Pferdeheilkunde 12 (1996) 4 (Juli August) 657–660

Linear Kinematics of Water Jumping in Olympic Show Jumpers

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Summary

Sagittal plane 60 Hz video recordings were made of horses jumping a 4.5 m wide water jump during the 1992 Olympic Games. The horizontal distance jumped, measured from the toe of the leading hind hoof at take off to the toe of the trailing front hoof at landing, ranged from 4.76 m to 7.89 m. The total distance jumped was negatively correlated with the take off distance ($r=-0.46$, $p<0.001$), positively correlated with the flight distance ($r=0.93$, $p<0.001$) and positively correlated with the landing distance ($r=0.63$, $p<0.001$). The flight distance, which accounted for the majority (mean 63.9%) of the total distance jumped, was negatively correlated with the height of the center of gravity at lift off ($r=-0.59$, $p=0.003$), positively correlated with the vertical velocity at lift off ($r=0.66$, $p<0.001$), but was not correlated with horizontal velocity at lift off or the height of the center of gravity at landing.

Keywords: kinematics, show jumping, horses, water jump

Lineare Bewegungsmuster beim Sprung über den Wassergraben bei Springpferden während der olympischen Spiele

Von 28 Pferden, die bei den olympischen Spielen 1992 einen 4,5 m breiten Wassergraben übersprangen, wurden Videoaufnahmen in sagittaler Ebene mit einer Frequenz von 60 Herz angefertigt. Die horizontale Weite der Sprünge (Gesamtweite), gemessen von der Zehe des vorderen Hinterhufs beim Absprung bis zur Zehe des zuerst landenden Vorderhufes, betrug zwischen 4,76 und 7,89 m. Die Gesamtweite war negativ korreliert mit der Absprungweite (Zehe des vorderen Hinterhufes bis Schwerpunkt; $r = -0,46$; $p < 0,001$), positiv korreliert mit der Flugweite (Gesamtweite minus Absprung- und Landungsweite; $r = 0,93$; $p < 0,001$) und positiv korreliert mit der Landungsweite (Schwerpunkt bis Zehe des zuerst landenden Vorderhufes; $r = 0,63$; $p < 0,001$). Die Flugweite, die den größten Teil (im Mittel 63%) der Gesamtweite ausmachte, war negativ korreliert mit der Höhe des Schwerpunktes beim Absprung ($r = -0,59$; $p = 0,003$), positiv korreliert mit der vertikalen Geschwindigkeit beim Absprung ($r = 0,66$; $p < 0,001$), jedoch nicht korreliert mit der horizontalen Geschwindigkeit beim Absprung oder der Höhe des Schwerpunktes bei der Landung.

Schlüsselwörter: Bewegungsmuster, Springpferde, Wassergraben

Introduction

In human long jumpers the total horizontal distance jumped has been considered to be the sum of three component parts: 1) the take off distance from the front of the take off board to the center of gravity (CG) at the instant the athlete leaves the ground; 2) the flight distance covered by the CG during the airborne phase; and 3) the landing distance from the CG at the instant of touchdown to the first mark in the sand (*Hay* 1986). The flight distance makes the largest contribution to the total distance jumped. It is influenced by the difference between the height of the CG at take off and at landing, which affects the duration of the flight phase, and by the direction and magnitude of the velocity at take off. The vertical component of the velocity determines how high the CG is raised and hence influences the airborne duration, while the horizontal component of the velocity determines how far the CG travels in a horizontal direction during the flight phase. Of the factors that influence the flight distance, the speed at take off is by far the most influential in human long jumpers (*Hay* et al. 1986).

Show jumping competitions sometimes include a water jump which has a width up to 4.5 m but no significant height. The purposes of this study were to subdivide the total horizontal distance covered by horses jumping a water jump into three component parts that are roughly equivalent to those studied by *Hay* (1) in the human long jump, to investigate the contribution of each component to the total distance jumped, and to determine which factors make a significant contribution to the flight distance.

