protraction and retraction angles was supported by our findings. The fifth hypothesis was unproven; no effect of surface on any outcome variables was detected.

Similar findings in both groups indicate that lengthening of the trot stride increases extension of the fetlock joints at midstance compared with collected trot. The suspensory apparatus moderates the extension of the fetlock [15,16, 32-34] and our findings suggests that lengthened paces may increase the strain placed both on the suspensory apparatus and the fetlock in forelimbs and hindlimbs. The magnitude of extension is greater in movements such as cantering and jumping [35], but currently there is no evidence to specify the magnitude or frequency of hyperextension necessary to increase risk of injury. A 6 to 8 degree increase in fetlock joint overextension has been observed due to fatigue in trotting horses [36]. The authors proposed this could increase strain on the suspensory ligament and the supporting structures of the fetlock joint. In this study we did not work the horses to fatigue but, based on the findings on trotters [33,34,36] and show jumpers [35], fatigue may affect the degree of fetlock extension seen in either pace. It should be a consideration when teaching horses collected or lengthened paces because they are likely to fatigue more rapidly when learning new movements. This study aimed to further our knowledge of how collected and extended trot affect fetlock extension so we can begin to understand the factors that are likely to provide an influence. It is expected that the degree of fetlock extension in medium and extended trots, and its potential risk of injury depends on many factors such as musculoskeletal strength and coordination, conformation (static and dynamic), training intensity, training frequency and training volume (potentially including how frequently and for how long the horse is asked to demonstrate lengthened paces), previous injury, and genetics [37]. Further work is warranted to understand the effect of these factors in horses performing different types of trot. No difference in hock flexion angle between collected and lengthened trot was observed in either group. This is contrary to previous results [7], which may be due to differences in sample size, horses' gait patterns, training levels and/or level of collection/extension used in this and the previous study.

The degree of change in fetlock extension for collected to lengthened trot was greater in Group 2 (mature) horses performing extended trot than the Group 1 (young) horses performing medium trot as seen by the greater regression coefficient value for Group 2 compared with Group 1. We aimed to test the types of pace that were considered acceptable for the horses' ages and levels of training. Young horses and those in the lower competitive levels are asked to show lengthened or medium gaits in competition [37], so medium trot was selected for Group 1, while Group 2 were trained to achieve greater collection and extension so could be tested with more exaggerated pace types.

Greater speed, stride length and reduced stride duration at medium trot compared with collected trot in Group 1 and at extended trot compared with collected trot in Group 2 were observed, as hypothesised. This is consistent with previous findings [1-3,5,17,18], although we observed slower collected, medium and extended trots with a shorter stride length than those observed in national level dressage horses [3] and with slower and shorter strides in the extended trot than recorded in Olympic competitors [5]. This may reflect differences in training level and athletic ability compared with the current study, in which horses were of mixed levels (e.g., Group 2 ranged from Advanced medium to Grand Prix). The type of dressage horse has also changed considerably over the last 20-25 years, so the populations are not directly comparable.

Fetlock angle has previously been linked to speed [13,38] so it could be suggested that an increase in fetlock extension could simply be due to the increase in speed at medium and extended trot compared with collected trot. Our findings suggest that temporal variables (speed and stride length) have an influence on fetlock angle, but because they are inherent components of pace it is hard to identify their pure effects in isolation. Pace is also made up of other components, such as duty factor and muscle activation, not all of which were measured in this study, but which would also be accounted for through inclusion of pace. Pace (type of trot) had the principle effect on MTCR and as such would also have accounted for some of these inherent component effects. However, as speed was retained in the MTCR model along with pace, this indicated that there was clearly a still statistically significant residual effect of speed, beyond that already accounted for by pace. Pace is quite a crude variable due to its complexity, but the model suggested that it was the best predictor for MTCR angle. This means that the effect of pace, through all its inherent components is to reduce MTCR in medium or extended trot (increases fetlock extension), but speed also has a slightly positive residual effect (reduces fetlock extension), which further improved the prediction of the model. Increased speed results in slightly reduced fetlock extension, but overall when also accounting for pace there is a net greater extension in medium and extended trot compared with collected trot. This means that medium and extended trot reduce MTCR compared with collected trot, but that reduction is slightly less if the horse is going faster.

