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Gait characterisation and classification in horses

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Summary

Although a large number of foot-fall sequences are possible in quadrupeds, few sequences are routinely used. The aim of this paper is to characterise, by foot-fall pattern, the gaits used by horses and develop a novel technique to classify symmetric and asymmetric gaits using one common criterion. To achieve this speed and relative foot-fall, timings of all four limbs of eight Icelandic horses were measured using accelerometers. Linear discriminant analysis (LDA) was performed to find criteria that are optimal for discriminating between the different gaits. This also allowed us to evaluate whether gaits should be considered a continuum or as discrete entities. Foot-fall timings (stance times, swing times, duty factors and stride frequencies) for walk, tolt, trot, pace, left canter, right canter, left gallop and right gallop during over-ground locomotion at a range of speeds are presented. In the gaits of walk, tolt, trot and pace, foot-fall timings were equal between left and right hindlimbs and forelimbs so these gaits can be considered as symmetrical. Differences in stance times and duty factors were observed between gaits but are unlikely to be of biological significance due to their similar magnitude and inconsistent relative trends. This implies that metabolics or peak limb forces derived from contact times are unlikely to be the principal driving factors in gait transition between walk, trot, pace, canters and gallops, although these factors may influence the use of tolt at the lower and higher speeds. Gaits did cluster in the LDA space and the running gaits (tolt, trot, pace, left and right canters and gallops) could be considered a kinematic continuum but the relative relationship with walk may be more complex. Thus, LDA analysis has enabled common criteria to be discovered to accurately classify equine gaits on the basis of foot-fall timings on a stride-by-stride basis.

Key words: equine, biomechanics, locomotion, walk, tolt, trot, pace, canter, gallop, linear discriminant analysis

Introduction

There are many possible foot-fall patterns that quadrupeds could use during locomotion. However, certain foot-fall patterns are used routinely whereas other patterns are rarely seen.

A gait is a repetitive '*manner of walking or running*' (Collins Concise English Dictionary, 3rd edition). Gaits are generally considered to be discrete patterns of foot-falls and are divided into symmetrical and asymmetrical. In symmetrical gaits, each limb (for bipeds), or each forelimb or hindlimb (for quadrupeds), is considered to be used equivalently with the same kinetics and kinematics (stance duration, swing duration, sweep angle) and left and right foot-contacts occur at equal time intervals. Common examples of symmetrical gaits in quadrupeds are walk, trot and pace. In asymmetrical gaits, the limbs are considered to be employed differently, as there are different limb forces, and foot–ground contacts are not spaced evenly in time. Common examples of asymmetrical gaits in quadrupeds are canter and gallop.

Identification of gait from foot-fall sequence is not new; in the 1800s, Ellenberger attached different sounding bells to the limbs of galloping horses [cited in Back and Clayton (Back and Clayton, 2001)]. Later, pressure-sensitive horse shoes and bracelets were used to measure foot-fall sequence [Marey 1872; as cited in Barrey (Barrey, 1999)]. Muybridge used photographic stills to record the relative stance times and foot-contacts of the limbs in many different species of animals (Muybridge 1887). More recently, Hildebrand has developed criteria to distinguish gaits. He considered symmetrical and asymmetrical quadrupedal gaits separately (Hildebrand, 1989) and characterised gaits from approximately 12 000 strides from over 150 different species of animals using the advanced placement of the left hindlimb to the left forelimb (i.e. the proportion of the stride that the forelimb foot-contact follows the hindlimb foot-contact) and the duty factor (proportion of the stride that a limb is in contact with the ground) of the left hindlimb for the symmetrical gaits. For the asymmetrical gaits, the lag between foot-contact of the pair of hind legs and the pair of front legs was plotted against the percentage of the stride time that one or both hindlimbs are in contact with the ground. Each gait occupied a discrete position on these plots, although mean data from a number of strides were presented.

Very recently, Abourachid presented a way of analysing both symmetrical and asymmetrical gaits by breaking the stride paradigm and emphasising the sequential movement of the limbs (starting with the forelimbs followed by the hind limbs) (Abourachid, 2003). However, we would like to develop a technique (within the traditional framework of the stride) that can be applied to the automated classification of both symmetrical and asymmetrical gaits using a common set of stride-timing-derived parameters. Such a method would be useful to automatically classify gaits and a desirable tool in gait selection, gait transition and lameness studies.

We want to explore if asymmetrical gaits and unusual symmetrical gaits (such as tolt) could be considered as part of a single gait continuum or if they are completely distinct. To investigate this, a method to represent symmetric and asymmetric gaits using one criterion, rather than using either Hildebrand's symmetrical or asymmetrical gait graph, is required.

There are two aims of this paper: to characterise stance time variations in gaits used by Icelandic horses with respect to speed and to test the hypothesis that, in horses, all gaits can be represented as a continuum and each gait falls into a cluster within this continuum. To test this hypothesis, foot-fall data were collected during the symmetrical (walk, tolt, trot and pace) and asymmetrical (canter and gallop) gaits of Icelandic horses at a range of speeds. Icelandic horses were chosen as they use the usual quadrupedal gaits of walk, trot, canter and gallop but can also use additional gaits of tolt and pace. Gaits were manually identified and linear discriminant analysis (LDA) was used to define criteria for automatic identification of gait. Symmetry of the 'symmetrical' gaits was assessed by comparison of right and left foot timings (stance times and swing times) and ratios of foot-contact times.

Materials and methods

Simultaneous speed and foot-fall data (foot-on and foot-off events) from eight Icelandic horses were collected. The horses were ridden at a range of speeds at walk, tolt, trot, pace, left and right canter and left and right gallop in an outdoor arena by an experienced rider. Each horse was ridden in both directions (clockwise and anti-clockwise) and the data were pooled.

Speed was measured throughout the exercise session using a GPS receiver (G30-L; Laipac Technology, Canada) attached to the rider's hat. The GPS receiver had a built-in data logger that sampled GPS NMEA data at a frequency of 1 Hz. This system is accurate to within 0.2 m s^{-1} for 56% of samples and 0.4 m s^{-1} for 82% of all samples, as described in Witte and Wilson (Witte and Wilson, 2005).

Foot-fall data from all limbs (foot-on and foot-off events) were measured using accelerometers attached to the dorsal hoof wall with hot melt glue and transmitted *via* an analogue radio-telemetry link mounted over the metacarpal or metatarsal bone as described in detail by Witte et al. (Witte et al., 2004). The mass of the accelerometer was 2 g and the mass of transmitter and battery was 376 g. This system is accurate to <3 ms for foot-on events for walk, trot and lead and non-lead canter and <5 ms for foot-off, as compared to the gold standard of force-platform data (Witte et al., 2004).

