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Stride Characteristics of Four Grand Prix Jumping Horses

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ABSTRACT. High speed cinematography (250 Hz) was used to film 4 Grand Prix jumping horses, each performing 4 trials over a vertical fence 1.55 m high. Temporal, linear and angular variables were measured and comparisons between successive strides were made using a one-way analysis of variance and Duncan's multiple comparison test. In the last stride before take off there was a significant reduction in horizontal velocity ($p<0.05$) and kinematic alterations in the forelimb stance phases resulted in the raising of the forehand, which had an effect on the upward trajectory. At take-off both hind limbs had significantly longer stance durations than in any other stride ($p<0.05$), which favoured the generation of a large impulse. At landing the metacarpal segment of the trailing forelimb was almost vertical (89°), whereas the leading forelimb was more acute (68°). The first stride after landing was only 3.35 m in length, which was significantly shorter than the 4.07 m recorded for approach stride 2 ($p<0.05$).

Key words: Kinematics; biomechanics; horses; show jumping.

INTRODUCTION

During jumping, the approach and take-off are largerly responsible for the height or distance jumped.[7] It is important to characterize the desirable features of this phase of the equine jumping behaviour to aid in the selection of horses with natural talent and to indicate ways of improving the performance of less capable individuals. During the landing and move-off from the fence, the horse regains dynamic equilibrium and forward momentum. Information regarding this phase will provide a greater understanding of the effects on jumping behaviour of different distances between fences.

Previous studies of the kinematics of equine jumping have concentrated on the 4 limb impacts preceding and following the fence,[8–10] with the exception of a study describing the limb displacements from the base of the fence for 10 impacts on the take-off side and 8 impacts on the landing side.[4] Most of the measurements have been taken from films recorded during competitions.[9,10] The purpose of this study was to investigate the changes in some of the kinematic measurements of the stride in a group of experienced jumping horses during successive strides in the approach, take-off, landing and move-off. It differs from the previous reports in that the use of 2 stationary cameras facilitated the collection of data from a larger number of limb impacts on each side of the fence. The experimental protocol allowed some of the variables to be controlled, so that one rider rode all the horses and each horse performed multiple trials over the same fence, rather than recording only one or two trials for each horse/rider combination as in a competition.

MATERIALS AND METHODS

The subjects were 4 Grand Prix jumping horses, which were sound and free from locomotor problems (Table 1). All the horses

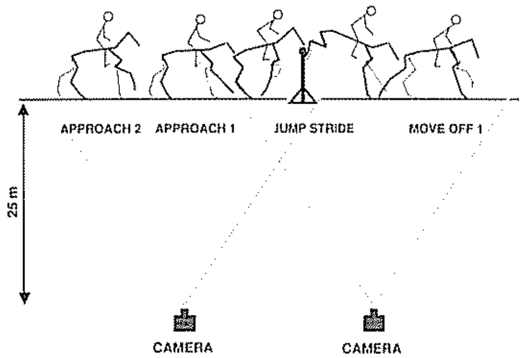

Fig 1 Camera set up and terminology for the strides (not to scale).

were ridden by the same, experienced rider. The studies were conducted outdoors in a sand arena, and were completed in one day. A vertical fence 1.55 m high was built using 2 standards and 5 striped rails, with the lowest rail placed on the ground vertically beneath the other rails. The rider was instructed to approach the fence alternately on the left and right leads at a speed consistent with the height of the fence, and to jump in the centre of the fence. After an appropriate warm up, each horse performed 4 trials, 2 each on the left and right leads.

Two high speed 16 mm cameras (Locam, Redlake Corp. Campbell, CA) were set up perpendicular to and 25 m from the horses' path of motion. The camera bodies were levelled at a height of 1.2 m, and the Angenieux zoom lenses were adjusted so that the camera on the take-off side recorded the 10 limb impacts preceding the jump and had a total field width of 15 m. The camera on the landing side recorded at least 7 limb impacts on the landing side and had a total field width of 12 m (Fig. 1). Calibration studies have indicated that the lens aberrations were small enough to be disregarded. The cameras were set to record at a frequency of 250 Hz, and a stopwatch was filmed for 3 seconds at the start and end of each film to calibrate the frame rate. The actual frame rates were used to calculate the temporal measurements. Errors were introduced into the temporal measurements due to the time elapsing between film frames and to the interpretive abilities of the film reader in determining the occurrence of impact and lift-off. These were estimated to involve a standard error of the order of 3 milliseconds (ms). A metre stick was filmed in the centre of each camera's field of view as a scale for determining the true displacement measurements.

