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Phenotypic correlations between jump and gaits characteristics measured by inertial measurement units in horse jumping training - preliminary results

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HIGHLIGHTS

- Correlations within gaits parameters are lower than correlations within jumping ones.
- Canter frequency is the only canter parameter moderately correlated with jumping.
- Walk characteristics are low connected with jumping parameters.
- Regularity and frequency correlation is higher in symmetrical than asymmetrical gaits.
- Trot symmetry correlates positively with frequency and negatively with elevation.

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ABSTRACT

High correlations between gaits and jump characteristics are expected because even specialized jumpers need quality of movement to fulfil temporal performance requirements. Twelve sport horses (5-11 years) of different training levels were examined during regular training under high-level riders in two training centers. They covered a 3-4 km distance overcoming up to 30 obstacles. The first 15 jumps were analyzed. They jumped randomly chosen obstacles of the known characteristics from the basic, perpendicular approach. Jumping and movements parameters (179 observations) were measured using Seaver® devices based on inertial measurement unit technique. The following jump data were analyzed: height, length, reserve, frequency of approach, angle at take-off, acceleration of take-off, velocity, spatial shifting and energy by landing. The device measured 10 movement parameters. Frequency, elevation and regularity of walk, trot and canter, as well as trot symmetry were available. Relationships between parameters were analyzed using Pearson/Spearmann correlations (SAS, CORR) and partial correlations corrected for fixed effects of obstacle type and height, successive jump number, training center/rider and horse age-experience (SAS, GLM). Pearson and Spearmann correlations within jumping parameters (-0.48 – 0.95) and within gaits parameters (-0.64 – 0.78) were significant at least for $p<0.05$. Obtained partial correlations between gaits and jumping (above 0.3) showed that some gait characteristics are connected with jump quality. However, most partial correlations were low. Moderate values were noted for jump and canter frequencies (0.44), which is treated in horse selection as a jump determinant and walk regularity and three jumping parameters (0.33-36).

1. Introduction

New forms of sport horse training are being developed constantly and result in new demands related to requirements of equestrian sports. Inertial measurement units (IMU) seem to be an important tool to fulfil these urgent needs in monitoring of training, thus broadening the knowledge on motion parameters. The monitoring of training allow to control progress in jumping and movement parameters by observation of changes, including direction of their changes. The IMU measurements of horse movement kinematics and dynamics are increasingly commonly

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accepted among both amateurs and equestrian professionals (Becker and Lewczuk, 2020; Gmel et al., 2020). Horses are animals with considerable athletic abilities and an extensive gait repertoire in spite of their large size and body mass (Clayton, 2016). Recognition of these skills is of special importance during different stages of specific, individual training in equestrian sports used after general background training. The success in equestrian sport requires mutual coordination in movements and proper dynamic in show jumping competitions (Gregic et al., 2016). Technological progress provides new opportunities in horse evaluation. It is expected to identify movement parameters connected with "good jump" characteristics, facilitating prediction of quality in jump horses. Leguillette et al. (2020) stated that each horse requires individual methods, especially in terms of the workload between jumps and flat work, which is currently unknown, but which needs to be balanced. In jumping competitions, the predisposition to discipline seems defined by the quality of canter, which can be a good forecast of success in sport, as an indicator of imbalance is correlated negatively on the genetic level with horse performance (0.2) (Becker et al., 2013). Janczarek et al. (2013) found during assessing jumping horses' ability at an approach, the position of the poll, as well as the angle of neck position are particularly important. If the horse jumps optimally and has good timing, the tip of the parabola is directly above the obstacle (Topolinski, 2013). Based on current scientific research, a large pool of possible performance-relevant parameters can be selected (Fercher, 2017). The horse jump can be divided into five phases — approach, take-off, suspension, landing and departure. Each of these parts has specific determining factors, which show either a mechanical or a mathematical relationship with jumping quality (Powers and Harrison, 1999). Finally, an adequately trained and specialist bred horse is the one promising good results in equestrian sports (Gregic et al., 2021).

