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High-level competition exercise and related fatigue are associated with stride and jumping characteristics in eventing horses

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Abstract

Background: Fatigue and related injuries to the musculoskeletal system are among the most frequent reasons for the withdrawal of high-level eventing horses from the sport. The safety of both horse and rider is very important, and early detection of fatigue is crucial.

Objectives: To investigate elite eventing horses in competitive events focusing on biomechanical, cardiovascular and metabolic variables across the cross-country test and to identify their potential associations with fatigue.

Study design: Prospective observational exploratory field study.

Methods: Observations on 54 cross-country tests of 33 horses at five competitive, high-level events were evaluated using sternal accelerometric analysis of stride parameters between and at the jumps. Blood lactate concentration and heart rate were determined 10 min after finishing. The differences in kinematic parameters between the course start and end were analysed with mixed models for repeated measures. Associations between blood lactate and heart rate recovery with the kinematic variables were quantified with Pearson correlation coefficients.

Results: We observed numerous stride characteristics between the jumps and the jumps changing over time during the courses. Blood lactate concentrations were positively correlated with the mean maximal strike power at the jumps in the last minute of the course ($r = 0.41$; $p < 0.001$), and the latter was negatively correlated with the mean stride height over the jumps ($r = -0.41$; $p = 0.003$).

Main limitations: The sample contained horses of varying breeds, sexes and ages, and different horses participated in different events.

Conclusions: We identified several kinematic changes during a cross-country test depending on event, speed and fatigue.

KEYWORDS
accelerometry, biomechanics, blood lactate level, fatigue, heart rate recovery, horse

1 | INTRODUCTION

Eventing is one of the most demanding equestrian sports, and the cross-country test requires high physical skills from the horse. Physiological, metabolic and biochemical responses in eventing training and competition have been studied previously[1,2] and fatigue and related injuries to the musculoskeletal system are among the most frequent reasons for the withdrawal of high-level eventing horses from the sport.[3–5] Factors associated with adverse outcomes for both horse and rider have been reported.[6–8] Early detection of fatigue and overstrain in the eventing horse is crucial but challenging. Assessment of heart rate recovery and blood lactate concentration in relation to exercise intensity is considered the gold standard to assess equine fitness[9–12] and potentially also predict fatigue.[9,12–15]

However, these parameters are indicators of the cardiovascular and energy balance of the horse. Other criteria like bone strain, an important cause of musculoskeletal injuries, potentially induced by the number of strides and load intensity per stride,[16] are not considered in this context. Novel accelerometric technology allows accurate assessment of the biomechanical factors of the horse in the field. In several studies, mostly in Thoroughbred racehorses, stride characteristics of the galloping horse have been determined. Additional variables at the cross-country fences, like length, height and strike power (the acceleration in the vertical axis) of the jumps, or the lateral and longitudinal balance of a horse between the jumps, might also be useful indicators of fatigue. This study aimed to investigate elite eventing horses in competitive trainings and competitions focusing on cardiovascular, metabolic and biomechanical variables. We aimed with this observational exploratory field study to (a) analyse kinematic changes between and at the jumps across a cross-country course and (b) identify candidate stride characteristics potentially associated with fatigue in horses during and at the end of a cross-country course.

2 | MATERIALS AND METHODS

2.1 | Study design and data collection

The study took place at the Institut équestre national Avenches (IENA) in Avenches, Switzerland, during the 2020 and 2021 seasons. The study was designed as a prospective observational exploratory design integrated in three national 4*-Masterclass competitive eventing trainings with cross-country tests held 3 weeks apart in July and August (twice) in the context of the COVID-linked program of the Swiss Equestrian Federation in 2020 for the Swiss national eventing team and riders, and was then extended by integration in an official 4* short format Concours Complet International competition (CCI4*-S) in June 2021 and the European Eventing Championships (E-CH), with a CCI4* long format, in September 2021 always at the same location. The topography of the IENA site is very flat, and turf going conditions were kept standardised at all times using artificial watering, that is, allowing comparison of results obtained from all five events in this study. According to the rules of the Fédération Equestre Internationale (FEI), cross-country fences had a maximal height of 120 or 140 cm when equipped with a brush. Study participants were recruited on a voluntary basis, consisting of 51% of the total competitors participating in the study. An a priori sample size calculation was not performed.

Following recruitment, on Wednesday (season 2021) or Thursday (season 2020) and before the cross-country test on Saturday, horses were subjected to physical examination by FEI-accredited veterinarians to assess their fitness to compete. Bodyweight measurement was performed with the mobile platform scale PS3000 (Salter Brecknell). On the day of the cross-country test, before leaving the stable, the saddle girth of all horses was equipped with a single sternal sensor for accelerometric assessment, which was then taken off immediately at the finish of the cross-country test when a heart rate monitor was placed for 15 min. Blood was withdrawn for lactate analysis 10 min after finishing.

