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Characteristics of the Flight Arc in Horses Jumping Three Different Types of Fences in Olympic Competition

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Abstract

Show jumping horses must execute fences of varying height and width, but the effect of this on jumping kinematics during the airborne phase have not been described. The aim of this study was to describe differences within- and between-horses in CM trajectory, trunk orientation and average trunk angular velocity in a group of elite horses executing three fences: vertical fence (1.60 m), spread fence (1.50 x 1.80 m), water jump (4.5 m) during an Olympic competition. Two-dimensional kinematic data (60 Hz) were collected from video cameras set perpendicular to each fence. After manual digitization, linear and angular variables related to the position and rotation of the CM and trunk were calculated. Linear fixed effects models evaluated within-group differences between fences and kinematic variables. Repeated measures correlation (rmcorr) evaluated within-horse associations between kinematic variables and fence type. Compared with the water jump, CM vertical velocity, CM peak height, and average trunk angular velocity were significantly higher ($p<0.05$) and CM horizontal velocity was significantly lower ($p<0.05$) for the vertical and spread fences. Peak CM height coincided approximately with the middle of the spread fence, toward the take-off for the water jump and landing for the vertical fence. The trunk was significantly more inclined at take-off for the vertical fence and significantly less inclined for the water jump at landing. Rmcorr analysis revealed that individual horses generally employ similar jumping techniques for each fence type. Findings provide original insight into the mechanical requirements for elite horses jumping different fence types.

Keywords: kinematics, show jumping, horse, center of mass, equine

1. Introduction

The sport of show jumping tests the horse and rider's skill in negotiating fences of different heights and widths. For each jumping effort, success is ultimately determined by the horse’s ability to project the center of mass (CM) with sufficient vertical and horizontal velocity at take-off, so that all body parts clear the fence during the aerial phase [1-3]. Show jumping horses compete over a course of varying fences that can reach heights of up to 1.70 m and widths of 2.00 m for spread fences, 2.20 m for triple bars and 4.50 m for water jumps [4]. Kinematic characteristics of show jumpers have been described under experimental conditions [5-7] and during competitions [8-14]. The effect of fence height and width on CM trajectory and velocity, as well as various linear, temporal and angular kinematic variables, have been described in ridden [5, 8, 14-17] and unridden horses [18, 19] during the approach, take-off and landing phases of the jump. However, the effect of fence type on CM and trunk movement during the aerial phase have not been described under competition conditions. Further, no studies have directly compared the kinematic requirements for executing upright vs. water jumps, which impose different demands on the show jumping horse [5, 11-13]. Consistent, within-horse jump techniques have been described in the longitudinal studies of Santamaria et al. [20, 21], who reported that many characteristics of jumping performance, including vertical velocity at take-off, vertical displacement of the CM during the aerial phase, and aerial phase duration were strongly correlated in the same horses jumping a vertical fence at 6 months and 4 years of age. High reliability and heritability coefficients for kinematic jumping parameters have also been reported in the field of population genetics, further supporting the apparently inherent and repeatable nature of within-horse jump technique [22-25]. Thus, horses may execute fences using a consistent, individual jump technique, but the effect of different fence heights and widths on within- and between-horse variation in jump technique has yet to be investigated.

The equine jump stride is initiated by the take-off phase, which comprises stance phases of both leading (LdH) and trailing (TrH) hind limbs [26]. During take-off, the hind limbs produce power to project the body into the air [10, 27, 28] and the resulting vertical impulse is a major determinant for the CM trajectory and angular momentum during jump suspension [1, 6, 10, 20, 28, 29]. This has been recently corroborated by St George et al. [7], who found that greater CM height was achieved in horses with a shorter contraction time of m. gluteus medius together with more rapid hind limb shortening/compression at take-off when jumping a sub-maximal fence. During the aerial phase of the jump stride, the horse’s body has been described as a projectile where its trajectory cannot be changed from take-off until landing [3]. Therefore, the horse must leave the ground with an appropriate velocity and sufficient angular momentum for all parts of the body to not only clear the fence, but also for the horse to land safely [1, 3]. It is for these reasons that the height and vertical velocity of the CM and hind limb power production at take-off represent the main factors that determine the success of the jumping effort, highlighting why take-off is generally considered the most important phase of the jump stride [1, 3, 6, 7, 13, 15].

