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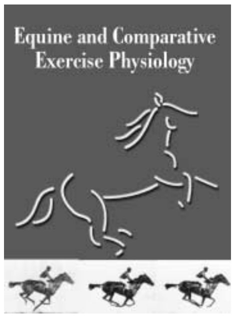

Effect of age on locomotion of Standardbred trotters in training

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Abstract

In Standardbreds, the main aim of early training (begun during the growth period) is the mechanization of athletes leading to a particular gait called the 'flying trot'. The present cross-sectional study was undertaken to investigate the biomechanical and physiological factors involved in this gait change, and aimed to analyse the effect of age on gait and energetic variables in a population of Standardbred horses under training. One hundred and forty-three horses aged from two to seven years were tested on a track at three speeds (8.5, 10 and 11.6 $m\,s^{-1}$) with a gait-analysis system. Gait variables (temporal and linear variables, symmetry, regularity, two-beat rhythm, dorso-ventral, longitudinal and lateral activities) were compared between four age groups (two-, three-, four-, and five-year-olds and above). After a standardized exercise test, two energetic variables (V_4 and V_{200}) were also compared between these groups. Most variables were influenced by age/training status. The results indicated that, from young to mature racehorses, stride length and duration increase; and gait becomes more symmetric and more regular. We also observed a decrease in dorso-ventral, longitudinal and lateral activities, i.e. a decrease of thoracic displacements. These differences could be elucidated at slow speed and were still obvious at high speed. V_4 and V_{200} also increased significantly with age/training status. All of these results indicate an improvement in co-ordination and a decrease in metabolic cost with increasing age/training status. Thus gait acquisition could be related to an improvement in trotting efficiency.

Keywords: gait; trot; biomechanics; co-ordination; racing

Introduction

Early identification of gait characteristics related to performance is the goal of any horseman in any equestrian activity. The development of equine gait-analysis systems has allowed the quantification of locomotor variables, but many factors of influence such as age or training have to be studied before establishing any correlations between these variables and performance. Concerning gait development in horses, some longitudinal studies have reported on the locomotion of the same horses at different ages[1–3]. All of them described the early modification of gait, i.e. from four to 26 months of age; these changes were mainly associated with growth of the horses. The influence of training on locomotor pattern has also been investigated. Drevemo *et al.*[4] reported the locomotor changes observed in four Standardbred trotters between four and seven years of age, resulting from the effect of training. Other studies have reported the effect of training by comparing the locomotion of young horses involved in a training programme with that of a control group[1,5]. Munoz *et al.*[6] reported changes associated with a 28-week training programme in 18 adult Andalusian horses. In addition, a cross-sectional experiment has been carried out to compare the kinematic variables of young and older Andalusian horses[7].

In Standardbreds, which begin training at two years old during the growth phase, it was assumed that trot co-ordination and the energetic cost of the trot change quickly with the maturation of motility and metabolism. Age-related changes in gait and physiological variables should be observed at the early stages of training. In addition, trotting at high speed (the so-called ‘flying trot’) requires good mechanization in order to reduce the energetic cost of that unnatural gait. All of these early functional changes should be determined to analyse the results of exercise tests in training assessment. It appeared interesting to investigate the biomechanical and physiological factors involved in these phenomena. Therefore, the aim of the present cross-sectional study was to analyse the effect of age on gait and energetic variables in a population of Standardbred horses under training.

Material and methods

Horses

A total of 143 horses, aged from two to seven years, were included in this cross-sectional study. They were all French Trotters, in full training, and clinically sound. They were divided into four groups in accordance with their age: two-year-olds ($n = 39$), three-year-olds ($n = 36$), four-year-olds ($n = 33$) and five-year-olds and older ($n = 35$). All of the horses were measured at the withers.

All horses were exercised employing a traditional training schedule: two high-intensity training sessions per week completed by two or three low-intensity training sessions. High-intensity workouts were usually composed of two bouts of 2500 or 3000 m at medium speed (i.e. $\sim 9\,\mathrm{m\,s^{-1}}$ for two-year-olds to $11\,\mathrm{m\,s^{-1}}$ for old horses), ending with 500 m at maximal speed. Low-intensity workouts usually consisted of 30 to 45 min at an average speed of $7.5-8\,\mathrm{m\,s^{-1}}$.

Two-year-olds were not involved in competition, in contrast with three-year-old and older horses.

Exercise test

The horses performed an exercise test at increasing speed. All tests were realized on three similar racetracks. The absence of differences in physiological and biomechanical variables induced by a track effect has been ascertained[8].

For all horses, the locomotor test was performed after a 10 min warm-up and consisted of a straight line of 400 m at three increasing velocities: 8.5, 10 and $11.6\,\mathrm{m\,s^{-1}}$. An experienced driver controlled the velocity with a tachometer (Speed Puls Equus™; Baumann et Haldi, Fleurier, Switzerland). Following the locomotor test, the physiological exercise test consisted of three steps of 3 min each. The speed of the horse was measured with a tachometer (composed of a magnet and an electromagnetic wave detector) fixed on a wheel of the sulky and connected to a display screen, to maintain the speed as constant as possible during each step. The speed was maintained constant during the steps and incremented from one step to another. The increment between the steps was in accordance with the age and training level of the subjects. For two-year-old horses, the velocities of each step were 8, 9 and $10\,\mathrm{m\,s^{-1}}$; for three-year-olds, the velocities were 8.5, 9.3 and $10.5\,\mathrm{m\,s^{-1}}$; and finally for the four-year-old and older horses, the velocities were 8.5, 10 and $11\,\mathrm{m\,s^{-1}}$.

The third step provided a blood lactate concentration higher than $4\,\mathrm{mmol\,l^{-1}}$ in accordance with the recommendation of Persson *et al.*[9].

