How gait analysis by accelerometry can improve breeding programs in jumping horses?

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Summary

Gait analysis by accelerometry (trot, canter, and walk) of 1477 young jumping horses was recorded during 27 events in 2015 and 2016. Genetic analysis used mixed model methodology with an animal model involving 10,907 ancestors for the animal effect and velocity, sex, age, event for the fixed effects. Genetic correlations with jumping were calculated using all performances in competition since birth year 1998, i.e. 23,2952 horses, 406,750 ancestors and 458,269 annual performances from 2002 to 2016. Genome-wide analysis was performed including 541,175 SNP after quality control. Results showed a high heritability for dorsoventral displacement and stride frequency (>0.41), moderate for longitudinal activity (>0.19) and low for lateral activity (<0.07). The same characteristics at trot and canter were genetically correlated (>0.56). Genetic correlation with jumping performance was null except one negative correlation (-0.22*) for longitudinal activity at canter. GWAS revealed the importance of withers height on gaits and explained the choice to include this trait as covariate to investigate gaits at constant height and velocity. For the breeding objective, the selection of jumping horse is nearly independent of the gait characteristics except longitudinal activity at the canter.

Keywords: horse, jumping, gait, accelerometer, genomic, genome-wide association study, heritability

Introduction

Gait characteristics represent a double challenge in horse breeding for jumping competition: are they a useful indirect tool for early selection in jumping or better adapted for dressage feature? Consequently, are they positive or negative factor for jumping ability? The aim of this study was to calculate genetic parameters and to perform genomic association analysis of gaits measured by accelerometers, jumping performances in competition and height at withers for French sport horses.

Material and methods

Horses population, gait analysis, genotyping and performance records

During spring 2015 and 2016, 1477 young sport horses aged 4 (42%) and 5 (58%) were
recorded with an accelerometer Equimerix® (Barrey et al., 1996) at walk, trot and canter under saddle. These horses were 50% females, 35% geldings and 15% males. Their breed was 83% Selle Français (SF), 10% foreign sport horses, 3% Anglo Arabs and 4% unregistered horses. About the third were recorded in 2015 and the remaining in 2016. Combination of locations and day of recording gave 26 levels of “event” effect.

Acceleration of the horse was recorded with a 3-dimension accelerometer device fixed onto the girth. Riders were asked to perform a quick gait test including the 3 gaits in an arena including diagonal lines of 60 meters to have a sufficiently long measurement time. A sample of 10 seconds for each gait was extracted for gait measurements calculation. Raw data were acceleration recorded at 100Hz per axis in the dorsoventral, longitudinal and lateral axis of the horse. Five gaits were distinguished: walk (W), working trot, medium trot, working canter, medium canter. Then, 8 measurements were calculated: velocity (V), stride frequency (SF), regularity (R), symmetry (S, except for canter), dorsoventral displacement (DVD), dorsoventral power or activity (DVA), longitudinal activity (LGA) and lateral activity (LTA) (methods of calculation described in Barrey et al. (1994, 1995) and Leleu et al., (2004). Logarithm transformation was applied to normalize the symmetry and activities measurements (except for dorsoventral at trot) in order to reach better Gaussian distribution. Thus, the 5 gaits of each horse were characterized by a total of 38 measurements.

Among these horses, 702 were genotyped with the Affymetrix Axiom Equine genotyping array that includes 670,806 SNP. After quality control (minimum allele frequency>2%, p-value Hardy-Weinber equilibrium test>10⁻⁶, call rate > 90%), 541,175 SNP were retained.

These horses performed in jumping competition from 2014 to 2016, 1219 at 4 years old (yo), 994 at 5 yo and 290 at 6 yo. More than half of them had 2 (42%) or 3 (14%) performances per year and 44% only one. Analysis of jumping competition data was performed with the complete dataset of official jumping competition since birth year 1998, including 232,952 horses, 406,750 ancestors and 458,269 annual performances from 2002 to 2016. Performance was measured by logarithm of annual sum of points distributed according to the rank and the technical difficulty of each event.

Height at withers was routinely measured for 97% of these horses (mean 166.75 cm, s.d. 4.16).

Statistical methods

Different models and methods were applied to respond to specific questions on the data and are detailed in the Appendix.

Results

Are the traits of working and medium gaits (trot & canter) genetically the same?