The effect of fence type and height on kinematics during the final approach stride and take-off have been described. During the approach strides, stride velocity is adjusted by altering stride length and stride frequency to ensure that the take-off is executed from an appropriate position based on fence height and width [5, 8, 15]. Hoof placements relative to the fence on the take-off and landing sides have been reported for fences of various heights and profiles [5]. Placement of the fore and/or hind limbs relative to the fence at take-off did not differ between a vertical fence and a square-profile spread fence of the same heights, ranging from 1.10 to 1.40 m [5, 16, 17]. A comparison of different fences from Grand Prix (1.30 m vs. 1.52 m vertical fences) and Olympic (1.50 x 1.90 m vs. 1.60 x 1.00 m spread fences) show jumping competitions also showed that differences in fence height and spread did not significantly alter hind limb position relative to the fence at take-off [8, 14]. Horses ridden over a vertical puissance wall also showed little variation in hind limb placements from fences ranging in height from 1.80 to 2.19 m [15] but the hind limbs were placed 0.44 – 0.58 m further from the base of the puissance wall than from fences 1.10 - 1.40 m high [5]. Thus, although horses appear to alter hind limb placement as fence height and width increases, for each of the study situations, it is clear that horses account for different fence profiles by altering their flight trajectory [5, 15].

The action of the forelimbs and head and neck contribute to elevation of the trunk during take-off [3, 6, 12]. In the final approach stride, the forelimbs initially dissipate energy then generate energy to elevate the forehand and rotate the trunk in a nose up direction [28]. With increasing fence height, horses also exhibit increased elevation and vertical velocity of the CM and a more upright body/trunk position at take-off. Horses have also been reported to take off with a more elevated trunk angle when jumping a spread fence versus a vertical fence and when covering a longer horizontal distance over a water jump [11, 12, 17]. Walker et al. [17] reported that elite show jumping horses executing a combination consisting of a 1.35 m high upright fence and a 1.35 m high x 1.37 m wide spread fence, set one stride apart, showed a significantly greater thoracolumbar angle relative to the horizontal (more upright trunk angle) during take-off at the spread fence element. Horses with ability to successfully execute a 4.5 m wide water jump at the Olympic games also exhibited a significantly greater trunk angle and CM projection angle at take-off, compared to their non-successful counterparts [11, 12]. Along with a more upright trunk angle, successful horses also generated greater vertical velocity of the CM and displayed a greater “gather technique” during take-off at a water jump, which was significantly related to the total horizontal distance jumped [11, 12]. Interestingly, Colborne [30] reported similar differences in horizontal and vertical distance jumped and CM horizontal velocity at take-off for horses that executed the middle section of a fan jump versus those that executed the wider, “fanned” end of the same jump at an Olympic competition. Although the fan jump dimensions and differences in widths between the two take-off locations were not reported, horses that jumped the wider end of the fence showed significantly greater hindlimb distance from the fence base, CM horizontal and vertical velocity at take-off, and greater horizontal and vertical distance jumped [30]. Thus, to successfully execute higher and/or wider fences, horses adjust the position of the trunk, CM and limbs relative to the fence and increase vertical impulse during take-off, which dictates the CM trajectory during the aerial phase [3, 5, 11, 12, 15, 30].

Considerable information is available to describe the kinematics and kinetics of the approach, take-off and landing phases in relation to differences in fence type and height, but less information has been published regarding the aerial phase which is when most faults are accrued. Further, no studies have directly compared the kinematic effects of water jumps with upright or spread fences. A better understanding of the characteristics of the aerial phase when jumping different fence types should help riders to make appropriate adjustments in the approach to the fence. This information would also be useful for course designers who need to understand the challenges of jumping different fence types and the effects of altering inter-fence distances. Thus, the aim of this study was to describe differences within and between horses in CM trajectory, trunk orientation and average angular velocity of trunk rotation in a group of elite horses executing three different fence types: a vertical fence, a spread fence and a water jump during an Olympic competition. The experimental hypotheses are that, within the group of horses, the peak of the parabolic flight arc coincides with the mid-point of the fence profile (width) and that the vertical and spread fences will have higher vertical and lower horizontal CM velocities at take-off compared with the water jump. ~~A secondary hypothesis is~~ It was also hypothesized that elite horses employ similar strategies to execute the different fence types, resulting in non-significant differences between horses in CM trajectory, trunk orientation and average trunk angular velocity for each fence type.