Data analysis

Audio transcription software (Barras et al., 1998) was used to manually identify foot-on and foot-off timings from the accelerometer voltage output (Witte et al., 2004; Pfau et al., 2005; Pfau et al., 2006). Foot-on and foot-off events from each limb were plotted, and gaits were manually identified as stated in Table 1. Here, both canters and gallops were of the transverse rather than rotary type and defined by the sequence of foot-falls: in canter, the second limb to contact the ground after the aerial phase was a forelimb or a forelimb and hindlimb together, whereas in gallop the second foot-contact was made by a hindlimb. In canter or gallop, the last forelimb to contact the ground before the aerial phase is known as the lead limb. If this leg was the left forelimb (LF) then the stride would be a left canter or a left gallop, if the lead limb was the right forelimb (RF) then it would be a right canter or gallop. Hence, the foot-fall contact sequence for left lead canter would be RH (right hind), RF, LH (left hind) then LF (but foot-contacts of the RF and LH could occur simultaneously) and the sequence for left gallop is RH, LH, RF then LF. The start of individual strides was defined by the foot-on event of the LF, and foot-on and foot-off times of the other legs were expressed relative to this time. Any strides that could not be identified were 'unclassified'. The speed for each stride was taken as the speed measured closest to the midpoint of the stride.

To assess the symmetry of foot timings, the ratio between the foot-on time of the left and right forelimbs and the left and right hindlimbs was calculated as:

$$\text{Forelimb ratio} = (RF_{on} - LF_{on})/t = RF_{on}/t\,, \quad (1)$$

$$\text{Hindlimb ratio} = |RH_{on} - LH_{on}|/t\,, \quad (2)$$

where t is stride time. As the foot-on time of the LF defined the beginning of the stride (and thus was set to zero), LF_{on} can be removed from Eqn 1. For example, if the foot-on time of the LF proceeded the time of foot-contact of the RF by exactly half of the stride time, the value of this ratio would be 0.5.

Statistics

Assessment of gait

Stride temporal variables (stance times, swing times and duty factors) were compared across gaits, speeds and horses using a general linear model with Bonferroni *post-hoc* corrections (SPSS v.13.0; SPSS Ltd, Chicago, IL, USA), with stance time, swing time and duty factor as dependent variables, gait and speed category as fixed factors and horse as a random factor. Stance times, swing times and duty factors between the

Table 1. *Gait definitions*

Gait	Foot-fall contact order	Number of limbs in contact with the ground at any time	Presence of aerial phase	Notes
Symmetric gaits				
Walk	LH, LF, RH, RF	2–3 or 3–4	No	Foot-fall contacts occur at approximately even intervals in time.
Tolt	LH, LF, RH, RF	1–2	No	
Trot	(LH+RF), (RH+LF)	0–2	Possible	LF and RF stance times are of approximately equal length, and LH and RH stance times are of approximately equal length.
Pace	(LH+LF), (RH+RF)	0–2	Possible	
Asymmetric gaits				
Left canter	RH, RF before or at the same time as LH, LF	0–3	Yes	Canters and gallops are distinguished by the order of foot-falls.
Right canter	LH, LF before or at the same time as RH, RF	0–3	Yes	Stance times are not necessarily equal between left and right forelimbs or between left and right hindlimbs.
Left gallop	RH, LH, RF, LF	0–3	Yes	
Right gallop	LH, RH, LF, RF	0–3	Yes	

Gaits were identified from observation of foot-fall sequence (where LF is the left forelimb, RF is the right forelimb, LH is the left hindlimb and RH is the right hindlimb), the number of limbs in contact with the ground and the presence of aerial phases. Any strides that were unusual and could not be identified were designated 'unclassified'.

right and left forelimbs and right and left hindlimbs were assessed using a paired *t*-test. The average forelimb and hindlimb ratios were also calculated for each gait. A value of $P<0.05$ was considered significant.

Linear discriminant analysis

An LDA was performed to identify the factors that distinguished between different gaits. For this analysis, the following factors were entered into a non-biased LDA (SPSS): speed, stride time, LF stance time, RF on, RF stance time, LH on, LH stance time, RH on, and RH stance time. The LDA factors were determined and the accuracy of the classification assessed.

In order to be able to visualise the distribution of the unclassified strides in relation to the strides of the other gaits, the LDA matrix, which was calculated for the known strides, was applied to the unclassified strides.

Results

Stride variables

Stride data (N=9687) from the LF were collected from horses at walk between 0.6 and 3.2 m s^{-1} (N=1755), tolt between 1.2 and 7.6 m s^{-1} (N=2878), trot between 1.8 and 6.7 m s^{-1} (N=2147), pace between 2.8 and 10.6 m s^{-1} (N=662), left canter between 4.0 and 8.2 m s^{-1} (N=267), left gallop between 4.9 and 8.2 m s^{-1} (N=112), right canter between 4.8 and 8.9 m s^{-1} (N=871) and right gallop between 4.7 and 8.8 m s^{-1} (N=178) (Tables 2, 3). A total of 817 strides were not consistent with the gait definitions in Table 1 and were therefore designated 'unclassified'.

Stance time and swing time decreased significantly with speed (Fig. 1A,B; Tables 2, 3). There were small but significant differences in LF stance time between all the symmetrical gaits. The only non-statistically significant differences occurred between left canter and the other asymmetrical gaits and pace, between left gallop and right canter, and between right gallop and pace. Typically, the mean differences in stance times were inconsistent between gaits and typically less than 30 ms (15%) between all gaits (except between tolt and walk at the lower speeds).

There were small but significant differences in LF swing time between most of the gaits; the only non-statistically significant differences were between pace and the gaits of tolt, right gallop and left gallop and also between left gallop and right gallop. The actual differences in swing times between gaits were small, typically less than 6%.

Duty factor decreased with speed in a similar manner for all gaits, except for tolt at the lower speeds (i.e. between 1 and 3.5 m s^{-1}), where it remained fairly constant (Fig. 1E). There were significant differences in LF duty factor between all the symmetrical gaits. The only non-statistically significant differences in LF duty factor were between left canter and the gaits of right canter, pace and right gallop and between tolt and trot. Typically, the mean differences were less than 0.05 between all gaits (excluding between tolt and walk at the lower speeds).

Stance times were different between leading and trailing limbs in canter and gallop (Table 3); the lead forelimb and the lead hindlimb tended to have longer stance times than the trailing limbs, and greater differences in stance times were measured between the forelimbs than between the hindlimbs.

Hindlimb stance time was longer than forelimb stance time for most gaits and speeds (Fig. 1C). Average hindlimb stance time was 2.7% longer for walk, 9.2% longer for tolt, 1.6% shorter for trot, 5.1% longer for pace, 0.9% shorter for left canter, 3.2% longer for right canter, 3.0% longer for left gallop and 4.1% longer for right gallop. Hindlimb stance and swing

Table 2. *Stance and swing times for each limb for the symmetrical gaits of walk, tolt, trot and pace*