Local mean ambient temperature (in °C), mean relative humidity (in %), mean sunshine time (in min/h) and mean wind speed (in km/h) at the respective times of the horses competing in the cross-country test were obtained from the Federal Office of Meteorology and Climatology MeteoSwiss.

2.2 | Horses and event conditions

In total, 45 privately owned internationally competing eventing horses from Switzerland, Italy, Ireland, Finland and Denmark (32 geldings, 11 mares and 2 stallions from 8 to 19 years old) participated in the study, each taking part between one to five times in an event, with a total of 77 cross-country test observations. Event conditions of the five cross-country test events and the number of participating horses are described in Table 1.

2.3 | Blood lactate analysis

Blood samples were withdrawn from the left jugular vein and immediately evaluated on-site by direct measurement of blood lactate concentrations using a portable hand-held device (Lactate Pro2, Axon Lab AG), previously validated[17] and tested in horses.[18]

2.4 | Biomechanical measurements

Biomechanical data were collected using the Alogo Move Pro equine Sensor (Alogo Analysis SA), sized 11.5 cm × 5.8 cm × 2.6 cm and weighing 127 g. This recently independently validated[19] system is specifically designed to record kinematic data and trajectories of horses during showjumping and cross-country test sessions using accelerometric and navigation system technology. We fixed the single sensor on the median line on the top of the saddle girth using a leather pouch (see Figure 1).

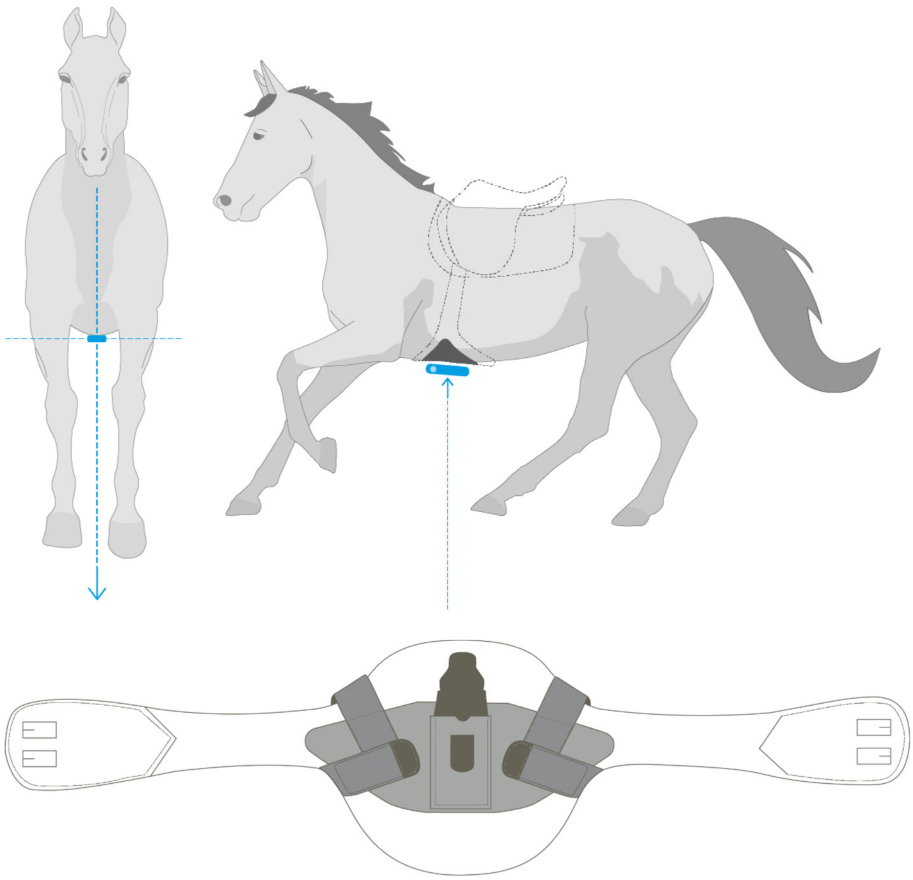
Each cross-country test was registered in the form of a time series with a sampling interval of 10 ms corresponding to a frequency

TABLE 1 Event conditions and participating horses at the five competitive cross-country test events.

Event	Date	Distance (m)	Speed (m/min)	Optimal time (min.s)	Number of obstacles (*N*)	Number of participating horses (*N*)
Masterclass 1	21 Jul 2020	2850	570	5.00	26	12
Masterclass 2	01 Aug 2020	2850	570	5.00	26	10
Masterclass 3	22 Aug 2020	2850	570	5.00	27	17
CCI4*-S	26 Jun 2021	3680	570	6.27	34	21
European Championships CCI4*-L	25 Sep 2021	5770	570	10.07	42	17

Abbreviations: CCI4*-L, official 4* long format Concours Complet International competition; CCI4*-S, official 4* short format Concours Complet International competition; *N*, number.