2. Materials and Methods

2.1 Video Protocol

Sagittal plane 60 Hz video recordings were made during the first round of ~~the~~ a team competition at the ~~1992~~ Olympic Games. The performances of the horse-rider combinations were recorded over the fourth, fifth and sixth fences on the course. All three fences had a straight approach and departure. The fourth fence, which was a 1.60 m high vertical fence, was filmed from a left lateral view at a camera distance of 35 m. The fifth fence, which was a 1.50 m high and 1.80 m wide spread fence, was recorded from a right lateral view at a camera distance of 38 m. The sixth fence, which was a 4.50 m wide water jump, was recorded from a right lateral view at a camera distance of 30 m. Photographs of the face views and diagrams of the profiles of the three fences are shown in Figure 1.

Insert Figure 1.

A camera was set perpendicular to each fence with the zoom lens adjusted to include a distance of 5 m on either side of the fence. For the vertical and spread fences, a rectangular calibration frame with 8 non-colinear markers was recorded in several positions along the plane of the direction of movement for scaling the linear data. Horses were selected for analysis if their direction of movement in the sagittal plane crossed the middle part of the fence (i.e. they jumped midway along the fence poles from left to right). For the water jump, the horse's limbs were obscured by an arena railing if the horse jumped over the right half of the fence. Therefore, the analysis was confined to horses that jumped no more than 2 m from the left side of the jump and the calibration frame was filmed 1 m from that side.

2.2 Subjects

The subjects were 12 horse-rider combinations (horse height 164 – 176 cm) that cleared all three fences, and that were observed to follow a path perpendicular to the fence, crossing the middle part of the vertical and spread fences, and the left side of the water jump. Ethical approval for this study was not required as there was no contact between researchers and human (riders) and animal (horses) participants. All riders signed a consent form to allow their data to be analyzed for the study.

2.3 Data Reduction

The period of interest was the jump suspension. It started at the first frame in which both hind limbs were visibly separated from the ground at take-off and ended the frame before there was visible contact between the TrF and the ground at landing. The aerial time was calculated for each jumping effort.

Twenty anatomical landmarks on the right side of the horse’s body were digitized manually in each video field [11], including five frames before the start and after the end of the jump suspension to improve the accuracy of the end points after filtering the raw data. Custom software used the digitized coordinates to construct 3 axial body segments (head, neck, trunk) and 11 limb segments on the right side of the body (shoulder, brachium, antebrachium, metacarpus, fore pastern, fore hoof, femur, crus, metatarsus, hind pastern, hind hoof). Due to the unilateral nature of the data collected, kinematic symmetry of the left and right contralateral limbs was assumed, which is a reasonable assumption during the jump suspension [10, 11, 13, 26].

The raw data were transformed and scaled using a direct linear transformation modified for two-dimensional data. The transformed data were smoothed with a fourth order Butterworth digital filter. The cut off frequency was determined individually for each point using the criterion that the second derivative trace should appear smooth while the third derivative trace was not smooth. The segment CM, determined from the digitized coordinates according to anthropometric data of Buchner et al. [31], were used to calculate the coordinates of the total body CM [31-33].

The X direction was defined as horizontal and positive in the direction of movement. The Y direction was defined as vertical and positive upward. The path of the body CM in the X-Y (sagittal) plane was tracked throughout the jump suspension, and the maximum height of the CM during take-off, jump suspension and landing phases of the jump stride ~~at the start (take-off height of CM) and end (landing height of CM) of the jump suspension~~ were determined. The relative linear distance (m) between the horizontal location at the point of maximum CM height ~~of the CM during the jump suspension was recorded (maximum and the horizontal (x direction) location of the peak height was used to calculate the from~~ and the center (midpoint) of the fence profile was calculated (horizontal distance from maximum CM height to fence midpoint)~~peak CM height from fence midpoint~~); a negative value indicated that the flight arc peaked on the take-off side of the ~~reference~~ fence profile midpoint, a positive value indicated that the flight arc peaked on the landing side of the ~~reference~~ fence profile midpoint. The horizontal and vertical velocities of the CM at take-off were derived from the displacement data using a finite difference method.

The angle of the trunk segment was defined as the angle between the horizontal and a line connecting the tuber ischium to the manubrium. This angle was negative when the manubrium was higher than the tuber ischium and positive when the tuber ischium was higher than the manubrium [34]. Trunk segment angle at the start (trunk segment angle at take-off) and end (trunk segment angle at landing) of the jump suspension were determined. Angular velocity of the trunk segment was calculated by time integration of the displacement data. Average trunk angular velocity was calculated over the jump suspension phase.