In the forelimb fetlock extension model, we observed that at medium/extended trot forelimb fetlock extension was increased compared with the collected trot, but the increase in fetlock extension was slightly reduced when the stride length was greater. These findings could relate to the faster speed or increased stride length of the medium and extended trots compared with collected trot, potentially influencing stance duration and therefore loading time. It suggests that although speed and stride length are part of the change in pace, the influence of pace is made up of lots of different constituents, including stance duration and duty factor, all of which need to be thoroughly investigated to understand the mechanism, the impact and potential practical implications of these findings.

There were different associations between fetlock angle and other limb joint angles in the forelimbs and hindlimbs. As previously documented [14-16], the forelimbs and hindlimbs are kinematically different at midstance, which potentially affects the way they moderate forces at midstance. As hypothesised, the forelimb shoulder and carpus angles were associated with forelimb fetlock angle at midstance, although no association with elbow angle at midstance was observed. This suggests that the forelimb as a unit is influenced by trot type and therefore the kinematic and kinetic changes influence many of the structures of the forelimb, not just the suspensory apparatus and fetlock.

In the hindlimb the reciprocal apparatus provides a connection between the stifle and hock, and also has a connection to the fetlock via the deep digital flexor tendon [39]. However, we observed no association between hindlimb fetlock extension and the angle of any of the hindlimb joints at midstance. In the hindlimb, coxofemoral joint (hip) angle was positively associated with hock angle, which may have implications for loading of the hip and hock. With increased speed and/or greater hindlimb protraction and retraction the hock is more flexed at midstance [13]. The results of the current study indicate that this flexion may be moderated by the action of the hip.

It was previously suggested that an explanation for increased fetlock extension and increased hock flexion during lengthened paces might be an alteration in protraction and retraction of the hindlimbs between extended and collected trot [7]. In the current study hindlimb protraction and retraction were associated with hock angle, with an increase in protraction/retraction resulting in a decrease in hock flexion angle at midstance. However, hindlimb protraction and retraction angles were not affected by different trot types. Thus the mechanism which causes increased fetlock extension in lengthened, compared with collected trot remains unclear and merits further investigation.

Increased hindlimb fetlock extension at medium and extended trots supports previous findings [7]. There is an association between static or dynamic hindlimb fetlock overextension and injury of the hindlimb suspensory apparatus [12, 37]. The current findings suggest that although hindlimb fetlock extension occurred in both groups of horses, the mean value for each trot type did not indicate dynamic hyperextension at the trot, previously defined as the fetlock marker being distal to the coronary band marker at peak fetlock extension [7]. Horses in the current study were subjectively considered to be well-conformed. Horses with a small dorsal fetlock angle may be more at risk of hyperextension compared with better-conformed horses, which may increase risk of injury to the suspensory apparatus [12, 40]. Our findings are only relevant to the trot and other gaits and movements (e.g., canter pirouette) may have different results.

Surfaces A and B were selected because it was hypothesised that their functional properties would be different. However, no effect of arena surface type was observed in the final models for either collected or extended trot. Lower GRF and decreased maximal fetlock extension were observed on deep, wet sand compared with firm, wet sand [23], suggesting that these two surfaces were functionally dissimilar. Surface material is known to behave differently according to composition, preparation and maintenance [20,41,42]. It is possible that despite differences in surface type and moisture content, the overall make-up and maintenance of surfaces A and B meant functional properties were comparable. Increased fetlock extension at midstance was reported on one surface when it was harrowed versus rolled, however data grouped all gaits together (walk, trot and canter) [41]. Canter would be expected to produce greater fetlock extension [35], which might explain these findings compared with the present study, conducted only in trot. The sample population included horses with a variety of conformations; static or dynamic conformation and the surfaces on which the horses normally train may influence preference of surface type. Fetlock extension was highly variable and heterogeneity within the sample population may explain why no significant difference was found between surfaces.