Materials and methods

Terminology

The kinematic variables measured in this study are defined as follows:

stance phase – duration of ground contact for a specified limb

swing phase – period when the limb is not in contact with the ground

suspension – phase when none of the limbs is in contact with the ground

The stride in which the horse jumps a fence is called the jump stride. It has an extended airborne phase, known as the jump suspension, between the stance phases of the hind limbs and the front limbs. The jump suspension is preceded by the take off phase (stance phases of the hind limbs) and followed by the landing (stance phases of the front limbs).

Subjects

Recordings were made during the team show jumping competition at the 1992 Olympic Games in Barcelona, Spain. The subjects were 28 horses, which had a height range of 164–182 cm.

Video protocol

Sagittal plane, 60 Hz video recordings were made as the horses jumped a 4.5 m wide water jump moving from left to right across the field of view. The sampling theorem states that the sampling rate should be at least double, and preferably 4 to 5 times greater than the highest frequency present in the signal itself (*Winter* 1990). Evaluation of horses moving at different gaits and speeds at sampling frequencies from 200 Hz down to 25 Hz have shown that a sampling rate of 60 Hz is more than adequate for kinematic analysis of horses moving at the speeds recorded in this study (*Argue,* personal communication).
A rectangular calibration frame was recorded in the center of the horse's plane of motion, 31 m from the camcorder, to scale the linear measurements. During the data analysis, a correction algorithm was applied to correct for deviations of the horses from the plane in which the calibration frame was recorded.

Data reduction

The period of interest was the jump suspension which began at the last frame in which there was visible contact of the hind hooves with the ground at take off, and ended at the first frame in which the trailing front limb made visible ground contact at landing. Digitization began 5 frames before and ended 5 frames after the period of interest to improve accuracy of the end points after filtering the data. In each video frame, 20 points were digitized on the right side of the horse to define 14 body segments. Because the horses were being recorded during a competition, skin markers were not used. This avoided errors due to skin displacement, but introduced the possibility of human error in identifying the landmarks. All of the digitization in this study was performed by the same highly experienced technician, which we have found to produce consistent results. White noise in the digitizing was removed subsequently by filtering.
It was assumed that the right limbs were representative of the contralateral limb pairs; this is a reasonable assumption since the contralateral limbs were almost superimposed on each other throughout the jump suspension, except for a slight separation of the trailing and leading front limbs in preparation for landing. Since the distal limb segments account for only a small percentage of body weight, errors due to these slight asymmetries of the trailing and leading limbs are small enough to be ignored.
The X direction was defined as horizontal and positive in the direction of movement. The Y direction was vertical and positive in an upward direction. The Y axis was zeroed along the line of progression of the hooves. Based on the size of the field of view, the physical limitations of the digitizing hardware, and the number of measurements made, the digitizing error was estimated to be ±0.24 cm.

The raw data were transformed and scaled, and were smoothed using a fourth order Butterworth digital filter at cut off frequencies in the range of 4–6 Hz. The optimal cut-off frequency was determined individually for each point according to the criterion that the second derivative trace was smooth, while the third derivative trace was not smooth.
The CG of each of the 14 body segments was determined using published anthropomorphic data in the manner described previously by *Clayton* et al. (1995). The coordinates of the total body CG were determined by summation of the segment CGs.
In the horizontal (X) direction the following distances were computed: the distance from the leading hind hoof to the CG at lift off (take off distance), the distance covered by the CG during the jump suspension (flight distance), and the distance from the CG to the trailing front hoof at landing (landing distance). These distances are illustrated in figure 1. The sum of the 3 components was the total distance jumped. The components were also expressed as percentages of the total distance. In the vertical (Y direction) the height of the CG was measured at lift off and at contact of the trailing front limb during landing.