Gait-analysis system

A three-dimensional accelerometer device (Equimetrix™; Centaure Metrix, Fontainebleau, France) was used for measuring the gait variables. It comprised an accelerometric transducer, connected to a small data logger. The transducer consisted of three orthogonal accelerometers measuring accelerations at the sternum, along the dorso-ventral, longitudinal and lateral axes of the horse. The accelerometers were moulded together to form a small block (4 cm × 2.2 cm × 1.7 cm), which was inserted into a small case on a specific girth harness. Thus, the transducer was located over the sternum of the horse, which provided good stability against the body of the horse, at about 60 cm from the centre of gravity of the animal at rest. The range of acceleration was $\pm 10\,\boldsymbol{g}$. The data logger was inserted into a leather pocket fixed on the left shaft of the sulky. This recorder collected data continuously for up to 38 min, at a sampling rate of 100 Hz. The data were transferred to a laptop computer at the end of the test.

Data analysis

The instantaneous speed and track of the horses were recorded, as a function of time, by a global positioning system (GPS) (Garmin 12™; Garmin Corp., Olathe, KS) placed on the left shaft of the sulky. An in-house programme permitted synchronization of the GPS and acceleration signals. In addition, we could identify those segments of the accelerometer signals corresponding to the horse trotting in a straight line on the track, and knew the exact speed of the horse along this straight line. Samples of 20.48 s, at constant speed, in a straight line along the racing track were analysed. The analysis was realized using signal analysis procedures, developed under a scientific software environment (Matlab 5™; The MathWorks Inc., Natick, MA), to extrapolate both dynamic and temporal stride variables.

Gait variables measured

Stride is defined as a full cycle of limb motion and, at a constant speed, the trot can be considered as a sum of stationary periodic motions.

- Velocity ($\mathrm{m\,min^{-1}}$): measured by two independent systems, the electromagnetic tachometer (Speed

Puls Equus™) and the GPS system (Garmin 12™). Data were compared by a regression analysis.

- Stride frequency (strides s^{-1}): the number of strides per second and also equal to the inverse of stride duration. It was measured by finding the frequency of the main peak of the power spectrum, calculated by a fast Fourier transform (FFT) of the dorso-ventral acceleration signal.
- Stride length (m): the mean distance between two successive footprints of the same front hoof and deduced from the relationship $SL = V/SF$, where SL is stride length, V is velocity and SF is stride frequency.

Stride temporal variables: these variables were calculated by plotting specific points on the dorso-ventral acceleration curve[10]. They were all expressed as a percentage of the stride duration.

- Right stance duration: time between the right diagonal hoof landing and the same diagonal toe-off.
- Right braking duration: time between the right forelimb hoof landing and the right mid-stance position.
- Vertical displacement (cm): dorso-ventral displacement of the sternum was estimated by double integration of the dorso-ventral acceleration signal.
- Stride regularity (/200): a sum of the coefficients of correlation corresponding to the peaks of the autocorrelation function of the dorso-ventral acceleration, measured at a time equal to the half-stride duration and the stride duration. It measures the acceleration pattern similarity of successive strides.
- Stride symmetry (%): a coefficient of correlation, corresponding to the peak of the autocorrelation function of the dorso-ventral acceleration measured at a time equal to the half-stride duration. It measures the acceleration pattern similarity of the right and left diagonals.
- Percentage of two-beat rhythm (%): trot being a two-beat gait, this percentage is calculated to determine how the ideal rhythm is reached. It is the module of energy of $2 \times SF$ divided by the total amount of power spectrum.
- Vertical activity ($g^2 Hz^{-1}$): the integral (cumulative sum of the energy modules between 0 and 25 Hz) of the power spectrum obtained by FFT from the dorso-ventral acceleration signal. This variable measures the activity of suspension and loading of the limbs.
- Longitudinal activity ($g^2 Hz^{-1}$): the integral of the power spectrum obtained by FFT from the longitudinal acceleration signal. This variable measures the amount of deceleration and acceleration along the longitudinal axis.
- Lateral activity ($g^2 Hz^{-1}$): the integral of the power spectrum obtained by FFT from the lateral acceleration signal. This variable measures the amount of deceleration and acceleration along the lateral axis.

Physiological measurements

The procedure for determination of physiological variables was similar to those previously described by Couroucé *et al.*[11]. The reproducibility of this standardized exercise test under field conditions was described by Dubreucq *et al.*[12]. All horses were equipped with a device recording both heart rate and velocity during the test (Speed Puls Equus™). After downloading the heart-rate and velocity data, the average values during the three steps were determined. Because of the linear relationship between heart rate and velocity, linear regression was used to calculate the speed at a heart rate of 200 beats min^{-1} (V_{200}).

Blood samples were drawn, from the jugular vein, into tubes containing anticoagulant (fluoride–oxalate) both before the test and at the end of the three steps of 3 min. Four blood samples of 200 μl were deproteinized with 2 ml of 0.6 N perchloric acid within an hour following the end of the test. The blood lactate concentration was determined by the enzymatic method of Boehringer.

After each standardized test, the relationship between blood lactate (La) and V was analysed using the exponential model described by Valette *et al.*[13]:

$$La = \exp(AV + B) + C,$$

where A is the coefficient of curvilinearity, B and C are constants. La is expressed in $mmol\,l^{-1}$ and V in $m\,min^{-1}$. V_4 corresponds to the average velocity that resulted in a blood lactate concentration of 4 $mmol\,l^{-1}$.

Statistical analysis

A repeated-measures analysis of variance (ANOVA) with the effect of speed and age was conducted for locomotor variables using statistical software (NCSS 1997™; NCSS, Kaysville, UT). Duncan's *post hoc* test was applied if a significant effect was found. A one-factor ANOVA was used to test the influence of age on the physiological variables V_4 and V_{200}. A correlation matrix was also calculated to study the relationships between age, energetic and gait variables.

A level of significance of $P < 0.05$ was used throughout this study for all tests.

