Journal of Equine Veterinary Science 120 (2022) 104166

Contents lists available at ScienceDirect

Journal of Equine Veterinary Science

journal homepage: www.j-evs.com

Original Research

# Determining Objective Parameters to Assess Gait Quality in Franches-Montagnes Horses for Ground Coverage and Over-Tracking - Part 2: At Trot

Annik Imogen Gmel [a,b,*], Eyrún Halla Haraldsdóttir [b], Filipe Manuel Serra Bragança [c], Antonio M Cruz [d], Markus Neuditschko [a], Michael Andreas Weishaupt [b]

[a] Agroscope, Animal GenoPhenomics, Posieux, Switzerland
[b] Equine Department, Vetsuisse Faculty University of Zurich, Zurich, Switzerland
[c] Department of Clinical Sciences, Faculty of Veterinary Medicine, Utrecht University, Utrecht, The Netherlands
[d] Klinik für Pferdechirurgie und Orthopädie, Justus-Liebig Universität Giessen, Giessen, Germany

ARTICLE INFO

*Article history:*
Received 19 February 2022
Received in revised form 16 November 2022
Accepted 16 November 2022
Available online 20 November 2022

*Keywords:*
Horse
Speed
Stride length
Kinematics

ABSTRACT

In gait quality assessments of horses, stride length (SL) is visually associated with spectacular movements of the front limbs, and described as ground coverage, while the movement of the hind limb under the body is supposedly essential to a longer over-tracking distance (OTD). To identify movement patterns with strong associations to SL and OTD, limb and body kinematics of 24 Franches-Montagnes (FM) stallions were measured with 3D optical motion capture (OMC) on a treadmill during an incremental speed test at trot (3.3–6.5 m/s). These measurements were correlated to the scores of ground coverage and over-tracking from six breeding experts. The amount of explained variance of parameters on SL and OTD were estimated using linear mixed-effect models in two models: a full model with all parameters measurable with OMC, and a reduced model with a subset of parameters measurable with inertial measurement units (IMUs). The front limb stance duration (16%) and OTD (7%) measured with OMC, or the OMC parameters front limb stance duration (24%) and suspension duration (14%) measurable with IMUs explained most variance in SL. However, four of six breeding experts were also significantly correlated ($r>|0.41|$) to front limb protraction angle. OTD variance was explained with OMC parameters suspension duration (10%) and hind limb contralateral pro-retraction angles (9%) or IMU-measurable parameters suspension duration (20%) and maximal pelvis pitch (5%). Four experts' scores for over-tracking were correlated to suspension duration. These results underscore the need for precise definitions of gait quality traits.



## 1. Introduction

Gait quality is a major breeding goal of European sport horses [1]. The functionality and aesthetics of the movement are expected to predict future athletic ability, especially in dressage. However, selecting horses based on gait quality is difficult, as it includes several textually described criteria, such as cadence, impulsion, elasticity, or harmony. Textual definitions are a powerful tool to describe complex traits; on the other hand, such definitions also allow subjective interpretation. Problems in textual phenotype description include ambiguity (the same word is used in different contexts, e.g., "rhythm"), use of metaphorical expressions (e.g., "harmony") and various forms of qualifiers (e.g., "subtle", "marked", etc.) [2]. In addition, there may be differences in interpretation due to subtle differences in translations into different languages. In multilingual Switzerland, the subjective assessment of equine movement patterns of 24 Franches-Montagnes (FM) stallions showed poor inter-rater reliabilities, suggesting differences in interpretation of the scored traits [3–5]. In the FM breed, three gait quality traits are routinely assessed by one of the nine federal experts of the breed on a linear profiling scale in 3-year-old horses at the trot: ground coverage, impulsion and elasticity. In the FM,

*Conflicts of interest statement:* The authors declare no conflict of interest. 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.

*Animal welfare/ethical statement*: This study was conducted under the animal experiment permit number VD 3164 complying to Swiss Federal Legislation. No animal was harmed during the experiment.

* Corresponding author at: AI Gmel, PhD, Agroscope, Animal GenoPhenomics, Posieux, Switzerland.

*E-mail address:* annik.gmel@agroscope.admin.ch (A.I. Gmel).

https://doi.org/10.1016/j.jevs.2022.104166
0737-0806/

ground coverage is defined as "how far and how wide the front limb travels [...] the longer the stride, the more ground is covered" [3]. Impulsion represents "the activity of the hindquarters and the transmission of stored energy from the hindquarters to the forehand" and elasticity movements "with high flexibility of the head, neck, back and a free movement of the tail" [3]. Genetic analyses of these three gait quality traits showed that they were phenotypically correlated ($r > 0.73$), which might also suggest that they are not evaluated independently [6].

To improve the textual definition of gait quality traits, as well as determine kinematic parameters which allow for a more objective quantification of gait quality, 24 FM stallions underwent an incremental speed test on an instrumented treadmill at the walk (c.f. Part 1 [5]) and trot, equipped with a set of reflective markers to measure limb and body kinematics using optical motion capture (OMC). Despite the high-quality data from OMC studies of horses on the treadmill, it is unlikely that such kinematic measurements could be obtained for several hundred or thousands of horses, which would be a desirable sample size for genetic studies. Furthermore, horses would have to be measured at a particular test site, and would have to be habituated first to treadmill locomotion. Fortunately, new field-based measurement systems such as inertial measurement units (IMUs) have been developed to extract the same data under less practical constraints. Therefore, it is necessary to determine which parameters can and should be measured for each system (OMC or IMUs) to quantify certain aspects of gait quality, as there may be differences in the measurements due to the system [7].

Previously, we determined that stride length (SL) was the gold standard measurement to quantify ground coverage at the walk, as the longer the stride, the more ground is covered in one stride. The kinematic parameters explaining most of the variance were the maximal retraction angle of the front limbs ($Ret_{max}$_FL), the range of yaw of the forehand ($YawFore_{ROM}$), the maximal fetlock hyperextension of the front limb ($A_{fetlock}$_FL) and the maximal front limb protraction angle ($Prot_{max}$_FL), when measuring with OMC, and the maximum and range of motion of pelvis pitch ($PelPitch_{max}$, $PelPitch_{ROM}$) and the maximal protraction angle of the metacarpus ($Prot_{max}$_MC) using only parameters that are measurable with IMUs [5]. This finding also concured with the textual definition of ground coverage, describing the visual impression of the horse's front limbs reaching upwards and onwards during forward movement, represented by $YawFore_{ROM}$, $Prot_{max}$_FL and $Prot_{max}$_MC. Furthermore, the ability to adjust SL at the trot was also one of the best associated parameters with dressage performance in general [8], in addition to the propulsion vector [9] and the stance duration (StD) [8,10]. SL, stride duration and hind limb StD – have also shown medium to high heritabilities in Pura Raza Español horses measured on the treadmill [11].

At the walk, FM breeding experts also consider the the over-tracking distance (OTD), sometimes also overreach distance[12–14], which is the length between the hoof print of a front hoof and the following hoof print of the ipsilateral hind hoof in the direction of travel [12–14]. Interestingly, OTD also explained most of the variance in SL in a sample of ridden Warmblood horses at the trot [14]. While at the walk, breeding experts traditionally estimate the over-tracking distance by observing the hoof tracks in the arena, at the trot, the over-tracking distance is harder to infer from observing the hoof prints due to the diagonal nature of the footfall sequence and the suspension phase of the horse [15]. Therefore, experts likely tend to rely on the movements of the hind limbs and back as visual aids [16] to score the subjective trait "over-tracking", despite the fact that the parameters influencing the measured OTD have not been determined at the trot yet.