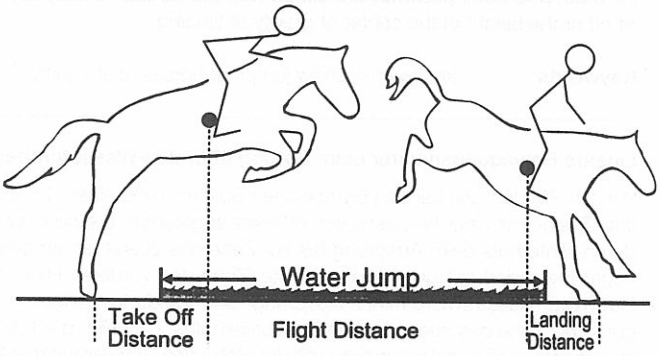

Fig. 1: The take off distance, flight distance and landing distance.

The flight duration depends on the horizontal and vertical velocities at take off, and the difference between the heights of the CG at take off and landing. The vertical velocity determines how long it takes for the upward movement of the CG to be reversed under the influence of gravity. The difference between the maximum height and the take off and landing heights influences the relative durations of the ascent and descent phases, respectively. The horizontal velocity determines the horizontal distance covered during the flight phase.
Statistical tests were performed using SPSS for Windows (Statistical Packages for the Social Sciences, Chicago, IL). Descriptive statistics were computed for all the measured variables. The three components of the total jump distance were expressed in absolute (m) and relative (%) terms. Pearson correlation coefficients were used to explore relationships between the total distance jumped and its three components, and between the flight distance and the factors that affect might influence it. A significance level of 0.05 alpha was used for all statistical tests.

Results

Descriptive statistics for the total horizontal distance jumped, its component parts, and the variables influencing the flight distance are shown in table 1. The correlation coefficients showed that the total distance jumped was negatively correlated with the take off distance expressed in absolute ($r=-0.46$, $p<0.001$) and relative terms ($r=-0.81$, $p<0.001$), positively correlated with the flight distance expressed in absolute ($r=0.93$, $p<0.001$) and relative terms ($r=0.57$, $p<0.005$) and positively correlated with the absolute value of the landing distance ($r=0.63$, $p<0.001$).

Tab. 1: Descriptive statistics for the measured variables.

	Mean Value	Std Dev	Minimum	Maximum
Total Distance (m)	6.41	0.78	4.76	7.89
Take Off Distance (m)	1.43	0.21	1.08	1.88
Flight Distance (m)	4.12	0.73	2.38	5.33
Landing Distance (m)	0.86	0.31	0.27	1.46
Take Off Distance (%)	22.8	5.4	14.3	39.5
Flight Distance (%)	63.9	5.4	50.0	73.2
Landing Distance (%)	13.2	3.9	4.4	18.9
Vertical Velocity (m/s)	1.79	0.32	1.3	2.47
Horizontal Velocity (m/s)	7.43	0.55	6.16	8.79
CG Height at Take Off (m)	1.58	0.17	1.34	2.01
CG Height at Landing (m)	1.56	0.20	1.24	1.91

The flight distance had a strong positive correlation with the vertical velocity at lift off ($r=0.66$, $p<0.001$) and a negative correlation with CG height at take off ($r=-0.57$, $p=0.004$). The flight distance was not significantly correlated with horizontal velocity at lift off or with CG height at landing (fig. 2).

Discussion

The majority of studies on jumping mechanics have been performed with human track and field athletes, and it is interesting to compare the mechanics of equine and human jumping. In the horse, the two front limbs are thrust forward in the final approach stride to initiate the upward movement of the forequarters and backward rotation of the trunk. This short stance phase imparts a braking force as the horizontal movement is converted to upward movement through a vaulting action of the superincumbent trunk over the forelimbs (*Merkens* et al. 1991). This action is similar to the mechanism described by *Hay* and *Nohara* (1990) whereby human long jumpers lengthen their final approach stride to lower their body's center of gravity, and to increase the duration of the support phase of the jump stride, during which vertical velocity can be generated for lift off. *Koa* and *Hay* (1990) also described the placement of the foot for the support phase of the approach and jump strides. The approach strides were characterized by "active" landings, in which a backward sweeping motion of the landing leg reduced the horizontal braking forces at touchdown of the foot and generated horizontal velocity. The touchdown for the jump stride was less active and incorporated a "blocking" technique, which was associated with a large horizontal braking force and the generation of vertical velocity as the body came forward over the foot. In horses the two hind limbs are responsible for reversing the direction of rotation of the trunk and providing the horizontal and vertical impulse for the airborne phase of the jump (*Clayton* and *Barlow* 1991). This is accomplished through a short-duration braking force at initial contact, then a large propulsive force for the remaining 75% of the support phase (*Merkens* et al. 1991).