Results

Morphometric changes

Mean (standard deviation) height at the withers was (cm): 157.3 (4.9) for two-year-olds, 160.2 (4) for three-year-olds, 162.5 (3.3) for four-year-olds and 163.6 (4.4) for five-year-old and older horses. These differences were all significant ($P < 0.05$) except between the two older groups (four- and five-year-olds and older).

Speed- and age/training-related changes in gait variables

As shown in Table 1, most variables varied significantly with speed: stride frequency, stride length, regularity, percentage of two-beat rhythm, vertical, longitudinal and lateral activities, and stance duration. All except stance duration were also age-dependent. Only two variables appeared not to be dependent on speed and only age-dependent: vertical displacement and right braking duration ($P > 0.05$). Finally, for symmetry, regularity and two-beat rhythm, significant interactions between the effects of speed and age indicated that both are interdependent.

Age/training-related changes in linear and temporal variables

As shown in Table 2, stride frequency (Fig. 1), stride length, right stance duration and right braking duration were not significantly different in the four age groups at the speed of $8.5\,m\,s^{-1}$. At the velocity of $10\,m\,s^{-1}$ (Table 3), stride frequency, stride length and right stance duration were still similar in the four age groups. However, right braking duration was significantly higher in three-year-olds compared with two- and five-year-olds ($P < 0.05$). Finally, as shown in Table 4, at high speed only right stance duration appeared similar among age groups, all other variables being age-dependent. Stride frequency, stride length and right braking duration were significantly different between the three-year-old and five-year-old horses, the young horses showing a higher stride frequency, a shorter stride and a longer right braking duration ($P < 0.05$).

Table 5 shows Spearman's correlations between age and the linear and temporal variables. Considering all data, no significant correlation was observed; however, considering only high-speed data, negative correlations were found between age and stride frequency ($r = -0.21$, $P < 0.05$) and between age and right braking duration ($r = -0.22$, $P < 0.05$).

Age/training-related changes in other gait variables

Symmetry

Symmetry (Fig. 2) was found to be significantly different between age groups at the three steps. At velocities of 8.5 and $10\,m\,s^{-1}$, symmetry was significantly lower

Table 1 Results of the analysis of variance

	Effect of speed	Effect of age	Interaction
Velocity ($m\,s^{-1}$)	<0.001	NS	NS
Stride frequency ($strides\,s^{-1}$)	<0.001	0.01	NS
Stride length (m)	<0.001	0.001	NS
Symmetry (%)	<0.001	0.086	0.007
Regularity (/200)	<0.001	<0.001	<0.001
Two-beat rhythm (%)	<0.001	<0.001	0.002
Vertical displacement (cm)	NS	<0.001	NS
Vertical activity ($\boldsymbol{g}^2\,Hz^{-1}$)	<0.001	<0.001	NS
Longitudinal activity ($\boldsymbol{g}^2\,Hz^{-1}$)	<0.001	<0.001	NS
Lateral activity ($\boldsymbol{g}^2\,Hz^{-1}$)	<0.001	<0.001	NS
Right stance duration (% stride)	<0.001	NS	NS
Right braking duration (% stride)	NS	0.003	NS

NS – not significant ($P > 0.05$).

Table 2 Mean (standard deviation) value of locomotor variables at a speed of $8.5\,m\,s^{-1}$

	Two-year-olds ($n = 39$)	Three-year-olds ($n = 36$)	Four-year-olds ($n = 33$)	Five-year-olds and older ($n = 35$)	P-value
Velocity ($m\,s^{-1}$)	8.48 (0.13)	8.45 (0.12)	8.49 (0.12)	8.5 (0.11)	NS
Stride frequency ($strides\,s^{-1}$)	1.83 (0.07)	1.84 (0.08)	1.87 (0.06)	1.84 (0.1)	NS
Stride length (m)	4.63 (0.22)	4.6 (0.22)	4.53 (0.14)	4.61 (0.25)	NS
Symmetry (%)	93 (3)[a]	94 (4)[b]	96 (2)[b]	96 (2)[b]	0.0008
Regularity (/200)	171 (7)[a]	172 (8)[a]	180 (5)[b]	180 (6)[b]	0.000001
Two-beat rhythm (%)	73 (6)[a]	73 (6)[a]	79 (4.5)[b]	78 (5.6)[b]	0.00005
Vertical displacement (cm)	7.4 (0.98)[a]	6.96 (0.81)[b]	6.63 (0.72)[b]	6.79 (0.81)[b]	0.003
Vertical activity ($\boldsymbol{g}^2\,Hz^{-1}$)	89 (18)[a]	80 (13)[b]	77 (11)[b]	76 (10)[b]	0.001
Longitudinal activity ($\boldsymbol{g}^2\,Hz^{-1}$)	80 (34)[a]	61 (27)[a,b]	52 (21)[b]	50 (18)[b]	0.00006
Lateral activity ($\boldsymbol{g}^2\,Hz^{-1}$)	45 (28)	45 (20)	50 (20)	36 (12)	NS
Right stance duration (% stride)	27 (2.9)	26.9 (2.7)	27.9 (2.8)	27.5 (2.8)	NS
Right braking duration (% stride)	10.3 (2.4)	11 (2.3)	11.5 (1.5)	10.6 (1.6)	NS

NS – not significant ($P > 0.05$).
Different superscript letters indicate that values are significantly different from one another.

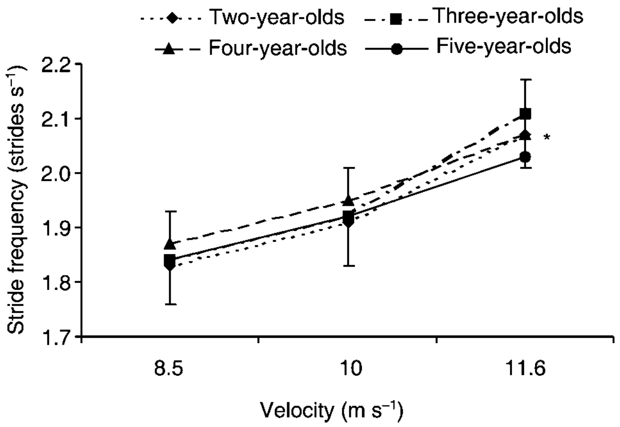

Fig. 1 Velocity-related changes in stride frequency in the four age groups. *Three-year-olds significantly different from five-year-olds

in two- and three-year-olds compared with four- and five-year-old horses ($P < 0.05$). At high speed, lower symmetry was observed in two-year-olds compared with three-year-old and older horses ($P < 0.05$).