The aim of the study was to identify kinematic and temporal parameters explaining the highest amount of variance in SL and OTD at the trot, measurable either with OMC or IMUs, to make practical recommendations for field applications where OMC measurements may not always be practicable. In a second step, the parameters were correlated with expert scores for ground coverage and over-tracking, to interpret whether certain objective kinematic measurements reflect the subjective scores for the two gait quality traits. We hypothesize that the identified kinematic parameters at the trot will be different from those at the walk due to the suspension phase, while the parameters best correlated with expert scores might be the same (front and hind limb protraction angles, stride rate).

## 2. Material and Methods

### 2.1. Data Collection

As previously described in Part 1 [5], 24 clinically sound FM stallions (mean ± SD; age = 8.8 ± 4.1 years, height at withers = 1.57 ± 0.03 m, and weight = 526.3 ± 32.7 kg) were measured at the equine performance laboratory of the veterinary clinic of the University of Zurich on a high-speed instrumented treadmill (Mustang 2200, Ansorix Systems AG, Switzerland) extracting time, force and spatial variables [17], and 10 infra-red 3D optical motion capture (OMC) cameras (Oqus 7+) recording kinematic parameters by registering the position of multiple skin mounted spherical reflective makers (SRM) (for detailed marker positions see Part 1 [5] and Figure S1). Both systems were synchronized in time, and the horses were recorded on video at the walk and trot during an incremental speed test. The trotting speeds ranged from 3.3 to 6.5 m/s at 0.5 m/s increments above 4.0 m/s. The common speeds at which all stallions reached steady state were 3.3, 4.0, 4.5 and 5.0 m/s at the trot. The stallions were measured during 20 seconds for each speed increment. The individual valid number of strides per speed at the trot were summarized in Table S1. For further details, refer to Part 1 [5].

### 2.2. Data Processing

Briefly, temporal and linear parameters measured by the instrumented treadmill were calculated with the treadmill software (HP2, University of Zurich, Switzerland) [17]. Marker tracking was done with the Qualisys motion capture software QTM (version 2.9, Qualisys AB, Sweden). Raw 3D coordinates of each SRM were exported into Matlab (version R2020a) and further processed with custom-written scripts to extract specific parameters. Kinematic analysis was limited to markers of the midline and the left side of the body except for parameters comparing angular differences between contralateral or diagonal limbs, as the videos shown to the experts of the breed for scoring contained only horses filmed from the left hand side.

### 2.3. Parameter Selection

In collaboration with the official teacher of the FM breeding experts and the authors, a list of putative kinematic measurements to objectively quantifying ground coverage and over-tracking was compiled and summarized in Table 1. For ground coverage, kinematic parameters related to the front limbs, hind limbs and pelvis were associated to stride length (SL). For over-tracking, only kinematic parameters related to the hind limbs and the pelvis were associated to over-tracking distance (OTD). For each parameter we measured using OMC in the controlled environment of the equine performance laboratory, we determined whether it could theoretically also be measured with IMU sensors placed on the head, withers, pelvis and limbs [5].

**Table 1**
List of parameters and their abbreviations, putatively associated to ground coverage (GC) or over-tracking (OT) measured with the instrumented treadmill and optical motion capture (OMC), with a mention of which parameters can be measured with inertial measurement units (IMUs). The axes are defined as in Clayton and Hobbs [18]. All values are the mean over all available strides unless otherwise stated.

| Parameter | Definition | Units | Trait | Measurable Using IMUs |
|---|---|---|---|---|
| **Spatial parameters** | | | | |
| SL | Stride length; derived from the stride duration based on the hoof-on moments for the left front hoof and the speed of the treadmill | [m] | GC | yes |
| OTD | Over-tracking distance of the left hind hoof in relation to the left front hoof | [m] | GC/OT | no |
| Hoof-TC | Horizontal distance of the left hind hoof relative to the vertical from the ipsilateral tuber coxae during hind limb protraction | [m] | GC/OT | no |
| **Front limb parameters** | | | | |
| $Prot_{max}$_front | Maximum protraction angle of the left front limb (marker tuber spina scapula to fetlock in relation to the vertical) | [deg] | GC | no |
| $Prot_{max}$_MC | Maximal metacarpus protraction angle of the left front limb (cluster rotation around the transverse axis) | [deg] | GC | yes |
| $Ret_{max}$_front | Maximal retraction angle of the left front limb (marker tuber spina scapula to fetlock in relation to the vertical, negative value) | [deg] | GC | no |
| $Ret_{max}$_MC | Maximal metacarpus retraction angle of the left front limb (cluster rotation around the transverse axis, negative value) | [deg] | GC | yes |
| $Prot_{height}$_front | Maximal limb protraction height of the left front limb, normalized for withers height. Vertical position of the hoof marker relative to the ground | [m] | GC | no |
| $Prot_{height}$@$Prot_{max}$_front | Maximum limb protraction height at maximal protraction angle of the left front limb, normalized for withers height | [m] | GC | no |
| $A_{fetlock}$_front | Maximum fetlock hyperextension angle of the left front limb during midstance | [deg] | GC | no |
| CLProRet_front | Absolute maximal difference in the protraction-retraction angles of contralateral front limbs, combined FL-FR, FR-FL | [deg] | GC | no |
| CLProRet_MC | Absolute maximal difference in the protraction-retraction angles of contralateral metacarpi, combined FL-FR, FR-FL | [deg] | GC | yes |
| $Yaw_{ROM}$_forehand | Range of forehand yaw. Range of rotation of the L/R tuber spina scapulae vector around the vertical axis, corrected for the longitudinal orientation of the trunk (virtual vector from the center of the tuber spina scapulae to S6) | [deg] | GC | no |
| **Hind limb parameters** | | | | |
| $Prot_{max}$_hind | Maximum protraction angle of the left hind limb (hip to fetlock maker in relation to the vertical) | [deg] | GC/OT | no |
| $Prot_{max}$_MT | Maximal metatarsus protraction angle for left hind limb (cluster rotation around the transverse axis) | [deg] | GC/OT | yes |
| $Ret_{max}$_hind | Maximal retraction angle of the left hind limb (hip to fetlock marker in relation to the vertical, negative value) | [deg] | GC/OT | no |
| $Ret_{max}$_MT | Maximal metatarsus retraction angle for left hind limb (cluster rotation around the transverse axis, negative value) | [deg] | GC/OT | yes |
| $A_{fetlock}$_hind | Maximum fetlock hyperextension from the left hind limb during stance (angles between hoof – fetlock and MC cluster markers) | [deg] | GC/OT | no |
| CLProRet_hind | Absolute maximal difference in the protraction-retraction angles of contralateral hind limbs, combined HL-HR, HR-HL | [deg] | GC/OT | no |
| CLProRet_MT | Absolute maximal difference in the protraction-retraction angles of contralateral metatarsi, combined HL-HR, HR-HL | [deg] | GC/OT | yes |
| $DiagProt_{diff}$ | Difference in protraction angles between the diagonal front and hind limbs when the protraction is maximal in the front limb; combined FL-HR, FR-HL (negative value: hind limb protraction is higher) | [deg] | GC/OT | no |
| $DiagProt_{diff}$_MCMT | Difference in maximal protraction angles calculated from the diagonal metacarpus and metatarsus clusters when MC protraction is maximal; combined FL-HR, FR-HL (negative value: metatarsal protraction is higher) | [deg] | GC/OT | yes |
| **Pelvis parameters** | | | | |
| $Z_{ROM}$_pelv | Vertical range of movement of the S1 marker | [m] | GC/OT | yes |
| $Pitch_{max}$_pelv | Maximum pelvis pitch calculated as the rotation of the S1–S6 vector around the transverse axis of the horse | [deg] | GC/OT | yes |
| $Pitch_{ROM}$_pelv | Range of pelvis pitch calculated as the rotation of the S1–S6 vector around the transverse axis of the horse | [deg] | GC/OT | yes |
| $Yaw_{max}$_pelv | Maximum pelvis yaw calculated as the rotation of the S1–S6 vector around the vertical axis | [deg] | GC/OT | yes |
| $Yaw_{ROM}$_pelv | Range of pelvis yaw calculated as the rotation of the S1–S6 vector around the vertical axis | [deg] | GC/OT | yes |
| $Roll_{max}$_pelv | Maximum pelvis roll calculated as the rotation of the L and R sacrum vector around the longitudinal axis | [deg] | GC/OT | yes |
| $Roll_{ROM}$_pelv | Range of pelvis roll calculated between the L and R sacrum vector around the longitudinal axis | [deg] | GC/OT | yes |
| **Temporal parameters** | | | | |
| SR | Stride rate (inverse of the stride duration) | [1/s] | GC | yes |
| StD_front | Stance duration of the left front limb | [s] | GC | yes |
| StD_hind | Stance duration of the left hind limb | [s] | GC/OT | yes |
| SpD | Suspension duration | [s] | GC/OT | yes |
| $Prot_{time}$_front | Time from maximum protraction angle of the left front limb to left front limb hoof-on | [s] | GC | no |
| $A_{fetlock}$-%StD_front | Percent of stance duration when maximal front limb hyperextension occurs | [%] | GC | no |
| $A_{fetlock}$-%StD_hind | Percent of stance duration when maximal hind limb hyperextension occurs. | [%] | GC/OT | no |