The trailing hind limb, leading hind limb, trailing forelimb and leading forelimb are referred to by the abbreviations TrH, LdH, TrF and LdF, respectively. The stride is defined as starting at impact of the TrH and ending at the next impact of the TrH. The last 2 complete strides preceding take-off are called approach 2 (A2) and approach 1 (A1) in chronological order. The stride in which the horse jumps the fence is called the jump stride (JS). It is subdivided into the take-off (stance phases of the 2 hind limbs), the jump suspension (period from lift-off of the last hind limb to impact of the first forelimb) and the landing (stance phases of the 2 forelimbs). The stride following the jump stride is called move-off 1 (M1). The terminology for the strides has been described in detail[3] and is illustrated in Fig. 1.

Precision motion analysis was accomplished with the aid of a motion analyzer (Vanguard Instrument Corp, Mellville, NY) interfaced with a sonic digitizer (Graf-Pen, Science Accessories Corp, Southport, CT) and linked on-line with a personal computer (Compaq III Portable Computer, Compaq Computer Corp, Houston, Tx). Stride length was measured as the distance between successive impacts of the TrH, and the val-

Table 1. *Horses used in the study*

Horse	Breed	Age (yrs)	Height (cm)
1	Westphalian	10	167
2	Irish	12	169
3	Dutch	7	164
4	Selle Français	9	164

Table 2. *Mean values and (standard deviations) for the linear and temporal variables of the stride*

Variable	Approach stride 2	Approach stride 1	Jump stride	Move off stride 1
Horizontal velocity ($m\ s^{-1}$)	7.34^{abc} (0.41)	6.30^{a} (0.95)	5.93^{b} (0.11)	6.46^{c} (0.28)
Stride length (m)	4.07^{abc} (0.19)	2.39^{ade} (0.39)	4.87^{bdf} (0.15)	3.35^{cef} (0.28)
Stride duration (ms)	555^{ab} (29)	382^{acd} (44)	820^{bce} (22)	519^{de} (38)
Stance TrH (ms)	157^{a} (21)	145^{b} (23)	197^{abc} (23)	147^{c} (12)
Stance LdH (ms)	179^{ab} (10)	129^{acd} (17)	195^{bce} (21)	171^{de} (19)
Stance TrF (ms)	149^{ab} (22)	188^{acd} (21)	140^{ce} (15)	174^{bde} (17)
Stance LdF (ms)	134^{abc} (19)	159^{a} (14)	176^{b} (11)	168^{c} (13)

Superscripts indicate means that are significantly different ($p<0.05$) using a one-way ANOVA and Duncan's multiple comparison test. TrF = trailing forelimb, LdF = leading forelimb, TrH = trailing hind limb, LdH = leading hind limb.

ues were scaled to metric units using the metre stick. Stride duration was calculated from the number of frames of film elapsing between successive impacts of the TrH divided by the frame rate. Similarly, the stance duration of each limb was determined by counting the number frames elapsing between impact and lift-off. The average horizontal velocity of each stride was computed from the stride length divided by the stride duration. The angulation of the metapodial segment at impact and lift-off was determined by projecting the image onto a sheet of white paper on which a line was drawn. The line was superimposed on the long axis of the metapodium and used to determine the angle of the segment to the horizontal on the palmar or plantar aspect of the limb.

Statistical analyses were performed using a commercial software package (Statistical Packages for the Social Sciences, SPSS Inc., Chicago, IL). Descriptive statistics (mean, standard deviation) were computed for each variable. A one-way analysis of variance (ANOVA) was used to test the hypothesis that there was no significant difference between the values of the stride variables in the 4 strides (A2, A1, JS, M1). When the F statistic indicated that the mean values of the variables were probably unequal, Duncan's multiple comparison test was used to determine which strides were significantly different from each other. A probability level of 0.05 alpha was used for all the statistical tests.

RESULTS

In each of the 16 trials the horses cleared the fence. Lead changes did not occur during the approach or the move-off. The descriptive statistics, together with the results of the ANOVA and multiple comparison test, are shown for the temporal and linear variables in Table 2 and for the angular variables in Table 3. The temporal relationships between the limbs are represented in Fig. 2.

