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Kinematic Analysis of Jumping Sequences of Olympic Show Jumping Horses

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ABSTRACT Limb contact variables of the approach, jump, and recovery strides were analyzed for competing horses at the 1988 Summer Olympic Games during Show Jumping competition. Two 16 mm motion picture cameras (200 frames s^{-1}) filmed perpendicular to the plane of motion over Fence 6 (1.5 m high, 1.9 m spread), and Fence 10 (1.6 m high, 1.0 m spread). Forty-one horses in Round 1 of the Team Show Jumping were filmed, with films of 29 jumping both fences analyzed. For the two jumps velocities, stride lengths and stride frequencies averaged, respectively, for the approach stride 7.92 ± 0.17 m s^{-1} (mean ± SE), 2.74 ± 0.05 m, and 2.89 ± 0.04 s^{-1}; for the jump stride 5.91 ± 0.05 m s^{-1}, 6.28 ± 0.05 m, and 0.94 ± 0.01 s^{-1}; and for the recovery stride 7.76 ± 0.09 m s^{-1}, 3.87 ± 0.04 m, and 2.01 ± 0.02 s^{-1}. Certain kinematic variables of each stride in the jumping sequences were found to be associated with superior performances. This study provided the first objective documentation of the limb contact patterns for the jumping sequence of world-class show jumping horses

Key words Biomechanics; kinematics; gaits; locomotion; jumping; horses.

INTRODUCTION

Many texts have discussed the practical aspects of motion desirable in a jumping horse.[3,4] The motion characteristics of jumping in Grand Prix show jumping horses,[9] and in eventing horses jumping a steeplechase fence[8] have been documented. However, few studies have been conducted on jumping in horses.[6–9]

Research has not yet associated kinematics of jumping with successful athletic performance in horses.[6,7] World-class show jumpers are the equine athletes most highly trained and specialized in jumping skills. The objectives of this study were to document the limb contact kinematics of the approach, jump, and recovery strides of world-class show jumping horses, and to associate variation in limb contact variables of each stride with scores in the Team Show Jumping competition at the 1988 Seoul Summer Olympic Games.

This study of equine kinematics was confined to linear and temporal variables delimited by limb impacts and lift-offs, since these represent the summary result of all rotational and translational movements of body limb segments through the jumping sequence.

MATERIALS AND METHODS

Filming procedure

Limb contact variables were determined for the jumping sequences. Horses were filmed with two 16 mm motion picture cameras, filming at 200 fps, aimed perpendicular to the plane of motion over Fence 6 and/or Fence 10. The exposure time was 1/600 s per frame. The projected image size was 4.8 to 5.9 cm per real meter, with a field width of 15 to 20 real m.

Forty-one of the 64 competitors were filmed during the first of 2 rounds of Team

Show Jumping competition, with sequences available for 29 horses over both fences. Horses filmed were selected from the nations considered strong in the sport of show jumping, since film availability was limited.

Film data collection

Limb contact timing variables were calculated from frame-by-frame determinations from projected film images of limb impacts and lift offs, utilizing previously established methods and nomenclature.[1-3] All linear and temporal measurements were demarcated by the impact or lift-off of one or more hooves. The hoof impact frame was defined as the first frame following partial obscuring of the hoof sole and preceding rapid dorsiflexion of the fetlock joint. The hoof lift-off frame was defined as the first frame after limb contact in which the relative flexion angle between the cannon and pastern was less than 180°, or for the take-off, the first frame in which the distal edge of the hoof image was completely visible. Linear distances were calculated from conversions of projected image distances utilizing a reference meter stick filmed in the plane of motion. Stride lengths were determined by converted linear measurements of horizontal hoof displacements between successive impacts of the hind trailing limb. Stride frequencies were determined by counting the number of frames for an entire stride, then dividing by 200 fps to yield stride duration, then calculating the inverse to obtain stride frequency. Velocities were calculated for each stride as the product of stride length and stride frequency.

Scoring

Show jumping is scored on fence knockdowns and completing the course within the prescribed time limit. Refusals to jump incur additional penalties. The total penalties for 2 jumping rounds constituted the score for each competitor. Although only the first round was filmed, the average of the Round 1 and Round 2 jumping penalties (average knockdown penalties), as well as the average of the Round 1 and Round 2 time penalties (average time penalties), were utilized in the data analyses. They were considered more representative of the horse's jumping performance on that particular day.