The study had some limitations. All motion capture was in two dimensions. Three-dimensional analysis would be useful to evaluate other movement planes which may influence strain on the suspensory apparatus and loading of the fetlocks. All testing was carried out on an artificial surface which can influence the measurements acquired and the definition of impact. Rotation of the hoof into the surface may have influenced the accuracy of the MTCR calculation. It also made it difficult to accurately measure stance duration and therefore duty factor. All recruited horses were Warmblood dressage horses which were grouped according to age and training level, however there are likely to be considerable differences in natural athletic ability of the horses, which may influence the findings. Extrapolation of these findings must therefore be done with care, because they may not apply to different breed populations or to horses with different gait characteristics e.g., Andalusian, Lusitano or Lipizzaner. Rider skill may also have had some influence on the gaits of the horse [43]. All horses underwent a subjective conformation assessment, but an objective assessment was not performed and would have been preferable. Each horse and rider combination was evaluated on a single day on both surfaces, and a cross-over design was used for both pace and surface in order to minimise order effect. However in the second session there may have been an influence of previous warm up/mobility and/or fatigue. Testing over multiple days could have reduced these effects; however we aimed to keep the environmental conditions as similar as possible for each horse, because this can influence surface functional properties [44]. Horse performance can also vary from day to day for a variety of reasons. Comparisons between medium and extended trot, or between working and medium trot were not performed due to time constraints. Further work is warranted to assess the difference between working, collected, medium and extended paces and specific movements, such as pirouettes.

CONCLUSIONS

Medium or extended trot increase extension of the forelimb shoulder, carpal and fetlock joints and the hindlimb fetlock joint compared with collected trot in both young and mature dressage horses, respectively.

MANUFACTURERS' ADDRESSES

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[2] Stata SE 12.1, College Station, Texas, USA.

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FIGURE LEGENDS

Figure 1: A) Marker placement for data collection: 1) rostral aspect of the facial crest 2) wing of atlas 3) proximal aspect of the scapular spine 4) over the cranial eminence of the greater tubercle of the humerus 5) the lateral epicondyle of the humerus over the lateral collateral ligament of the elbow 6) lateral styloid process of the radius 7) proximal aspect of the third metacarpal bone at the junction with the base of the 4th metacarpal bone 8) distal aspect of the third metacarpal bone over the lateral collateral ligament of the metacarpophalangeal joint 9)lateral collateral ligament of the distal interphalangeal joint (designated coronary band) 10) dorsal aspect of the coronary band 11) dorsal aspect of the coronary band 12) lateral collateral ligament of the distal interphalangeal joint (designated coronary band) 13) distal aspect of the `third metatarsal bone over the collateral ligament of the metatarsophalangeal joint 14) proximal aspect of the third metatarsal bone at the junction with the base of the 4th metatarsal bone 15) mid talus 16) lateral aspect of the tibial crest 17) medial epicondyle of the distal femur 18) proximal aspect of the greater trochanter of the femur 19) ischiatic tuberosity 20) top of tail 21) proximal aspect of the tuber coxae 22) tuber sacrale 23) spinous process of the 4th lumbar vertebra 24) spinous process of the 6^{th} thoracic vertebra. B) Arena set up for testing; showing field of view and runway used.

Figure 2: Angles measured from high speed motion capture at midstance. In the forelimb:1) Shoulder angle; calculated from the proximal aspect of the scapular spine, the cranial eminence of the greater tubercle of the humerus, the lateral epicondyle of the humerus over the lateral collateral ligament of the elbow. 2) Elbow angle; calculated from the cranial eminence of the greater tubercle of the humerus, the lateral epicondyle of the humerus over the lateral collateral ligament of the elbow, the lateral styloid process of the radius. 3) Carpus angle; calculated from, the lateral epicondyle of the humerus over the lateral collateral ligament of the elbow,

lateral styloid process of the radius, proximal aspect of the third metacarpal bone at the junction with the base of the 4th metacarpal bone. 4) Forelimb fetlock (metacarpophalangeal) angle; calculated from the proximal aspect of the third metacarpal bone at the junction with the base of the 4th metacarpal bone, distal aspect of the third metacarpal bone over the lateral collateral ligament of the metacarpophalangeal joint, lateral collateral ligament of the distal interphalangeal joint (designated coronary band). In the hindlimb: 5) Hip angle; calculated from the proximal aspect of the tuber coxae, proximal aspect of the greater trochanter of the femur, the medial epicondyle of the femur. 6) Stifle angle; calculated from proximal aspect of the greater trochanter, medial epicondyle of the distal femur, lateral aspect of the tibial crest. 7) Hock (tarsal) angle; calculated from the lateral aspect of the tibial crest, mid talus, proximal aspect of the third metatarsal bone at the junction with the base of the 4th metatarsal bone. MTCR; metatarsal coronary band ratio is calculated as the difference between marker 12; lateral collateral ligament of the distal interphalangeal joint (designated coronary band) and marker 13: distal aspect of the third metatarsal bone over the collateral ligament of the metatarsophalangeal joint along the Y axis.