Very high genetic correlations between working and medium gait allowed considering measurements in the two gaits as the same trait (Table 1 and Table 2). Exception was for regularity and symmetry at trot which showed a different picture: they were very low heritable (mostly <=0.07) traits, no significantly different from 0 and very low repeatable (0.08 to 0.25). In fact, these sensitive traits have not been measured satisfactorily. The calculation made did not reflect correctly the aim of these traits as they did not correspond to a stable gait characteristic in long straight line (arena turns and diagonals).

In the rest of the text, we will consider the trot (T) as a single gait, with 2 repeated
measurements as well as for the canter (C).

**How can we summarize the main characteristics of the walk, trot and canter?**

The principal component analysis of the horse effects on the 8 measurements at each gait was illustrated in Figure 1. Trot and canter had similar patterns. The first component was the opposition between DVD and SF (a low stride frequency gave a high displacement). The second component (for the trot) and the third (for the canter) was the importance of LGA associated with LTA and SF for trot and SF only for canter. The last component taken into account (third for trot, and second for canter) was LTA (with slight association with DVD, SF and negatively with LGA for trot). These 3 first principal components represented 82% of variance for the trot and 89% for the canter. For walk, the first component was DVA and DVD associated with R and S but not SF which was represented in the second component associated with LA. The third was SF slightly opposed to R and DVA. In the rest of the text, the PCs will be named according to their rank (1, 2 3), the gait (T, C, W) and the most important variable (ex: first component for trot is PCT1_DVD).

**What is the influence of the height in the gait characteristics?**

Results of GWAS (Figure 2) on the first principal component for trot showed a highly significant test (p_values = from 1.0x10^{-6} to 1.0x10^{-8}) for the region on chromosome 3 (g.105152868 to g.106128177) closed to the one linked to height at withers already found by Signer-Hasler et al. (2012), Frischknecht et al. (2016) and Makvandi et al. (2012). So we performed also a GWAS on height at withers and we found exactly the same region which even a much lower p_value= 4x10^{-35}. The explanation was straightforward: at a given speed, a tall horse has a lower stride frequency, a higher stride length and higher dorsoventral displacement than a smaller horse. The objective to measure gaits characteristics was not to distinguish tall and small horses. Thus, we decided to differentiate the two criteria with a structured equation model: gaits components will be analysed using height effect and height will be added to the genetic analysis as a supplementary trait.

**Genetic analysis of gaits and height à withers**

Results of the 10 multiple traits were in table 3. For trot and canter, heritabilities were higher for PC_DVD (0.53, 0.41) than PC_LGA (0.33, 0.19) and low for PC_LTA. They were higher for trot than canter. Heritabilities for walk were low (<=0.16). Heritability for height at withers was moderate compared to usual for such trait (0.33). No significant correlation between traits for the same gait was found. Genetic correlation for similar trait between canter and trot were high (0.56, 0.73) except for LTA. The PCW2_SF, which included activities, were correlated to similar PC at trot and canter. It was also negatively correlated to PCT1_DVD which included negative SF variable. In spite of the regression already included with height, genetic correlation between height and PCT2_LGA and PCT2_LTA was found.

**Link to performance in jumping competition**

Heritability of annual logarithm sum of points was 0.31 (s.e. 0.01) and annual repeatability 0.52 (s.e. 0.002). Only one genetic correlation between gait and jumping performance was significantly different from zero: -0.22 (s.e. 0.10) with PCC3_LGA. A high longitudinal activity at canter with high stride frequency was genetically associated with lower
performances. The phenotypic correlation was -0.06 (s.e. 0.03).

Discussion and Conclusion

Gait analysis by accelerometry gave reliable measurement for gaits except for regularity and symmetry measured with a rider turning in an arena. More work must be done to convert signals to these two concepts or to record more strides to have a repeatable measurement.

At trot and canter, horses are characterised first by their stride frequency linked to dorsoventral activity, then by their longitudinal activity and third by lateral activity. At walk, the first component was the dorsoventral activity and regularity and the second, stride frequency and longitudinal activity.

Heritability, after correction for velocity and height at withers, was high for DVA, moderate for LGA and low for LTA. Trot and canter had the same genetically shape. Walk was somehow different, but with still a high correlation concerning SF.

Genetic correlation with jumping was almost zero, except a negative correlation for LGA. High longitudinal activity (mechanical power) was a favorable factor for speed but not for a balance canter required for show jumping.