Dependencies of subjectively assessed jumping and dressage traits were investigated both at phenotypic (Molina et al. 1999; Olsson et al., 2000) and genetic levels (Ricard et al., 2000, Hellsten et al., 2006, 2009; Ruhlmann et al., 2009). However, phenotypic results are less available (Rustin et al., 2009) and less objective (Lewczuk, 2013). It seems that their importance is underestimated, although they may be very useful for horse users. They support understanding of training methods. Connections between dressage and jumping traits in different training methods and training progress could help to identify proper training methods. That is of special importance, as genetic correlations between dressage and show jumping traits are reported mostly as negative (Rovere et al., 2017) and it is not necessarily adequate for phenotypic observations, as phenotypic correlations present the connections between traits within a specific environment. At an advanced competition level horses need to cover all obstacles without penalty points in the possible shortest time (Gego, 2006; FEI Jumping Rules 26th edition chapter VI, art.235-239). This requires not only jumping potential, but also rideability and good gaits, at least canter. Such research on the phenotypic background, is not only rare, but also based only on subjective judge scoring or linear profiling. There is a lack of such correlations in biomechanics of sport horses, although considerable knowledge is available (Clayton and Hoobs, 2017; Fercher, 2017). Research provided on jumping biomechanics does not cover relationships with movement characteristics (Santamaria et al., 2004, 2005; Lewczuk, 2006, 2007: Lewczuk and Durco, 2012; Janczarek et al., 2012; de Godoi et al., 2014); however, first studies have been published on genetic parameters of the biomechanics parameters using acceleometry (Dugué et al., 2021; Ricard et al.2021). Phenotypic correlations provide information on relationships between various traits and allow to choose for training the horse with adequate skills and training methods. On the basis of one trait, we can predict the potential of a horse on another trait. Phenotypic correlations inform on the occurrence and strength of the relationship between observed performance traits, thus they can support faster decisions conserning the specialization of a horse for equestrian sports (dressage or show jumping). In contrast to genetic correlation they do not inform on genes connections, but about skills connections – genetic skills trained in a specific environment.

The aim of this study was to estimate relationships between jumping and movement traits of adult sport horses based on usual jumping training data coming from IMU measurements. Partial correlations between movement and jumping parameters corrected for significant factors from the statistical model were evaluated. Obtained partial correlation were corrected for the training/rider, horse age-experience group, obstacle size and type, as well as successive number of the jump. Partial correlations were used earlier in analysis of the horse behavioural traits (Ingólfsdóttir and Sigurjónsdóttir, 2008; Wolframm and Meulenbroek, 2012; Rothmann et al., 2014; Shima and Suzuki, 2020) or physiological traits (Koizumi et al., 1989; Bartolomé et al., 2013), and allowed to control significant effects by measuring the relationship. Additionally simple Pearson and Spearmann correlations between parameters within jumping traits and within movement traits were presented. High correlations between some gaits and jump quality were expected, because even highly specialized jumpers need high quality movement to fulfil temporal performance requirements. It is expected to verify the hypothesis that jumper horses require high quality gallop and the used IMU technologies enable such research.

2. Materials and methods

Jumping and movement parameters were collected (179 observations) of 12 Warmblood sport horses (5 to 11 years old geldings and mares) with different experience: 5-6-year old without any competition experience (3 horses), 5-6 year old with competition experience (4 horses) and above 6 years old with competition experience (5 horses). Competition experience was defined as at least 5 competitions on the national level of L-P classes with the obstacle height of 100-110cm. Investigated parameters were measured using Seaver® devices (US pat. 2020/0196901 98 PCT/EP2018/068812) based on the inertial measurement unit technique (60Hz) with a build-in the heart rate monitor (10s interval). Data collected by the IMU were sent via a Bluetooth to a smartphone and stored on an online server. Movement parameters were obtained using device algorithms after calibration to the horse's and rider's body mass. All horses were measured on a flat ground at girth height (the distance between the ground and the device location at the lowest position of girth) and half-shoulder-girth length (the distance between the middle of the shoulder in the widest part and girth position) by the investigator (experienced horse rider) according to the User manual (www.seaverhorse.com). The Seaver tape for body measurements was used. Riders were two men, 178 and 183cm in height with 79 and 84kg in weight, respectively. Horses were 171.5 $\pm$ 4.25 cm high at the withers and weighed 589.8$\pm$19kg. A girth device with sensors sized 14 $\times$ 22cm and weighing 375g was mounted on the saddle girth, while an additional electrode (35g) for the heart rate measurement (HR) was placed behind the withers on the left flank of the horse, where the saddle comes in contact with the horse. The device monitored training parameters that describe the horse and the ride, condition, gaits and jumping. Horses were monitored during regular training in two training centers under riders having first sport class certification in the national show jumping classification (each rider mounted 6 horses) and covered an approx. 3-4km distance, overcoming up to 43 obstacles, of 80 - 140 cm in height and 90 cm in width. The obstacles were spread and vertical, build with poles as single obstacles. The riders were asked to jump in the middle of the obstacle front, from the approach perpendicular to the obstacle front. The total time of training was 40 minutes (sd=7) with the mean velocity of 16.08 km/h (sd=3.28). The heart rate during training reached values of 107-186 bpm (beats per minute). Horses spent 16.69 minutes (sd=4.25) in walk, 18.34 (sd=1.45) in trot and 2.15 (sd=1.75) in canter. In total, horses were trained 52% in the straight direction, 25% in the left and 23% the right direction. These working directions were almost identical for trot and walk, except for canter, where the straight direction accounted for 45%, left 30% and right 25% of the time spent in this gait. Riders selected obstacles at random. Both types of obstacles (vertical and spread) as well as different obstacle heights (<100, 100-120, >120) were jumped by the participating horses. The details of the course covered by every horse and rider were noted as potential factors that can affect jumping parameters and they were used for data correction in the statistical model by calculations.

