Variation in free jumping technique within and among horses with little experience in show jumping

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Objective—To quantify variation in the jumping technique within and among young horses with little jumping experience, establish relationships between kinetic and kinematic variables, and identify a limited set of variables characteristic for detecting differences in jumping performance among horses.

Animals—Fifteen 4-year-old Dutch Warmblood horses.

Procedure—The horses were raised under standardized conditions and trained in accordance with a fixed protocol for a short period. Subsequently, horses were analyzed kinematically during free jumping over a fence with a height of 1.05 m.

Results—Within-horse variation in all variables that quantified jumping technique was smaller than variation among horses. However, some horses had less variation than others. Height of the center of gravity (CG) at the apex of the jump ranged from 1.80 to 2.01 m among horses; this variation could be explained by the variation in vertical velocity of the CG at takeoff (*r*, 0.78). Horses that had higher vertical velocity at takeoff left the ground and landed again farther from the fence, had shorter push-off phases for the forelimbs and hind limbs, and generated greater vertical acceleration of the CG primarily during the hind limb push-off. However, all horses cleared the fence successfully, independent of jumping technique.

Conclusions and Clinical Relevance—Each horse had its own jumping technique. Differences among techniques were characterized by variations in the vertical velocity of the CG at takeoff. It must be determined whether jumping performance later in life can be predicted from observing free jumps of young horses. (*Am J Vet Res* 2004;65:938–944)

Several studbooks have developed strategies to select good show jumpers. French Saddle horses are selected on the basis of their annual performance in competition, whereas the selection of Hanovarian and other German horses is made on the basis of several traits such as free jumping, walking, trotting, galloping, cross-country riding, and the ease with which they can be ridden.[1] In the Netherlands, 3- to 4-year-old horses are initially selected on the basis of their conformation and movements during walking and trotting. Judges then evaluate the jumping ability of the horses during free jumping. For this evaluation, the Royal Dutch Warmblood Studbook created a scoring system based on qualitative assessments of takeoff (direction and velocity); forelimb technique; hind limb technique; and use of the back, power, elasticity, and carefulness of the horse during the jump. Stallions that have sufficiently high scores are included in the Dutch breeding program, and their genetic value is subsequently evaluated by their performance in competitions and the aptitude of their offspring as show jumpers.

Use of a scoring system to evaluate jumping performance in young stallions presumes the existence in foals of recognizable and consistent kinematic patterns in jumping technique that are stable in ontogeny and indicative of show jumping talent. Few studies have focused on the quantification of jumping technique of young horses and its relationship with jumping ability. In 1 study,[1] investigators concentrated on the relationship between the scores of judges and stride frequency of horses during the approach to the fence and acceleration peaks generated by forelimbs and hind limbs at takeoff in two hundred 3-year-old horses that jumped without a rider during selection events. In another study,[2] investigators filmed 31 untrained 3- to 5-year-old horses during free jumping and compared kinematic variables between good and poor jumpers. However, variance in the jumping technique within and among these young horses was not studied. We are aware of only 1 study[3] in which it has been reported that jumping technique was consistent within each horse during jumps performed by experienced adult horses being ridden by their own riders.

In determining whether kinematic patterns of young horses can be used to predict their show jumping performance as adult horses and whether early training can improve future jumping ability, a large-scale prospective study was initiated that involved forty 6-month-old Dutch Warmblood foals. Those horses were evaluated during free jumping over a vertical fence. A description of linear and temporal jumping kinematics of that group of horses as foals and a comparison with data collected for other adult horses have been published.[4] Those foals were then allocated to 2 equal groups (1 experimental group was included

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in a training regimen for free jumping, whereas the other nontrained group remained at pasture).