FL, left front limb; FR, right front limb; HL, left hind limb; HR, right hind limb.

### 2.4. Expert Scoring

The entire incremental speed test was filmed from hind, left hand side and front view cameras (HDR-CX760, Sony, Japan). The video sequences used for the scoring by the experts contained one common speed and the peak speed of each stallion at the walk and trot (in order of speed: walk at 1.7 m/s, peak walk, trot at 4.5 m/s, peak trot) and are publically available [19]. The standardized speed for walk and trot were set at one increment below the peak speed for the slowest stallions. Individual peak speed for walk was determined as the last increment at which the stallions moved regularly with a clear four-beat, while at trot, peak speed was determined as the last increment before the stallion switched to canter. were prepared for each stallion

In the FM breed, there are nine federal experts of the breed assessing all foals and 3-year old horses in a rotation. At least one federal expert has to be present at every breeding show. After passing a basic foundation course with the official teacher, the federal experts are elected by a delegation of breeders for a period of 4 years, for a maximum of three consecutive mandates. For this study, six breed experts designated by a letter from A to F appraised the 24 FM on the prepared video clips on two separate occasions [4,19].

The experts used scoring sheets of 14 gait quality traits, which were described in detail by Gmel at al [3], but only the scores for ground coverage and over-tracking at the trot were considered here. The scale ranged from one ("undesirable") to nine ("ideal"). Briefly, the six experts saw the videos twice in different orders, and the second scoring was retained as the inter-rater reliability was slightly higher [4]. For the second scoring, the experts were regrouped based on their native language (French or Swiss-German) in two trios (A-B-C, D-E-F), reappraising the videos in an randomized order specific to each group. Further details about the study design and the summary statistics for the scores are provided in Gmel et al [3].

### 2.5. Statistical Associations

The mean, standard deviations and correlations of the parameters to SL and/or OTD were calculated at each speed increment. Linear mixed effect models (LMEs) were computed with SL or OTD as predictor variables, the kinematic and temporal parameters as fixed effects and the horse and speed as random effects using the R package *lmerTest*. The fixed effects were selected to be measureable either with OMC and/or IMUs. As speed is the product of stride length and stride rate, the latter was not included in the LMEs for SL and OTD. The collinearity of the remaining parameters was checked using the package *performance*, and variables with a variance inflation factor (VIF) > 10 were removed from the model [20]. Effect sizes ($\eta^2$) were estimated using the R package *effectsize* on the fixed effect parameters. Effect sizes above 0.04 can be considered as medium effects, above 0.14 as large [21]. Appraisal scores from each expert were correlated to the measurements at the two speeds (standard and peak) using Pearson's correlation coefficients. Correlations of expert's scores to a parameter equal to or above 0.41 in absolute values were considered substantial for 24 horses [22].

## 3. Results

### 3.1. Inter-Correlation of the Parameters at the Trot at Standard Speed (4.5 m/s)

Stride length (SL) and over-tracking distance (OTD) increased linearly with speed. Descriptive statistics and correlation between SL and putative parameters affecting ground coverage at each trotting speed are presented in Table S2 for the front limbs. Descriptive statistics for the hind limb parameters at each speed increment are summarized in Table S3, while correlations between hind limb parameters and SL as well as OTD are detailed in Table S4. The inter-correlations of all parameters measured at the trot at a standard speed of 4.5 m/s were visualized in a cross-correlation matrix (Fig. 1).

### 3.2. Association Between Front and Hind Limb Kinematic Parameters and Stride Length

The parameters Hoof-TC and $Ret_{max}$_hind were excluded from the model due to high VIF. The coefficient of determination ($R^2$) of the LME was $R^2 = 0.99$, and 20 of 32 tested kinematic parameters significantly associated with SL (Table 2). Four parameters had medium ($\eta^2 > 0.04$) to high ($\eta^2 > 0.14$) effect sizes: StD_front, OTD, CLProRet_hind and SpD, which explained 16%, 7%, 5% and 5% of the SL variance in the model, respectively.

The ground coverage scores from experts A, D, and F were correlated with SL at the standard speed, and those from experts A, E, and F at peak speed. None of the expert scores were significantly correlated to StD_front, which explained the highest variance in SL at the trot. The parameters correlating with the most expert scores were OTD and SpD. In total, 21 of 32 parameters were correlated with the over-tracking score of at least one expert for either standard (12 parameters) or peak speed (18 parameters) (Table 2). Considering the two parameters excluded due to high VIF, the score from expert D correlated with Hoof-TC at both speeds, and the score from expert A was correlated with $Ret_{max}$_front at peak speed. The scores from Experts A and D were correlated with SR at standard speed, and the scores from expert A and C at peak speed.

### 3.3. Stride Length Model Based on Movement Parameters Measurable With IMUs

For the reduced LME with the OMC parameters that can be measured with IMUs, we included only $Prot_{max}$_MC, $Ret_{max}$_MC, $Prot_{max}$_MT, $Ret_{max}$_MT, CLProRet_MC, CLProRet_MT, $Z_{ROM}$_pelv, $Pitch_{max}$_pelv, $Pitch_{ROM}$_pelv, $Yaw_{max}$_pelv, $Yaw_{ROM}$_pelv, $Roll_{max}$_pelv, $Roll_{ROM}$_pelv, and StD_hind. The collinearity between variables was low and none had to be excluded from the model. The coefficient of determination of the reduced LME reached an $R^2 = 0.99$. Most of the tested kinematic parameters (13 of 17) were significantly associated with SL (Table 3). The front limb stance duration (StD_front) had a high ($\eta^2 > 0.14$) effect size explaining 24% of the variance in SL in this model, while four additional parameters had medium effect sizes ($\eta^2 > 0.04$): the suspension duration (SpD), the maximal pelvic pitch ($Pitch_{max}$_pelv), the metacarpal protraction angle ($Prot_{max}$_MC) and the vertical range of motion of the pelvis ($Z_{ROM}$_pelv), explaining 14%, 9%, 6% and 5% of the variance in the SL restricted IMU-model, respectively.