	Stride time		LF			RF			LH			RH		
Speed	Mean ± s.d.	*N*	Stance	Swing	*N*	Stance	Swing	*N*	Stance	Swing	*N*	Stance	Swing	*N*
Walk														
1	1121±120	88	733±98	388±37	88	743±102	378±50	86	763±94	359±51	87	775±114	349±36	68
1.5	904±79	1021	540±60	364±37	1021	543±58	362±41	979	563±53	340±44	1006	553±44	347±43	955
2	887±77	623	526±53	361±40	623	531±50	359±44	604	532±39	341±43	512	541±39	355±50	541
2.5	714±113	18	384±99	330±38	18	368±82	346±60	18	390±59	318±92	17	407±83	313±53	15
3	654±106	5	307±60	347±54	5	309±63	345±48	5	336±39	318±123	5	341±49	330±72	4
Tolt														
1	543±15	2	225±20	318±5	2	207±13	336±2	2	246±16	297±1	2	260±21	283±35	2
1.5	659±85	5	295±101	364±26	5	336±125	323±50	5	326±62	333±39	5	349±100	311±8	5
2	587±71	10	262±60	325±29	10	271±71	316±25	10	285±46	302±44	10	30±67	292±39	7
2.5	583±74	33	264±45	319±50	33	264±60	318±54	33	317±70	273±38	30	303±45	280±59	32
3	571±48	188	254±31	317±36	188	250±27	321±34	188	285±29	285±31	174	287±31	289±40	138
3.5	538±32	611	225±21	313±28	611	224±21	315±26	604	253±20	28±27	587	251±17	287±31	526
4	524±28	824	210±15	315±27	824	211±14	316±23	767	229±17	294±23	741	230±15	295±24	796
4.5	501±28	658	194±14	307±28	658	193±13	309±21	569	207±14	293±26	639	210±12	290±21	632
5	486±21	434	184±16	302±24	434	181±13	306±22	373	194±13	291±23	434	196±11	288±23	398
5.5	479±24	67	168±17	311±22	67	169±15	312±22	59	186±15	291±24	63	190±18	287±29	63
6	468±18	30	157±15	311±23	30	158±11	312±21	28	181±23	287±29	30	177±16	291±27	29
6.5	449±24	7	138±14	311±13	7	145±11	304±16	7	158±8	290±26	7	162±9	287±18	7
7.5	422±10	9	119±6	303±10	9	123±4	299±11	9	139±5	283±13	9	139±6	283±13	9
Trot														
2	649±46	4	302±60	347±26	4	340±60	309±17	4	335±64	314±20	4	321±51	328±13	4
2.5	651±43	9	328±72	323±54	9	303±18	348±35	9	305±11	346±37	9	314±26	337±40	9
3	637±57	80	327±66	309±55	80	288±21	351±53	78	287±22	352±54	78	293±26	346±51	78
3.5	600±39	445	259±23	341±37	445	259±17	345±37	399	258±20	347±47	398	254±13	356±36	343
4	569±36	618	223±18	346±30	618	225±17	347±29	572	218±15	354±37	573	225±15	345±32	601
4.5	542±36	594	206±17	336±32	594	204±15	341±29	535	203±13	341±36	535	205±13	338±32	578
5	511±36	277	200±33	311±44	277	185±14	326±34	258	191±14	321±37	258	191±13	321±39	223
5.5	516±39	78	180±16	336±37	78	175±10	348±32	71	181±12	340±33	73	181±15	335±42	74
6	500±28	29	173±8	327±24	29	174±6	332±14	27	171±9	329±23	29	171±5	329±29	29
6.5	482±13	13	158±7	324±9	13	167±3	315±13	13	159±4	323±14	13	157±8	325±12	13
Pace														
3	600	1	269	331	1	250	350	1	273	327	1	261	339	1
3.5	568±35	8	231±25	337±19	8	227±20	341±21	8	228±30	349±33	7	236±22	341±16	7
4	551±21	24	207±17	344±18	24	214±15	334±28	26	220±15	321±24	21	220±20	327±32	26
4.5	520±31	41	184±16	336±23	41	186±15	334±23	41	193±13	324±23	35	191±15	331±22	39
5	499±32	49	177±15	323±28	49	179±16	322±30	46	182±13	312±20	38	184±14	315±32	45
5.5	478±25	64	162±13	315±22	64	165±14	314±24	62	173±10	301±22	60	173±13	305±26	64
6	471±27	67	155±14	316±25	67	155±16	317±27	65	165±13	303±26	62	164±16	307±32	67
6.5	459±30	59	147±10	312±28	59	147±12	315±34	52	156±11	301±30	51	150±12	309±30	59
7	444±25	70	138±18	307±24	70	139±14	310±28	60	148±13	287±24	52	145±12	300±28	70
7.5	431±29	77	132±12	298±28	77	132±9	299±29	77	147±16	280±28	68	140±12	291±28	77
8	426±25	73	125±9	301±23	73	128±10	298±26	73	138±8	288±25	72	136±9	290±25	73
8.5	427±23	44	128±18	300±31	44	121±10	306±22	44	131±6	296±20	44	129±7	298±20	44
9	399±16	25	126±16	273±22	25	110±7	288±16	25	122±12	278±16	23	120±9	281±18	19
9.5	400±14	38	114±6	287±15	38	112±8	289±18	38	121±12	281±20	36	110±5	297±9	24
10	389±8	14	113±4	276±9	14	113±4	276±10	14	125±8	264±15	14	155±30	303±30	633
10.5	386±21	8	110±3	276±18	8	111±5	275±23	8	117±3	274±18	7	274±18	274±18	7

Mean (± s.d.) and number of cases per speed category (*N*) for stride time (ms) and stance times and swing times (ms) for each limb (LF, left forelimb; RF, right forelimb; LH, left hindlimb; RH, right hindlimb).

Table 3. *Stance and swing times for each limb for the asymmetrical gaits of left canter and gallop and right canter and gallop*