2.4 Statistical Analysis

Descriptive statistics (mean, standard deviation, range) were calculated for each of the measured kinematic variables across the group of horses for each fence type. Between-horse ~~Within-group~~ differences between fences were calculated for each kinematic variable using linear fixed effects models. Linear models were conducted using SPSS Statistics for Windows (version 27.0., IBM Corp., NY, USA) and the mean difference and 95% confidence intervals of the difference are presented.

Repeated measures correlation (rmcorr) [35] was used to determine common intra-individual (within-horse) associations between each measured kinematic variable and fence type. The rmcorr coefficient (r_{rm}) represents the strength of linear association between two variables and allows the user to assess the overall or common intra-individual association between two measures, without violating independence assumptions or requiring averaging of the data [35]. Rmcorr plots are produced to illustrate the best linear fit for each participant using parallel regression lines [35]. Thus, rmcorr enabled us to evaluate within-horse associations between each kinematic variable and fence type, with rmcorr plots allowing us to visualize whether this association was shared ~~amongst~~ across the group of horses, which permitted the assessment of between-horse differences or similarities for each kinematic variable across fence types. Statistical significance was set at $p < 0.05$ for both linear models and rmcorr analyses. The magnitude of correlations between fence type and measured variables was interpreted as follows: <0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; 0.9-1.0, almost perfect [36].

Finally, the flight path of the best performing horse-rider combination, defined by having no faults and the highest individual placing in the competition (Supplementary Table S1), was estimated from the measurements to illustrate the difference in flight path between fence types. The equations of motion during flight were used to plot the theoretical flight path of the CM of the horse using take-off conditions against the flight path using measured peak CM location. Trunk segment angle during flight was used to estimate the effect of drag forces and vertical lift.

3. Results

Descriptive statistics for the measured variables are shown in Table 1. Pairwise comparison results from linear models are presented in Table 2. Significant differences between fences were observed for each measured variable. Compared with the water jump, CM vertical velocity was higher and horizontal velocity was lower for the vertical and spread fences. As a result of the higher vertical velocity, maximum height of the CM was higher and aerial time was longer. Peak height of the CM was close to the middle of the spread fence, toward the take-off side for the water jump and toward the landing side for the vertical fence. Trunk angle was significantly more inclined in a nose-up direction at take-off for the vertical fence and significantly less inclined in a nose-down direction for the water jump at landing. Average angular velocity of the trunk during the aerial phase was significantly higher for the vertical fence. Figure 2 presents an illustrative comparison of the flight path of the best performing horse-rider combination and the theoretical flight path of the CM over the three fence types studied.

Insert Figure 2.

Results from rmcorr are presented in Figure 3 and in Supplementary Figures S1 – S7 as rmcorr plots. Repeated measures correlations revealed significant and very large or large, positive correlations between fence type (direction of change: vertical, spread, water) and CM horizontal velocity at take-off ($r_{\text{rm}} = 0.85$, $p < 0.0001$) and trunk angle at take-off ($r_{\text{rm}} = 0.56$, $p < 0.0001$). Fence type (direction of change: vertical, spread, water) was very largely or largely and negatively correlated with take-off height of CM ($r_{\text{rm}} = -0.56$, $p < 0.0001$), maximum height of CM ($r_{\text{rm}} = -0.72$, $p < 0.0001$), CM vertical velocity at take-off ($r_{\text{rm}} = -0.62$, $p < 0.0001$), trunk segment angle at landing ($r_{\text{rm}} = -0.74$, $p < 0.0001$) and aerial time ($r_{\text{rm}} = -0.82$, $p < 0.0001$). Small and non-significant negative correlations were observed between fence type (direction of change: vertical, spread, water) and landing height of CM ($r_{\text{rm}} = -0.26$, $p > 0.05$), ~~peak CM height from fence midpoint~~ horizontal distance from maximum height of CM to fence midpoint ($r_{\text{rm}} = -0.21$, $p > 0.05$) and trunk average angular velocity ($r_{\text{rm}} = -0.23$, $p > 0.05$) and are presented in Figure 3. To illustrate potential relationships between within-horse differences and performance, observations from the two best and worst performers from the competition (see Supplementary Table S1) are highlighted in Figures 3 and Supplementary Figures S1 – S7, in blue and red, respectively

Table 1: Descriptive statistics (mean ± standard deviation (range)) for the measured variables.