FIGURE 1 Equipment of the horses with the Alogo Move Pro equine sensor.[19]



rate of 100 Hz. The digital signals from the inertial sensor have a resolution of 16 bits. Output data are produced by fusing the GPS positions and velocities with the inertial data using the Extended Kalman Filter.[19] The sensor records acceleration data (az, axe, ay) on the *z*-axis (vertical direction of movement pointing downwards), the *x*-axis (horizontal direction of movement pointing ahead) and the *y*-axis (lateral direction of movement pointing to the right), the navigation system based rotation angles around the three-dimensional axes (roll, pitch and yaw angles; for definitions see Table 2), the position vectors in the earth-centred, earth-fixed (ECEF) coordinate system (rx, ry, rz), and the velocity vectors (vx, vy, vz). Proprietary algorithms allow differentiation between strides and overjumps after the registration of each individual step. All data recorded by the sensor are then transferred by Bluetooth technology to an internet-based server. The system allows a review of the horse's performance after completing the course by GPS path mapping, including synchronous timing. For our study, each time period of interest in the cross-country test was selected and marked, and the resulting data was exported using Excel 2016 (Microsoft). Data were subdivided into sections designated 'between jumps' and 'jumps' (last stride before fence, stride over the fence and first stride after fence). The obtained parameters are described in Table 2.

2.5 | Analysis of heart rate

Heart rate recordings were performed with the Polar Vantage V2 system at the CCI4*-S and the E-CH, as described previously.[20] The Polar

TABLE 2 Accelerometric variables of sections 'between jumps' and 'jumps', their definitions and units.

Section	Parameter	Definition	Unit
Between jumps	Mean speed	Average horizontal velocity per selected session	m/min
	Maximal speed	Maximal velocity recorded per selected session	m/min
	Mean stride frequency	Average number of strides per min	strides/min
	Mean straightness	Average straightness of the horse per stride compared to its direction of movement (corresponding to the 'yaw' angle of the rotation around the vertical axis)	°[a]
	Mean lateral balance	Average left/right balance of the horse per stride (corresponding to the 'roll' angle of the rotation around the front-to-back axis)	°[a]
	Mean longitudinal balance	Average balance between the shoulders and the hips of the horse per stride (corresponding to the 'pitch angle' of the rotation around the side-to-side axis)	°[b]
	Mean stride length	Average distance per stride	m
	Mean stride height	Average highest elevation over the ground per stride	m
	Mean maximal strike power	Average maximum value of the acceleration on the *z*-axis per stride: $(m/s^2)/9.807$	acceleration *g*
Jumps	Mean stride length over the jumps	Average distance jumped from the take-off to the landing per jump	m
	Mean stride height over the jumps	Average highest elevation from the ground per jump	m
	Mean maximal strike power at jumps	Average maximum value of the acceleration on the *z*-axis per stride: $(m/s^2)/9.807$	acceleration *g*
	Mean speed at jumps	Average horizontal velocity per jump	m/min
	Mean maximal pitch at jumps	Average maximum angle of the jumps' trajectory in relation to the ground	°
	Mean stride length before jumps	Average distance per last stride before the jump	m
	Mean stride height before jumps	Average highest elevation over the ground per last stride before the jump	m
	Mean stride length after jumps	Average highest elevation over the ground per first stride after the jump	m
	Mean stride height after jumps	Average highest elevation over the ground per first stride after the jump	m

[a]Positive values indicate a shifting to the right side, negative to the left side.
[b]Positive values indicate a shifting to the hips, negative to the shoulders.

belt was fixed around the chest of the horses with the transmitter placed on the left thorax of the horses. The Polar system records cardiac beat-to-beat (RR) intervals. From the RR intervals, heart rate was calculated and analysed with Kubios HRV Software (Biomedical Signal Analysis Group, Department of Applied Physics, University of Kuopio, Finland).[20] Mean heart rates after 5, 10 and 15 min were assessed by averaging over 30-s intervals, starting at 4 min 30 s, 9 min 30 s and 14 min 30 s after finishing the cross-country course.