Data analyses

The strides analyzed were the final stride preceding the jump (approach stride), the jump (jump stride) and the first stride after the jump (recovery stride).[1-3] Interrelationships between total penalties and kinematic variables were examined for each stride in the jumping sequence by means of multiple linear regression techniques. Limb contact data were subjected to multiple linear regression analyses of variance[1-3,10] to segregate and individually determine the effects of the fence, lead, total penalties, stride length, and stride frequency on linear and temporal variables for each stride. The inclusion of lead, total penalties, stride length and stride frequency as covariables permitted the calculation of least square means for kinematic variables for each stride for each fence on an equivalent-lead,[2] equivalent-score,[3] and equivalent-velocity[1] basis. Simple correlations were also calculated to determine the interrelationships between scores and between stride length, stride frequency, and velocity.

Combinations of linear or temporal variables associated with scores were determined for each stride by stepwise multiple regression,[9,10] using the maximum r^2 improvement method with a $p<0.15$ level for inclusion in the model and a $p>0.15$ level for deletion. Models selected and presented herein are those regression equations ($p<0.05$) in which the number of variables most closely approached the C_p statistic.[10]

RESULTS AND DISCUSSION

The individual gold medalist is depicted in Fig. 1 jumping Fence 10. For the approach stride, the impact locations of the right fore trailing limb and left fore leading limb are shown, closely followed by the jump stride impact locations for the left hind trailing

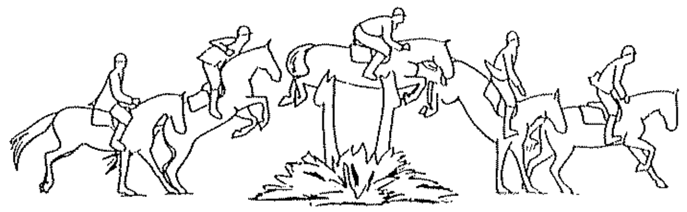

Fig 1 Depiction of Fence 10 jumping sequence of the 1988 Olympic Show Jumping individual gold medalist, Jappeloup

limb and the right hind leading limb in the take-off. Following the execution of the jump, the impact locations are shown for the right fore trailing limb and the left fore leading limb in the completion of the jump stride during the landing. Subsequently, in the recovery stride, the placements of the left hind trailing limb and the right hind leading limb are shown.

For all horses jumping both fences, the hind lead impact distance before the first rail upon take-off did not differ ($p>0.10$) from the distance of the fore lead impact after the final rail. The distance between hindlimb impacts in the take-off averaged <25 cm, while the distance between forelimb impacts in the landing averaged >90 cm. Consequently, the distances before the first rail of the fore trail impact, fore lead impact, and hind trail impact were each significantly ($p<0.05$) closer to the fence than the subsequent impacts in landing of the fore leading limb, hind trailing limb, and hind leading limb, respectively.

Scoring

Total score for Team Show Jumping competitors averaged 22.5±2.2 penalty points (mean ± SE), range 4.25 to 78.25 penalty points. Average knockdown penalties for the 2 rounds was 11.1±1.1 points, range 2.0 to 38.0, while average time penalties was 0.29±0.06 points, range 0 to 1.75.

Average knockdown penalties were found to be closely related to total penalty points (correlation coefficient 0.985, $p<0.0001$), while average time penalties were not significantly associated with total penalty points (correlation coefficient 0.177, $p<0.20$). An inspection of the scores revealed that average knockdown penalties correctly ranked all competitors finishing both jumping rounds, while average time penalties only reflected the rank of horses within groups completing both rounds with equal knockdown penalties.

Lead effects

Fence 6 was approached from a clockwise turn, followed by a wide counter-clockwise turn. Accordingly,[9] approach strides were predominantly right lead (Fig. 2), while jump and recovery strides were predominantly left lead. However, the frequency distribution of leads for each stride in the jumping sequence did not reach significance ($x^2=9.4$, $df=6$, $p<0.16$).