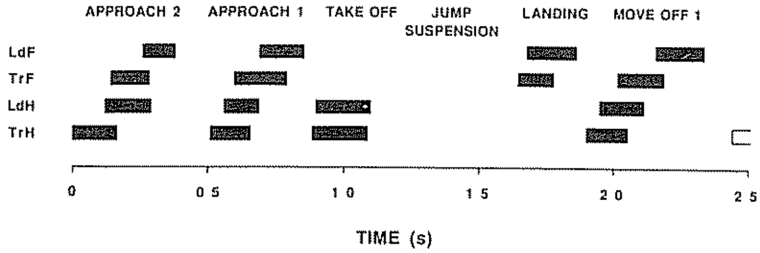

Fig 2 Relationship between the temporal variables. The bars represent the stance phases of the limbs TrH = trailing hind limb, LdH = leading hind limb, TrF = trailing forelimb, LdF = leading forelimb.

Approach stride 2

The horses approached the fence in a collected canter, with a 3-beat rhythm and a marked elevation of the head and neck. The stride length was 4.07 m and the stride duration was 555 ms. The average horizontal velocity of 7.34 m s^{-1} was significantly faster than in any other stride ($p<0.05$).

Approach stride 1

In stride A1, the canter had a 4-beat rhythm, and the head and neck were stretched forward and down in preparation for take-off. The stride duration of 382 ms was significantly shorter in stride A1 than in any other stride, and the horizontal velocity of 6.30 m s^{-1} was significantly reduced compared with the preceding stride ($p<0.05$). The LdH had a very short stance duration (129 ms) and the horse did not rotate over this limb as in a normal stride. Consequently the metatarsal angulation at lift-off (65°) was more acute than in strides A2, JS or M1 ($p<0.05$). The forelimbs initiated the upward movement of

Table 3. *Mean values and (standard deviations) of the angle between the metapodial segment and the horizontal measured in degrees on the palmar or plantar aspect of the limb*

Variable	Approach stride 2	Approach stride 1	Jump stride	Move off stride 1
Impact	55^{ab}	52^{cd}	43^{ace}	77^{bde}
TrH	(4)	(5)	(5)	(3)
Lift off	109^{abc}	79^{ade}	98^{bdf}	121^{cef}
TrH	(16)	(11)	(5)	(3)
Impact	46^{a}	49^{bc}	43^{bd}	57^{acd}
LdH	(3)	(6)	(5)	(7)
Lift off	105^{ab}	65^{acd}	96^{bce}	111^{de}
LdH	(13)	(12)	(6)	(9)
Impact	66^{ab}	58^{acd}	89^{bce}	64^{de}
TrF	(5)	(3)	(3)	(5)
Lift off	141^{ab}	128^{acd}	148^{bce}	139^{de}
TrF	(4)	(5)	(4)	(3)
Impact	60^{ab}	50^{acd}	68^{bce}	59^{de}
LdF	(5)	(4)	(4)	(4)
Lift off	125^{abc}	109^{ade}	144^{bdf}	132^{cef}
LdF	(10)	(4)	(3)	(3)

Superscripts indicate means that are significantly different ($p<0.05$) using a one-way ANOVA and Duncan's multiple comparison test TrF = trailing forelimb, LdF = leading forelimb, TrH = trailing hind limb, LdH = leading hind limb.

the forehand. They were stretched forward at impact, and the impact and lift-off angles of the metacarpal segments of both forelimbs were more acute in stride A1 than in any of the other 3 strides ($p<0.05$). Also the TrF had a particularly long stance duration in stride A1 (188 ms). The stick figures in Fig. 1 illustrate the collected frame in stride A2 compared with the gathered position in stride A1.

Jump stride

The jump stride was distinguished from the preceding and following strides by the inclusion of the jump suspension, which resulted in significant increases in stride length and duration. During the take-off, the stance durations of both hind limbs were significantly longer than in strides A2, A1 and M1 ($p<0.05$). At landing, the metacarpal segment of the TrF was almost vertical (89°), while that of the LdF was somewhat more acute (68°). The impact and lift off angles of both metacarpal segments were significantly greater than in any other stride ($p<0.05$).

Move-off stride 1

In this stride the impact angles of both metatarsal segments, and the lift off angle of the TrH, were greater than in strides A2, A1 and JS ($p<0.05$), and the canter had a 4-beat rhythm, as shown by the separation of the LdH and TrF impacts in Fig. 2.

DISCUSSION

The horizontal speed of approach in stride A2 was 7.33 m s^{-1}, which is less than 50% of the horse's estimated maximum velocity at the gallop. This suggests that the generation of a fast approach speed is relatively less important in the horse than in human high jumpers, long jumpers and pole vaulters, in which the speed of the approach run has an important effect on the success of the jumping effort.[1,2,7] In stride A1, the horses showed a significant reduction in the horizontal velocity ($p<0.05$). It is suggested that the deceleration allows more time to coordinate the body movements and to maximize the impulse during take-off.