	Stride time		LF			RF			LH			RH		
Speed	Mean ± s.d.	*N*	Stance	Swing	*N*	Stance	Swing	*N*	Stance	Swing	*N*	Stance	Swing	*N*
Left canter														
4	454	1	167	287	1	161	293	1	205	249	1	–	–	–
4.5	455±1	2	172±8	283±10	2	165±3	290±4	2	187±1	269±2	2	182±9	274±11	2
5	472±35	13	176±21	296±21	13	166±11	306±26	13	178±15	293±26	13	179±10	292±28	13
5.5	480±21	40	173±17	307±21	40	167±8	314±18	40	175±10	306±15	40	171±7	310±17	40
6	463±27	55	164±18	299±18	55	158±12	305±21	55	161±10	302±21	55	162±10	301±24	55
6.5	427±23	29	149±10	278±19	29	142±9	285±21	29	145±10	283±23	29	153±10	274±29	28
7	434±19	77	148±9	286±18	77	138±10	296±21	77	140±8	294±23	77	141±11	293±26	72
7.5	441±19	39	144±6	297±19	39	134±7	308±19	39	133±9	308±22	39	135±16	306±30	39
8	431±8	11	132±3	300±8	11	125±5	306±12	11	124±11	307±15	11	125±10	307±12	11
Left gallop														
5	472±21	4	176±19	295±5	4	167±2	305±20	4	181±7	290±16	4	187	310	1
5.5	487±21	17	168±13	319±16	17	167±4	320±19	17	179±12	308±15	17	176±6	317±11	15
6	465±26	14	155±12	311±21	14	154±7	311±23	14	165±11	300±21	14	160±6	305±24	14
6.5	428±31	11	150±16	278±17	11	143±10	285±24	11	151±14	277±20	11	154±11	275±27	10
7	415±18	39	142±11	273±16	39	135±10	281±13	39	144±9	271±14	39	148±11	267±20	39
7.5	419±30	15	145±13	274±23	15	132±11	287±27	15	140±11	279±23	15	145±11	274±32	15
8	393±12	12	136±6	258±17	12	119±5	275±15	12	125±3	268±11	12	134±6	260±17	12
Right canter														
5	496±24	80	172±10	324±18	80	184±11	312±23	80	184±9	308±19	73	189±7	307±23	77
5.5	476±29	255	163±10	313±24	255	172±13	304±28	255	173±9	300±24	229	178±8	297±31	225
6	472±29	232	159±8	314±26	232	167±14	306±31	227	165±11	303±26	206	167±9	306±30	195
6.5	442±34	166	149±7	293±33	166	155±17	293±33	135	155±9	286±29	140	152±7	288±36	136
7	430±24	69	141±11	289±20	69	146±10	285±22	64	147±12	279±17	62	141±8	286±21	59
7.5	417±31	31	135±10	282±26	31	140±11	276±25	31	143±12	272±24	30	130±6	281±29	20
8	429±26	26	129±7	300±26	26	134±11	296±31	26	141±13	281±28	20	124±4	319±26	13
8.5	417±21	10	127±6	290±23	10	131±12	287±28	10	134±7	283±23	10	122±1	333±2	2
9	398±8	2	122±2	277±6	2	133±6	265±3	2	142±8	256±17	2	166±18	298±31	727
Right gallop														
4.5	486±32	2	157±14	329±18	2	174±1	312±31	2	180±6	306±25	2	194±4	292±36	2
5	491±20	5	163±14	328±11	5	176±12	315±10	5	179±16	312±15	5	178±12	313±16	5
5.5	485±23	23	158±9	326±20	23	170±13	315±21	23	171±16	314±24	23	182±12	303±23	23
6	472±25	61	156±10	316±23	61	167±11	305±27	61	165±11	304±24	51	169±10	303±26	61
6.5	467±26	35	151±8	316±22	35	160±8	307±27	35	154±7	310±28	26	155±6	312±26	35
7	434±27	14	138±8	295±27	14	142±10	292±28	14	148±9	280±23	12	146±10	290±25	13
7.5	415±25	19	129±8	286±25	19	136±10	279±28	19	141±7	269±23	17	134±7	281±23	19
8	412±23	19	119±4	294±23	19	121±3	292±23	19	129±4	277±20	16	121±4	291±22	19

Mean (± s.d.) and number of cases per speed category (*N*) for stride time (ms) and stance times and swing times (ms) for each limb (LF, left forelimb; RF, right forelimb; LH, left hindlimb; RH, right hindlimb).

times also decreased with speed such that the differences between fore- and hindlimb times remained similar across the speed range.

Stride frequency increased in a linear manner with speed for all gaits (Fig. 1F).

Symmetry

Left and right stance times for the hindlimbs and forelimbs were very similar for all gaits. Forelimb ratios and hindlimb contact ratios were 0.5 for the symmetrical gaits (Table 4). The greatest deviation in ratios for the symmetrical gaits was for pace, and right gallop had the greatest standard deviation for all gaits (Table 4).

Gait identification – linear discriminant analysis

LDA was used to classify the eight different gaits (a total of 7135 strides as foot-fall data from all four limbs was required). The LDA generated seven (number of gaits minus one) functions (Table 5) generated from limb stance times, speed and RF, LH and RH on times. The first three LDA functions cumulatively explained over 95% of the variance between the different gaits (Table 5) and distinguished the gaits clearly and reliably (Fig. 2).

Function 1 was primarily a function of stance times from all limbs (so divided between the slower and faster gaits) and explained 47% of the variance between gaits. Function 2 was primarily constructed of the foot-on of the RF (measured relative to the LF) and therefore divided between the symmetrical and the right and left asymmetrical gaits. Function 2 explained 31% of the variance between gaits. Function 3 consisted of a combination of all the stance times, speed and stride length and further divided between the symmetrical and left and right asymmetrical gaits. This function explained 19% of the variance between gaits.

The LDA classified 95% of the original and cross-validated cases correctly (i.e. consistent with the manual classification) (Table 6). For the symmetrical gaits, 99% of walk strides, 96% of tolt strides, 99% of trot strides and 77% of pace strides were correctly classified. For the tolt strides 2% were incorrectly classified as pace, and for the pace strides 19% were incorrectly classified as tolt. For the asymmetric gaits 76% of left canter strides were correctly classified, as were 97% of left gallop, 99% of right canter and 70% right gallop. Those strides