### 3.4. Association Between Hind Limb Parameters and Over-Tracking Distance

The parameter $Ret_{max}$_hind was excluded from the model due to high VIF, and 16 of the 19 remaining parameters (all but $Yaw_{max}$_pelv, $Roll_{max}$_pelv and $DiagProt_{diff}$_MCMT) were significantly associated with OTD (Table 4). The coefficient of determination of the final LME, rose to $R^2 = 0.98$. None of the parameters reached a high effect size ($\eta^2 > 0.14$) in this model. SpD had the largest effect on OTD in this model and explained 10% of the variance, followed by CLProRet_hind, $A_{fetlock}$_hind and Hoof-TC, with 9%, 6%, and 5%, respectively.

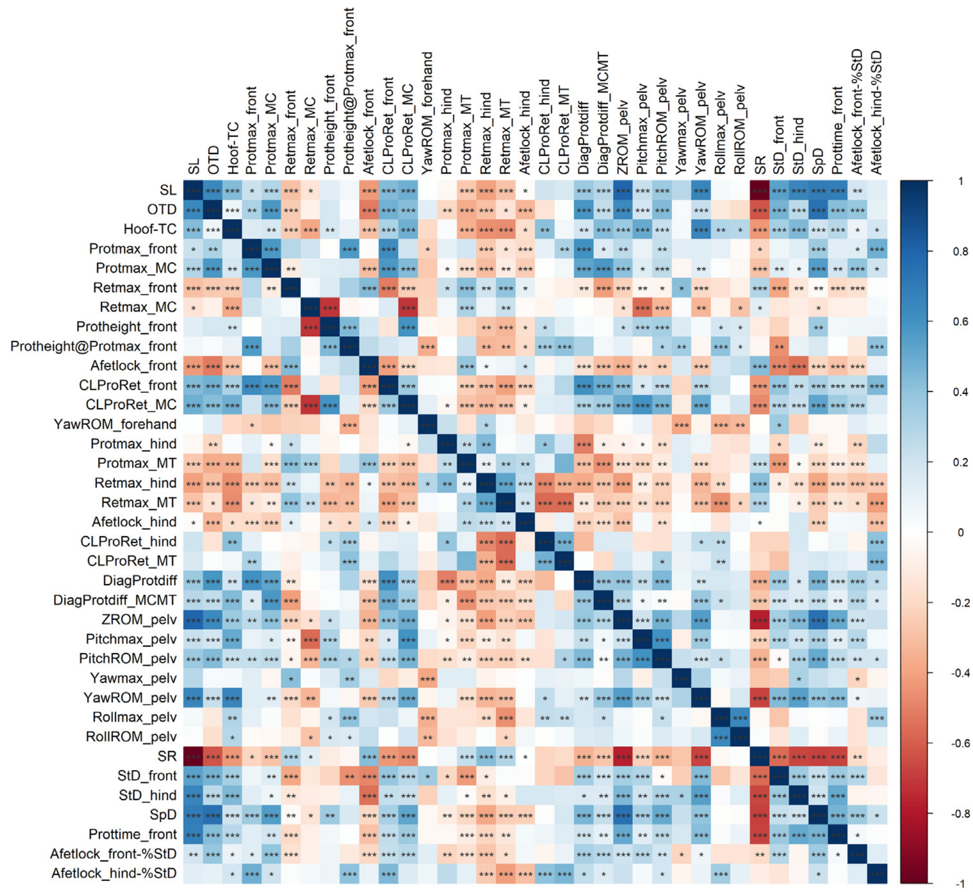


**Fig. 1.** Cross-correlation matrix of all measured parameters at the trot, measured at 4.5 m/s, using Pearson's correlations. The significance level is expressed as: * = $P < .05$, ** = $P < .01$, *** = $P < .001$. For the definitions of the parameter abbreviations, see Table 1.

The scores from experts A, B, C and F were significantly correlated with OTD at standard speed (for expert F, also at peak speed). Most of the expert scores (except for D and E) were significantly correlated with SpD, the parameter explaining the highest amount of variance in the model. Four scores were also correlated to both StD_hind and $Ret_{max}$_MT (A, B, C and F). The scores from experts C and F were also negatively correlated with $Ret_{max}$_hind, which had to be excluded from the LME due to high VIF. The score from expert D was not significantly correlated with any parameter. The scores from experts A, B, C, and F were significantly negatively correlated with SR at standard speed but not peak speed.

### 3.5. Over-Tracking Distance Model Based on Hind Limb Parameters Measurable With IMUs

For the reduced LME with the parameters that can be measured with IMUs, the collinearity between variables was low and none had to be excluded from the model. The coefficient of determination of the final LME was high ($R^2 = 0.97$). Eight of 13 tested kinematic parameters were significantly associated with OTD (Table 5). SpD had the highest effect size, explaining 20% of the variance in OTD in this IMU-specific model, followed by the $Pitch_{max}$_pelv with 5%.

## 4. Discussion

### 4.1. Ground Coverage

Although most (20 of 32) of the parameters were significantly associated with SL, only four parameters - StD_front, OTD, CLProRet_hind and SpD - had medium to high effect sizes. It has been already shown that StD_front and StD_hind decreased over-proportionally while adapting for higher speeds [23]. Shorter StD_front was significantly correlated with a positive judge score in Dutch Warmblood horses measured on the treadmill at 4.0 m/s [24]. Both shorter StD_front [8] and StD_hind [10] were also correlated to higher dressage scores in competition horses, and distinguished elite from normal Spanish riding horses [25]. However, StD_hind did not have similarly large influence on SL in this study compared to StD_front, although scores from four experts were significantly correlated with StD_hind. In spite of the general definition that the trot is a two-beat symmetrical gait, and one could therefore expect StD_front and StD_hind to be the same, the timing of hoof-on and hoof-off moments is generally not perfectly equal in diagonal footfalls at the trot [10,14,23]. In fact, horses touching ground first with the hind limb within the diagonal limb pair obtained better scores in dressage competitions because this was associated with the perception of an uphill posture of the horse [10,26]. These timing variables are likely related to the gait quality trait “regularity”, and need to be analysed in a future study.

The effect of OTD on SL was expected, as Clayton et al [14] previously showed that ridden dressage horses increased their SL mainly by increasing OTD. In addition, SpD had a medium effect size, which is again in agreement with findings from Clayton et al [14] that SpD was significantly different only between collected and working versus medium and extended trot, not between all four types of trot. However, these Warmblood horses were ridden over-ground [14], so the results are not entirely comparable to our study of FM horses on the treadmill. CLProRet_hind explained 5% of the variance in SL, but was only correlated to SL at peak indi-

**Table 2**
Associations between linear, kinematic and temporal parameters and stride length at the trot, with speed (3.3 m/s-6.5 m/s) and horse (n = 24) as random factors, with the effect sizes $\eta^2$ and their 95% confidence intervals (CI). Experts (defined by a letter from A to F) whose ground coverage scores are correlated above the threshold of r > |0.41| are reported in the last two columns, with a superscript for the direction of correlation. Parameters which were significantly correlated to three or more experts are in bold font. Parameter abbreviations are defined in Table 1.