Variable	Vertical fence	Spread fence	Water jump
Aerial time (s)	0.62 ± 0.04 (0.54, 0.69)	0.64 ± 0.04 (0.57, 0.73)	0.50 ± 0.07 (0.41, 0.61)
Take-off height of CM (m)	1.79 ± 0.09 (1.64, 1.92)	1.75 ± 0.06 (1.63, 1.84)	1.62 ± 0.10 (1.44, 1.75)
Landing height of CM (m)	1.81 ± 0.05 (1.76, 1.92)	1.61 ± 0.06 (1.51, 1.74)	1.53 ± 0.12 (1.26, 1.73)
Maximum height of CM (m)	2.33 ± 0.10 (2.18, 2.49)	2.25 ± 0.9 (2.12, 2.48)	1.93 ± 0.13 (1.68, 2.11)
~~Peak CM height from fence midpoint~~ Horizontal distance from maximum height of CM to fence midpoint (m)	0.32 ± 0.24 (-0.18, 0.63)	-0.02 ± 0.15 (-0.34, 0.22)	-0.15 ± 0.20 (-0.53, 0.15)
CM vertical velocity at take-off (m/s)	2.93 ± 0.32 (2.37, 3.37)	2.74 ± 0.27 (2.09, 3.16)	2.10 ± 0.32 (1.75, 2.79)
CM horizontal velocity at take-off (m/s)	5.47 ± 0.54 (4.31, 6.31)	5.35 ± 0.45 (4.89, 6.45)	7.96 ± 0.62 (6.77, 8.68)
Trunk segment angle at take-off (deg)	-30.72 ± 0.83 (-32.29, 29.30)	-26.92 ± 2.71 (-30.34, -21.44)	-20.74 ± 3.60 (-28.33, -16.29)
Trunk segment angle at landing (deg)	37.78 ± 3.21 (31.34, 41.56)	36.60 ± 3.27 (30.41, 41.73)	25.35 ± 4.94 (18.32, 34.94)
Trunk average angular velocity (deg/s)	110.38 ± 9.63 (99.46, 128.52)	99.71 ± 8.62 (84.04, 111.80)	93.60 ± 11.90 (73.36, 112.49)

Table 2. Pairwise comparison results from linear fixed effects model analysis, presented as mean difference (MD), 95% confidence intervals of this difference (95% CI) and p values (P) for each measured variable between each fence type. Bold text indicates means that differ significantly (P<0.05).

Kinematic variable		Vertical vs. spread	Spread vs. water	Water vs. vertical
Aerial time (s)	MD	-0.02	**0.15**	**-0.13**
	P value	0.32	**<0.0001**	**<0.0001**
	95% CI	-0.05, 0.02	**0.11, 0.18**	**-0.16, -0.10**
Take-off height of CM (m)	MD	0.05	**0.13**	**-0.17**
	P value	0.10	**<0.0001**	**<0.0001**
	95% CI	-0.01, 0.10	**0.07, 0.18**	**-0.23, -0.12**
Landing height of CM (m)	MD	**0.20**	**0.08**	**-0.28**
	P value	**<0.0001**	**0.01**	**<0.0001**
	95% CI	**0.14, 0.26**	**0.02, 0.15**	**-0.35, -0.22**
Maximum height of CM (m)	MD	**0.08**	**0.32**	**-0.41**
	P value	**0.02**	**0.03**	**<0.0001**
	95% CI	**0.02, 0.15**	**0.26, 0.39**	**-0.47, -0.34**
~~Peak CM height from fence midpoint~~ Horizontal distance from maximum height of CM to fence midpoint (m)	MD	**0.34**	0.13	**-0.47**
	P value	**<0.0001**	0.07	**<0.0001**
	95% CI	**0.20, 0.48**	-0.01, 0.27	**-0.61, -0.33**
CM vertical velocity at take-off (m/s)	MD	0.19	**0.64**	**-0.84**
	P value	0.11	**<0.0001**	**<0.0001**
	95% CI	-0.05, 0.43	**0.40, 0.88**	**-1.07, -0.60**
CM horizontal velocity at take-off (m/s)	MD	0.12	**-2.62**	**2.50**
	P value	0.50	**<0.0001**	**<0.0001**
	95% CI	-0.23, 0.46	**-2.96, -2.27**	**2.15, 2.85**
Trunk segment angle at take-off (deg)	MD	**-3.80**	**-6.18**	**9.98**
	P value	**<0.0001**	**<0.0001**	**<0.0001**
	95% CI	**-5.73, -1.87**	**-8.11, -4.25**	**8.05, 11.91**
Trunk segment angle at landing (deg)	MD	1.18	**11.25**	**-12.44**
	P value	0.32	**<0.0001**	**<0.0001**
	95% CI	-1.23, 3.59	**8.84, 13.67**	**-14.85, -10.02**
Trunk average angular velocity (deg/s)	MD	**10.67**	6.11	**-16.78**
	P value	**<0.0001**	0.07	**<0.0001**
	95% CI	**3.92, 17.42**	-0.64, 12.86	**-23.53, -10.02**

Insert Figure 3.