The Spearman matrix (Table 5) indicated a strong and positive correlation between age and symmetry ($r = 0.36$, $P < 0.05$ for all data; $r = 0.50$, $P < 0.05$ at high speed).

Regularity and percentage of two-beat rhythm

At slow speed, regularity (Fig. 3) and percentage of two-beat rhythm were significantly lower in the two- and three-year-old groups compared with four- and five-year-old horses ($P < 0.05$). At $10\,\mathrm{m\,s^{-1}}$, regularity was significantly lower in two- and three-year-olds compared with four- and five-year-olds. For percentage of two-beat rhythm, a significant difference was observed between the two- and three-year-old horses compared with four-year-olds ($P < 0.05$). Finally, at high speed, regularity was significantly different in all age groups ($P < 0.05$), with older horses showing a higher score of regularity. Percentage of two-beat rhythm was lower in the two-year-old group compared with the three-year-old group. The three-year-olds had also a significantly lower percentage of two-beat rhythm than horses aged four years and above.

The correlations (Table 5) found between age and regularity were significant ($r = 0.44$, $P < 0.05$ for all data; $r = 0.70$, $P < 0.05$ at high speed). For percentage

Table 3 Mean (standard deviation) value of locomotor variables at a speed of $10\,\mathrm{m\,s^{-1}}$

	Two-year-olds ($n = 39$)	Three-year-olds ($n = 36$)	Four-year-olds ($n = 33$)	Five-year-olds and older ($n = 35$)	*P*-value
Velocity ($\mathrm{m\,s^{-1}}$)	9.94 (0.27)	9.94 (0.26)	9.9 (0.24)	9.95 (0.22)	NS
Stride frequency ($\mathrm{strides\,s^{-1}}$)	1.91 (0.08)	1.92 (0.08)	1.95 (0.06)	1.92 (0.09)	NS
Stride length (m)	5.2 (0.22)	5.17 (0.21)	5.07 (0.2)	5.19 (0.29)	NS
Symmetry (%)	93 (4)[a]	93 (5)[a]	95 (3)[b]	96 (3)[b]	0.0002
Regularity (/200)	163 (14)[a]	163 (11)[a]	175 (8)[b]	177 (6)[b]	0.000001
Two-beat rhythm (%)	69 (8)[a]	69 (7)[a]	75 (6)[b]	73 (9)[a,b]	0.001
Vertical displacement (cm)	7.49 (0.92)[a]	6.92 (0.75)[b]	6.75 (0.54)[b]	6.73 (0.6)[b]	0.00007
Vertical activity ($\boldsymbol{g}^2\,\mathrm{Hz^{-1}}$)	106 (18)[a]	97 (18)[b]	94 (10)[b]	93 (12)[b]	0.0006
Longitudinal activity ($\boldsymbol{g}^2\,\mathrm{Hz^{-1}}$)	106 (42)[a]	85 (37)[a,b]	71 (28)[b]	68 (30)[b]	0.0008
Lateral activity ($\boldsymbol{g}^2\,\mathrm{Hz^{-1}}$)	66 (31)[a]	73 (25)[a]	71 (29)[a]	54 (15)[b]	0.004
Right stance duration (% stride)	26.4 (2.7)	26.1 (3.4)	26.8 (2.4)	25.9 (2.8)	NS
Right braking duration (% stride)	10.5 (2.6)[a]	11.8 (2.3)[b]	11.2 (2.2)[a,b]	10.2 (1.8)[a]	0.009

NS – not significant ($P > 0.05$).
Different superscript letters indicate that values are significantly different from one another.

Table 4 Mean and (standard deviation) value of locomotor variables at a speed of $11.6\,\mathrm{m\,s^{-1}}$

	Two-year-olds ($n = 39$)	Three-year-olds ($n = 36$)	Four-year-olds ($n = 33$)	Five-year-olds and older ($n = 35$)	*P*-value
Velocity ($\mathrm{m\,s^{-1}}$)	11.66 (0.31)	11.64 (0.27)	11.56 (0.24)	11.64 (0.19)	NS
Stride frequency ($\mathrm{strides\,s^{-1}}$)	2.07 (0.06)[a,b]	2.11 (0.08)[a]	2.07 (0.1)[a,b]	2.03 (0.07)[b]	0.01
Stride length (m)	5.63 (0.2)[a,b]	5.51 (0.17)[a]	5.57 (0.26)[a]	5.72 (0.23)[b]	0.007
Symmetry (%)	90 (6)[a]	95 (3)[b]	95 (2)[b]	97 (2)[b]	0.0001
Regularity (/200)	138 (16)[a]	155 (14)[b]	163 (12)[c]	170 (6)[d]	0.000001
Two-beat rhythm (%)	54 (10)[a]	61 (9)[b]	69 (7)[c]	69 (9)[c]	0.000001
Vertical displacement (cm)	7.47 (0.86)[a]	6.53 (0.62)[b]	6.82 (0.88)[b]	6.6 (0.64)[b]	0.0002
Vertical activity ($\boldsymbol{g}^2\,\mathrm{Hz^{-1}}$)	132 (15)[a]	114 (18)[b]	114 (16)[b]	110 (13)[b]	0.0001
Longitudinal activity ($\boldsymbol{g}^2\,\mathrm{Hz^{-1}}$)	160 (45)[a]	124 (35)[b]	93 (35)[c]	87 (33)[c]	0.000001
Lateral activity ($\boldsymbol{g}^2\,\mathrm{Hz^{-1}}$)	83 (24)[a]	99 (29)[b]	85 (23)[a]	75 (15)[a]	0.007
Right stance duration (% stride)	25.4 (2.7)	26.3 (2.2)	25.9 (2.6)	25.6 (2.6)	NS
Right braking duration (% stride)	11.5 (2.8)[a,b]	12.1 (2)[a]	11 (2.3)[a,b]	10.3 (2.1)[b]	0.05

NS – not significant ($P > 0.05$).
Different superscript letters indicate that values are significantly different from one another.