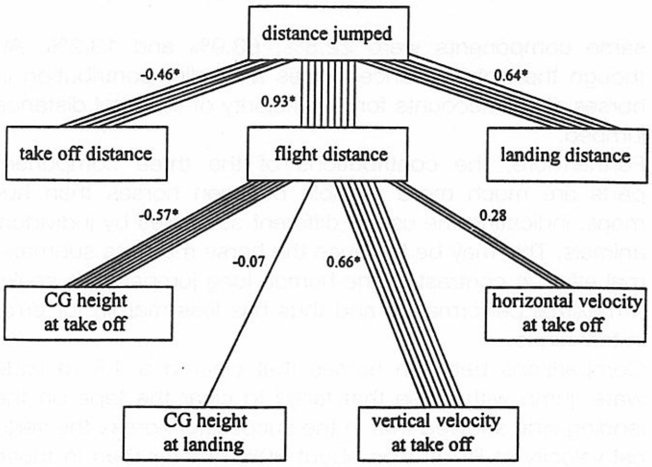

Fig. 2: Correlations with the total distance jumped. Significant correlations are indicated with an asterisk. To emphasize the relationships according to their magnitude, the coefficients are indicated by the lines linking the variables: one line indicates a correlation of 0.1, two lines indicate a correlation of 0.2, and so on, between the two boxes joined by the lines.

The take off and landing distances measured in this study were not exactly equivalent to those measured in the human long jump. In the long jump, the take off distance is measured from the edge of the take off board rather than from the take off foot, which is appropriate because one of the objectives is to place the take off foot as close as possible to the edge of the board. This is not the case in the equine jumper, who can take off 1–2 m before the water jump and still clear the required width. Therefore, the distance of the CG from the LdH was considered a more appropriate and reliable measure of take off distance in the equine jumper. In one study of human long jumpers, the take off, flight and landing distances were 5.1%, 90.0% and 4.9%, respectively, of the total jump distance, which averaged 8.02 m (*Hay* et al. 1986) and in another study they were 3.5%, 88.5% and 8.0% respectively (*Nigg* 1974). *Hay* and *Miller* (1985) found no correlation between take off distance and distance jumped; however, there was a negative correlation between take off distance and the average vertical force under the foot during the take off. Whether this resulted from the increased time of support that is concomitant with a longer take off distance, or the ability of the jumper to exert vertical forces effectively when the CG is placed more forward of the supporting foot remains to be elucidated. In this study of equine jumpers, the contributions by the same components were 22.8%, 63.9% and 13.2%. Although the flight distance makes a smaller contribution in horses, it still accounts for the majority of the total distance jumped.

Furthermore, the contributions of the three component parts are much more variable between horses than humans, indicating the use of different strategies by individual animals. This may be because the horse makes a submaximal effort in contrast to the human long jumper who seeks a maximal performance and thus has less margin for error in technique.

Comparisons between horses that cleared a 4.5 m wide water jump with those that failed to clear the tape on the landing side showed that in the successful horses the vertical velocity at lift off was about 30% greater than in those that were unsuccessful, while the horizontal velocity did not differ between groups (*Clayton* et al. 1995). It was also shown that vertical velocity was positively correlated with trunk angle at lift off, and negatively correlated with the horizontal distance between the leading hind hoof and the center of gravity at lift off (*Colborne* et al. 1995). The results reported here confirm that vertical velocity at lift off has much higher correlation with the distance jumped than horizontal velocity. In conclusion, this study showed that the total distance jumped was negatively correlated with the take off distance and positively correlated with the flight distance and landing distance. The flight distance, which accounts for the majority of the total distance jumped, is positively correlated with the vertical velocity at lift off and negatively correlated with the height of the CG at lift off.

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