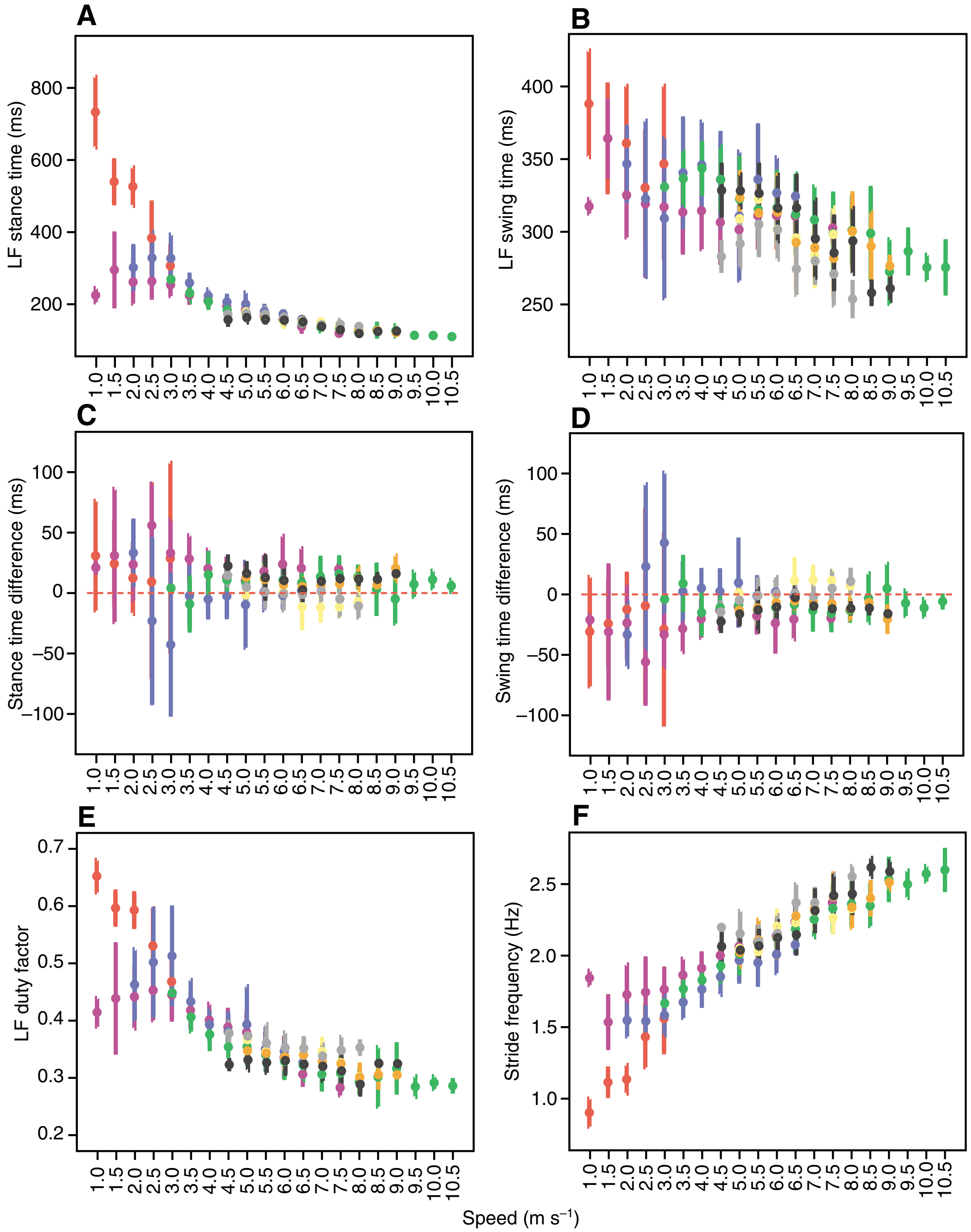

Fig. 1. Stride variables: (A) left forelimb stance time, (B) left forelimb swing time, (C) left hindlimb–left forelimb stance time, (D) left hindlimb–left forelimb swing time, (E) left forelimb duty factor and (F) stride frequency against speed for each gait [red is walk (*N*=1755), blue is trot (*N*=2147), purple is tolt (*N*=2878), green is pace (*N*=662), yellow is left canter (*N*=267), black is left gallop (*N*=112), orange is right canter (*N*=871) and grey is right gallop (*N*=178)]. Total *N*=8870, 1–1021 strides per gait per speed category. Error bars represent ± 1 s.d.

Table 4. *Forelimb and hindlimb ratios for all gaits*

Gait	Forelimb ratio (*N*)	Hindlimb ratio (*N*)
Walk	0.50±0.01 (1714)	0.50±0.02 (1481)
Tolt	0.50±0.03 (2658)	0.50±0.03 (2506)
Trot	0.50±0.03 (1973)	0.49±0.03 (1782)
Pace	0.51±0.04 (638)	0.49±0.04 (566)
Left canter	0.73±0.04 (267)	0.32±0.04 (262)
Left gallop	0.78±0.03 (112)	0.29±0.03 (106)
Right canter	0.27±0.03 (830)	0.67±0.05 (628)
Right gallop	0.28±0.06 (178)	0.41±0.17 (158)

Values are means ± s.d. and are accurate to two decimal places.

that were incorrectly classified were defined as an alternative gait of the same lead limb (i.e. left canter instead of left gallop).

Discussion

Simultaneous foot-fall data from all four limbs can be measured from horses at a range of speeds and gaits using accelerometers. Gaits can be determined from foot-fall patterns using LDA functions based on stride time, speed, foot-on timings and stance times for each limb.

The use of accelerometers (present study) or gyroscopes (Keegan et al., 2004), rather than motion analysis systems or force platforms, allows a large volume of foot-fall data from all limbs to be recorded accurately and efficiently during over-ground locomotion. Hoof-mounted accelerometers have been used in gait analysis studies (Witte et al., 2004; Pfau et al., 2005; Pfau et al., 2006) but stride temporal variables from all four limbs have never been recorded from large numbers of strides at a variety of gaits and speeds. There are some limitations to the method used in this study, as discussed below, but the stride timings measured in this study are consistent with previously published data.

Limitations

Determination of gaits

Correct gait identification for each stride was essential so that comparisons could be made between gaits. Gait identification was made on a stride-to-stride basis by observation of foot-fall timings of all available limbs. If classification was questionable (i.e. the stride was not consistent with the gait requirements as stated in Table 1) the strides were designated 'unclassified'. For example, imagine a stride that resembles a walk–tolt hybrid where in the first half of the stride one limb is in contact with the ground but in the second half of the stride three limbs are in contract with the ground. Such a stride is inconsistent with the gait definitions in Table 1 and was therefore described as unclassified.

Of the gaits, trot strides were the easiest to identify and pace strides were the most difficult, due to a tendency for significant asymmetry between subsequent flight phases in pace, resulting in a broader distribution of foot-fall ratios. 817 strides could not be identified and were designated unclassified.

LDA

The LDA presented here was based on speed, stride time, stance times and foot-on timings and correctly classified 95.1% of strides. In this analysis, no gait bias was assumed. However, if groups were biased using the number of strides in each gait, 94.9% of strides would have been correctly classified. If a reduced set of variables was used, for example if speed values were excluded, 94.2% of cases would have been correctly classified, and if missing parameters in our data set were replaced by mean values (increasing the number of classified strides to a total of 8944) 87.5% of strides would have been correctly classified.

Table 5. *Structure matrix and Eigenvalues showing the construction and relative significance of each LDA function*

	LDA function						
	1	2	3	4	5	6	7
LH stance	0.94*	0.11	–0.20	–0.05	0.10	0.14	0.15
RH stance	0.92*	0.11	–0.21	–0.07	0.08	0.05	0.09
RF stance	0.89*	0.12	–0.26	0.07	0.06	0.12	–0.24
LF stance	0.85*	0.15	–0.25	0.069	0.05	0.22	–0.20
LH_{on}	0.74*	–0.04	0.22	–0.02	0.03	0.55	–0.20
Stride length	0.72*	0.15	–0.29	0.04	0.12	0.55	–0.04
RF_{on}	0.66*	0.54	–0.01	0.01	–0.00	0.48	–0.04
Speed	–0.49	–0.14	0.27	0.79*	–0.10	–0.09	0.13
RH_{on}	0.09	0.06	0.05	0.08	0.99*	–0.03	–0.03
Eigen value	13.41	8.84	5.35	1.14	0.09	0.03	0.01
% of variance	46.5	30.6	18.5	3.9	0.3	0.1	0.0
Cumulative %	46.5	77.1	95.6	99.6	99.9	100.0	100.0

Variables are ordered by absolute size of correlation within function and are accurate to two decimal places. * indicates the largest absolute correlation between each variable and any discriminant function.