Table 5 Correlation matrix of variables: all data and at high speed only

	All data ($n = 429$)			High speed only ($n = 143$)		
	Age	V_4	V_{200}	Age	V_4	V_{200}
Velocity ($m\,s^{-1}$)	NS	NS	NS	NS	NS	NS
Stride frequency ($strides\,s^{-1}$)	NS	NS	NS	−0.21	NS	NS
Stride length (m)	NS	NS	NS	0.18	NS	NS
Symmetry (%)	0.36	0.16	0.18	0.50	0.31	0.31
Regularity (/200)	0.44	0.23	0.27	0.70	0.46	0.49
Two-beat rhythm (%)	0.28	0.21	0.22	0.53	0.40	0.41
Vertical displacement (cm)	-0.30	-0.17	-0.17	-0.27	-0.19	-0.18
Vertical activity ($\boldsymbol{g}^2\,Hz^{-1}$)	-0.18	NS	NS	-0.36	-0.22	-0.20
Longitudinal activity ($\boldsymbol{g}^2\,Hz^{-1}$)	-0.31	NS	NS	-0.50	NS	NS
Lateral activity ($\boldsymbol{g}^2\,Hz^{-1}$)	NS	NS	NS	-0.18	-0.23	-0.25
Right stance duration (% stride)	NS	NS	NS	NS	NS	NS
Right braking duration (% stride)	NS	NS	NS	-0.22	NS	NS
V_4 ($m\,min^{-1}$)	0.45	–	0.96	0.45	–	0.96
V_{200} ($m\,min^{-1}$)	0.47	0.96	–	0.47	0.96	–

NS – not significant ($P > 0.05$).

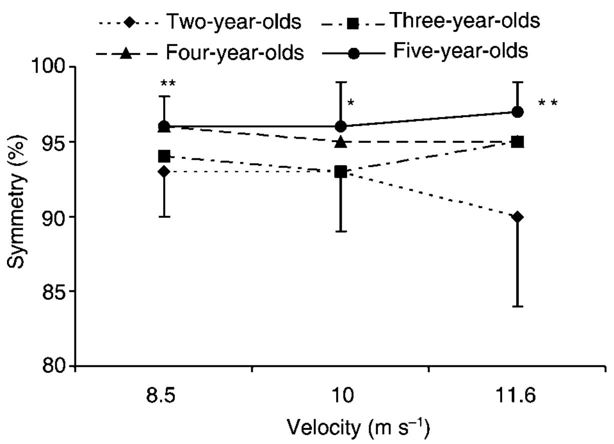

Fig. 2 Velocity-related changes in symmetry in the four age groups. *Two- and three-year-olds significantly different from four- and five-year-olds; **two-year-olds significantly different from three-, four- and five-year-olds

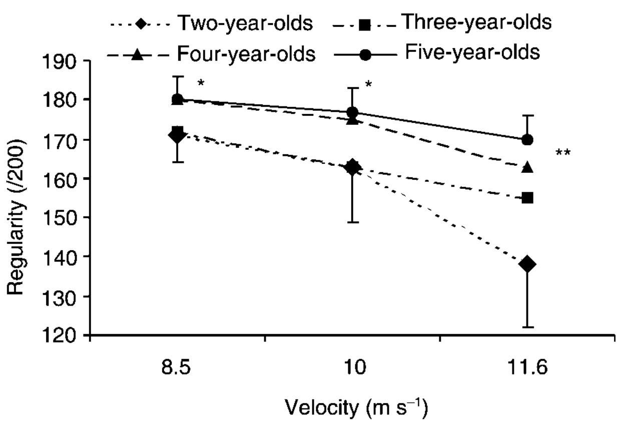

Fig. 3 Velocity-related changes in regularity in the four age groups. *Two- and three-year-olds significantly different from four- and five-year-olds; **two-, three-, four- and five-year-olds all significantly different from one another

of two-beat rhythm, the correlations observed were also significant ($r = 0.28$, $P < 0.05$ for all data; $r = 0.53$, $P < 0.05$ at high speed).

Activities and vertical displacement

At the velocity of $8.5\,m\,s^{-1}$, vertical displacement (Fig. 4), vertical activity (Fig. 5) and longitudinal activity (Fig. 6) were significantly higher in the two-year-old group compared with the three-, four- and five-year-old groups ($P < 0.05$). Lateral activity (Fig. 7) was similar in the four age groups. At $10\,m\,s^{-1}$, vertical displacement, vertical activity and longitudinal activity were still significantly higher in the two-year-olds compared with the three-, four- and five-year-olds ($P < 0.05$). However, lateral activity was significantly lower in five-year-olds compared with two-, three- and four-year-olds ($P < 0.05$). Finally, at high speed, higher vertical displacement and vertical activity were observed in the two-year-old horses compared with the three-year-old and older horses ($P < 0.05$).