Conclusion was that mostly the selection of horse according to their suitable gaits (whatever they are) was possible without conflict, but without gain, with selection for jumping competition. Special attention must be done on LGA with high SF unfavourable for jumping. Distinct selection for height, whatever the goal (increase or decrease), is possible with the use of genetic evaluation based on this structural equation model.

List of References

Table 1. Heritability, genetic correlation and phenotypic correlation between working and medium trot (s.e. in brackets).

<table>
<thead>
<tr>
<th></th>
<th>Heritability Working</th>
<th>Heritability Medium</th>
<th>Genetic correlation</th>
<th>Phenotypic correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (V)</td>
<td>0.03 (0.04)</td>
<td>0.10 (0.07)</td>
<td>0.98 (0.58)</td>
<td>0.42 (0.02)</td>
</tr>
<tr>
<td>Stride Frequency (SF)</td>
<td>0.52 (0.10)</td>
<td>0.40 (0.09)</td>
<td>0.99 (0.03)</td>
<td>0.66 (0.02)</td>
</tr>
<tr>
<td>Regularity (R)</td>
<td>0.02 (0.03)</td>
<td>0.07 (0.05)</td>
<td>0.36 (0.80)</td>
<td>0.25 (0.03)</td>
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<tr>
<td>Symmetry (S)</td>
<td>0.06 (0.06)</td>
<td>0.00 (0.04)</td>
<td>-</td>
<td>0.08 (0.03)</td>
</tr>
<tr>
<td>Dorsoventral displacement (DVD)</td>
<td>0.51 (0.09)</td>
<td>0.42 (0.09)</td>
<td>0.92 (0.05)</td>
<td>0.63 (0.02)</td>
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<tr>
<td>Dorsoventral activity (DVA)</td>
<td>0.32 (0.08)</td>
<td>0.34 (0.09)</td>
<td>0.97 (0.04)</td>
<td>0.70 (0.01)</td>
</tr>
<tr>
<td>Longitudinal activity (LGA)</td>
<td>0.37 (0.09)</td>
<td>0.35 (0.09)</td>
<td>0.97 (0.03)</td>
<td>0.79 (0.01)</td>
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<tr>
<td>Lateral activity (LTA)</td>
<td>0.21 (0.07)</td>
<td>0.12 (0.06)</td>
<td>1.00 (0.09)</td>
<td>0.65 (0.02)</td>
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</table>

Table 2. Heritability, genetic correlation and phenotypic correlation between working and medium canter (s.e. in brackets).

<table>
<thead>
<tr>
<th></th>
<th>Heritability Working</th>
<th>Heritability Medium</th>
<th>Genetic correlation</th>
<th>Phenotypic correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (V)</td>
<td>0.18 (0.07)</td>
<td>0.08 (0.06)</td>
<td>0.90 (0.28)</td>
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<td>Stride Frequency (SF)</td>
<td>0.41 (0.09)</td>
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<td>1.00 (0.03)</td>
<td>0.65 (0.02)</td>
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<tr>
<td>Regularity (R)</td>
<td>0.16 (0.07)</td>
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<td>0.98 (0.50)</td>
<td>0.23 (0.03)</td>
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<tr>
<td>Dorsoventral displacement (DVD)</td>
<td>0.52 (0.09)</td>
<td>0.50 (0.09)</td>
<td>1.00 (0.05)</td>
<td>0.50 (0.02)</td>
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<tr>
<td>Dorsoventral activity (DVA)</td>
<td>0.31 (0.08)</td>
<td>0.29 (0.08)</td>
<td>1.00 (0.06)</td>
<td>0.59 (0.02)</td>
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<td>Longitudinal activity (LGA)</td>
<td>0.17 (0.07)</td>
<td>0.21 (0.08)</td>
<td>0.86 (0.10)</td>
<td>0.66 (0.02)</td>
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<td>Lateral activity (LTA)</td>
<td>0.12 (0.07)</td>
<td>0.01 (0.05)</td>
<td>-</td>
<td>0.50 (0.02)</td>
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</table>
Table 3. Heritability(diagonal), genetic correlation (above the diagonal) and phenotypic correlation (below the diagonal) between principal component traits of gaits\(^1\) and height at withers, standard error in brackets, coloured box for significant estimates.