The study reported here focused on analysis of kinematic data collected during free jumps performed by the untrained group when they were 4 years old. This group of horses is representative of the naive horses that participate in selection events in The Netherlands despite the fact that they have little jumping experience. In the analysis, we concentrated on variables that were deemed related to jumping performance (ie, variables extracted from the time course for position, velocity, and acceleration of the center of mass as well as protraction of the limbs).[2,3,5] The specific goals of the study were to quantify variation in these variables within and among horses, establish relationships between these variables, and identify a limited set of variables that can be considered characteristic for detecting differences in jumping performance among horses and, hence, may serve to discriminate among horses with respect to their jumping potential during selection events.

Materials and Methods

Animals—Fifteen 4-year-old Dutch Warmblood horses (4 females and 11 males) owned by the Institute for Horse Husbandry in Lelystad, The Netherlands, were used in the study. Mean ± SD height at the top of the shoulders was 1.70 ± 0.05 m, and mean weight was 619 ± 43 kg.

Training—When foals (n = 20) were 6 months old, they were evaluated kinematically during jumping a fence that was 0.6 m in height. After the evaluation, they were placed on pasture during the spring and summer and maintained in loose housing during autumn and winter; they did not receive any additional training. When the horses were 3 years old, they were transported to the Dutch training Center at Deurne, The Netherlands, where they were trained to jump during a 5-week period. Horses performed 3 sessions of free jumping and 8 sessions of jumping with a rider.

Subsequent training required restriction of group size because of economic constraints. Thus, only the best 15 horses (with respect to behavior and mobility [ie, no lameness]) were selected for additional training because it was believed that they had the best chance to be sold at a good price following completion of the study. After a rest period, those 15 horses returned to the training center, when they were appoximately 44.5 months old. During the next 3 months, the horses were trained 6 d/wk (1 day in a horse walker, 1 day working on the lunge, and 4 days of dressage [walking, trotting, and some galloping]). Horses began jumping over a fence (0.6 m in height) with a rider 14 days before data collection. In addition, horses were also trained in free jumping twice during the 3-week period before data collection.

Experimental protocol—Before each data collection, horses warmed up by walking in a horse walker for 1 hour. For the data collection, each horse was taken to an indoor arena (20 × 40 m). Markers were attached to specific anatomic locations on the left side of the body, medial side of the right forelimb (ie, carpus, metacarpophalangeal [fetlock] joint, and hoof), and medial side of the right hind limb (hoof; **Figure 1**).

The jumping track consisted of 3 vertical fences placed along 1 of the long sides of the arena. The first fence was placed so that a horse would approach it after completing a left turn. The second fence was 6.4 m from the first fence, and the third fence was 7.0 m from the second fence. The third fence was the target (measurement) fence, but the first 2 fences prevented the most energetic horses from approaching the target fence too fast because the distances between them restricted the horses to only 1 canter stride between fences. This arrangement was similar to that used during official selection sessions conducted by the Royal Dutch Warmblood Studbook.

The kinematic markers were monitored by use of 6 infrared cameras[a] operating at 240 frames/s. The cameras were placed in a semicircle in the center of the arena at a distance of 9 to 10 m from the jumping track. The field of view was 10 m, including the last canter stride before the third fence, the jump over this fence, and the first canter stride after the landing.

Data collection—Data were initially recorded when the horse was standing on the jumping track for conformational analysis. Before performing jumps to be used in the analysis, each horse performed 3 sets of 3 practice trials. After each set, the height of the fences was increased so that by the end of the practice trials, the first fence was at a height of 0.4 m, the second at a height of 0.6 m, and the third at a height of 1.05 m. The height of the third fence was selected on the basis that it was a height that all horses could jump comfortably. Each horse was hand-walked to a distance a few meters before the first fence and then released to complete the jumps. Data were collected for 10 to 15 jumps over the third fence. Jumps in which markers were not detectable by the cameras were deleted.