The preliminary results (SAS analysis, analysis of variance with the rider/training and horse age effects) found no statistically significant differences between horses in terms of most training characteristics (heart rate, distance covered, number of jumps, low (<110 bpm) and high (>180 bpm) intensity training except for the total duration of training and time of medium intensity training (110-180 bpm).

3. Analyzed parameters

3.1. Jumping parameters

For the jump the following parameters were analyzed: height [cm] - height of jump above the obstacle at the device location; length [cm] - distance between hind limbs when taking off and fore limbs when landing; reserve [cm] - difference between height of jump and height of the obstacle; frequency of approach strides [strides/min] - stride frequency of five strides before the jump; angle at take-off [°], acceleration of take-off [g] and velocity at take-off [km/h], horse body spatial shifting [°] - difference between horse body spatial orientations when taking off and when landing; energy by landing [kJ] - energy absorbed by the horse when landing (Table 1). The jump data were monitored for every jump.

3.2. Gait parameters

For the movement characteristics the following parameters were measured (Table 2): stride frequency of walk, trot and canter [strides/min] - number of strides in time; elevation at walk, trot and canter [cm] - vertical displacement of the horse's body; regularity of movement at walk, trot and canter [%] – similarity of frequency at each gait; symmetry of trot [without the unit] - left to right average stride frequency ratio. Data were collected as the mean for performed movements and gaits, as presented in Table 2.

4. Statistical analysis

The correlation analysis was conducted using Pearson's correlation between jumping and gait characteristics, except for two parameters called the reserve and spatial shifting traits, where Spearman's rank correlations were used because of their distribution characteristics. The relationships between jumping and gait parameters were analyzed across the cohort (all jumps) using partial correlations (SAS v.9.4, GLM with the Manova option) with the statistical model including fixed effects of obstacle type (vertical, spread), obstacle height (<100, 100-120, >120), successive jump number (1-15), training center (1,2) and the age-experience effect (1-3). The correlations were presented according to the Quinnipiac University scale (Akoglu, 2018), so the correlations below 0.3 were treated as weak or negligible, and those above 0.3 as moderate. The variables in the partial analysis met test assumptions as partial correlations can be calculated for continuous and categorical data (Lin et al., 2010).

5. Results

Most of the jumping parameters were characterized by moderate variability. The reserve of the jump, which depends on obstacle height, showed greater variability. The spatial shifting from the definition being left-right is an extremely variable parameter; however, it seems connected with the obstacle characteristic. Variability of all the gait parameters was small, except for the elevation of walk being the greatest

Table 1
The description of measured jumping parameters.

Training parameter		Source/ description	mean	sd	Range
JUMPING	Height of jump [cm]	Seaver device - height of jump above the obstacle	122.52	12.20	96-172
	Reserve of jump [cm]	Calculated from Seaver data - the difference between height of jump and height of the obstacle	10.06	7.17	10-39
	Length of jump [cm]	Seaver device – the distance between hind limbs when taking off and fore-limbs when landing	305.6	119.4	136-602
	Angle at take-off [°]	Seaver device – based on height and length of jump measured as angle from the horizontal ground line	23.27	4.85	15-36
	Frequency of take-off [strides/min]	Seaver device – stride frequency of five strides before the jump	112.79	28.15	39-194
	Acceleration at take-off [g]	Seaver device – vertical acceleration at take-off	1.36	0.16	1.12-1.92
	Velocity [km/h]	Seaver device – velocity at the take-off ascending phase	23.19	5.30	14.1-35.8
	Spatial shifting [°]	Seaver device – difference between horse spatial orientations when taking off and when landing	-1.71	7.72	-45-20
	Energy at landing [kJ]	Seaver device - energy absorbed by the horse when landing	2.08	0.85	0.72-4.85
	Symmetry at take-off [-]	Seaver device – the ratio of right to left limb acceleration at take–off landing	1.07	0.27	0.64-3.0

one. The correlations were corrected ($p<0.05$) for age-experience effect in 15 out of 20 investigated parameters, for obstacle type in 10/20 and for obstacle type in 2/20, for the successive jump number in 3/20.

5.1. Correlations between jumping parameters

Data are presented in Table 3. The relationships between jumping parameters are in the wide range of values (-0.91-0.98). Some of them seem predictable, such as connections between energy and acceleration (0.98; p=0.0001), while some are less obvious e.g. energy at landing and velocity at approach (0.57; p=0.0001).