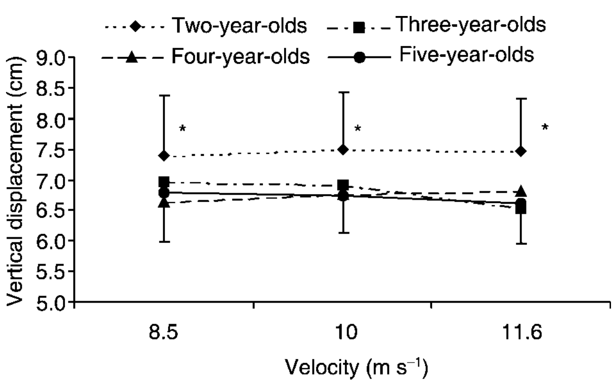

Fig. 4 Velocity-related changes in vertical displacement in the four age groups. *Two-year-olds significantly different from three-, four- and five-year-olds

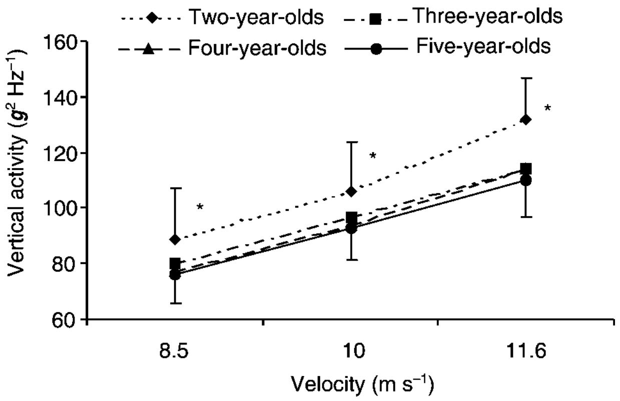

Fig. 5 Velocity-related changes in vertical activity in the four age groups. *Two-year-olds significantly different from three-, four- and five-year-olds

Longitudinal activity was higher in the two-year-olds compared with the three-year-olds, which in turn were also significantly different from the four-year-old and older horses. For lateral activity, a significant difference was observed between three-year-olds and five-year-olds, the younger horses showing a higher value ($P < 0.05$).

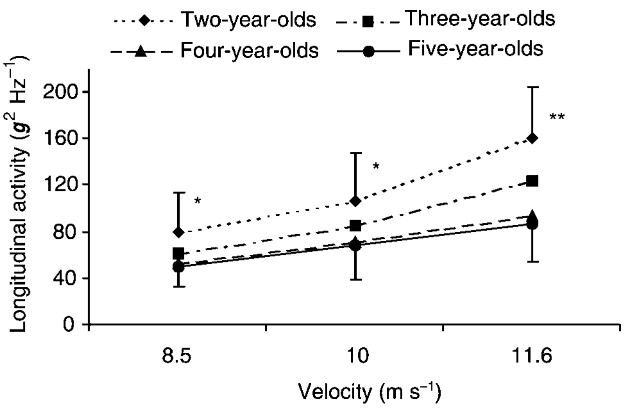

Fig. 6 Velocity-related changes in longitudinal activity in the four age groups. *Two-year-olds significantly different from four- and five-year-olds; **two-year-olds significantly different from three-year-olds, different from four- and five-year-olds

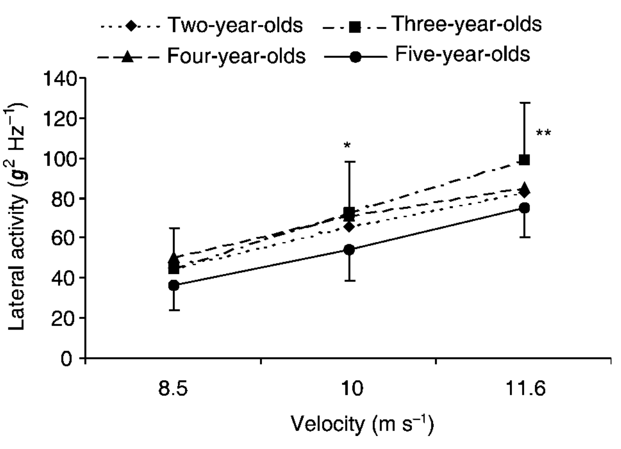

Fig. 7 Velocity-related changes in lateral activity in the four age groups. *Two-, three- and four-year-olds significantly different from five-year-olds; **three-year-olds significantly different from others

Table 5 shows the correlation between age and the different activities. Taking all data into account, no significant correlation was observed between age and lateral activity. However, vertical displacement, vertical and longitudinal activities were all significantly and negatively correlated to age ($r = -0.30$, -0.18 and -0.31, respectively, $P < 0.05$). At high speed, these correlations were more obvious ($r = -0.27$, -0.38 and -0.50, respectively, $P < 0.05$).

Age/training-related changes in physiological variables

Figure 8 shows the mean values of physiological variables observed in the four age groups. Both V_4 and V_{200} values were highly significantly different between age groups ($P < 0.05$):

- V_4 values increased significantly between two- and three-year-olds, and also between three-year-old and four-year-old and older horses;
- V_{200} values were significantly different in all age groups, with younger horses showing a lower V_{200}.

Table 5 indicates a significant and positive correlation between energetic variables and age. For V_4 and V_{200}, the coefficients of correlation were respectively $r = 0.45$ and $r = 0.47$ (all data, $P < 0.05$).

Correlations between gait and physiological variables

No significant correlation was found between physiological variables and linear or temporal variables. Nor could a correlation be observed between physiological variables and longitudinal activity. However, significant correlations were found between V_4 and V_{200} and symmetry, regularity, two-beat rhythm, vertical displacement, and vertical and lateral activities. Significant

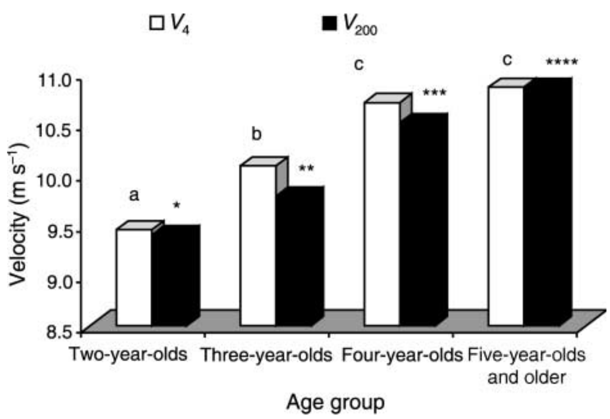

Fig. 8 Means of the physiological variables V_4 and V_{200} in the four age groups. a, b, c significantly different from one another; *, **, ***, **** significantly different from one another

correlations were found at high speed for V_4 and symmetry ($r = 0.31$, $P < 0.05$), V_4 and regularity ($r = 0.46$, $P < 0.05$), V_4 and percentage of two-beat rhythm ($r = 0.40$, $P < 0.05$), V_4 and vertical displacement ($r = -0.19$, $P < 0.05$), V_4 and vertical activity ($r = -0.22$, $P < 0.05$) and V_4 and lateral activity ($r = -0.23$, $P < 0.05$).