Fence 10 was approached from a clockwise turn, followed by a straight approach to the water jump with a visible increase in velocity. There were differences in lead fre-

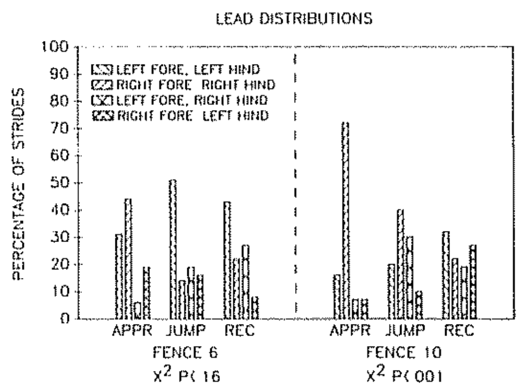

Fig 2 Lead distributions of approach, jump, and recovery strides in the jumping sequences for Fences 6 and 10, expressed as percentages of that particular stride. $n=27$ jumping sequences for each fence

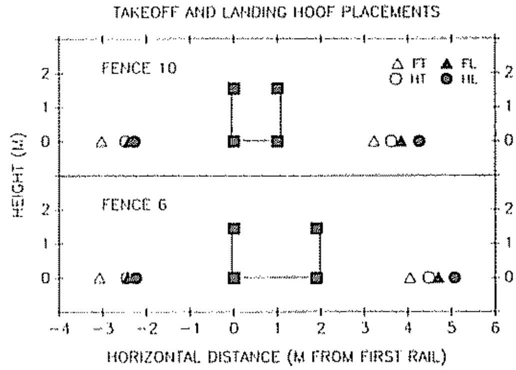

Fig 3 Mean hoof placements for take-offs and landings relative to the first rail of Fences 6 and 10. $n=27$ jumping sequences for each fence. H = Hind, F = Fore, L = Lead, T = Trail

quencies according to stride in the jumping sequence for Fence 10 ($x^2=22.5$, 6 *df*, $p<0.001$). Approach strides were 72% right lead, while recovery strides were only 22% right lead.

Fence effects

Fence 6 was 94% of the height and 190% of the width of Fence 10. When data were standardized for velocity effects, there were no significant differences between fences in the distance of the hoof placements before the first rail, nor in the distance of the hoof placements after the final rail (Fig. 3). The distances between pre-fence and post-fence hoof impact locations were all longer ($p<0.0001$) for Fence 6 than Fence 10. The differences were approximately the difference between the fences in the width between the first and final rails.

The stride lengths, stride frequencies and velocities for each stride for each fence are shown in Table 3. Both fences were approached at ~7.8 m s^{-1} with a short stride of quick duration. The horizontal velocity slowed significantly during the jump to ~5.9 m s^{-1} with a long jump stride duration of ~1.06 s. The recovery stride was a normal gallop stride[1-3] of 7.6 to 7.9 m s^{-1} with a

Table 1. *Effects of fence and stride on successive hoof impact distances*

	Approach stride		Jump stride		Recovery stride		
Fence	6	10	6	10	6	10	SD
Velocity (m s^{-1})	7.8^{a}	8.0^{a}	5.9^{c}	6.1^{c}	7.6^{b}	7.9^{a}	0.8
Stride length (m)*	2.55^{a}	2.74^{a}	6.25^{c}	6.37^{c}	3.90^{b}	3.81^{b}	0.36
Stride frequency (s^{-1})‡	3.04^{a}	2.89^{b}	0.93^{c}	0.96^{c}	1.95^{d}	2.08^{c}	0.21
Hoof impact distances							
HT→HL (m)	0.60^{a}	0.67^{a}	0.25^{b}	0.18^{b}	0.63^{a}	0.54^{a}	0.30
(%)	23.1^{a}	24.3^{a}	4.1^{c}	2.7^{c}	16.3^{ab}	13.9^{b}	10.0
HL→FT (m)	1.34^{a}	1.59^{b}	5.54^{d}	5.73^{e}	2.01^{c}	1.90^{c}	0.35
(%)	53.6^{a}	57.1^{a}	88.2^{b}	90.2^{b}	52.0^{a}	50.0^{a}	8.7
FT→FL (m)	0.65^{ab}	0.67^{b}	0.66^{b}	0.60^{a}	0.92^{c}	0.93^{c}	0.12
(%)	25.5^{a}	23.7^{a}	10.8^{b}	9.3^{b}	23.6^{a}	24.5^{a}	3.2
FL→HT (m)	-0.07^{a}	-0.05^{a}	-0.28^{c}	-0.19^{bc}	0.40^{d}	0.45^{d}	0.17
(%)	-3.2^{a}	-2.9^{a}	-4.7^{a}	-3.2^{a}	9.7^{b}	11.7^{b}	4.5

Values are least square means adjusted to an average total score and lead effect. Values in each row without common letter superscripts differ ($p<0.05$). $n=29$ strides for Fence 6, 27 strides for Fence 10. H = Hind, F = Fore, L = Lead, T = Trail.