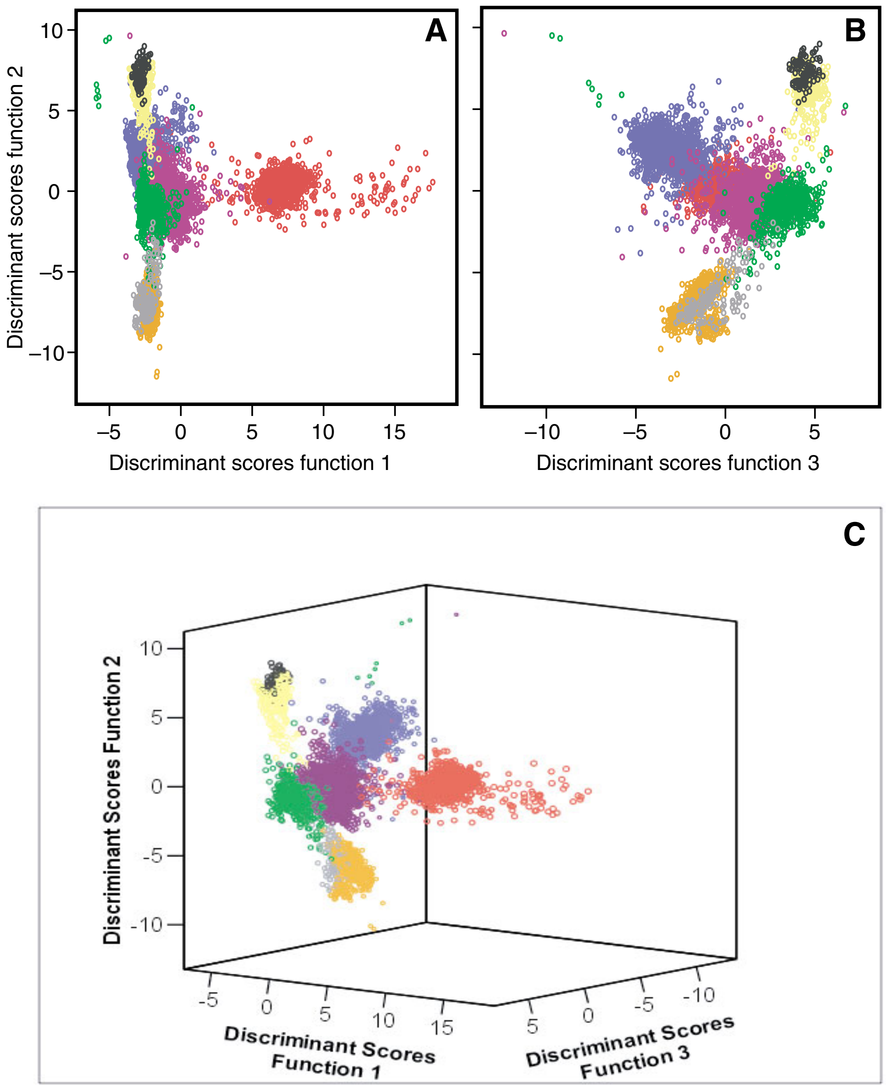

Fig. 2. Linear discriminant analysis results: (A) function 2 against function 1, (B) function 2 against function 3 and (C) function 1, function 2 and function 3 for walk (red circles, *N*=1414), tolt (purple circles, *N*=2279), trot (blue circles, *N*=1777), pace (green circles, *N*=262), left canter (yellow circles, *N*=597), left gallop (black circles, *N*=106), right canter (orange circles, *N*=542) and right gallop (grey circles, *N*=158).

Experimental findings

Stride variables

The values for foot-fall timings measured here are similar to previously published values of walk (Witte et al., 2004), tolt (Zips et al., 2001; Nicodemus and Clayton, 2003; Biknevicius et al., 2004), trot (Drevemo et al., 1980a; Drevemo et al., 1980b; Drevemo et al., 1980c; Clayton, 1994a), pace (Wilson et al., 1987a) and gallop (Hildebrand, 1959; Deuel and Lawrence, 1986; Clayton, 1994b; Back et al., 1997) in horses.

As in previous studies, hindlimb stance times tended to be longer in comparison with forelimb stance times (Hildebrand, 1965; Drevemo et al., 1980a; Wilson et al., 1987b; Clayton, 1994a; Clayton, 1994b). Forelimb and hindlimb stance and swing times were similar for all gaits with respect to speed. Similarly, stance times and duty factors decreased with speed for all gaits as expected. This is consistent with previous findings for horses (Drevemo et al., 1980a; Kram and Taylor, 1990; Clayton, 1994a). Swing times also decreased slightly with speed for all gaits, which is consistent with that of trotting Standardbreds (Drevemo et al., 1980a) and with running humans (Weyand et al., 2000).

Symmetry

There were statistically significant differences in stance time between the left and right limbs for walk, tolt, trot and pace. This could be due to the horses going around a bend (although the turns were not sharp, occurred to both the left and the right and the majority of the strides were collected on the straight). However, the differences were sufficiently small (maximum mean difference between the right and left forelimbs or hindlimbs was 3.7 ms) and within the error range for the method used that there is probably no biological significance to these differences.

Stance times and ratios were more variable in the hindlimbs than the forelimbs, as had been found previously in trotting Standardbreds (Drevemo et al., 1980b). Of the symmetrical gaits, pace had the greatest variation in forelimb and hindlimb ratios, possibly because ‘handedness’ is more apparent in pace than the other gaits. However, as similar maximum differences

Table 6. *Cross-validated LDA classification results for each gait*

	Percentage correctly predicted group membership									
Gait	Walk	Tolt	Trot	Pace	Left canter	Left gallop	Right canter	Right gallop	Total	Number of cases
Walk	98.8	1.1	0.1	0	0	0	0	0	100	1414
Tolt	0.2	96.4	0.8	2.3	0.2	0	0.1	0	100	2279
Trot	0	0.1	99.4	0.1	0.2	0.1	0	0.2	100	1777
Pace	0	19.4	1.3	77.1	0.4	0	0	1.8	100	542
Left canter	0	1.1	0	1.5	76.3	21	0	0	100	262
Left gallop	0	0	0	0	2.8	97.2	0	0	100	106
Right canter	0	0.2	0	0	0	0	98.5	1.3	100	597
Right gallop	0	4.4	0	3.8	0	0	21.5	70.3	100	158

In cross-validation, each case was classified by the functions derived from all cases other than that case. 95.1% of original grouped cases were correctly classified, and 95.0% of cross-validated grouped cases were correctly classified.

occurred between LF and RF stance times (approximately 11 ms) for all gaits and speeds, it is unlikely that there are large gait-dependent asymmetries or handedness. The variation in relative timings between the pairs of limbs was similar for the symmetrical and asymmetrical gaits (although more variation occurred in right lead gallop – the reason for this is unclear).

The forelimb and hindlimb contact ratios were 0.5 for all the symmetrical gaits. As there are also no biologically significant differences in stance times, the gaits of walk, tolt, trot and pace in sound Icelandic horses can be considered to be symmetrical in terms of foot-fall timings.

Gait identification

An LDA can be used to identify gaits. The LDA used in this study correctly identified the gait of 95% of strides based on stance times, stride time, speed and foot-on events of the limbs. Incorrect classification was usually a result of canter and gallop misclassification, which are the classes with the lowest numbers of strides in the dataset. Increasing the number of collected strides for these gaits is likely to reduce this misclassification. The second highest misclassification rate occurs between tolt and pace, particularly pace strides being classified as tolt. This supports the observation by Zips that tolt, especially at the higher speeds, resembles a four-beat pace (Zips et al., 2001), so a misclassification of these gaits is likely. In addition, there are considerably less strides for pace than for the other symmetrical gaits, thus additional collection of pace stride timing data might improve the classification rate.