| *Parameter* | *F Value* | *P Value* | *Effect Size $\eta^2$* | *CI* | *Expert r > \|0.41\| at 4.5 m/s* | *Expert r > \|0.41\| at Peak Speed* |
|---|---|---|---|---|---|---|
| StD_front | 514.57 | < .0001 | 0.16 | [0.13, 0.18] | | |
| **OTD** | **205.62** | **< .0001** | **0.07** | **[0.05, 0.09]** | ***$A^+$, $B^+$, $C^+$, $F^+$*** | ***$A^+$, $E^+$, $F^+$*** |
| CLProRet_hind | 147.41 | < .0001 | 0.05 | [0.04, 0.07] | | *$E^+$* |
| **SpD** | **142.12** | **< .0001** | **0.05** | **[0.03, 0.07]** | ***$A^+$, $B^+$, $C^+$*** | ***$A^+$, $B^+$, $E^+$, $F^+$*** |
| **$Z_{ROM}$_Pelv** | **106.76** | **< .0001** | **0.04** | **[0.02, 0.05]** | ***$A^+$, $D^+$*** | ***$A^+$, $E^+$, $F^+$*** |
| $Prot_{time}$_front | 115.13 | < .0001 | 0.04 | [0.03, 0.06] | | |
| $Prot_{max}$_MC | 51.45 | < .0001 | 0.02 | [0.01, 0.03] | *$B^+$* | *$E^+$* |
| $Yaw_{ROM}$_forehand | 48.71 | < .0001 | 0.02 | [0.01, 0.03] | | *$D^-$* |
| $A_{fetlock}$_front | 24.54 | < .0001 | 0.02 | [0.01, 0.05] | *$B^+$* | *$B^-$, $F^-$* |
| $Pitch_{max}$_pelv | 11.98 | .0006 | 0.02 | [0.00, 0.05] | *$B^+$, $C^+$* | |
| **$DiagProt_{diff}$** | **34.95** | **< .0001** | **0.01** | **[0.01, 0.02]** | ***$A^+$, $B^+$, $C^+$, $D^+$*** | |
| $A_{fetlock}$_hind | 9.76 | .0018 | 0.01 | [0.00, 0.03] | | |
| $Yaw_{max}$_pelv | 40.99 | < .0001 | 0.01 | [0.01, 0.02] | | |
| $Yaw_{ROM}$_pelv | 25.02 | < .0001 | 8.91E-03 | [0.00, 0.02] | | *$C^+$* |
| $Prot_{max}$_MT | 16.73 | < .0001 | 5.99E-03 | [0.00, 0.01] | | |
| $A_{fetlock}$_hind-%StD | 13.77 | .0002 | 4.92E-03 | [0.00, 0.01] | | *$E^+$* |
| $Roll_{max}$_pelv | 10.82 | .0010 | 3.89E-03 | [0.00, 0.01] | | |
| $Roll_{ROM}$_pelv | 6.14 | .0133 | 2.22E-03 | [0.00, 0.01] | | |
| $Ret_{max}$_front | 4.47 | .0345 | 1.61E-03 | [0.00, 0.01] | | |
| $Ret_{max}$_MC | 4.28 | .0386 | 1.54E-03 | [0.00, 0.01] | | *$F^-$* |
| **StD_hind** | **3.80** | **.0515** | **1.41E-03** | **[0.00, 0.01]** | ***$B^+$, $D^+$, $E^+$, $F^+$*** | |
| $A_{fetlock}$_front-%StD | 2.62 | .1055 | 9.44E-04 | [0.00, 0.00] | | |
| CLProRet_MT | 2.50 | .1142 | 8.99E-04 | [0.00, 0.00] | | |
| **$Prot_{height}$@$Prot_{max}$_front** | **1.70** | **.1920** | **6.11E-04** | **[0.00, 0.00]** | ***$E^+$*** | ***$A^+$, $D^+$, $E^+$*** |
| CLProRet_MC | 1.36 | .2432 | 4.90E-04 | [0.00, 0.00] | | *$E^+$, $F^+$* |
| $Pitch_{ROM}$_pelv | 1.25 | .2635 | 4.64E-04 | [0.00, 0.00] | *$B^+$, $C^+$* | *$E^+$, $F^+$* |
| $Prot_{height}$_front | 1.28 | .2587 | 4.58E-04 | [0.00, 0.00] | | *$E^+$, $F^+$* |
| **$Ret_{max}$_MT** | **0.50** | **.4799** | **1.83E-04** | **[0.00, 0.00]** | | ***$A^-$, $B^-$, $E^-$, $F^-$*** |
| $Prot_{max}$_hind | 0.17 | .6785 | 6.20E-05 | [0.00, 0.00] | | |
| **CLProRet_front** | **0.17** | **.6809** | **6.11E-05** | **[0.00, 0.00]** | ***$A^+$, $B^+$, $C^+$*** | ***$A^+$, $B^+$, $E^+$*** |
| **$Prot_{max}$_front** | **0.13** | **.7207** | **4.60E-05** | **[0.00, 0.00]** | ***$B^+$, $C^+$, $D^+$, $E^+$*** | ***$B^+$, $E^+$*** |
| $DiagProt_{diff}$_MCMT | 0.05 | .8207 | 1.84E-05 | [0.00, 0.00] | | *$F^-$* |

**Table 3**
Associations between kinematic and temporal parameters, measurable with IMUs, and stride length at the trot, with speed (3.3 m/s–6.5 m/s) and horse (n = 24) as random factors, with the effect sizes $\eta^2$ and their 95% confidence intervals (CI). Experts (defined by a letter from A to F) whose ground coverage scores are correlated above the threshold of r > |0.41| are reported in the last two columns, with a superscript for the direction of correlation. Parameters which were significantly correlated to three or more experts are in bold font. Parameter abbreviations are defined in Table 1.

| *Parameter* | *F Value* | *P Value* | *Effect size $\eta^2$* | *CI* | Expert r > \|0.41\| at 4.5 m/s | Expert r > \|0.41\| at Peak Speed |
|---|---|---|---|---|---|---|
| StD_front | 949.26 | < .0001 | 0.24 | [0.17, 0.27] | | |
| **SpD** | **473.52** | **< .0001** | **0.14** | **[0.11, 0.16]** | ***$A^+$, $B^+$, $C^+$*** | ***$A^+$, $B^+$, $E^+$, $F^+$*** |
| $Pitch_{max}$_pelv | 63.56 | < .0001 | 0.09 | [0.05, 0.13] | *$B^+$, $C^+$* | |
| $Prot_{max}$_MC | 203.58 | < .0001 | 0.06 | [0.05, 0.08] | | |
| $Z_{ROM}$_pelv | 168.92 | < .0001 | 0.05 | [0.04, 0.07] | | |
| $Yaw_{max}$_pelv | 50.70 | < .0001 | 0.02 | [0.01, 0.03] | | |
| CLProRet_MC | 33.01 | < .0001 | 0.01 | [0.00, 0.02] | | *$E^+$, $F^+$* |
| **$Ret_{max}$_MT** | **28.65** | **< .0001** | **9.85E-03** | **[0.00, 0.02]** | | ***$A^-$, $B^-$, $E^-$, $F^-$*** |
| $Pitch_{ROM}$_pelv | 27.55 | < .0001 | 9.09E-03 | [0.00, 0.02] | *$B^+$, $C^+$* | *$E^+$, $F^+$* |
| $Yaw_{ROM}$_pelv | 23.19 | < .0001 | 7.58E-03 | [0.00, 0.01] | | *$C^+$* |
| $Roll_{max}$_pelv | 22.72 | < .0001 | 7.45E-03 | [0.00, 0.01] | | |
| CLProRet_MT | 18.98 | < .0001 | 6.22E-03 | [0.00, 0.01] | | |
| **StD_hind** | **10.07** | **.0015** | **3.37E-03** | **[0.00, 0.01]** | ***$B^+$, $D^+$, $E^+$, $F^+$*** | |
| $Ret_{max}$_MC | 2.28 | .1312 | 7.51E-04 | [0.00, 0.00] | | *$F^-$* |
| $Prot_{max}$_MT | 1.96 | .1621 | 6.45E-04 | [0.00, 0.00] | | |
| $DiagProt_{diff}$_MCMT | 1.18 | .2781 | 3.88E-04 | [0.00, 0.00] | | *$F^-$* |
| $Roll_{ROM}$_pelv | 0.98 | .3215 | 3.24E-04 | [0.00, 0.00] | | |

vidual speed, which suggests that this parameter is one of the last to change in relation to speed.