2.6 | Data analysis

Statistical analysis was performed using the software NCSS 2022 (NCSS Statistical Software). Horse/rider combinations were excluded from the analysis when they did not finish the cross-country test due to a withdrawal, fall or other elimination, when they had more than one refusal, when they were too slow (overtime by more than 10% of the optimal time), or when there were technical problems with the attachment of the accelerometric system. Our final sample size of 54 cross-country tests and 33 horses achieved 90% power to detect small effect sizes (as measured by Cohen's *d*) of 0.4 and 0.5, respectively (PASS Power Analysis and Sample Size software, NCSS). Descriptive statistics, histograms and normality tests were performed before further analysis. Non-parametric Kruskal–Wallis tests were used to examine differences between events in blood lactate concentrations, heart rates and bodyweight. The level of significance was set at $p < 0.05$. For the analysis of accelerometric variables, the most divergent time periods of the cross-country test were considered in order to maximally discriminate the effects of high-level competition exercise: (a) start to 60 s ('first minute'), (b) 60–120 s ('second minute') and (c) the last 60 s before finishing ('last minute'). However, as the data from the 'first minute' could potentially be biased due to the temperament of the horse in addition to the riding strategy of the rider throughout the cross-country test, only data from the 'second minute' versus those from the 'last minute' were considered for analysis. Due to the unbalanced nature of the data set, with different horses participating at different events and few horses participating at multiple events, mixed models for repeated measures were used for the comparisons between the time period 'second minute' versus 'last minute' incorporating the individual horse as a subject variable, the event as a within factor and mean speed between the jumps as a variable potentially influencing the outcome (cofactor).

For the analysis of lactate concentrations and heart rate recovery after the total session and the last minute of the session, Pearson correlation coefficients were calculated between all variables. Furthermore, the found associations were also confirmed with mixed regression models with the horse as a subject factor, the event as a fixed factor and the mean speed between the jumps as a cofactor. Scatter plots were used to visually show the associations found (see Figure S1).

3 | RESULTS

All participating horses were judged to be fit to compete. Observations on 54 cross-country tests of 33 horses were analysed after exclusions due to withdrawal of the horse ($N = 3$), fall of horse ($N = 1$), fall of rider ($N = 2$), more than one refusal ($N = 5$), too slow riding ($N = 7$) and technical problems with the attachment of the accelerometric system ($N = 5$). Five horses were not available for blood collection and lactate analysis 10 min after the cross-country test. Details of the analysed horses and the number of analysed jumps per cross-country session and event are given in Table S1. The mean bodyweight was 530.73 + 40.08 kg (53 observations) with no difference between events (Kruskal–Wallis test, $p = 0.55$). Neither bodyweight nor sex and age were correlated with blood lactate concentrations, and heart rates 10 min after finishing the cross-country course (all $p > 0.1$). Weather conditions varied little and mean meteorological conditions for the horses in each event are shown in Table S2.

Comparing the raw data of time periods second minute versus the last minute of the cross-country tests identified several kinematic changes, and most were influenced by the mean speed between the jumps and the event. We observed a slight decrease in mean stride frequency (113.42 ± 4.21 vs. 112.12 ± 5.15 strides/min) and an increase in mean stride length (5.23 ± 0.30 vs. 5.28 ± 0.36 m) and mean stride height (0.13 ± 0.02 vs. 0.14 ± 0.02 m) (all $p < 0.001$). The detailed comparative results for the measured stride characteristics are illustrated in Table 3, including the results from the mixed models analysis for repeated measures (Table 4).

Mean heart rate after 5 min at the CCI4*-S was 103 ± 13 beats per min (bpm) and at the E-CH 111 ± 12 bpm (5 vs. 13 horses each: Kruskal–Wallis test, $p = 0.22$), after 10 min 95 ± 8 bpm at the CCI4*-S and 97 ± 11 bpm at the E-CH (6 vs.14 horses each: Kruskal–Wallis test, $p = 0.6$), and after 15 min at the CCI4*-S 90 ± 10 bpm and at the E-CH 95 ± 7 bpm (5 vs. 7 horses: Kruskal–Wallis test, $p = 0.3$). Heart rate 10 min after finishing the cross-country test was associated with blood lactate concentrations ($r = 0.61$; $p = 0.008$) and with the mean maximal strike power at the jumps in the last minute of the test ($r = 0.53$; $p = 0.03$).

The mean blood lactate concentration of the horses 10 min after the cross-country test was 16.00 ± 5.38 mmol/L with no differences between the events (49 observations: Kruskal–Wallis test, $P = 0.9$). The detailed correlation analysis and p values of the mixed regression models between blood lactate values versus the stride characteristics are illustrated in Table 5. Blood lactate concentrations were positively associated with the mean speed between the jumps over the total cross-country test ($r = 0.25$). Compared to the stride parameters measured in the last minute of the test, a positive association with the mean maximal strike power at the jumps ($r = 0.41$) as well as with the means of the last strides' length and height before the jumps ($r = 0.25$ and $r = 0.35$) was found (all $p < 0.05$).

Focusing on the mean maximal strike power at the jumps and evaluating possible associations with kinematic characteristics measured in the second minute, in the last minute and in the total cross-country test, several significant correlations were identified, shown in detail in Table 6. Mean maximal strike power at the jumps was, throughout and in the last minute of the tests negatively, correlated with the mean stride height over the jumps ($r = -0.40$) and positively correlated with the mean maximal pitch at the jumps ($r = 0.53$) and with the longitudinal balance between the jumps ($r = 0.43$) (all $p < 0.5$), while all these findings were not observed in the second minute of the tests (all $p > 0.1$).