Figure 3: Metatarsal coronary band ratio (MTCR). This is calculated as the difference between marker 12; lateral collateral ligament of the distal interphalangeal joint (designated coronary band) and marker 13: distal aspect of the third metatarsal bone over the collateral ligament of the metatarsophalangeal joint along the Y axis. This is determined at midstance-defined as the point of maximal fetlock extension. The image is calibrated to give a value in centimetres.

Figure 4: Forelimb and hindlimb protraction and retraction angles. Maximal hindlimb retraction (A) was defined as the angle of a line between the dorsal aspect of the coronary band

marker to the tuber ischii, relative to vertical. This was measured just before the toe left the surface. Maximal hindlimb protraction (B) was defined as the angle of a line between the dorsal aspect of the coronary band to the proximal aspect of the tuber coxae relative to vertical. This was measured just before hoof/surface impact. Maximal forelimb protraction (C) was defined as the angle of a line between the dorsal aspect of the coronary band at the toe to the cranial eminence of the greater tubercle of the humerus relative to vertical. This was measured just before hoof/surface impact. Maximal forelimb retraction (D) was defined as the angle of a line between the dorsal aspect of the coronary band marker to the cranial eminence of the greater tubercle of the humerus, relative to vertical. This was measured just before the toe left the surface.

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Table 1: Surface composition for the 2 arena surfaces (1 and 2) on which 20 dressage horses were assessed at collected and medium/ extended trot. Estimate of composition were based on a mean (n = 3 samples per surface) [27].

Component %	**Surface A**		**Surface B**	
	Mean	**sd**	**Mean**	**sd**
Moisture	11	2	6	2.6
Sand	76	1.9	46	5.8
Fibre/rubber	11	2.5	45	5.1
Wax	2	0.1	2	0.7
Composition	Small strand fibre <5cm, small grain rubber <1cm diameter, some large felt fibre up to 12cm in length.		Small felt fibre <5cm length, mainly small grain rubber <1cm diameter, some large grain rubber >1cm diameter	

Table 2: Mean and standard deviation (sd) for all kinematic variables of the forelimbs and hindlimbs measured in 20 dressage horses: Group 1 (≤ 6 years of age, n=10) and Group 2 (≥9 years of age, n=10), assessed in straight lines in collected and medium trot and collected and extended trot, respectively. Shading denotes outcome variables and non-shading denotes predictor variables.

Variable	Group 1- collected		Group 1- medium		Group 2- collected		Group 2 – extended	
	Mean	**sd**	**Mean**	**sd**	**Mean**	**sd**	**Mean**	**Sd**
Forelimb fetlock angle (°)	**246.2**	**9.3**	**249.3**	**10.5**	**246.1**	**13.9**	**251.1**	**13.4**
Hock angle (°)	**151.9**	**5.0**	**150.2**	**5.0**	**149.2**	**6.0**	**146.6**	**6.0**
MTCR (cm)	**2.3**	**0.5**	**1.8**	**0.6**	**1.8**	**0.2**	**1.0**	**0.4**
Stride Duration (secs)	0.8	0.01	0.7	0.01	0.8	0.1	0.7	0.1
Speed (m/s)	2.7	0.3	3.7	0.4	2.7	0.4	4.0	0.4
Stride Length (m)	2.1	0.2	2.7	0.3	2.3	0.4	2.9	0.5
Mid stance shoulder angle (°)	126.2	8.4	125.5	7.4	122	8.7	121.9	8.8
Mid swing shoulder angle (°)	127.3	7.9	128.8	6.8	123.	8.3	125.	8.8
Mid stance elbow angle (°)	211.5	6.0	212.1	6.2	212.6	6.2	214.5	5.8
Mid swing elbow angle (°)	250.7	10.1	253.2	9.4	253.6	7.5	256.4	9.6
Mid stance carpus angle (°)	183.0	5.5	182.7	5.9	180.5	5.4	180.8	4.5
Mid swing carpus angle (°)	128.5	8.5	123.2	8.7	129.7	8.5	122.1	8.2
Mid swing fetlock angle (°)	175.1	9.4	170.5	10.8	179.9	14.0	174.8	14.6