4. Discussion

This original study has measured and compared, for the first time, variables describing CM trajectory, trunk orientation and trunk angular velocity during the jump suspension in elite horses executing three different fence types at an Olympic competition. The vertical fence and water jump in this study are maximal size for Olympic competition while the spread fence is only slightly smaller than the Olympic maximum. Thus, this study offers a unique investigation of elite horses executing different fence types during top-level competition, which can provide reliable information about near-optimal jumping kinematics [10]. Findings from this study revealed that fence type had a significant effect on each of the measured kinematic variables. Our first experimental hypothesis was accepted, as the vertical and spread fences were found to require significantly higher vertical and significantly lower horizontal CM velocities at take-off, compared with the water jump. However, our findings do not fully support the hypothesis that the peak of the CM flight arc coincides with the mid-point of the fence profile (width), as peak height of the CM was located toward the take-off side for the water jump and toward the landing side for the vertical fence, but did remain close to the mid-point of the spread fence. Finally, an examination of within-horse associations between each measured variable and fence type, using rmcorr analysis, revealed that the group of horses employed similar CM trajectory and trunk orientation for executing each fence type, but landing height of CM, horizontal distance from maximum height of CM to fence midpoint ~~peak CM height from fence midpoint~~, and trunk average angular velocity were not significantly correlated with fence type. This finding suggests that, for these three variables, individual horses may employ differing strategies to execute each of the three fence types. Thus, our second experimental hypothesis, that elite horses employ similar strategies to execute different fence types, can only be partially accepted and should be examined further in future studies.

4.1 Effect of fence type on kinematic variables

Previous studies have described the importance of the hind limbs for generating energy during take-off, which is paramount to jumping success [1, 6, 7, 10, 27-29, 37]. In order to be a successful show jumper, a horse must not only have the ability to generate energy at take-off to accelerate its body into the air [1, 6, 10, 20, 28, 29] but must also judge/alter the direction and magnitude of vertical and horizontal velocity over fences of different heights and widths, as illustrated by the significant differences for the three fence types in this study. The vertical velocity of the CM at take-off determines how high the CM is raised, which also influences the airborne duration, while the horizontal velocity at take-off determines how far the CM travels in the horizontal direction during the airborne phase [13]. Given the long, low profile of the water jump, it is therefore not surprising the horses in this study took off with a significantly greater CM horizontal velocity and a significantly lower CM vertical velocity compared with jumping the higher vertical and spread fences. Interestingly, a study of factors influencing success in clearing the width of a water jump, of the same dimensions as this study, have shown that successful horses have the ability to generate significantly greater CM vertical velocity and a significantly greater trunk projection angle at take-off than those that were unsuccessful [11, 12].

Further, vertical velocity of the CM and trunk angle at take-off have also been reported as significantly and positively correlated with the total distance jumped over a water jump of the same dimensions as that studied here [12, 13]. Thus, although the height of the water jump is small, and requires significantly lower CM vertical velocity and a significantly less elevated trunk angle at take-off than the vertical and spread fences, the horse still needs to leave the ground with sufficient vertical velocity and trunk elevation to stay airborne for long enough to cover the width of the jump [11-13]. Further, although it may not be a predictor of success for water jump execution [11, 12], horses are still required to take-off with significantly greater CM horizontal velocity than for the higher vertical and spread fences, which ensures that the horizontal distance travelled by the CM is adequate for clearing the width of the water jump [13].