4 | DISCUSSION

By monitoring specific accelerometric variables, this observational exploratory field study identified several kinematic changes in eventing horses between and at the jumps across 4*-cross-country tests. This complements two recent studies using another inertial measurement unit and examining sport horses before and after their training sessions.[15,21] New candidates for kinematic characteristics during competitive exercise, such as the maximal strike power at the jumps, were identified in our study to be associated with an altered jumping profile and potentially indicating the onset of fatigue.

4.1 | Kinematic observations between jumps

In racehorses, stride frequency and stride length have been studied in detail in competition and training. A recent study evaluating two rounds of four horse races over 2400 m on turf showed a decrease in running speed, stride frequency and stride length from the first to the second round.[22] When statistically controlled for speed, stride frequency and diagonal step length of the horses still showed a decrease, while the length of the hind step, fore step, airborne step, and stride increased with fatigue in the second lap. The accelerometric system used in our study does not allow differentiation of the distances covered by each limb due to its median placement at the girth, but our

TABLE 3 Descriptive statistics of stride variables between and at the jumps.

			Time period															
			Second minute in cross-country test								Last minute in cross-country test							
Section	Parameter	Unit	Mean	Median	Min	Max	SD	Lower 95% CI	Upper 95% CI	*p* Value normality test[a]	Mean	Median	Min	Max	SD	Lower 95% CI	Upper 95% CI	*p* Value normality test[a]
Between jumps	Mean speed	m/min	583.31	582.87	509.00	662.00	35.64	573.59	593.04	n.s.	578.92	578.00	474.00	682.00	47.46	565.97	565.97	n.s.
	Maximal speed	m/min	735.58	728.32	634.00	850.00	45.85	723.06	748.09	n.s.	751.05	740.00	632.00	846.00	52.02	736.85	765.25	n.s.
	Mean stride frequency	strides/min	113.42	113.00	102.00	126.00	4.21	112.22	114.62	<0.05	112.12	111.50	97.00	129.00	5.15	110.66	113.58	n.s.
	Mean straightness	°	1.70	1.61	−0.59	3.63	1.12	1.40	2.01	n.s.	1.19	1.03	−2.22	3.30	1.34	0.82	1.56	<0.01
	Mean lateral balance	°	−0.09	−0.82	−18.21	13.71	6.55	−1.90	1.71	n.s.	0.61	1.57	−14.20	14.33	6.22	−1.09	2.30	n.s.
	Mean longitudinal balance	°	−4.28	−4.36	−13.42	4.58	4.57	−5.53	−3.04	n.s.	−4.37	−5.58	−13.20	14.50	5.64	−5.91	−2.83	<0.01
	Mean stride length	m	5.23	5.22	4.50	5.88	0.30	5.15	5.31	n.s.	5.28	5.26	4.50	6.13	0.36	5.18	5.38	n.s.
	Mean stride height	m	0.13	0.13	0.10	0.17	0.02	0.13	0.14	n.s.	0.14	0.14	0.10	0.19	0.02	0.14	0.15	n.s.
	Mean maximal strike power	acceleration *g*	3.14	3.01	2.50	5.20	0.47	3.02	3.27	<0.01	3.40	3.12	2.54	7.40	0.99	3.13	3.68	<0.01
Jumps	Mean stride length over the jumps	m	6.93	6.83	5.78	9.26	0.77	6.72	7.13	<0.05	7.26	7.26	3.23	8.92	0.99	6.98	7.53	<0.01
	Mean stride height over the jumps	m	1.56	1.56	1.47	1.68	0.05	1.55	1.58	n.s.	1.56	1.58	1.16	1.70	0.10	1.53	1.59	<0.01
	Mean maximal strike power at jumps	acceleration *g*	4.36	4.20	2.80	8.60	1.09	4.07	4.66	<0.01	4.81	4.50	3.30	9.40	1.02	4.53	5.09	<0.01
	Mean speed at jumps	m/min	414.85	416.50	345.00	557.04	46.67	402.11	427.59	<0.05	441.46	436.00	320.00	562.00	48.75	428.16	454.77	n.s.
	Mean maximal pitch at jumps	°	35.88	35.28	23.08	55.13	6.29	34.16	37.60	n.s.	39.99	36.48	24.36	78.54	10.80	37.04	42.94	<0.01
	Mean stride length before jumps	m	3.63	3.61	2.74	5.12	0.50	3.49	3.77	n.s.	3.86	3.86	3.02	4.84	0.40	3.74	3.97	n.s.
	Mean stride height before jumps	m	0.11	0.11	0.07	0.16	0.02	0.11	0.12	n.s.	0.13	0.12	0.09	0.22	0.03	0.12	0.14	<0.01
	Mean stride length after jumps	m	1.98	1.99	1.06	3.29	0.43	1.87	2.10	n.s.	2.08	2.11	1.29	3.58	0.45	1.96	2.20	<0.05
	Mean stride height after jumps	m	0.08	0.08	0.04	0.19	0.03	0.07	0.09	<0.01	0.09	8.59	0.04	0.32	0.04	0.08	0.10	<0.001

Note: $N = 54$ observations on 33 horses in five competitive cross-country test events.
Abbreviations: n.s., non significant; SD, standard deviation.
[a]Normality test: Shapiro–Wilk test.