* Comparisons made on an equivalent stride frequency basis

‡ Comparisons made on an equivalent stride length basis.

Table 2. *Effects of fence and stride on limb contact temporal variables*

	Approach stride		Jump stride		Recovery stride		
Fence	6	10	6	10	6	10	SD
Stride duration (s)*	0.33^{a}	0.35^{a}	1.07^{e}	1.05^{d}	0.52^{c}	0.48^{b}	0.04
Limb contact durations (s)							
HT	0.114^{a}	0.136^{b}	0.195^{d}	0.196^{d}	0.164^{c}	0.166^{c}	0.019
HL	0.105^{a}	0.115^{a}	0.190^{c}	0.183^{bc}	0.177^{b}	0.184^{bc}	0.018
FT	0.165^{ab}	0.174^{a}	0.152^{c}	0.151^{c}	0.164^{b}	0.165^{ab}	0.019
FL	0.156^{bc}	0.157^{c}	0.181^{d}	0.183^{d}	0.149^{ab}	0.143^{a}	0.014
Limb non-contact durations (s)							
HT	0.216^{a}	0.217^{a}	0.878^{e}	0.853^{d}	0.352^{c}	0.318^{b}	0.032
HL	0.226^{a}	0.237^{a}	0.883^{e}	0.866^{d}	0.338^{c}	0.301^{b}	0.032
FT	0.165^{a}	0.179^{a}	0.920^{e}	0.898^{d}	0.352^{c}	0.320^{b}	0.035
FL	0.175^{a}	0.196^{b}	0.891^{f}	0.866^{e}	0.367^{d}	0.341^{c}	0.032
Limb impact intervals (s)							
HT → HL	0.049^{b}	0.063^{a}	0.011^{d}	0.025^{c}	0.042^{b}	0.045^{b}	0.019
HL → FT	0.033^{a}	0.029^{a}	0.830^{d}	0.795^{c}	0.091^{b}	0.089^{b}	0.030
FT → FL	0.062^{b}	0.075^{c}	0.037^{a}	0.037^{a}	0.125^{d}	0.120^{d}	0.019
FL → HT	0.187^{a}	0.185^{a}	0.194^{a}	0.193^{a}	0.257^{c}	0.229^{b}	0.030

Values are least square means adjusted to an average total score and lead effect. Values in each row without common letter superscripts differ ($p<0.05$). $n=29$ strides for each fence. H = Hind, F = Fore, L = Lead, T = Trail

* Comparisons made on an equivalent stride length basis.

moderate stride length. Velocities and stride frequencies of the recovery strides of Fence 10 were significantly higher than for Fence 6. The differences in recovery strides were presumably due to the necessity to increase horizontal velocity after Fence 10 on the approach to a 4.6-m-wide water jump.

Across all strides, velocity and stride length were positively related (correlation coefficient 0.90, $p<0.0001$), as were velocity and stride frequency (correlation coefficient 0.37, $p<0.01$). However, stride length and stride frequency were not significantly related, confirming the ability of the horse to independently adjust step lengths and timings of limb motions.[1]

The effects of fence and stride on successive hoof impact distances are given in Table 1, and the effects on limb contact temporal variables are in Table 2.

Fence 6, with a wider spread, was approached at a higher stride frequency than fence 10. On an equivalent-velocity basis, several differences ($p<0.05$) were determined in stride kinematics between Fences 6 and 10 jumping sequences. Approach strides for Fence 6 had shorter distances between hind lead and fore trail impacts, and lower hind trail contact durations. Similarly, jump strides for Fence 6 had longer non-contact durations for all limbs, shorter time intervals between hindlimb impacts, and longer time intervals between hind lead and fore trail impacts than Fence 10. Fence 6 jump strides also had a greater distance between the forelimbs upon landing. In recovery strides following Fence 6, there were shorter contact durations for both hindlimbs and a shorter time interval between hindlimb impacts than for Fence 10. Fence 6 recovery strides