Data processing—Time course of the marker coordinates was smoothed by use of a fourth-order, zero-lag Butterworth filter with a cutoff frequency of 6 Hz. The smoothed data were used to calculate the time course for the x- and y-coordinates of the **center of gravity (CG)** of each horse in accordance with a segmental model defined elsewhere.[6] For calculation of the position of the CG, it was assumed that the left and right limbs of each horse moved symmetrically. Strictly speaking, this introduced errors, but these errors were small because the missing right limbs each constitute only about 6% of the body weight. Time courses of the CG coordinates were differentiated to yield the **CG horizontal velocity** ($\dot{x}_{CG}$), **CG vertical velocity** ($\dot{y}_{CG}$), **CG horizontal acceleration** ($\ddot{x}_{CG}$), and **CG vertical acceleration** ($\ddot{y}_{CG}$). **Effective energy** (E_{eff}), which was the energy contributing to the absolute height reached by the CG at the

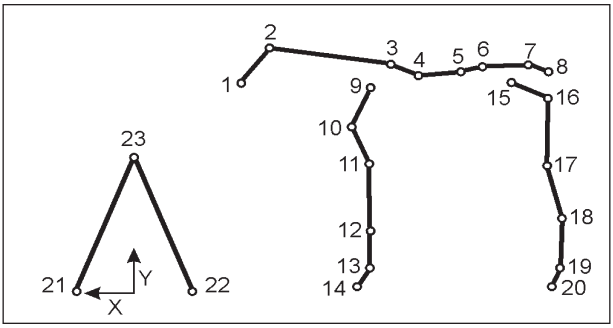

Figure 1—Illustration of the sites at which markers were affixed to anatomic landmarks on each horse and to a fence. Locations were as follows: 1, crista facialis; 2, atlas; 3, top of the shoulders (ie, spinous process of T6); 4, spinous process of T13; 5, spinous process of L2; 6, L5; 7, S2; 8, S5; 9, spine of the scapula; 10, center of rotation for the scapulohumeral joint; 11, center of rotation for the humeroradial joint; 12, carpus; 13, center of rotation for the metacarpophalangeal joint; 14, hoof of the forelimb; 15, tuber coxae; 16, center of rotation for the coxofemoral joint; 17, center of rotation for the femorotibial joint; 18, tarsus; 19, center of rotation for the metatarsophalangeal joint; 20, hoof of the hind limb; 21, ground 1; 22, ground 2; and 23, top of the fence. Markers were also attached on the medial aspect of right limbs (not shown).

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apex of the jump, was defined as the sum of potential energy and kinetic energy attributable to $\dot{y}_{CG}$. Throughout the remainder of this report, velocity and acceleration refer to the CG unless stated otherwise.

A jump may be subdivided into a push-off phase and an airborne phase. The push-off phase can be further subdivided into a phase in which the forelimbs generate force and a phase in which the hind limbs generate force. At the transition between forelimb and hind limb push, $\ddot{y}_{CG}$ has a local minimum that can easily be detected. To detect the exact moment of takeoff, we first found the exact moment that $\ddot{y}_{CG}$ decreased to zero, then fit a straight line to the **time history of ÿcg ($\ddot{y}_{CG}[t]$)** around this exact moment, and finally extrapolated this line to the exact moment that $\ddot{y}_{CG}$ reached a value of -9.81 m/s^2, which was typically 35 milliseconds later. This ensured that oscillations in $\ddot{y}_{CG}(t)$ had little effect on the detection of the exact moment of takeoff. A similar procedure was used to detect the exact moment of landing, signifying the end of the airborne phase. We also detected the exact moment at which **height of the CG (y_{CG})** became maximal (ie, apex of the jump). Finally, we detected the exact moment of clearance for the forelimbs and hind limbs, respectively, which was defined as the exact moment that the markers on the left metacarpophalangeal and metatarsophalangeal (ie, fetlock) joints, respectively, were directly over the top of the fence. It has been reported[b] that horses most often hit the fence with their fetlocks rather than with their hooves.