TABLE 4 Mixed models results of stride variables between and at the jumps.

	Time period (second vs. last minute) *p* value	Event ID *p* value	Mean speed (m/min) *p* value
Between jumps			
Mean speed	n.s.	**<0.01**	
Maximal speed	**<0.01**	n.s.	**<0.01**
Mean stride frequency	**<0.01**	**<0.01**	**<0.01**
Mean straightness	**<0.05**	n.s.	n.s.
Mean lateral balance	n.s.	n.s.	**<0.05**
Mean longitudinal balance	n.s.	n.s.	n.s.
Mean stride length	**<0.01**	n.s.	**<0.01**
Mean stride height	**<0.01**	**<0.05**	**<0.01**
Mean maximal strike power	**<0.05**	n.s.	n.s.
Jumps			
Mean stride length over the jumps	**<0.01**	**<0.01**	**<0.01**
Mean stride height over the jumps	n.s.	**<0.05**	**<0.01**
Mean maximal strike power at jumps	**<0.05**	n.s.	n.s.
Mean speed at jumps	**<0.01**	**<0.01**	**<0.01**
Mean maximal pitch at jumps	**<0.05**	**<0.05**	n.s.
Mean stride length before jumps	**<0.01**	**<0.01**	**<0.01**
Mean stride height before jumps	**<0.01**	**<0.01**	n.s.
Mean stride length after jumps	n.s.	n.s.	n.s.
Mean stride height after jumps	n.s.	**<0.01**	n.s.

Note: Horse ID is set as a subject variable, Event ID as a within factor and Mean speed as a cofactor. $N = 54$ observations on 33 horses in five competitive cross-country test events. Significant differences at $p < 0.05$ are highlighted in bold print.
Abbreviations: ID, identity; n.s., non significant.

data also show a slight overall increase in stride length and, in addition, stride height during a cross-country test as well as a slight decrease of the stride frequency. Contrary to that and other observations in Thoroughbred racehorses,[23] another recent study reports that horses in multiple racing competitions demonstrate a decrease in speed and stride length, while stride frequency increased with race progression.[24] However, the greater the race distance, the fewer strides per 200 m and longer stride durations were recorded, thereby approaching conditions and results similar to our cross-country tests and supporting our findings. Indeed, as opposed to racing, in cross-country riding, a more strategic and personalised running speed is aimed for during the test. There is no head-to-head competition between horses, and they finish individually at the end of the course without being directly influenced by other competitors. In addition, longer distances at a lower and mostly sub-maximal speed are covered in the cross-country test than in races.

Stride frequency and length show good stability at a gallop in an individual horse.[25] A decrease in stride frequency and other kinematic changes in human sports are generally interpreted as a sign of inadequate training, fatigue and risk for injury.[26] In horses, limited scientifically evaluated data exist: In an 80 km endurance race, a shorter hindlimb stride length in 15 horses at the end of the ride was found, but no change of stride frequency.[27] A recent study on speed and stride characteristics over successive race starts in Thoroughbred horses showed decreasing speed and stride length over multiple races was linked to musculoskeletal injury.[28] On the other hand, in a training study on Thoroughbreds in National Hunt racing, a significant increase in stride frequency without difference in maximum running speed after 6 months was demonstrated.[29] As our study was not limited to only kinematic evaluations, it was also possible to evaluate blood lactate concentration and heart rate measured at the end of the cross-country tests. Lactate and heart rate recovery have been shown in multiple studies to be important indicators of fitness in horses.[5,11,30] They are also considered good biomarkers of fatigue,[9,12–15] the latter defined in many studies as the reduction in the ability to produce a given force or power.[31] In our analysis regarding blood lactate concentrations in relation to kinematic characteristics between the jumps, we found an association with the mean running speed over the whole cross-country test. This is in line with the observations in more than 1400 cross-country starts at different levels between 2010 and 2019, where an increase in mean speed of 30 m/min was associated with an increase of blood lactate 10 min after finishing of approximately 41%.[32] We found only a weak association between lactate concentrations and mean stride frequency and mean stride length; future studies should focus on reducing the variability of the sample and test these associations under more controlled conditions.