Discussion

Modifications of linear and temporal variables

In our study, some significant differences between age groups in the temporal variables were observed at high speed. With increasing age/training, we found a significant decrease in stride frequency (i.e. an increase of stride duration), a significant increase in stride length, no change in stance duration and finally a decrease in braking duration. The first explanation for such results is the phenomenon of growth, expressed by the significant increase in height at the withers between two- and four-year-olds. These findings are in accordance with previous studies investigating the effect of training on locomotor variables. Drevemo *et al.*[4] compared the temporal variables of four Standardbred trotters on the track at the age of four and then three years later. At a velocity of $12\,m\,s^{-1}$, they found a significant increase in stride and swing duration, and no significant change in stride length and stance duration. As in our study, their most remarkable feature was that the increase in stride duration was almost exclusively a result of a longer swing phase. However, Cano *et al.*[7] found different results when comparing the temporal and linear variables of seven four-year-old with those of nine 12-year-old Andalusian horses. At a similar speed of $4\,m\,s^{-1}$, there were no significant differences in stride duration and length, or in stance duration, between the two age groups. Back *et al.*[5] also studied the influence of training on locomotion, comparing the kinematics of 12 Dutch Warmbloods (two-and-a-half years old) trained during 70 days with those of a pastured control group. Their results revealed no significant changes in stride or stance durations in the forelimbs between the two groups; only a decrease of stance duration in the hind limbs in the trained group was found. Finally, Munoz *et al.*[6] compared the linear and temporal variables of 18 Andalusian horses aged three to four years before and after a training period of 28 weeks. At trot ($4\,m\,s^{-1}$), stride duration and length decreased significantly and there was no significant change in stance and braking durations. In growing horses, increases in stride length, stride and stance duration owing to an increase in height at the withers have also been reported[2,3]. Thus, conclusions in regard to the effects of training on gait variables are rarely unanimous. Many reasons could be proposed to explain the variability in response, such as the breeds studied and their own gait particularities (Standardbreds, Andalusians, Dutch Warmbloods), length of the training regimen (from 70 days up to > three years), the type of training (slow or fast gaits, mounted or harnessed) and the methods of evaluation (treadmill or track).

Modifications of dynamic gait variables

Symmetry

This variable quantifies the ability of the horse to produce the same pattern of acceleration with the right and left diagonals. In our study, this variable seemed particularly interesting in two aspects. First, even for sound horses, young ones (two and three years of age) were less symmetrical than old ones at slow and medium speed. Drevemo *et al.*[1] have studied longitudinally the symmetry of gait of two groups of five trotters at eight, 12 and 18 months of age. One group was being trained and the other used as a control. The locomotor test was performed on a treadmill at a velocity of $4\,m\,s^{-1}$. In contrast to our study, their main results were that, at 18 months of age, the trained group showed less symmetry (in diagonal dissociation, diagonal and fore step lengths) than the control group. The authors interpreted the increasing asymmetries with age as manifestations of already existing asymmetries or laterality, which might be influenced by physical activity and training. Second, at high speed in our study, the significant event was the great loss of symmetry in the two-year-old group. In contrast to old horses, the young ones appeared very speed-sensitive with respect to their ability to maintain a symmetric gait. In humans, optimization of symmetry in walking has been described in adults compared with children[14]. Asymmetry is a measure of gait typically used to identify immature locomotor patterns[15,16]. Moreover, according to Raibert[17], symmetry plays a role in simplifying the control of locomotion; a legged system could avoid controlling the detailed variations of each joint, concentrating instead on providing initial conditions on each stride that would lead to steady-state forward travel.

Regularity and two-beat rhythm

These two variables reflect, respectively, the capacity of the horse always to repeat the same stride consecutively and the ability to trot with an ideal two-beat rhythm, without asynchrony. The main characteristic of these variables was that they decreased with speed at any age. The improvement in regularity seemed to be a long process as it continued up to age five and above. These variables could characterize better co-ordination with increasing age and training. Another interesting similarity between our findings and human gait acquisition was the greater variability of variables in younger individuals compared with older ones. Brown and Parker[18] compared cross-sectionally the gait patterns of 29 children aged between five and seven years. Their evaluation of changes in the variability of limb and pelvic movements with age showed that the five-year-old children had significantly more variability in their movement than the older children. The same comment could be made for most of our gait variables. Variability of locomotor variables has also been described as being typical of a deteriorated and less efficient gait[19].

Activities

Activities (vertical, longitudinal and lateral) are a quantification of the amplitude and frequency of movement in three dimensions. All three activities were found to be age-dependent: young horses presented higher activities than old ones. Interestingly, the maturation of locomotor pattern seemed to occur in a chronological order. A period of change in vertical activity appeared to be the first and shortest one in the process of gait development. Vertical activity at three years of age was similar to that measured in the older groups. In the same way, vertical displacement was greater in two-year-olds compared with three-year-old and older horses. The hypothesis of better utilization of potential energy, well-described in walking acquisition of children, can be proposed. Longitudinal activity also decreased significantly between two and four years of age. Studying a population of 24 trotters aged from two to eight years, Barrey *et al.*[20] also found that older horses produced lower peaks of longitudinal activity. Their interpretation of this phenomenon was an improvement in locomotion efficiency. In the present study, achieving optimal longitudinal activity took more time than for vertical activity. Finally, lateral activity was significantly different between four and five years of age, indicating that optimization of lateral movements occurred later than for the two other axes. In humans, Miyamaru *et al.*[21] cross-sectionally investigated the development of running motion in 200 young children (from three to seven years old), focusing on the path of the centre of gravity. Their results revealed that the undulating path of the centre of gravity for young children changed to a flatter one in older children, i.e. the running motion of young children became less bouncy with increasing age.