<table>
<thead>
<tr>
<th></th>
<th>PCT1_DVD</th>
<th>PCT2_LGA</th>
<th>PCT3_LTA</th>
<th>PCC1_DVD</th>
<th>PCC2_LTA</th>
<th>PCC3_LGA</th>
<th>PCW1_DVD</th>
<th>PCW2_SF</th>
<th>PCW3_S</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCT1_DVD</td>
<td>0.53 (0.06)</td>
<td>-0.18 (0.15)</td>
<td>-0.31 (0.21)</td>
<td>0.56 (0.10)</td>
<td>0.00 (0.26)</td>
<td>-0.23 (0.18)</td>
<td>0.33 (0.20)</td>
<td>-0.54 (0.19)</td>
<td>0.13 (0.39)</td>
<td>0.00 (0.09)</td>
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<tr>
<td>PCT2_LGA</td>
<td>-0.06 (0.02)</td>
<td>0.33 (0.04)</td>
<td>0.07 (0.24)</td>
<td>-0.15 (0.16)</td>
<td>-0.37 (0.32)</td>
<td>0.73 (0.11)</td>
<td>-0.27 (0.23)</td>
<td>0.49 (0.19)</td>
<td>0.43 (0.51)</td>
<td>0.21 (0.11)</td>
</tr>
<tr>
<td>PCT3_LTA</td>
<td>0.02 (0.02)</td>
<td>0.16 (0.02)</td>
<td>0.11 (0.04)</td>
<td>-0.10 (0.23)</td>
<td>0.34 (0.42)</td>
<td>0.20 (0.28)</td>
<td>-0.13 (0.35)</td>
<td>0.52 (0.28)</td>
<td>0.16 (0.64)</td>
<td>0.36 (0.18)</td>
</tr>
<tr>
<td>PCC1_DVD</td>
<td>0.37 (0.02)</td>
<td>0.02 (0.02)</td>
<td>0.04 (0.02)</td>
<td>0.41 (0.06)</td>
<td>0.27 (0.26)</td>
<td>-0.31 (0.19)</td>
<td>0.25 (0.22)</td>
<td>-0.11 (0.21)</td>
<td>0.04 (0.42)</td>
<td>0.08 (0.010)</td>
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<td>PCC2_LTA</td>
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<td>0.20 (0.01)</td>
<td>0.08 (0.02)</td>
<td>0.28 (0.02)</td>
<td>0.07 (0.03)</td>
<td>-0.41 (0.41)</td>
<td>-0.20 (0.42)</td>
<td>-0.10 (0.38)</td>
<td>0.14 (0.81)</td>
<td>-0.06 (0.21)</td>
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<td>0.07 (0.02)</td>
<td>0.19 (0.02)</td>
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<td>0.19 (0.05)</td>
<td>-0.24 (0.27)</td>
<td>0.48 (0.22)</td>
<td>0.60 (0.62)</td>
<td>0.00 (0.13)</td>
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<td>PCW1_DVD</td>
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<td>0.04 (0.02)</td>
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<td>0.09 (0.02)</td>
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<td>0.00 (0.02)</td>
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<td>-0.68 (0.69)</td>
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<td>0.21 (0.02)</td>
<td>0.19 (0.02)</td>
<td>0.05 (0.02)</td>
<td>0.16 (0.02)</td>
<td>0.23 (0.02)</td>
<td>0.00 (0.07)</td>
<td>0.15 (0.06)</td>
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<td>-0.21 (0.16)</td>
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<td>PCW3_S</td>
<td>-0.02 (0.02)</td>
<td>0.09 (0.02)</td>
<td>0.04 (0.02)</td>
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<td>0.06 (0.02)</td>
<td>0.00 (0.03)</td>
<td>0.00 (0.03)</td>
<td>0.04 (0.06)</td>
<td>-0.07 (0.32)</td>
</tr>
<tr>
<td>Height</td>
<td>0.00 (0.03)</td>
<td>0.07 (0.03)</td>
<td>0.07 (0.03)</td>
<td>0.03 (0.03)</td>
<td>-0.01 (0.03)</td>
<td>0.00 (0.03)</td>
<td>0.05 (0.04)</td>
<td>-0.05 (0.04)</td>
<td>-0.01 (0.04)</td>
<td>0.33 (0.08)</td>
</tr>
</tbody>
</table>

\(^1\) Code: PCYx_AAA : PC=Principal Component, Y=T for Trot, C for canter, W for Walk, x the rank of the principal component from 1 to 3, AAA = abbreviation for the main measurement involved in the principal component, DVD=dorsoventral displacement, LGA=longitudinal activity, LTA= lateral activity, SF= stride frequency, S=symmetry
Figure 1. Principal component analysis of trot (A), canter (B) and walk (C).
Figure 2. Manhattan plot of GWAS for (A) first principal component of trot (PCT1_DVD) involving dorsoventral displacement and stride frequency, (B) height at withers and (C) and PCT1_DVD corrected for height.
Appendix 1. Statistical Models.