TABLE 5 Pearson correlation coefficients between blood lactate levels 10 min after the cross-country test vs. the stride parameters between and at the jumps measured in the total cross-country test and the last minute of the test in 33 horses in five competitive cross-country test events.

		Time period					
		Total cross-country test			Last minute of cross-country test		
Section	Parameter	*N*	Coef	*p* Value	*N*	Coef	*p* Value
Between jumps	Mean speed	49	0.25	**<0.01**	49	0.02	0.40
	Maximal speed	49	0.20	0.83	49	0.07	0. 5
	Mean stride frequency	45	−0.05	0.09	45	−0.19	0.07
	Mean straightness	49	−0.21	0.15	49	−0.18	0.06
	Mean lateral balance	49	0.10	0.61	49	0.01	0.9
	Mean longitudinal balance	49	0.11	0.87	49	0.14	0.37
	Mean stride length	49	0.30	0.06	49	0.09	0.06
	Mean stride height	49	0.13	0.25	49	0.19	0.13
	Mean maximal strike power	49	0.19	0.37	49	0.18	0.09
Jumps	Mean stride length over the jumps	49	0.12	0.10	49	0.01	>0.9
	Mean stride height over the jumps	48	−0.08	0.81	48	−0.16	0.33
	Mean maximal strike power at jumps	49	0.30	0.11	49	0.41	**<0.01**
	Mean speed at jumps	49	0.15	0.45	49	0.11	0.3
	Mean maximal pitch at jumps	49	0.23	0.41	49	0.15	0.2
	Mean stride length before jumps	49	0.17	0.98	49	0.25	**0.01**
	Mean stride height before jumps	49	0.20	0.85	49	0.35	**0.01**
	Mean stride length after jumps	49	0.09	0.78	49	0.12	0.6
	Mean stride height after jumps	49	0.02	**0.03**	49	−0.05	0.5

Note: *p* Values of mixed regression models with the Horse ID as subject factor and the Event ID as fixed factor; Mean speed between the jumps was used as a cofactor. The first mixed model ('mean speed') only contains mean speed as the main explanatory variable. Significant differences at $p < 0.05$ are highlighted in bold print.
Abbreviations: Coef, Pearson correlation coefficient; N = number of observations.

Additional parameters between the jumps measured in our study, like straightness, lateral and longitudinal balance of the horses, did not change throughout the cross-country test, and no associations with blood lactate concentrations and heart rate recovery were found. The empirical assumption that a horse might start to lean on his forehand, changing its longitudinal balance when tired, was not confirmed.

4.2 | Kinematic observations at jumps

This study is the first to also include observations on stride characteristics at the fences in the cross-country test. A moderate association between blood lactate accumulation in the horses with their mean maximal strike power at the jumps was identified. Mean maximal strike power at the jumps tended to increase during the cross-country tests, and also mean length of the jumps over the fences increased by 0.33 m. Interestingly, although the mean stride height over the fences did not change significantly compared to the second and the last minute, the standard deviation of the values doubled, and the range (min vs. max values) increased from 0.21 to 0.54 m. In addition, when analysing potential associations with the mean maximal strike power at the fences, a negative correlation with the mean stride height of the jumps over the fences could be observed in the last minute of the cross-country test, that is, in the potentially tired horses, versus being undetectable in the second minute, when they were still fresh. We interpret this change of relationship and inability to maintain the jumping height of certain individual horses as a sign of onset of fatigue, supported by the supplementary observation of a moderate correlation between mean maximal strike power at the jumps in the last minute of the cross-country and heart rate 10 min after finishing. Indeed, in humans, it has been shown in several studies that countermovement jump height loss in the context of running training is a good indicator of fatigue in individual human athletes and shows a strong relationship with blood lactate.[33] The frequency of fences in a cross-country course seems to have a high impact on the exercise intensity of eventing horses. In a recent study, it was found that an increase in total distance (without a proportional increase in jumping efforts) resulted in a decrease in heart rate and lactate concentrations, whereas an increase in jumps led to an increase in these two

TABLE 6 Pearson correlation coefficients between the mean maximal strike power at the jumps measured in the second minute, in the last minute, and in the total cross-country test vs. the stride parameters between and at the jumps in the corresponding time periods in 33 horses in five competitive cross-country test events.