Both StD_front and SpD can also be measured with IMUs, and had even higher effect sizes in the IMU-specific LME. The medium effect size for $Z_{ROM}$_pelv is not surprising, as it reflects the height of the suspension phase, and therefore also its duration; this is for example, reflected in the relatively high correlation of r = 0.74 between $Z_{ROM}$_pelv and SpD at a speed of 4.5 m/s. Two additional parameters, $Pitch_{max}$_pelv and $Prot_{max}$_MC, already had medium effect sizes for the IMU-specific models for predicting SL at the walk in Part 1 of this study [5]. Larger $Pitch_{max}$_pelv has previously been associated with better dressage performance in Warmblood horses as it is related to collection [27]. $Pitch_{ROM}$_pelv however did not have a medium effect size at the trot in contrast to the walk [5], probably because the movement of the spine is axially more stabilised at the trot in comparison to the walk [28]. This

**Table 4**
Associations between linear, kinematic and temporal parameters and over-tracking distance at the trot, with speed (3.3 m/s–6.5 m/s) and horse (n = 24) as random factors, with the effect sizes $\eta^2$ and their 95% confidence intervals (CI). Experts (defined by a letter from A to F) whose over-tracking scores are correlated above the threshold of r > |0.41| are reported in the last two columns, with a superscript for the direction of correlation. Parameters which were significantly correlated to three or more experts are in bold font. Parameter abbreviations are defined in Table 1.

| *Parameter* | *F value* | *P value* | *Effect Size $\eta^2$* | *CI* | Expert r > \|0.41\| at 4.5 m/s | Expert r > \|0.41\| at Peak Speed |
|---|---|---|---|---|---|---|
| **SpD** | **300.78** | **< .0001** | **0.10** | **[0.08, 0.12]** | **$A^+$, $B^+$, $C^+$, $F^+$** | **$F^+$** |
| CLProRet_hind | 281.92 | < .0001 | 0.09 | [0.07, 0.12] | | $F^+$ |
| $A_{fetlock}$_hind | 82.76 | < .0001 | 0.06 | [0.04, 0.09] | | $E^-$ |
| **Hoof-TC** | **125.07** | **< .0001** | **0.05** | **[0.04, 0.07]** | **$B^+$** | **$B^+$, $C^+$, $F^+$** |
| **CLProRet_MT** | **76.63** | **< .0001** | **0.03** | **[0.02, 0.04]** | | **$B^+$, $E^+$, $F^+$** |
| **StD_hind** | **86.19** | **< .0001** | **0.03** | **[0.02, 0.05]** | **$A^+$, $B^+$, $E^+$, $F^+$** | **$F^-$** |
| $Prot_{max}$_hind | 55.16 | < .0001 | 0.02 | [0.01, 0.03] | | |
| **$Ret_{max}$_MT** | **60.84** | **< .0001** | **0.02** | **[0.01, 0.04]** | **$A^-$, $B^-$** | **$A^-$, $B^-$, $C^-$, $F^-$** |
| **$Z_{ROM}$_Pelv** | **44.81** | **< .0001** | **0.02** | **[0.01, 0.03]** | **$B^+$, $C^+$, $F^+$** | |
| $Yaw_{ROM}$_pelv | 60.38 | < .0001 | 0.02 | [0.01, 0.03] | $B^+$, $C^+$ | $B^+$, $C^+$ |
| $Pitch_{ROM}$_pelv | 25.37 | < .0001 | 9.33E-03 | [0.00, 0.02] | | $F^+$ |
| $Prot_{max}$_MT | 19.97 | < .0001 | 7.38E-03 | [0.00, 0.02] | $C^-$ | |
| $DiagProt_{diff}$ | 19.54 | < .0001 | 7.23E-03 | [0.00, 0.01] | $C^+$ | |
| $Roll_{ROM}$_pelv | 13.33 | .0003 | 4.93E-03 | [0.00, 0.01] | | |
| $Yaw_{max}$_pelv | 10.64 | .0011 | 3.93E-03 | [0.00, 0.01] | | $E^+$ |
| StD_hind-%StD | 10.07 | .0015 | 3.73E-03 | [0.00, 0.01] | | $B^+$ |
| $Pitch_{max}$_pelv | 2.13 | .1452 | 1.90E-03 | [0.00, 0.01] | | |
| $DiagProt_{diff}$_MCMT | 0.55 | .4570 | 2.05E-04 | [0.00, 0.00] | | |
| $Roll_{max}$_pelv | 0.49 | .4823 | 1.84E-04 | [0.00, 0.00] | | |

**Table 5**
Associations between kinematic parameters measurable with IMUs and over-tracking distance, with speed (3.3 m/s to 6.5 m/s) and horse (n = 24) as random factors, with the effect sizes $\eta^2$ and their 95% confidence intervals (CI). Experts (defined by a letter from A to F) whose over-tracking scores are correlated above the threshold of r > |0.41| are reported in the last two columns, with a superscript for the direction of correlation. Parameters which were significantly correlated to three or more experts are in bold font. Parameter abbreviations are defined in Table 1.

| *Parameter* | *F Value* | *P Value* | *Effect Size $\eta^2$* | *CI* | Expert r > \|0.41\| at 4.5 m/s | Expert r > \|0.41\| at Peak Speed |
|---|---|---|---|---|---|---|
| **SpD** | **764.99** | **< .0001** | **0.20** | **[0.14, 0.23]** | **$A^+$, $B^+$, $C^+$, $F^+$** | **$F^+$** |
| $Pitch_{max}$_pelv | 12.11 | .0006 | 0.05 | [0.01, 0.12] | | |
| **$Z_{ROM}$_pelv** | **54.76** | **< .0001** | **0.02** | **[0.01, 0.03]** | **$B^+$, $C^+$, $F^+$** | |
| $Pitch_{ROM}$_pelv | 55.73 | < .0001 | 0.02 | [0.01, 0.03] | | $F^+$ |
| **StD_hind** | **67.80** | **< .0001** | **0.02** | **[0.01, 0.04]** | **$A^+$, $B^+$, $E^+$, $F^+$** | **$F^-$** |
| $Prot_{max}$_MT | 42.20 | < .0001 | 0.01 | [0.01, 0.02] | $C^-$ | |
| **$Ret_{max}$_MT** | **26.35** | **< .0001** | **0.01** | **[0.00, 0.02]** | **$A^-$, $B^-$** | **$A^-$, $B^-$, $C^-$, $F^-$** |
| $Yaw_{ROM}$_pelv | 32.54 | < .0001 | 0.01 | [0.00, 0.02] | $B^+$, $C^+$ | $B^+$, $C^+$ |
| $Roll_{ROM}$_pelv | 2.47 | .1161 | 8.18E-04 | [0.00, 0.00] | | |
| **CLProRet_MT** | **2.42** | **.1201** | **7.94E-04** | **[0.00, 0.00]** | | **$B^+$, $E^+$, $F^+$** |
| $DiagProt_{diff}$_MCMT | 2.28 | .1309 | 7.62E-04 | [0.00, 0.00] | | |
| $Roll_{max}$_pelv | 0.23 | .6326 | 7.53E-05 | [0.00, 0.00] | | |
| $Yaw_{max}$_pelv | 0.00 | .9908 | 4.46E-08 | [0.00, 0.00] | | $E^+$ |

underscores again that the same gait quality trait may have to be quantified differently due to specificities of the different gaits. The marginal $R^2$ was nearly equal for the restricted IMU-specific LME compared to the full OMC model ($R^2$ = 0.99), which was not surprising as two of three parameters with the highest effect size in the full OMC model could also be included in the restricted IMU model.