Table 3. *Effects of jump stride sequence linear variables on scores*

Dependent variable	Independent variables	Independent variable B values	Standard errors	R-square
Approach stride				
Total penalties	Intercept	24.22		0.11
	FL→HT distance (m)	25.98	11.50	
Average time penalties	Intercept	12.27		0.13
	FL→HT distance (m)	14.96	5.27	
Jump stride				
Total penalties	Intercept	49.26		0.35
	Velocity (m s^{-1})	9.68	4.15	
	FT→FL distance (m)	20.15	12.42	
	FT→rail distance (m)	−29.89	6.96	
	HT→HT distance (m)	20.73	6.79	
	HL→HL distance (m)	−20.53	6.11	
Average knockdown penalties	Intercept	41.14		0.27
	FT→rail distance (m)	−12.14	3.61	
	Rail→HT distance (m)	5.13	2.65	
	HT→HT distance (m)	10.02	3.84	
	HL→HL distance (m)	−10.43	3.42	
Average time penalties	Intercept	−0.55		0.16
	HT→rail distance (m)	−0.82	0.38	
	HL→rail distance (m)	1.26	0.43	
Recovery stride				
Average time penalties	Intercept	0.12		0.14
	Stride length (m)	−0.36	0.20	
	HL→FT impacts (m)	0.26	0.13	
	FT→FL impacts (m)	1.13	0.54	

Equations are the results of stepwise multiple linear regression ($p<0.05$). H = Hind, F = Fore, T = Trail, L = Lead.

also had longer non-contact durations for the hind trailing limb, the hind leading limb, and the fore trailing limb; as well as longer time intervals beween the fore leading limb impact and the hind trailing limb impact of the subsequent stride. These differences may reflect differences in biomechanical techniques and muscular forces required to propel the center of mass over a 90% greater distance in executing the jump over Fence 6 than over Fence 10.

Relationships between kinematic variables and score

Tables 3 and 4 contain the results of stepwise multiple linear regression analyses relating scores to linear and temporal variables of the approach, jump, and recovery strides. The r^2 values from the stepwise multiple linear regressions represent the proportion of variability in scores that can be associated with variability in the group of kinematic parameters selected. Due to the homogeneity of the population, statistically significant rela-

Table 4. *Effects of jump stride sequence linear variables on scores*

Dependent variable	Independent variables	Independent variable B values	Standard errors	R-square
Jump stride				
Total penalties	Intercept	−116.94		0.19
	Velocity (m s⁻¹)	6.44	3.91	
	HT contact (s)	239.05	104.47	
	FL contact (s)	292.75	159.04	
Average knockdown penalties	Intercept	28.23		0.21
	HL contact (s)	183.62	55.04	
	HL→FT impacts (s)	−57.12	26.94	
	FT→FL impacts (s)	143.71	93.16	
Average time penalties	Intercept	−0.96		0.28
	Velocity (m s⁻¹)	0.21	0.12	
	FL contact (s)	5.33	5.07	
	HL non-contact (s)	8.97	3.47	
	FT non-contact (s)	−10.49	3.21	
	HL→FT impacts (s)	−5.78	3.32	
	FL→HT impacts (s)	4.11	2.36	
Recovery stride				
Total penalties	Intercept	32.36		0.18
	HL contact (s)	124.32	113.54	
	HT non-contact (s)	−228.78	72.05	
	HT→HL impacts (s)	113.39	98.63	
	FL→HT impacts (s)	159.26	72.16	
Average knockdown penalties	Intercept	14.18		0.22
	HT contact (s)	145.76	76.60	
	HL non-contact (s)	−52.81	55.33	
	FT non-contact (s)	22.44	57.96	
	HL→FT impacts (s)	−64.56	47.62	
	FT→FL impacts (s)	−98.96	47.22	
Average time penalties	Intercept	2.26		0.17
	Velocity (m s⁻¹)	−0.08	0.09	
	HL contact (s)	−8.86	3.62	
	FL contact (s)	6.15	3.72	
	FT non-contact (s)	−1.95	1.66	

Equations are the results of stepwise multiple linear regression ($p<0.05$). H = Hind, F = Fore, T = Trail, L = Lead.

tionships found in this study should be considered meaningful for world-class show jumping horses, even though some r^2 values may appear low. One might expect higher r^2 values from a more heterogeneous population.