An LDA has advantages over previous methods of gait identification, such as the gait plots of Hildebrand, as it uses the same technique to classify symmetrical and asymmetrical gaits and considers stride data for all four limbs rather than data from two limbs (as in the Hildebrand symmetrical gait approach, or averages from four limbs as in Hildebrand asymmetric approach). In Fig. 3, the symmetrical gait data of this study have been analysed by the method of Hildebrand and overlaid on his gait plot for the symmetrical gaits. Although the data do roughly line up, the gaits (especially tolt and pace) do not clearly separate into discrete clusters on the gait graph and so classification using the Hildebrand method would be challenging. Gaits (both symmetric and asymmetric) lay in more distinct clusters in the LDA feature space compared with the Hildebrand gait plots. However, 'biological' interpretation of LDA data is more difficult since the gait parameters are combined and merged into LDA factors. A novel approach to gait classification of both symmetrical and asymmetrical gaits was presented by Abourachid (Abourachid, 2003). Similar to our approach, that method relies on time lags between foot-falls, however it is highlighting that the sequence of foot-falls is initiated by the front legs and is followed by the movement of the hind legs. In contrast to our approach, which has been designed for automated classification of quadrupedal gait, that approach is emphasising the control mechanism for locomotion in quadrupeds.

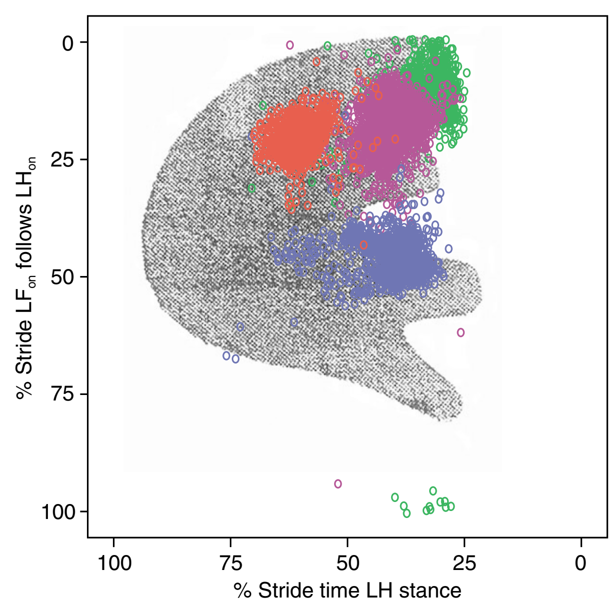

Fig. 3. The symmetrical gait plot of Hildebrand (Hildebrand, 1989) overlaid with the walk (red circles), tolt (purple circles), trot (blue circles) and pace (green circles) data from this study. The findings of this study do not perfectly match those of Hildebrand.

From the LDA results it appears that tolt, trot, pace, canter and gallop form a gait continuum in terms of ratios of foot-fall events. Walk strides occupy an area located towards higher values of LDA function 1 and they are nicely separated from the other gaits. This is unsurprising, since walk is confined to the slower speeds, thus LDA function 1, which is mainly correlated to stance times, should discriminate between gaits with higher and lower stance times.

Left canter and gallop strides separate clearly from right canter and gallop strides along the second LDA axis, the symmetrical gaits build clusters between them. Seemingly, in the LDA space, a left canter is thus more similar to a trot than to a right canter. This can be explained since the second LDA function is mainly correlated to RF_{on}, which is measured relative to LF_{on} (see Materials and methods). The relative time of RF_{on} thus increases from a right lead canter (where it occurs immediately after LF_{on}), to a trot (about 50% after LF_{on}) to a left lead canter (immediately before the next LF_{on}).

The biological significance of empty areas on the LDA plot is unclear. In order to be able to compare the unclassified strides with the rest of the dataset, the LDA matrix was applied to the stride parameters of the unclassified strides, and the resulting LDA features have been added to the LDA plots. Applying an LDA matrix to unclassified data is a standard approach in statistical pattern recognition tasks like automated speech recognition, where LDA is often incorporated in the feature extraction stage (Haeb-Umbach and Ney, 1992). The unclassified strides are distributed about the identified strides in a relatively uniform manner as shown in Fig. 4, further suggesting that gaits can be viewed as a continuum. This is supported by the observation during data analysis that many strides (except for trot) tended to resemble tolt, and different gaits could be considered as a shift in gait parameters from this baseline.

Use of an LDA would be a valuable method for automated gait identification in gait transition and perturbation studies (such as control of inter-stride variation). The LDA could be explored in the future by inclusion of gaits of other quadrupeds to generate a general gait classification model (rather than one that has been tested only on Icelandic horses) and to include motion data with foot-fall timings to aid correct identification of gaits.

Implications for gait selection

Differences in stance times and duty factors between walk and tolt occurred at the lowest speeds (which may be due to the classification of tolt strides), indicating that walk would be preferable to tolt below 3 m s^{-1} (as contact times were longer, so energetic cost may be less and duty factors greater, resulting in a lower peak limb force). Duty factors dropped to the lowest values recorded and stance times were comparatively low at the higher speeds of tolt relative to the other gaits. If the ground reaction force–time curve is of similar shape in both gaits [which it appears to be (Biknevicius et al., 2004)], this deviation in duty factors at the fastest tolts suggests that peak limb force would be approximately 10% greater at a tolt of 7 m s^{-1} than at the other gaits (duty factor of 0.29 *vs* 0.33). This contradiction to the results reported in Biknevicius et al. (Biknevicius et al., 2004) is interesting and worthy of further investigation. As the minimum duty factor during tolt was similar to the minimum obtained at pace at the highest speeds, peak limb force might perhaps be a limit to maximum tolt speed. At this highest speed, the energetic cost of tolt would be predicted to be approximately 15% greater than for the asymmetric gaits and pace based on stance times (Kram and Taylor, 1990). Therefore, peak limb forces or energetic cost might be driving factors to select canter, gallop or pace rather than tolt above 6 m s^{-1}. However, other factors such as limb interference are also likely to be involved. In future studies it would be desirable to measure, in addition to individual limb

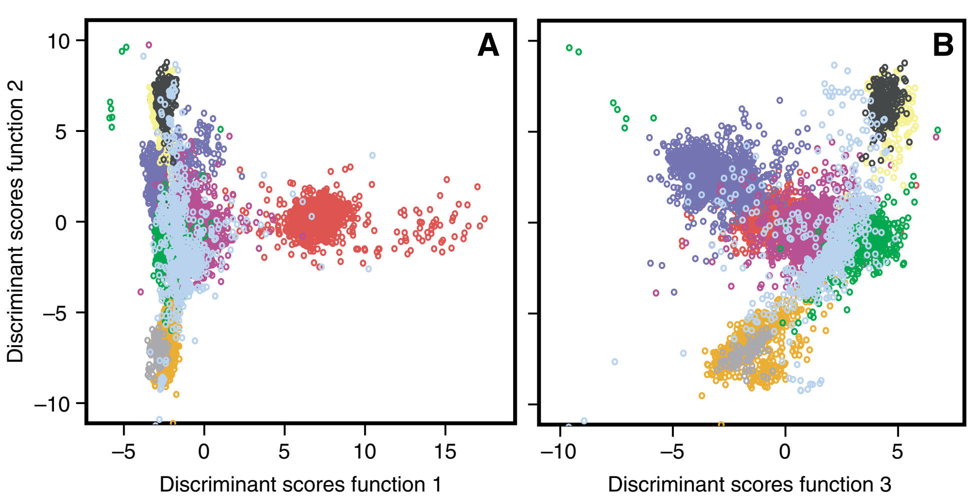

Fig. 4. Linear discriminant analysis results, including unclassified strides: (A) function 2 against function 1, (B) function 2 against function 3 for walk (red circles, *N*=1414), tolt (purple circles, *N*=2279), trot (blue circles, *N*=1777), pace (green circles, *N*=262), left canter (yellow circles, *N*=597), left gallop (black circles, *N*=106), right canter (orange circles, *N*=542), right gallop (grey circles, *N*=158) and all unclassified strides (light blue circles, *N*=806).

timing, limb forces, centre of mass movement and metabolic cost.