Despite the previously established relationship that a lower stride frequency is associated with higher dressage scores [9,29] and the interrelationship between SL and SR, the ground coverage scores from only three experts were significantly correlated with SR at the trot. This was somehow surprising, as most scores from the same experts were correlated with SR at the walk [5]. When the horses moved on the treadmill, it was impossible to estimate the speed of the horse as the background stayed the same (the horse moved in place), while in the field, the background (trees, houses, barriers) may help to evaluate how fast the horse is moving from one landmark to the next. This, in addition to the higher speeds, might partially explain why SR was not a helpful indicator for the experts when scoring horses based on videos on a treadmill.

Surprisingly, none of the front limb kinematic parameters that we expected to best represent the textual definition of ground coverage, such as $Prot_{max}$_front, $Prot_{height}$_front, $Prot_{height}$@$Prot_{max}$_front, had even a medium effect on SL at the trot, although the scores from three or four experts were significantly correlated with $Prot_{max}$_front and $Prot_{height}$@$Prot_{max}$_front at one of the speeds. Only $Prot_{max}$_MC had a medium effect size on SL in the restricted IMU model and reflected the front limb movement, but none of the experts' scores were significantly correlated to it. Our hypothesis that ground coverage can be equated to stride length may not be entirely accurate, as the front limb movement is less relevant for SL at the trot from a biomechanical perspective. Expert E in particular showed very high correlations with $Prot_{max}$_front and $Prot_{height}$@$Prot_{max}$_front at both walk [5] and trot, especially when measured at peak speed. Incidentally, expert E had the highest intra-rater reliability for ground coverage at both the walk and trot ($ICC_{walk}$= 0.49, CI 0.11–0.74; $ICC_{trot}$= 0.69, CI 0.40–0.80 [4]), suggesting that expert E observed these parameters consistently. Other experts were only correlated to $Prot_{max}$_front at the walk, where it explained the most amount of variance in SL [5]. Whether to prioritize front limb movement or SL as the best descriptor of ground coverage needs to be defined conclusively by breeding organizations and dressage federations. From this study, we can see that the definition for traits such as ground coverage needs to become more gait specific.

### 4.2. Over-Tracking at the Trot

SpD had the highest effect size for the LME with OTD as the outcome variable, followed by CLProRet_hind, $A_{fetlock}$_hind and Hoof-TC. Similarly to the SL LME, CLProRet_hind had a medium effect size for OTD, but was only correlated to OTD at peak individual speed, which indicates that this parameter is likely one of the last possible adaptations to increase SL and OTD with speed. While $A_{fetlock}$_hind was significantly associated with OTD and had a medium effect size, the sample size for this parameter was actually restricted as some of the measures had to be excluded from analysis due to marker slippage at higher speed. Therefore, this result is not well interpretable. $A_{fetlock}$_hind was greater in elite vs normal riding horses in a study of Swedish Warmblood horses [27], but not of Spanish horses [25], and was not significantly correlated to expert scores in the Warmblood horses evaluated on the treadmill at the trot at 4.0 m/S [24]. In theory, a higher degree of fetlock extension reflects an increase in the storage and release of elastic energy in the tendons, necessary for a more powerful push-off, and is related to the gait quality trait impulsion [30]. $A_{fetlock}$_hind was also not significantly correlated to any of the experts' scores for over-tracking at the trot, although it was significant and had a medium effect size for OTD at the walk [5]. Overall, $A_{fetlock}$_hind cannot be considered a reliable indicator for over-tracking based on our current dataset.

Hoof-TC was initially recommended as an indicator trait for the subjective trait over-tracking by the teacher of the experts [16]. At the trot, it explained 5% of the variance and had the fourth highest effect on OTD in the model for OMC parameters. and scores from three experts were also significantly correlated with this parameter at peak speed. Hoof-TC can therefore be considered an excellent indicator trait for over-tracking at the trot and should also be discussed more during expert training sessions, considering that the over-tracking scores from only half the experts were correlated to this parameter.

Only two parameters had medium to high effect sizes on OTD in the IMU-specific model: SpD and $Pitch_{max}$_pelv. Both also had medium to high effect sizes in the IMU-specific model for ground coverage at the trot. While the scores from four experts were significantly correlated with SpD, none were correlated with $Pitch_{max}$_pelv. Considering the importance of $Pitch_{max}$_pelv on both SL and OTD at the trot, it could be routinely measured in the field using an IMU in the future. The marginal $R^2$ was only slightly lower for the restricted IMU-specific LME compared to the full OMC model (0.97 vs. 0.98), as the parameter SpD had the highest effect size in the full OMC model and in the restricted IMU model.

Besides SpD and Hoof-TC, the scores from at least three experts were also significantly correlated with CLProRet_MT, $Ret_{max}$_MT and StD_hind. All three parameters were already correlated with most of the experts' scores for over-tracking at the walk [5]. This would suggest that the experts observe the same parameters for walk and trot despite gait-specific differences.

### 4.3. General Limitations of the Study

The sample size for this study is consistent with previous studies of gait quality traits on the treadmill [24,31], but is too small for genetic analyses of the parameters. Instead, we retained parameters with medium to large effect sizes that could be measured on a large number of horses in the field, by using IMUs for example. Exactly as at walk in Part 1 [5], the LME initially did not converge when considering withers height as a random factor, therefore the random structure only included speed and horse. It is highly likely that there would be differences in the results with a mix of breeds or with horses of the same breed showing a larger variance in height.

Despite being shorter in the mean (157 cm) than horses from previously mentioned studies investigating kinetic and kinematic parameters in relation to speed (168 cm [23], 173 cm [14]), the FM stallion sample had a higher maximal trotting speed than both the samples in [23] (5.80 m/S) or [14] (5.16 m/S), but had comparable SL at peak individualized speed (3.52 m for FM, 3.55 m for ridden Warmblood [14]). Further studies are needed between breeds to understand how wither's height and genetics influence SL in relation to speed. Experimental conditions would need to be standardized between studies: for example, the treadmill influenced certain parameters at the trot, so that StD_front was longer, and $Ret_{max}$_front and $Ret_{max}$_hind angles were larger compared to over-ground locomotion, due to the movement of the treadmill pulling the limb caudally [32]. Furthermore, the landmark placement and differences in the extraction of kinematic parameters may strongly affect the validity of comparing different studies. We have been able to show in this study that for example $Prot_{max}$_front, calculated from the tuber spinae scapula to the hoof marker is not equal to $Prot_{max}$_MC, extracted from the orientation of the cluster in relation to the transverse plane. Future studies need to take all these factors into account, especially in cases of meta-analyses of data involving different breeds, measuring conditions and systems.

As we showed previously at the walk, the scores from experts A, B and C were highly correlated [4,5], and we considered kinematic parameters to be relevant for experts when a given parameter was significantly correlated to three or more experts. Relating to speed, expert E in particular was more frequently significantly correlated to parameters at peak speed in comparison to standard speed, and this tendency was the same for expert F. Interestingly, both the present study and the field study showed lower inter-rater reliability in traits scored at the walk in comparison to the trot [3,4]. The language of the experts and the years of experience could be taken into account in more complex models instead of simpler correlation analyses. However, the effects of language and years of experience did not show clear effects on the reliability of the scoring [4]. One of the longest-serving experts (expert F) showed low intra-reliabilities, while one expert on his first mandate (expert E) had the highest intra-reliabilities. Therefore, we opted for a simpler form of analysis.