Vertical and horizontal velocity and height of the CM during take-off did not differ significantly between the vertical and spread fences, which may be due to relatively similar height of the vertical and spread fences at 1.60 m and 1.50 m, respectively, although all three variables increased for the slightly higher, vertical fence. This trend agrees with Powers [15], who reported that the execution of higher fences requires increased vertical displacement and velocity of the CM and a more upright trunk angle, which were significantly correlated with increasing fence height in a puissance competition. The differences in vertical velocity and height of the CM at take-off, observed across the three fences in this study, are also reflected in the peak height of the CM, which differed significantly between each of the three fence types and was progressively higher from the vertical (2.33 m) to the spread (2.25 m) and the water jump (1.92 m). Aerial time was also significantly shorter for the water jump compared to the vertical and spread fences, which agrees with the significant and positive correlation between airborne duration and CM vertical velocity at take-off, reported by Santamaria et al. [20, 21]. Thus, findings agree with previous studies that have reported significant correlations between CM vertical velocity at take-off and CM elevation during jump suspension [7, 20, 21], aerial time [20, 21], and fence height [15]. Results from this study therefore support the notion that alterations in trunk and CM elevation and CM vertical velocity at take-off, as well as the development of vertical impulse by the hind limb [7, 10], are crucial determinants of CM trajectory and angular momentum for clearing fences of differing heights and widths [5, 11-13, 15].

At take-off the trunk angle differed significantly between the three fence types and was progressively more elevated from the water jump (-20.7°) to the spread fence (-26.9°) and the vertical fence (-30.7°). As stated, trunk angle at take-off has been shown to be highly correlated with CM vertical velocity and the horizontal distance jumped in horses jumping a water jump [12]. The present study indicates that the association between CM vertical velocity and trunk angle at take-off also applies to different types of fences in addition to the water jump. Elevation of the trunk segment appears, therefore, to be an important determinant of the vertical velocity at take-off and maximal height of the CG during jump suspension. Interestingly, the finding that trunk angle was significantly greater for the vertical fence compared to the spread fence is not in accordance with Walker et al. [17], who reported that elite show jumping horses exhibited a more upright trunk angle at take-off for a 1.35 m high x 1.37 m wide spread fence, compared to a 1.35 m high upright fence. These conflicting findings may be due to differences in fence dimensions between studies, but are more likely to be related to the fact that the vertical and spread fence studied by Walker et al. [17] formed part of a triple combination where both fences were set one stride apart. Thus, findings from Walker et al. [17] may not be directly applicable to single fences, as employed in this study, especially as there are known linear and temporal kinematic differences between the intermediate strides within a combination and the approach and departure strides for single fences [38]. In accordance with CM vertical and horizontal velocity and peak CM height at take-off, trunk angle at landing was not significantly different between the vertical (37.8°) and spread fences (36.6°), but was significantly more acute for the water jump (25.3°).

4.2 Effect of fence type on between-horse differences in jump technique

Consistent, within-horse jump techniques have been described in the longitudinal studies of Santamaria et al. [20, 21], who also reported no long-term effects on jump technique or maximum jumping effort later in life [2]. These studies have illustrated the apparent inherent nature of jump technique, which suggest that individual horses have unique and consistent jumping characteristics that are present from foal age to ridden work at 4 - 5 years of age [2, 20, 21]. However, it is not known whether horses employ similar inter- and intra-individual movement strategies to execute fences of varying heights and widths. This is the first known study to evaluate within-horse associations between kinematic variables and fence type and whether this association was shared amongst the group of horses. These evaluations were conducted using rmcorr analysis, which showed significant correlations between fence type and seven out of ten measured variables. This indicates that individual horses generally employed similar techniques to execute the three different fence types and these associations also agreed with the kinematic differences observed between fences using linear fixed effects models (Tables 1 and 2).

Average trunk angular velocity, CM landing height, and ~~peak CM height from fence midpoint~~ horizontal distance from maximum height of CM to fence midpoint were not significantly correlated with fence type, indicating that within-subject associations between these kinematic variables and fence type were not shared between horses. It is interesting to investigate these findings in relation to the best and worst performers, as highlighted in the rmcorr plots in Figure 3. ~~Group averaged data~~ Mean data revealed that average trunk angular velocity was significantly greater for the vertical fence than the water and spread fences, which did not differ from each other. This trend for progressively greater trunk angular velocity from the water to the vertical fence was generally observed for individual horses in the rmcorr plot (Figure 3c) but comparison of the two best and worst performers reveals a clear trend for the worst performers to exhibit lower and more variable average trunk angular velocities across the three fence types. Although, rmcorr analysis revealed that CM vertical velocity at take-off was significantly correlated with fence type across the group of horses, a clear decrease in vertical velocity across fences for one of the worst performing horses was also observed (Supplementary Figure S4). Angular momentum, CM vertical velocity and CM trajectory are established at take-off through hind limb power production and the resultant vertical impulse which projects the body into the air [1, 6, 10, 20, 28, 29]. A significant and positive relationship been between CM vertical velocity at take-off and CM height at the instant of hind limb clearance, just prior to FL impact at landing, has also been reported [21]. In addition, the effect of increased trunk angular velocity is illustrated in Figure 2, where greater average angular velocity increased the vertical height of the flight arc. Greater vertical height due to increased angular momentum at take- off has been reported in simulations of human running jumps [39]. Taken together, the lack of common intra-individual associations between fence type and trunk angular velocity, CM height at landing and peak CM height in relation to the midpoint of the fence, may be related to a horse's ability to account for fence height and width during power generation at take-off, which establishes an appropriate CM trajectory for fence clearance. Although further research is required to investigate this theory, this is the first known study to employ rmcorr analysis for equine kinematic data and findings from this study illustrate its effectiveness for examining within and between-horse differences in equine biomechanics research.