In the case of parameters that characterise size of the jump, the height of jump is strongly correlated with its length (0.67; p=0.0001). The reserve of jump is much more connected with jump height (0.51; p=0.0001) than length (0.31; p=0.0002). It seems natural that angle at take-off is strongly positively correlated with jump height (0.52; p=0.0001) and shows a low negative correlation with jump length (-0.19; p=0.04). The acceleration of take-off and landing energy are very strongly correlated with jump height (both 0.95; p=0.0001) and length (0.73-0.80; p=0.0001). Such correlations are not so strong between velocity and jump height (0.43; p=0.0001), being almost two times weaker than with the length of jump (0.95; p=0.0001).

Symmetry of take-off shows a weak correlation with jump height

Table 2
The description of measured movement parameters.

Training parameter		Source/description	mean	sd	Range
GAITS	Frequency of walk [strides/sec]	Seaver device – mean number of strides per minute in walk during training	45.80	4.68	36-52
	Frequency of trot [strides/min]	Seaver device – mean number of strides per minute in trot during training	75.18	4.53	66-79
	Frequency of canter [strides/min]	Seaver device – mean number of strides per minute in canter during training	108.43	10.04	87-127
	Regularity of walk [%]	Seaver device – mean stability of frequency of walk during training	84.38	3.47	77-90
	Regularity of trot [%]	Seaver device – mean stability of frequency of walk during training	73.49	9.53	49-87
	Regularity of canter [%]	Seaver device – mean stability of frequency of walk during training	56.01	10.10	40-81
	Elevation at walk [cm]	Seaver device – mean horse vertical displacement in walk during training	2.24	0.84	1-4
	Elevation at trot [cm]	Seaver device – mean horse vertical displacement in trot during training	6.95	1.24	4-8
	Elevation at canter [cm]	Seaver device – mean horse vertical displacement in canter during training	15.33	1.04	14-18
	Symmetry of trot [-]	Seaver device – the ratio of right to left limb acceleration at trot	1.01	0.06	0.91-1.11

(0.21; p=0.01) and take-off angle (0.28; p=0.007); however, it is almost the opposite in the case of spatial shifting (-0.91; p=0.0001). The only jumping parameter not connected with any other description of jump is the frequency of strides at take-off.

5.2. Correlations between movement parameters

Data are presented in Table 4. The correlations between movement parameters are less spectacular than for jumping. The range of correlations is between -0.64 and 0.78. The greatest correlations were found between frequencies and regularities for symmetrical gaits (walk and trot) (0.7-0.78; p=0.0001). Such a correlation between canter regularity and canter frequency was much lower and reached 0.27 (p=0.004). It is worth noting that for the frequency of walk and canter regularity was strong and negative (-0.64; p=0.0001). The other relationships between frequencies and regularities of different gaits were positive and mostly low amounting to 0.18 (p=0.04), 0.27 (p=0.004) and 0.36 (p=0.0001). Correlations between frequencies of different gaits were not statistically significant. Most correlations between gait frequencies and elevations were relatively high and negative, ranging between -0.31 and - 0.51 (p≤<0.0005), except for one positive correlation between trot frequency and elevation (0.30; p=0.001).

Regularity connections between gaits were not statistically significant except for the correlation between walk and canter, which was moderate and negative (-0.39; p=0.0001). Elevation at canter was correlated at 0.21 (p=0.02) with trot elevation and at 0.59 (p=0.0001) with walk elevation. Elevations of walk and trot were independent.

5.3. Correlations between jumping and gait parameters

Data are presented in Table 5. The obtained results showed that correlations between walk and jumping parameters are statistically significant for 21 correlations out of the possible 27, however most of them were weak with three moderate values (above 0.3). Correlations above 0.3 were found only for walk regularity and jump height (0.33; p=0.003), acceleration of take–off (0.36; p=0.008) and energy by landing (0.35; p=0.02). Low positive correlations (0.24-0.29; p<0.007) were obtained for walk frequency and jumping parameters, as well as regularity of walk and three others jumping parameters (0.20-0.27; p≤0.01). Low negative correlations were recorded for the elevation of walk and jumping parameters ranging from -0.17 to -0.25 (p≤0.03). Statistically significant weak correlations between jumping and trot parameters were noted only for two parameters, being -0.17 (p=0.004) between approach frequency and elevation and 0.18 (p=0.04) for trot frequency and spatial shifting in jump.

A moderate correlation was obtained between frequencies of canter and approach jump strides (0.44; p=0.006). Canter regularity showed a low correlation (0.19; p=0.003) with frequency of jump approach strides. Negative correlations for jumping parameters and gallop characteristics were found between canter regularity and height of jump (-0.24; p=0.003) as well as elevation of canter and frequency of jump approach strides (-0.16;p=0.004).