All mixed model analysis used Wombat software (Meyer, 2007).

Are the traits of working and medium gaits (trot & canter) genetically the same?

To answer this question a bi-trait model was built for each of the 8 measurements between the working and medium trot on one side and working and medium canter on the other side. The following model was applied:

\[
(1),
\]

with \( y \) the vector of one of the 8 or 7 measurements for the 2 traits (working and medium gait), \( b \) vector of fixed effect, which included sex (female, male, gelding), age (4 or 5), velocity (covariate, except for the analysis of velocity itself), event (26 levels) and \( a \) the random polygenic effect (10907 horses including ancestors over 4 generations), \( e \) the vector of residuals. \( X \) and \( Z \) are incidence matrices. The variance-covariance matrices of random effects were: and with \( \otimes \) the direct product, \( A \) the relationship matrix from pedigree, \( G \) the 2x2 matrix of genetic variance-covariance between medium and working gait for each trait, \( I \) the identity matrix and \( R \) the 2x2 matrix of residual variance-covariance.

How can we summarize the main characteristics of the walk, trot and canter?

A principal component analysis was performed for each gait on the \( u \) estimates () of:

\[
(2),
\]

with \( y \) the vector of measurements for the walk, trot or canter, \( b \) vector of fixed effect as in (1) and with the fixed effect of the type of gait (working/medium) and \( u \) the random effect of the 1477 horses for repeated measurements (two for trot and canter), \( e \) the vector of residuals. \( X \) and \( Z \) are incidence matrices The variance-covariance matrices of random effects were: and.

In the rest of the study, the eigenvectors of the 3 first principal components of each gait (walk, trot, and canter) were used to compute 3 linear combinations of the measurements for each gait resulting in 9 synthetic gait traits (PC).

What is the influence of the height in the gait characteristics?

Gaits may be mechanically linked to several morphological traits such as the height at withers. First we neglected the relationship between morphology and gaits and we tried a genome-wide association study (GWAS) for the 9 PCs. As phenotype, we used the estimated effect of the permanent environment (of the model):

\[
(3),
\]

with \( y \) the vector of one of the 9 PCs, \( b \) vector of fixed effect, which included sex (female, male, gelding), age (4 or 5), velocity (covariate), event (26 levels) and \( a \) the random polygenic effect (10907 horses including ancestors over 4 generations), \( p \) the random
permanent environmental effect (for trot and canter repeated two times), \( e \) the vector of residuals. \( X \) and \( Z \) are incidence matrices. The variance-covariance matrices of random effects were; \( \mathbf{\Sigma} \) the direct product, \( A \) the relationship matrix from pedigree, \( G \) the 9x9 matrix of genetic variance-covariance between each PC trait, \( P \) the 9x9 matrix of genetic variance-covariance between permanent environmental effect of PC trait, \( I \) the identity matrix and \( R \) the 9x9 matrix of residual variance-covariance. Residual covariance between trot and canter were null by construction.

The GWAS was performed using GenABEL package (Aulchenko et al., 2007). We found a huge effect of the well-known QTL of chromosome 3 on height influencing the PCs linked to stride frequency. So we finally decided to use the following model to analyses gaits.

**Genetic analysis of gaits and height à withers**

The multivariate analysis of the gaits involved 10 traits: the 9 PCs and height at withers. The model included as covariate velocity and height at withers for the gaits components, so that the model was a structured equation model (Gianola & Sorensen, 2004, Rosa et al., 2011) and the multiple trait models (3) was applied with special pattern for residual correlations.

**Relationship with jumping performances**

Due to the size of the jumping data, analysis was performed repeatedly with 3 traits: one of the PCs, jumping performance and height at wither. The same model as before was used for PCs and model for jumping performance included a combination of year and age effect.