In human jumpers the transition from the approach run to the take-off is known as the "gather". Generally stride length increases through the approach until the penultimate stride, with the final stride being somewhat shorter. The knee is flexed during the penultimate stance phase, so that the centre of gravity (CG) is low when the take-off foot hits the ground. This avoids the need for the take-off limb to arrest any downward motion of the CG before driving the body mass into the air.[5] It has even been suggested that the amount of lowering of the CG during the gather bears a direct relationship to the height jumped.[5] In the last step before take-off the human high jumper lowers the hips, leans the trunk backwards and places the take-off foot further forward than normal.[7] Based on the results of this study, it is concluded that horses show a gather phase in stride A1, with a reduction in stride length similar to that in the human jumper. The hind limbs were lowered throughout their stance phases, giving the impression that the horse was "sitting" on the hindquarters, while the forelimbs reached forward to make impact at a more acute angle than normal. The head and neck were considerably lower than in stride A2 (Fig. 1). There are some obvious similarities between the horse's position in stride A1 and that of the human high jumper just prior to take-off.

At take-off the path of the CG and the angular momentum of the body around the CG are established and these properties cannot be changed during the airborne phase until the horse makes contact with an external object. With regard to the path of the CG, the body mass is projected into the air through the horse applying a force against the ground that is greater than the bodyweight. The reaction to the force in excess of bodyweight produces the upward acceleration. Impulse is the product of the force and its duration of action. Therefore, to be most effective the limbs should exert a large force through a long stance phase. In stride A1, the forelimbs initiate the upward movement of the forehand, and their action is responsible for determining the height of the forehand at take-off, which affects the trajectory of the jump. The long stance duration of the TrF in stride A1 favours the generation of a large impulse. At take-off, the hind limbs impart vertical acceleration to the body. The fact that the stance durations of the 2 hind limbs at take off were significantly greater than in any other stride ($p<0.05$), favoured the generation of a large impulse.

At take-off, the body acquires angular momentum which allows it to rotate forward around the CG throughout the jump suspension, so that the forelimbs make impact first at landing. One way in which angular momentum is acquired is through the application of an eccentric force to the CG at take-off. The direction of the propulsive force at take-off is of fundamental importance in relation to both the development of angular momentum and the jump trajectory. This aspect of jumping kinematics warrants further study. During the landing phase, the direction of the rotation around the CG must be reversed, otherwise the horse would continue into a forward somersault. The reversal is brought about by the force exerted against the ground by the forelimbs at landing. Since the line of action of this force lies ahead of the CG, it reverses the forward rotation and causes the hind limbs to swing beneath the trunk. The TrF was almost vertical at landing, a finding that was consistent between and within individual horses. The LdF was considerably more acute at landing (68°). A more complete understanding of the functional responsibilities of the limbs awaits the results of kinetic studies.

In stride M1 the horse regains dynamic equilibrium. It has been suggested that M1 is a longer stride than normal,[6] but in this study the stride length of M1 (3.35 m) was significantly shorter than A1 (4.07 ml), indicating that the first stride after landing is relatively short when the horse jumps a single fence.

Previous studies of equine jumping kinematics have focussed on the 4 limb impacts preceding and following the jump. The stance durations of the individual limbs recorded in our study were similar to those for horses jumping a coop and rail fence 1.52 m high,[10] but were considerably longer than those for horses jumping a steeplechase fence 1.4 m high.[9] Direct comparisons are not possible because approach speeds were not given in the other studies. However, it is reasonable to assume that the steeplechase horses used a faster approach speed, and the apparent reductions in stance durations were probably speed-dependent. In the steeplechase study the angle of approach of the limbs to the ground was measured for the 4 limb impacts preceding the jump.[9] The values were very similar to those reported here, varying by no more than 4°.

Based upon the results of this study it is concluded that, for a vertical fence 1.55 m high, the horse approached in a collected canter. In stride A1, the horse showed a "gather", which involved a reduction in the horizontal speed and stride length, and a lowering of the CG prior to impact of the TrF. At take-off the long stance durations of the hind limbs favoured the generation of a large vertical impulse. The application of an eccentric force to the CG at take-off caused the body to rotate forward around the CG throughout the jump suspension. At landing, the action of the forelimbs reversed the direction of rotation, causing the hind limbs to swing beneath the trunk. In stride M1 the stride length was short, as the horse regained balance and forward momentum.

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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