As previously noted, our gait variables behaved differently with regard to onset (early/late) and length of the maturation process. Some variables – such as symmetry, vertical activity and displacement, regularity and two-beat rhythm – started to change quite early (i.e. between two and three years of age) compared with variables that were modified later (lateral activity). The length of acquisition could also be very different, with variables being modified quickly (in one year) such as symmetry, vertical activity and displacement. On the contrary, some of them showed a very long process of modification (regularity). The chronology of these changes is shown in Fig. 9. A chronology in gait acquisition has also been described in humans. Jeng *et al.*[14] identified three stages of learning in the development of optimization of walking in children. They found an early manifestation of sensitivity to resonant frequency, subsequent development of the ability to modulate walking frequency and finally the establishment of an adult optimization form at age seven.

Economy of locomotion

Use of and interest in triaxial accelerometers to quantify the energy cost of physical activities have already been reported in humans[22,23]. In our study, some variables could reflect a better economy of locomotion with increasing age and training status. The ability to maintain a more symmetric, more regular locomotor pattern, limiting thoracic displacements (i.e. minimal vertical, longitudinal and lateral activities) might be a partial explanation of better gait economy. Interestingly, when listing 17 biomechanical factors related to better economy in human runners, Anderson[24] evoked freely chosen stride length, low vertical oscillations of the body's centre of mass, low peaks of ground reaction force (GRF) and low arm motions. Williams and Cavanagh[25] reported moderate to weak relationships between GRF and running economy. More economical runners exhibited significantly lower first peaks in the vertical component of GRF and tended to have smaller antero-posterior and vertical peak forces. Krahenbuhl and Williams[26] exposed the main characteristics of improvement in running economy and its changes with age during childhood and adolescence. In this review, the authors concluded that children were less economical than adults because of their higher resting metabolic rates, higher oxygen cost of respiration and disadvantageous stride rates and stride lengths (imposed by shorter limbs). In other species (pigs), there is also evidence that immature tendons are less able to store elastic energy than

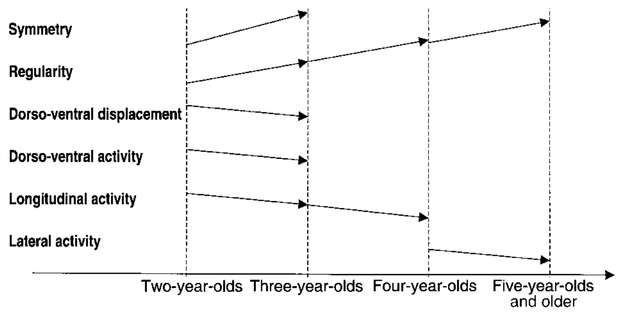

FIG. 9 Chronology of the maturation of gait variables

more mature tendons, and that they become stronger, stiffer and more resilient with growth and ageing[27]. According to Krahenbuhl and Williams[26], running economy improves steadily with age in normally active children and instruction on the techniques of running over a short term (two – three months) is ineffective in bringing about an improvement in running economy. However, over the longer term (years), improvements in running economy may be augmented through participation in running training programmes. Anderson suggested that training-related improvements in economy might be invoked by refinement of mechanical elements such as stride length and frequency, or integration and timing of muscle activity, so that elastic energy is stored and reused more efficiently. Changes in metabolic profiles within muscles may also make a contribution, as it has been shown that higher percentages of slow-twitch fibres are associated with better economy[28]. It has also been suggested that, in humans, economy may be improved through reduced heart rate and ventilation subsequent to training.

In our study, improvement in the economy of locomotion can be revealed by comparing energetic variables between age groups. Velocity that results in a blood lactate concentration of $4\,\mathrm{mmol\,l^{-1}}$ is considered a good indicator of endurance performance capacity in horses[9]. A previous study has described the relationship between V_4 and age in French Trotters[11]. Mean values of V_4 obtained here were very similar those given in this previous report. Moreover, the same difference between age groups was found: V_4 increases largely from two to four years of age and then stabilizes in five-year-old and older horses. Growth in young trotters (between one and three years old) results in an increase in muscle aerobic capacity based on muscle enzyme activities[29]. Whether the effect observed in the present study was due to age and/or training remains unanswered owing to the absence of a control group. These energetic considerations, expressed as better aerobic capacity in older horses, could also be in accordance with a more economical gait due to better mechanization of the athletes. Finally, the significant correlations found between energetic variables and symmetry, regularity, percentage of two-beat rhythm, vertical displacement, and vertical and lateral activities indicate the interdependence between metabolic cost and gait pattern.

Conclusion

In the present study, most locomotor variables studied varied with both speed and age/training status. Concerning age/training status, gait acquisition was observed between young and older horses, as all variables, except stance duration, were found to be significantly different between age groups. This maturation consisted of an increase in stride duration and length, an improvement in symmetry and regularity of the trot, and also a decrease of thoracic displacements in the three axes. Onset (early or late) and duration of the maturation of each gait variable were different. The biomechanical findings in this study indicated an improvement in co-ordination and could also partly explain the better economy of locomotion, which, in many physical activities, distinguishes the experienced athlete from the beginner. In conclusion, age and training status are important factors affecting the variation of gait variables in Standardbreds and should be taken into account in further biomechanical studies.

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