Thus generally the frequency of jump approach strides was the jumping parameter mostly connected with gait parameters, being positively moderately correlated with canter frequency and low correlated positively with regularity and low negatively correlated with gait elevations. The parameters of jump size (height, reserve, length) were correlated mainly at a low level with walk regularity. The dynamic parameters, i.e. acceleration, velocity and energy at landing, were also mostly weakly positive connected with walk regularity and weakly negatively correlated with walk elevation. The regularity of walk was the parameter mostly weakly connected with the highest number of jumping parameters; however, the highest, moderate correlation was observed between canter frequency and approach frequency.

Table 3
Pearson/Spearman's* correlations between jumping parameters and their significance (in bold for *P<0.05).

Jump parameters	Height	*Reserve	Length	Angle at take-off	Frequency of take-off	Acceleration at take-ff	Velocity	*Spatial shifting	Energy at landing	Symmetry of take-off
Height [cm]	*	**0.51**	**0.67**	**0.52**	-0.02	**0.95**	**0.43**	**-0.25**	**0.95**	**0.21**
Reserve [cm]	**0.51**	*	**0.31**	**0.31**	-0.02	**0.51**	0.19	0.08	**0.51**	0.11
Length [cm]	**0.67**	**0.31**	*	**-0.19**	-0.07	**0.73**	**0.95**	**-0.21**	**0.80**	0.00
Angle at take-off [°]	**0.51**	**0.31**	**-0.19**	*	0.00	**0.49**	**-0.48**	**-0.09**	**0.40**	**0.28**
Frequency of approach strides [strides/min]	-0.02	-0.02	-0.07	0.00	*	-0.04	-0.07	-0.13	-0.03	-0.02
Acceleration at take-off [g]	**0.95**	**0.51**	**0.73**	**0.49**	-0.04	*	**0.48**	**-0.24**	**0.98**	0.17
Velocity [km/h]	**0.43**	0.19	**0.95**	**-0.48**	-0.07	**0.48**	*	**-0.18**	**0.57**	0.04
Spatial shifting [°]	**-0.25**	0.08	**-0.21**	**-0.09**	-0.13	**-0.24**	**-0.18**	*	**-0.23**	**-0.91**
Energy at landing [kJ]	**0.95**	**0.51**	**0.80**	**0.40**	-0.03	**0.98**	**0.57**	**-0.23**	*	-0.18
Symmetry of take-off	**0.21**	0.11	-0.04	**0.28**	-0.02	0.17	0.04	**-0.91**	-0.18	*

* traits without normal distribution were correlated by Spearman's rank correlation

Table 4
Pearson's correlations between gait parameters and their significance (in bold for *P<0.05).

Gait parameters	Frequency of walk	Frequency of trot	Frequency of cater	Regularity of walk	Regularity of trot	Regularity of cater	Elevation at walk	Elevation at trot	Elevation at canter	Symmetry in trot
Frequency of walk [strides/ min]	x	0.02	-0.15	**0.70**	**0.18**	**-0.63**	**-0.40**	**0.30**	0.14	0.14
Frequency of trot [strides/ min]	0.02	x	0.04	-0.11	**0.78**	**0.36**	**-0.51**	0.06	**-0.35**	**-0.35**
Frequency of canter [strides/min]	-0.15	0.04	x	0.06	-0.18	**0.27**	**-0.31**	**-0.54**	**-0.43**	**-0.52**
Regularity of walk	**0.70**	-0.11	0.06	x	-0.13	**-0.39**	**-0.36**	-0.02	-0.01	-0.04
Regularity of trot	**0.18**	**0.78**	-0.18	-0.13	x	0.04	**-0.46**	**0.56**	-0.12	0.03
Regularity of canter	**-0.63**	**0.36**	**0.27**	**-0.39**	0.04	x	-0.18	**-0.48**	**-0.64**	**0.32**
Elevation at walk [cm]	**-0.40**	**-0.51**	**-0.31**	**-0.36**	**-0.46**	-0.18	x	0.12	**0.59**	**0.43**
Elevation at trot [cm]	**0.30**	0.06	**-0.54**	-0.02	**0.56**	**-0.48**	0.12	x	**0.21**	**0.63**
Elevation at canter [cm]	0.14	**-0.35**	**-0.43**	-0.01	-0.12	**-0.64**	**0.59**	**0.21**	x	0.11
Symmetry in trot [cm]	0.14	**-0.35**	**-0.43**	-0.01	-0.12	**-0.64**	**0.59**	**0.21**	0.11	x

Table 5
Partial correlations between gait and jumping parameters with their significance (in bold for *P<0.05).