Mid stance hip angle (°)	71.1	4.4	71.3	4.8	70.9	4.2	71.2	4.9
Mid swing hip angle (°)	64.1	3.8	63.4	4.4	62.7	3.2	61.9	3.4
Mid stance stifle angle (°)	101.6	7.2	101.4	8.0	99.6	6.4	99.2	7.6
Mid swing stifle angle (°)	98.8	9.3	96.9	10.4	96.8	14.9	95.8	14.7
Mid swing hock angle (°)	109.8	7.2	105.9	9.1	105.2	8.1	96.9	11.7
Mid swing fetlock angle (°)	150.1	13.9	149.5	14.1	150.7	12.5	149.0	12.1
HL Protraction angle (°)	11.9	1.9	12.9	1.7	11.6	2.2	13.4	2.4
HL Retraction angle (°)	16.1	1.9	18.0	2.4	15.1	2.2	18.5	1.8

Secs = seconds; m/s = metres per second; m = metres; ^{0} = degrees; MTCR = metatarsal coronary band ratio; cm = centimetres; HL = hindlimb.

Table 3: Summary of final models from mixed effect multiple linear regression analyses of i) forelimb fetlock angle (°) (n= 308), ii) hock angle (°) (n 320) and iii) metatarsal coronary band ratio (MTCR; cm) (n=308) with different predictor variables and horse (n=20) included as a statistically significant (P<0.0001) random effect variable in each model for two groups of dressage horse, young (group 1) and mature (group 2).

Outcome measure Predictor variable	Comparator for interpretation	Regression coefficient	Standard error	95% confidence interval of regression coefficient	P-value
Forelimb fetlock angle		***(unit = °)***			
Intercept	*Baseline fetlock angle*	*172.7*	*22.0*	*129.6 – 215.9*	-
Medium trot (Group 1)	Versus collected trot as baseline	+5.70	1.59	2.58 – 8.82	<0.001
Extended trot (Group 2)	Versus collected trot as baseline	+8.59	1.75	5.16 – 12.03	<0.001
Stride length	Per metre increase of stride length	-2.87	1.48	-5.77 – 0.04	0.05
Carpus angle	Per degree increase of carpus angle	+0.61	0.10	0.41 – 0.82	<0.001
Shoulder angle	Per degree increase of shoulder angle	-0.17	0.08	-0.33 – -0.01	0.042
Hock angle		***(unit = °)***			
Intercept	*Baseline hock angle*	*171.5*	*7.4*	*156.9 – 186.1*	-

Stride duration	Per second increase of stride duration	-20.9	4.94	-30.6 – -11.2	<0.001
Speed	Per metre per second increase of speed	-1.25	0.39	-2.02 – -0.48	0.002
Hip angle	Per degree increase of hip angle	+0.21	0.08	0.06 – 0.36	0.005
Hindlimb (HL) protraction angle	Per degree increase of HL protraction angle	-0.49	0.11	-0.71 – -0.26	<0.001
Hindlimb (HL) retraction angle	Per degree increase of HL retraction angle	-0.39	0.11	-0.60 – -0.17	<0.001
Metatarsal coronary band ratio		***(unit = cm)***			
Intercept	*Baseline MTCR distance*	*1.43*	*0.61*	*0.24 – 2.62*	-
Medium trot (Group 1)	Versus collected trot as baseline	-0.87	0.19	-1.24 – -0.50	<0.001
Extended trot (Group 2)	Versus collected trot as baseline	-1.23	0.24	-1.71 – -0.76	<0.001
Speed	Per metre per second increase of speed	+0.51	0.15	0.22 – 0.81	0.001
Hindlimb (HL) retraction angle	Per degree increase of HL retraction angle	-0.06	0.03	-0.11 – -0.05	0.032