Approach strides. Approach strides had the highest velocities and stride frequencies of the jumping sequence, although they had the shortest stride lengths. On an equivalent-velocity basis, approach strides compared to recovery strides had shorter distances between forelimb impacts, greater forelimb contact durations, and shorter distances between fore leading limb impacts and subsequent hind trailing limb impacts. Approach strides also had the longest time intervals between hindlimb impacts of any jump sequence stride and the briefest time intervals between hind leading limb and fore trailing limb impacts.

Fewer total and time penalties were associated with approach strides that had the fore leading limb impact placed closer to the first fence rail than the subsequent hind trailing limb placement of the jump stride. Fewer knockdowns were associated with an increased distance of the fore trailing limb placement before the first fence rail.

Jump strides. Horizontal velocities were the slowest of the sequence during the jump stride, since horizontal momentum and kinetic energy were converted to vertical momentum and potential energy as the horse projected the center of mass upward and forward. Stride lengths were longer and stride frequencies lower than approach or recovery strides. On an equivalent-velocity basis, the jump stride had the shortest linear distances and time intervals between hindlimb impacts and forelimb impacts, and the longest linear distances and time intervals between hind leading limb impacts and fore trailing limb impacts. The fore trailing limb contact duration of the jump stride upon landing was the briefest of the sequence. The termination of the jump stride had the briefest time interval between fore trailing limb impacts and subsequent hind trailing limb impacts, and the hind trailing limb impact of the recovery stride was placed the greatest distance behind the previous fore leading limb impact.

Fewer total penalties were associated with jump strides of lower velocities, decreased hind trail and fore lead contact durations, and shorter distances between forelimb placements. Fewer knockdowns were associated with a decreased distance between successive hind trailing limb impacts and an increased distance between successive hind leading limb impacts over the jump. This may have been accomplished by a shortened distance between hindlimbs in the take-off and a lengthened distance between the hindlimbs in the landing. Fewer knockdowns were also associated with landings that had a greater time interval between forelimb impacts, a shorter distance between forelimb placements, and with hind trail impacts closer after the final fence rail. Fewer time penalties were associated with take-offs in which the hindlimbs were placed closer together and the hind leading limb was placed closer to the first fence rail. Fewer time penalties were associated with landings with shorter fore leading limb contact durations and briefer time intervals between fore leading limb impacts and subsequent hind trailing limb impacts.

Recovery strides. The recovery stride, on an equivalent-velocity basis, had the longest hind leading limb contact duration and briefest fore leading limb contact duration of the sequence. The time interval between hindlimb impacts was shorter than the approach stride, while the time interval between hind leading limb impacts and fore trailing limb impacts was greater than the approach stride. The recovery stride also had longer distances and longer time intervals between forelimb impacts than the approach stride.

Fewer total penalties were associated with recovery strides that had a reduced time between hindlimb impacts, a reduced hind lead contact duration, and a decreased time interval between fore leading limb and subsequent hind trailing limb impacts. Fewer knockdowns were associated with recovery strides that had an increased time interval between hind leading limb and fore trailing limb impacts, and also an increased time interval between forelimb impacts. Fewer time penalties were associated with take-off strides that had greater velocities from longer stride lengths, in hastening to the next fence.

CONCLUSIONS

1. This study presents some reference values on the biomechanics of jumping in world-class horses.

2. Spread of the jump did not influence approach velocity, take-off distances from the fence or landing distances from the fence. A greater fence spread was associated with higher stride frequencies in the approach, shorter time intervals between take-off hindlimb impacts, longer time intervals between hind leading limb impact and the subsequent fore trailing limb impact in landing, and lower stride frequencies and slower velocities in the recovery stride.

3. In both take-offs and landings, the hind trailing limb usually was planted between the previous placements of the forelimbs, while the hind leading limb was placed ahead of the previous placement of the fore trailing limb.

4. Jump strides of horse with fewer total penalties had lower velocities, closer take-off hindlimb placements, and closer landing forelimb placements than those with greater penalty scores.

5. Recovery strides of successful compared to less successful horses, had briefer time intervals between hindlimb impacts, and briefer time intervals between fore leading limb impact and the initiation of the subsequent stride.

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