Conclusions

Foot-fall timings were collected from a total of 9687 strides of eight different gaits in Icelandic horses. Stance times, swing times and duty factors tended to decline with speed in a similar manner for all gaits. Foot-fall timings were found to be symmetrical (left and right forelimbs and left and right hindlimbs had equal stance times and ratios) for the 'symmetrical' gaits of walk, tolt, trot and pace. Although there were differences in stance times and duty factors, these differences were generally not consistent between gaits and were unlikely to be of biological significance due to their small magnitude. Consideration of peak limb force or energetics derived from contact times suggests that these factors may not be the principal driving factors in gait transition between walk, trot, pace, canters and gallops, although these factors may influence the use of tolt at the lower and higher speeds.

It was hypothesised that all gaits can be represented as a continuum and each gait falls into a cluster within this continuum. Each gait did indeed occupy clusters in an LDA space and it is concluded that the running gaits (tolt, trot, pace, left and right canters and gallops) could be considered as a continuum in the LDA space but the relationship with walk may be more complex. Therefore, LDA has enabled us to specify one set of criteria to distinguish accurately between the symmetric and asymmetric gaits.

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References

Abourachid, A. (2003). A new way of analysing symmetrical and asymmetrical gaits in quadrupeds. *C. R. Biol.* **326**, 625-630.

Back, W. and Clayton, H. M. (ed.) (2001). *Equine Locomotion* (1st edn), p. 8. London: W. B. Saunders.

Back, W., Schamhardt, H. C. and Barneveld, A. (1997). Kinematic comparison of the leading and trailing fore- and hindlimbs at the canter. *Equine Vet. J. Suppl.* **23**, 80-83.

Barras, C., Geoffrois, E., Wu, Z. and Liberman, M. (1998). Transcriber: a free tool for segmenting, labeling and transcribing speech. In *Proceedings of the First International Conference on Language Resources and Evaluation* (LREC'98), pp. 1373-1376. Granada, Spain: European Language Resources Association.

Barrey, E. (1999). Methods, applications and limitations of gait analysis in horses. *Vet. J.* **157**, 7-22.

Biknevicius, A. R., Mullineaux, D. R. and Clayton, H. M. (2004). Ground reaction forces and limb function in tolting Icelandic horses. *Equine Vet. J.* **36**, 743-747.

Clayton, H. M. (1994a). Comparison of the stride kinematics of the collected, working, medium and extended trot in horses. *Equine Vet. J.* **26**, 230-234.

Clayton, H. M. (1994b). Comparison of the collected, working, medium and extended canters. *Equine Vet. J. Suppl.* **17**, 16-19.

Deuel, N. R. and Lawrence, L. M. (1986). Gallop velocity and limb contact variables of quater horses. *J. Equine Vet. Sci.* **6**, 143-147.

Drevemo, S., Dalin, G., Fredricson, I. and Bjorne, K. (1980a). Equine locomotion: 3. The reproducibility of gait in standardbred trotters. *Equine Vet. J.* **12**, 71-73.

Drevemo, S., Dalin, G., Fredricson, I. and Hjerten, G. (1980b). Equine locomotion: 1. The analysis of linear and temporal stride characteristics of trotting standardbreds. *Equine Vet. J.* **12**, 60-65.

Drevemo, S., Fredricson, I., Dalin, G. and Bjorne, K. (1980c). Equine locomotion: 2. The analysis of coordination between limbs of trotting standardbreds. *Equine Vet. J.* **12**, 66-70.

Haeb-Umbach, R. and Ney, H. (1992). Linear discriminant analysis for improved large vocabulary continuous speech recognition. In *Proceedings of the International Conference on Acoustics Speech and Signal Processing*. Vol. 1, pp. 13-16. Piscataway, NJ: IEEE.

Hildebrand, M. (1959). Motions of the running cheetah and horse. *J. Mammal.* **40**, 481-495.

Hildebrand, M. (1965). Symmetrical gaits of horses. *Science* **150**, 701-708.

Hildebrand, M. (1989). The quadrupedal gaits of vertebrates. *Bioscience* **39**, 766-774.

Kram, R. and Taylor, C. R. (1990). Energetics of running: a new perspective. *Nature* **346**, 265-267.

Keegan, K. G., Yonezawa, Y., Pai, P. F., Wilson, D. A. and Kramer, J. (2004). Evaluation of a sensor-based system of motion analysis for detection and quantification of forelimb and hind limb lameness in horses. *Am. J. Vet. Res.* **65**, 665-670.

Nicodemus, M. C. and Clayton, H. M. (2003). Temporal variables of four-beat, stepping gaits of gaited horses. *Appl. Anim. Behav. Sci.* **80**, 133-142.

Pfau, T., Witte, T. H. and Wilson, A. M. (2005). A method for deriving displacement data during cyclical movement using an inertial sensor. *J. Exp. Biol.* **208**, 2503-2514.

Pfau, T., Witte, T. H. and Wilson, A. M. (2006). Centre of mass movement and mechanical energy fluctuation during gallop locomotion in the Thoroughbred racehorse. *J. Exp. Biol.* **209**, 3742-3757.

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J. and Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J. Appl. Physiol.* **89**, 1991-1999.

Wilson, B. D., Neal, R. J., Howard, A. and Groenendyk, S. (1987a). The gait of pacers. 1, Kinematics of the racing stride. *Equine Vet. J.* **20**, 341-346.

Wilson, B. D., Neal, R. J., Howard, A. and Groenendyk, S. (1987b). The gait of pacers. 2, Factors influencing pacing speed. *Equine Vet. J.* **20**, 347-351.

Witte, T. H. and Wilson, A. M. (2005). Accuracy of WAAS-enabled GPS for the determination of position and speed over ground. *J. Biomech.* **38**, 1717-1722.

Witte, T. H., Knill, K. and Wilson, A. M. (2004). Determination of peak vertical ground reaction force from duty factor in the horse (*Equus caballus*). *J. Exp. Biol.* **207**, 3639-3648.

Zips, S., Peham, C., Scheidl, M., Licka, T. and Girtler, D. (2001). Motion pattern of the toelt of Icelandic horses at different speeds. *Equine Vet. J. Suppl.* **33**, 109-111.