Jump parameters	Frequency of walk	Frequency of trot	Frequency of canter	Regularity of walk	Regularity of trot	Regularity of canter	Elevation at walk	Elevation at trot	Elevation at canter	Symmetry in trot
Height [cm]	**0.24**	0.04	-0.07	**0.33**	0.03	**-0.24**	**-0.18**	0.01	0.14	0.14
Reserve [cm]	0.14	-0.06	-0.07	**0.21**	-0.01	-0.11	-0.13	0.06	0.06	0.06
Length [cm]	0.15	0.03	0.01	**0.27**	-0.05	-0.04	-0.10	-0.09	-0.02	-0.02
Angle at take off [°]	0.10	-0.08	0.11	0.04	0.07	-0.14	0.02	-0.04	0.05	0.05
Frequency of approach strides [strides/min]	-0.15	0.11	**0.44**	0.07	-0.08	**0.19**	**-0.25**	**-0.17**	**-0.16**	**-0.16**
Acceleration at take off [g]	**0.29**	0.06	0.09	**0.36**	-0.09	-0.15	-0.19	-0.14	0.03	0.03
Velocity [km/h]	0.07	-0.01	0.07	**0.20**	-0.03	-0.03	-0.05	-0.05	-0.01	-0.01
Spatial shifting [°]	0.04	**0.18**	0.11	0.00	0.17	0.14	**-0.17**	-0.03	0.11	0.11
Energy by landing [kJ]	**0.27**	-0.02	0.00	**0.35**	0.00	-0.17	**-0.21**	-0.08	0.03	0.03
Symmetry of take-off	0.14	-0.14	0.04	-0.06	-0.04	-0.14	**0.19**	0.14	0.05	0.05

6. Discussion

6.1. Correlations between jumping parameters

Jumping parameters are strongly connected with each other. Some correlations seem obvious based on general physics (velocity – acceleration - energy), while some are rather unexpected, e.g. a stronger correlation of jump reserve with jump length rather than jump height. The negative correlations of jump velocity with the jump take-off angle seem consistent with jumping rules and training guidance (FEI; https://www.fei.org/stories/lifestyle/teach-me/two-grids-improve-jumping-technique), as horses (especially older with enough strength and balance) jumping with a lower velocity usually can take off closer to the obstacle with a greater take-off angle. The other new jumping trait relationships, such as correlations of spatial shifting with the other traits seem less evident being mostly negatively correlated with many traits. However, the strongest opposite correlation with symmetry of take-off seems reasonable, as more loading on one limb by taking off can cause unequal movement. The more perpendicular the jump to the obstacle front, the better jumping characteristics are achieved, and this depends on the quality of the take-off measured by symmetry. The influence could also be opposite – the rider's technique may influence jump spatial characteristics and its resulting jumping parameters. It is difficult to discuss this trait in more detail, as it had not been investigated earlier. The spatial shifting and its relationships may be strongly influenced by training progress and conditions (Lewczuk, 2008).

The research describing relationships between jumping traits was based on the linear evaluation of traits at their genetic level (Rovere et al.2017). Surprisingly, all free jumping linear traits evaluated during inspections were negatively correlated at the genetic level with jumping performance (from -0.52 to – 0.79). The possible explanation for such results could be provided by the influence of training progress, as these traits were recorded without riders. However, subjectively evaluated free jumping traits are highly correlated (0.92) with jumping performance (Hellsten et al., 2006).

Phenotypic correlations (Medeiros et al., 2020) concerning jumping traits evaluated by a linear scoring system (a more detailed descriptive system than the subjective judging point system, although still not measurable) underlined high correlations of limb biomechanics with overall impulsion and flexibility (0.15-0.46). These results cannot be compared directly using sensor data, as only reserve of limb above the obstacle can be calculated using the IMU system, which is not exactly the same as overall limb biomechanics (angles, position, speed). However, measurable acceleration at take-off and energy at landing correlate with the reserve at the same high level (0.5) as traits described in the cited study. According to Medeiros et al. (2020), jump distance (not defined precisely) was highly correlated with the power of jump (0.48) and evaluation of canter (0.32). In our study the length of jump (probably connected with the above-mentioned distance trait) was even more significantly (0.67-0.95) correlated with comparable traits: height of jump, acceleration of take-off, velocity and energy at landing. Unexpectedly there are no correlations between canter traits and length of jump, which is not consistent with the cited study. That seem explainable as our horses are trained, specialised jumping horses, not young stallions described in the cited study, so gait potential of sport horses shows a wider range. Such results of different gaits suitable for a good jumping horse at the genetic level were also found based on the accelerometer measurements (Ricard et al., 2020).

6.2. Correlations between movement parameters

Obtained results seem less predictable, as according to the training rules jumping horses should be able to perform at least good canter. The characteristics of canter are underlined as important for jumping specialist horses (www.KWPN.org, www.PZHK.pl). According to our study, the characteristic of trot and walk is closely correlated, while canter is less correlated with the other gaits in the investigated group of horses. Comparable results were found for the traits evaluated according to the linear descriptive evaluation (Medeiros et al., 2020). Both in our study and in the cited results walk and trot characteristics were more closely correlated with one another than with canter characteristics.