4.3 Limitations

Many of the limitations of this study are related to collecting data under competition conditions. For example, the use of high-speed video, two-dimensional measurements and manual digitization of ~~it was necessary to manually digitize~~ body landmarks was necessary because markers could not be worn in competition. Similarly, a repeated measures study design was not possible, as each horse executed each fence once during the competition. Further, each horse was ridden by a different rider and the effect of an experienced rider, as included in this study, on a horse's jumping kinematics have been documented [40-42]. Data from this study were collected during the 1992 Olympic Games and although the horse as a biological structure has not changed since these data were acquired, competitive advances in training, breeding and equitation science, to name a few, have undoubtedly influenced the sport horse population and the sport of showjumping. Although this should be considered when interpreting findings from this study, it is important to note that the elite horses in this study executed fence profiles that conform to current Olympic standards for maximum fence height and width of vertical and water jumps [4]. Future experimental studies may build upon the current study by evaluating kinematic differences across the same fences, using a repeated measures design, a larger sample of modern horses ridden by the same rider, and three-dimensional motion capture technologies. Despite these limitations, data from this study provide unique insight into the impact of fence height and width on the kinematics of elite horses competing at the highest level of equestrian sport, the Olympics.

5. Conclusions

Findings from this study reveal the significant effect of fence height and width on CM trajectory, trunk orientation and trunk angular velocity during jump suspension in horses competing at the ~~1992~~ Olympic Games. Compared to the vertical and spread fences, execution of the water jump was characterized by a significantly shorter aerial time, lower peak CM height that occurs on the take-off side of the fence, a lower CM height at lift-off and landing, and lower CM vertical velocity at take-off, but significantly greater horizontal velocity at take-off. The highest, vertical fence was characterized by significantly greater maximal CM height that occurred on the landing side of the fence, a steeper trunk angle at take-off, a higher CM height at landing, and greater average trunk angular velocity than the spread and water fences. Measured kinematic variables for the spread fence always fell between minimum or maximum values from vertical and water fences and did not significantly differ from the vertical fence for aerial time, CM height, vertical and horizontal velocity at lift off, and trunk angle at landing. Individual horses generally exhibited similar strategies for executing the three different fence types, but findings suggest that between horse differences in trunk angular velocity, CM height at landing and peak CM height in relation to the fence midpoint may be related to the ability to generate power at take-off, which should be adjusted to account for fence height and width. Findings from this study illustrate the suitability of repeated measures correlation (rmcorr) for quantifying within and between-horse differences in equine kinematics data. In practice, the reported effects of different fence types on kinematics may provide important information for riders and course designers in relation to executing or setting inter-fence distances for fences of varying widths and heights.

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Figure Headings

Figure 1: Photographs of the face view of the fences and dimensions of the three fences seen in profile. Above: fence 4 – vertical fence; center: fence 5 – spread fence; below: fence 6 – water jump.

Figure 2: Illustrative comparison of the flight path of the best performing horse-rider combination (white line) and the theoretical flight path (red dashed line) of the CM, calculated using the equations of motion during flight, over the three fence types studied: a) water jump, b) spread fence, c) vertical fence. Trunk orientation is illustrated as grey lines, occurring at CM positions (blue points) throughout the flight path at approximately 0.1 second intervals.

Figure 3: Scatter plots illustrating non-significant repeated measures correlations between fence type (1 = vertical, 2 = spread, 3 = water) and a) landing height of CM, b) ~~peak CM height from fence midpoint~~ horizontal distance from maximum height of CM to fence midpoint, c) trunk average angular velocity. Observations from each horse and the corresponding lines to illustrate the rmcorr fit are shown in the same color/greyscale. Observations from the best and worst performers are illustrated as blue (0 faults) and red (circle = 8.5 faults, square = 8 faults) data points/lines, respectively.

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