The results of this study at the trot, in combination with those at the walk from Part 1 [5], suggest that the experts observe specific parameters that are the same independently of the gait. However, one should not over-interpret these results, as for example correlations to StD are probably an artefact of high correlation to SL rather than a true correlation, as the temporal resolution of the human eye is substantially limited. Ideally, to understand which movement aspects the experts do consider, the experts should be equipped with eye-tracking devices, with horses presented and measured in the field, under the normal conditions for breed competitions.

## 5. Conclusions

In this study, SL could be quantified with OMC measuring StD_front, OTD, CLProRet_hind and SpD, or optionally with IMUs measuring StD_front, SpD, $Z_{ROM}$_Pelv, $Pitch_{max}$_pelv and $Prot_{max}$_MC in the field. OTD could be quantified with OMC measuring SpD, CLProRet_hind, $A_{fetlock}$_hind and Hoof-TC, or with IMUs measuring SpD and $Pitch_{max}$_pelv in the field. However, these parameters do not reflect the textual definitions of ground coverage or over-tracking involving the protraction movement of the front and hind limbs. Based on these results, breeding organizations have the option to redefine ground coverage and over-tracking according to theirs priorities (either SL and OTD, or the movement of the limbs).

## Acknowledgments

We are gratefully acknowledging the assistance of Ugo Maninchedda, Nina Waldern, Thomas Wiestner and Christian Gerber during data collection. We thank all the breeding experts participating in the experiments for their valuable time and insights, and private horse owners for providing the stallions for the study's purpose. We would also like to thank Dr Pierre-André Poncet, former director of the Swiss national stud farm and main instructor of the FM experts, for his valuable comments with regard to the formal definitions of traits.

*Financial disclosure*

This study was funded by the Swiss Federal Office for Agriculture (FOAG) under contract numbers 625000469 and 627001325.

## CRediT authorship contribution statement

**Annik Imogen Gmel:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Eyrún Halla Haraldsdóttir:** Methodology, Software, Formal analysis, Data curation. **Filipe Manuel Serra Bragança:** Methodology, Software, Investigation, Data curation. **Antonio M Cruz:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Markus Neuditschko:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Michael Andreas Weishaupt:** Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jevs.2022.104166.

## References

[1] Koenen E, Aldridge L, Philipsson J. An overview of breeding objectives for warmblood sport horses. Livestock Prod Sci 2004;88(1-2):77–84.
[2] Groza T, Hunter J, Zankl A. Mining skeletal phenotype descriptions from scientific literature. PLoS One 2013;8(2):e55656.
[3] Gmel AI, et al. Should we agree to disagree? An evaluation of the inter-rater reliability of gait quality traits in franches-montagnes stallions. J Equin Vet Sci 2020;88:102932.
[4] Gmel AI, et al. Gait quality scoring data of Franches-Montagnes stallions at walk and trot on a treadmill by experts of the breed and their reliability. Data Brief 2022;42:108123.
[5] Gmel AI, et al. Determining objective parameters to assess gait quality in Franches-Montagnes horses for ground coverage and over-tracking-Part 1: at walk. J Equin Vet Sci 2022;115:104024.
[6] Burren, A., et al., Züchterische Auswertung beim Freiberger Pferd, Hochschule für Agrar- Forst- und Lebensmittelwissenschaften, Editor. 2015: Internal report.
[7] Sapone M, et al. The protraction and retraction angles of horse limbs: an estimation during trotting using inertial sensors. Sensors 2021;21(11): 3792.
[8] Deuel NR, Park J-J. The gait patterns of Olympic dressage horses. Int J Sport Biomech 1990;6(2):198–226.
[9] Biau S, Barrey E. Relationship between stride characteristics and scores in dressage tests. Pferdeheilkunde 2004;20(2):140–4.
[10] Holmström M, Fredricson I, Drevemo S. Biokinematic differences between riding horses judged as good and poor at the trot. Equine Vet J 1994;26(S17):51–6.
[11] Valera M, et al. Genetic parameters of biokinematic variables of the trot in Spanish Purebred horses under experimental treadmill conditions. Vet J 2008;178(2):219–26.
[12] Leach D, Ormrod K, Clayton H. Standardised terminology for the description and analysis of equine locomotion. Equine Vet J 1984;16(6):522–8.
[13] Clayton HM. Comparison of the stride kinematics of the collected, medium, and extended walks in horses. Am J Vet Res 1995;56(7).
[14] Clayton HM. Comparison of the stride kinematics of the collected, working, medium and extended trot in horses. Equine Vet J 1994;26(3):230–4.
[15] Hildebrand M. Symmetrical gaits of horses. Science 1965;150(3697):701–8.
[16] Poncet, P.-A., Useful observational criteria for scoring Franches-Montagnes Horses. 2019, Personal Communication to A.I. Gmel.
[17] Weishaupt MA, et al. Instrumented treadmill for measuring vertical ground reaction forces in horses. Am J Vet Res 2002;63(4):520–7.
[18] Clayton HM, Hobbs S-J. The role of biomechanical analysis of horse and rider in equitation science. Appl Anim Behav Sci 2017;190:123–32.
[19] Gmel AI, et al. Video clips of Franches-Montagnes stallions at walk and trot on a treadmill during an incremental speed test. Mendeley Data; 2022. https://data.mendeley.com/datasets/bwfkyvy593/1. [Accessed 28 November 2022].
[20] Lüdecke D, et al. performance: an R package for assessment, comparison and testing of statistical models. J Open Source Softw 2021;6(60):1–8. 3139.
[21] Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol 2013;4:863.
[22] Krehbiel TC. Correlation coefficient rule of thumb. Dec Sci JInnov Educ 2004;2(1):97–100.
[23] Weishaupt M, et al. Velocity-dependent changes of time, force and spatial parameters in Warmblood horses walking and trotting on a treadmill. Equine Vet J 2010;42:530–7.
[24] Back W, et al. Kinematic detection of superior gait quality in young trotting warmbloods. Vet Q 1994;16(sup2):91–6.
[25] Morales J, et al. Angular kinematic patterns of limbs in elite and riding horses at trot. Equine Vet J 1998;30(6):528–33.
[26] Hobbs SJ, Bertram JE, Clayton HM. An exploration of the influence of diagonal dissociation and moderate changes in speed on locomotor parameters in trotting horses. PeerJ 2016;4:e2190.
[27] Holmström M, Drevemo S. Effects of trot quality and collection on the angular velocity in the hindlimbs of riding horses. Equine Vet J 1997;29(S23):62–65.
[28] Goff L, et al. Quantification of equine sacral and iliac motion during gait: a comparison between motion capture with skin-mounted and bone-fixated sensors. Equine Vet J 2010;42:468–74.
[29] Barrey E, et al. Early evaluation of dressage ability in different breeds. Equine Vet J 2002;34(S34):319–24.
[30] Hobbs SJ, et al. A scoping review of determinants of performance in dressage. PeerJ 2020;8:e9022.
[31] Back W, Schamhardt H, Barneveld A. Are kinematics of the walk related to the locomotion of a warmblood horse at the trot? Vet Q 1996;18(sup2):79–84.
[32] Buchner H, et al. Limb movement adaptations in horses with experimentally induced fore-or hindlimb lameness. Equine Vet J 1996;28(1):63–70.