Frequency and regularity evaluated in our study are strongly correlated for both gaits – walk and trot, which is not the case in canter. Such results may be connected with the symmetrical character of the two former gaits (Clayton, 2016). It is also underlined that the elevation of trot is characteristic for dressage horses (KWPN). In our study jumping horses had the elevations markedly correlated. The possible effect of the training level should not be significant in this case, because the data obtained for breeding using the accelerometer technology underlined that different types of gaits (working – medium gait being performed at a different training level) are correlated with each other (mostly above 0.6), being also higher for trot than for canter (Ricard et al., 2020). Because of the restricted amount of research in that field and other traits measured, the results cannot be compared directly. However, in the study cited above (Ricard et al., 2020) the correlations between stride frequency in walk and characteristics for displacements and activity in trot and canter were in the comparable range of values, from -0.04 up to 0.23, similarly as our results. The correlations between walk symmetry and the described trot and canter characteristics were much lower, ranging from -0.02 to 0.09. It can also be added that height at the withers was connected with acceleration movement results at an unequal, low level (Ricard et al., 2020). The group of our investigated horses was uniform in that respect.

The regularity and symmetry of trot should be correlated on a high level (Lewczuk and Maśko, 2021), while in our study, there was no relationship between these parameters. The explanation came from the definitions of these parameters. As symmetry presented in our current study depended on the left/right limb ratio (as given by the device), and according to the plus/minus ratio value, it shows a specific limb, it facilitates sidedness comparison underlined as important (Ničová and Bartošová, 2022).

6.3. Correlations between jumping and gait parameters

Jump height and length are described as basic jump measurements (Janczarek and Kędzierski, 2011). As such, the connection with the descriptions of the jump parabola should be the most important item. The height of jump was correlated with walk regularity and frequency. A low negative correlation was observed between jump height and canter regularity (-0.23). Such a result indicates that horse-rider pairs often perform a "strong, high" jump at the cost of losing regularity of stride in the approach. This situation may also take place when the horse is afraid of the obstacle, as a result of which the horse slows down and jumps too high. This correlation indicates that a strong, even irregular canter can facilitate a long jump. Corresponding results provided by the accelerometer technique were recorded by Ricard et al. (2020). The longitudinal activity (amount of deceleration and acceleration along the longitudinal horse axis) were correlated genetically at -0.22 with jumping performance. The genetic correlations do not always follow phenotypic ones; however, this relationship is based on the same background. The genetic correlations between gaits and jumping performance were estimated usually as medium and low (Ducro et al., 2007; Hellsten et al., 2006); however, higher values were always noted for canter than for walk or trot (0.28-0.43 vs. 0.06-0.14). Genetic correlations were also stronger than phenotypic ones (Ducro et al., 2007). Most scientific papers cover the subject of the genetic relationship between traits (evaluated in a linear, descriptive manner or subjective judging). That provides information on the genetic level of trait relationships, but is not as useful in the training evaluation as phenotypic correlations.

In our study jump reserve was weakly correlated with walk regularity (0.21). Walk regularity and frequency were also connected with jump length (0.2-0.3). These positive correlations between jumping reserve and length and gait regularity might indicate that jumping is connected with the health status, although it is not on a strong level. High horse gait regularity and symmetry indicated good health condition (Barrey et al., 1994). Probably that is why regularity of gaits, mainly walk regularity, is connected with many jumping traits (take-off acceleration - 0.36; jump velocity – 0.22; energy at landing – 0.35). That may also be connected with the horse temperament, as some papers underline the connections between jumping and temperament (Ruhlmann et al.2009). Temperament seems expressable also in horse walk patterns.

According to literature data, jump success is determined during take–off (Powers, 2002). Take-off frequency was correlated with frequency of gallop (0.36) and walk (0.21), as well as canter regularity (0.28). The quality of the approach consists in such elements as regularity of strides – their regular rhythm also according to the practical guidelines (FEI- https://www.fei.org/stories/lifestyle/teach-me/showjumping-exercises-improve-rhythm). Our observation indicates that horses that approach the obstacle hurrying excessively do not make extensive jumps, as frequency of take-off is not correlated with jump length. Opposite data, although with some margins of standard error, were found in the linear traits describing the horse's jumping technique, as the stride of canter is less correlated at the phenotypic level with jump quality compared with impulsion (Ducro et al., 2007).

The spatial shift during the jump airborne phase correlated with trot frequency (0.22). This result may be related to the training progress. The more experienced a horse is (as indicated by the lower frequency of strides in the trot), the lesser the problem with the symmetry of jump, which may be related with accepting the rider's "leg-aid" and reacting to his body position. Negative, moderately strong correlations (-0.40) were found between other trot characteristics - elevation at trot and take-off frequency. This means that horses that trot too well have difficulty approaching the obstacle properly.