		Time period								
		Second minute of cross-country test			Last minute of cross-country test			Total cross-country test		
Section	Parameter	*N*	Coef	*p* Value	*N*	Coef	*p* Value	*N*	Coef	*p* Value
Between jumps	Mean speed	54	0.13	0.22	54	−0.18	0.60	54	−0.00	0.6
	Maximal speed	54	0.22	0.36	54	−0.24	0.19	54	−0.01	0.8
	Mean stride frequency	50	0.27	0.64	50	−0.26	0.12	50	0.02	0.5
	Mean straightness	54	−0.07	0.16	54	0.04	0.28	54	0.04	0.7
	Mean lateral balance	53	−0.11	0.68	54	−0.14	0.64	54	0.09	0.6
	Mean longitudinal balance	54	0.24	0.12	54	0.43	**<0.01**	54	0.28	**<0.01**
	Mean stride length	54	0.03	0.78	54	−0.09	0.28	54	−0.04	0.4
	Mean stride height	54	−0.24	0.19	54	0.21	0.71	54	0.06	0.4
	Mean maximal strike power	54	0.40	**0.02**	54	0.67	**<0.01**	54	0.54	**<0.01**
Jumps	Mean stride length over the jumps	54	0.10	0.24	54	−0.16	0.89	54	−0.03	0.6
	Mean stride height over the jumps	53	−0.15	0.37	53	−0.40	**0.01**	53	−0.36	**<0.01**
	Mean speed at jumps	54	0.15	0.17	54	0.13	**0.01**	54	0.17	0.1
	Mean maximal pitch at jumps	54	0.15	0.51	54	0.53	**<0.01**	54	0.50	**<0.01**
	Mean stride length before jumps	54	−0.11	0.51	54	0.13	0.08	54	−0.04	0.9
	Mean stride height before jumps	54	−0.15	0.05	54	0.39	**0.03**	54	−0.03	0.4
	Mean stride length after jumps	54	0.12	0.67	54	0.15	0.32	54	0.15	0.4
	Mean stride height after jumps	54	−0.20	0.13	54	0.21	0.36	54	−0.01	0.4

Note: *p* Values of mixed regression models with the Horse ID as subject factor and the Event ID as fixed factor; Mean speed between the jumps was used as a cofactor. The first mixed model ('mean speed') only contains mean speed as the main explanatory variable. Significant differences at $p < 0.05$ are highlighted in bold print.
Abbreviations: Coef, Pearson correlation coefficient; *N* = number of observations.

parameters and this phenomenon was explained by the fact that the technical difficulties of the cross-country fences make the process of jumping slower provoking faster galloping between the fences with reduced muscle recovery.[32]

The negative correlation of the maximal strike power found in our study with the height of the jumps over the fences and the concurrent positive association with the maximal, but not overall pitch at the jumps might confirm the empirical observation of trainers and riders that the jumping curve of a tired horse shows a different profile. We hypothesise that this finding represents a compensation for high-intensity exercise-induced decline in muscle strength by an increase in strike power (defined as acceleration in the vertical axis) at the jumps. However, this assumption must be investigated in further studies, as to the authors' knowledge, no scientific investigations regarding this topic exist in eventing or showjumping. In any case, all these findings are of crucial importance for cross-country design, especially fatigue-related jumping characteristics and changes in the length of stride during a cross-country test with direct consequences for positioning of later elements of combined obstacles. Indeed, it was recently hypothesised that fatigue of horse and rider is an important cause of falls the longer a course is and the higher the number of fences.[6]

5 | LIMITATIONS

There are several limitations in this field study focusing on horses in high-level eventing competitions, and some biases cannot be excluded. Our sample contained horses of varying breed, sex and age, which we partially took into account in the statistical analysis. There were varying cross-country course designs, distances, weather conditions, riders' skills and strategies (including rider's choice of speed), but we did consider them in the statistical models. The length of the E-CH cross-country test was much longer than the other courses. Substantial efforts were undertaken to standardise test conditions (e.g., same going, topography, methodology), and robust statistical multivariable methods were applied.

6 | CONCLUSIONS

In conclusion, our study identified several stride characteristics changing over time during high-level competitive cross-country tests and potentially related to the onset of fatigue. Monitoring these variables may contribute to knowledge of the physiology of equine athletes and may help improve their management.

AUTHOR CONTRIBUTIONS

Dominik Burger and Alessandra Ramseyer conceptualised the study and developed the methodology. Alessandra Ramseyer, Vinzenz Gerber, David Deillon, Antonia Müller, Milena Scheidegger and Rebekka Käser contributed to the data collection. Statistical analysis was undertaken by Beatriz Vidondo and Dominik Burger. Dominik Burger drafted the initial manuscript. All authors contributed to the interpretation of the results, revised the manuscript critically, and gave final approval of the manuscript. Dominik Burger had full access to all the data in the study and is responsible for data integrity and accuracy of the data analysis.

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CONFLICT OF INTEREST STATEMENT

David Deillon is executive director of Alogo Analysis SA and received a part-time salary for this work. Other authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ETHICAL ANIMAL RESEARCH

The study had been approved by the Animal Health and Welfare Commission of the Canton of Vaud (*permit number VD3585*). The study was also approved by the eventing committee of the Swiss Equestrian Federation and by the FEI.

INFORMED CONSENT

Written owner/rider informed consent was obtained at enrolment into the study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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