Negative correlations, lack of correlations or low correlations were found between gaits and jumping characteristics at the phenotypic level for the linear scoring system (Medeiros et al., 2020). Most of them were statistically non-significant (26 results out of 30 calculated), walk was connected with jumping at a low level of 0.1, while trot was negatively correlated at -0.13 - -0.17. Genetic correlations were higher and positive for the trot estimations.

Out of 100 calculated correlations in our study, 21 were statistically significant. Obtained results (correlations at approx. 0.3) support the hypothesis that some gait characteristics are connected with jump quality. However, such correlations were low to moderate, especially for canter, which is treated in horse selection as a jump determinant. The relationships between gaits and jumping should be investigated further, as the amount of information on the environmental level is extremely low, especially when we take into consideration that training progress may change the discussed relationships. The regularity and symmetry increases in early training and then decreases after the age of six years (Barrey and Biau, 2002), which can influence results. Regular exercise testing implementation and monitoring of training sessions may have an important added value in the assessment of performance. That should be important also from the genetic point of view, as some relationships between traits seem highly varied and ambiguous (Rustin, 2017; Ricard et al., 2020), while the novel monitoring system based on sensors is accurate (Fries et al., 2017) and applicable (Gmel et al., 2020). Furthermore, differences between the line patterns used for dressage and show jumping horses are limited to a few specific characteristics (Duensing et al., 2014), thus different methods should be investigated in more detail.

6.4. Limitations

The limitation of the study is connected with the low number of horses. It is difficult to find many high class riders and different aged horses trained under comparable conditions. Further research should solve this problem. The other limitation is connected with the unknown error of the Seaver measurements. The device being commercially produced is expected to generate the same error with every use, so the data received for the same equipment will be fully comparable. All the groups and horses were measured using the same device and the possible bias is the same for all the horses. Discussed limitations influence the power of our results, which should be treated as preliminary. The presented study is the first step to further analysis of a higher amount of horse data. More data or an additional group of less specialised horses can change the meaning of the current results. Future studies and research comparisons would benefit from scientific validation of the Seaver system. However, a highly equipped horse biomechanical laboratory is required for such a process.

6.5. Development and practical aspect

Investigations in this direction should be carried out, as it was stated at the genomic level that walk characteristics (evaluated objectively using accelerometers) are connected with the functional longevity of horses (Dugue et al., 2021). In equestrian sports, measured new parameters can also have a significant impact on the monitoring activity time budgets (Maisonpierre et al., 2019). Objectivization of the biomechanics of jump (both during competition and training) is aimed at a precise selection of loads and maintaining a high health status of horses in training (Fercher, 2017).

Obtained results indicate that highly correlated jumping traits describe closely related movement processes. It seems that measurements of the limited number of jump characteristics facilitate the prediction of other jumping characteristics. Less correlated gait movement characteristics indicate that horse gaits can have different qualities in different gaits. This underlines the need for observation of all gaits by selecting future horse usage. Walk regularity and canter frequency are movement parameters informative for the jumping skills. However, the high of these relationships does not allow for unambiguous prediction.

7. Conclusion

Jumping characteristics are more strongly correlated with each other than gaits parameters, so in the horse selection for the discipline each gait should be evaluated and taken into account. In contrast to common opinions, canter parameters cannot determine jump characteristics in sport jumping horses. Canter frequency is the only parameter correlated with the frequency of the approach strides at the low-medium level. Walk regularity is correlated with some jumping parameters above 0.3, probably because of the temperament or health issues. On the basis of this preliminary research it seems difficult to predict horse jumping skills on the basis of movement characteristics. Contrary to the current opinion that take-off determines other jump characteristics – the frequency of approach strides cannot determine any of the jumping parameters, as well as take-off angle (some correlations are even approx. 0.5). The symmetry of take-off can regulate airborne spatial shifting. The relationship between gait frequency and regularity is higher in symmetrical walk and trot than in asymmetrical canter. Trot symmetry being extremely important in lameness diagnosis seems negatively correlated with frequency and positively with limb elevation, which could be taken into account by the lameness evaluation. Further research on larger amount of the data should be provided for a more detailed analysis of different effects influencing horse performance. Underlined movement-jumping traits correlations were significant from the statistical point and observed as mostly low positive and negative values. Currently, calculated correlations between movement and jumping traits do not allow for predicting performance, but the relationships obtained in statistical analysis seem informative.

Author Contribution

Idea - BK, DL, review of literature - BK, data collection - BK, data analysis - BK, DL, writing original draft – BK, DL; critical review of the manuscript – DL

Declaration of Competing Interest

None.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.livsci.2022.105112.

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