Data from the medial markers on the right forelimb helped us to observe that the forelimbs frequently did not flex symmetrically during clearance or did not clear the fence simultaneously. Because the forelimb that is leading the canter in the approach to the fence could affect the determination of the exact moment of clearance by the forelimbs, it was decided that we would only use those jumps in which horses approached with the left forelimb in the lead, which is the preferred leading limb for horses.[7,8] Three horses had to be excluded from the analysis because they had a preference to approach the jump by leading with their right forelimb and made an insufficient number of jumps when leading with their left forelimb. At the exact moment of clearance of the hind limbs, it was observed that the markers placed on both hind hooves were in a relatively symmetric position; therefore, the leading hind limb during push-off was not used as a criterion when selecting jumps to be analyzed.

Statistical analysis—To assess variation within and among horses, a 1-way ANOVA was performed by use of commercially available software[c] on results for the 12 horses with jumps accomplished by leading with the left forelimb (4 jumps/horse). Correlations between variables were evaluated. Pearson correlation coefficients were calculated by use of the mean value for each variable for the 4 jumps of each horse.

Results

Typical time courses of the y_{CG} and derived variables were calculated for separate jumps of each horse (**Figure 2**). To gain confidence that the calculations were valid, we compared 2 estimates of the **vertical displacement of the CG after takeoff ($\Delta y_{CG,air}$)**. The first estimate (ie, $\Delta' y_{CG,air}$) was calculated by subtracting the y_{CG} at takeoff from the maximal y_{CG}. The second estimate (ie, $\Delta'' y_{CG,air}$) was calculated from the $\dot{y}_{CG}$ at takeoff in accordance with following the equation:

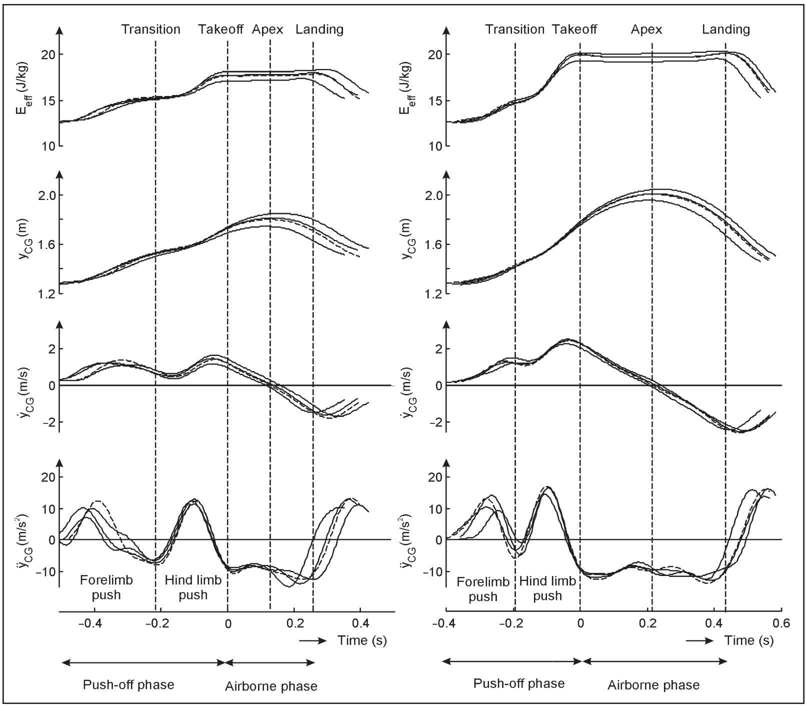

Figure 2—Graphs of the time course for several variables derived from the motion of the center of gravity (CG) for 4 jumps of a representative horse with low vertical velocity ($\dot{y}_{CG}$) at takeoff (left) and a representative horse with high $\dot{y}_{CG}$ at takeoff (right). Variables calculated included height of the CG (y_{CG}), $\dot{y}_{CG}$, vertical acceleration ($\ddot{y}_{CG}$), and effective energy (E_{eff}). Notice that each horse jumped quite consistently. In both horses, 1 of the 4 jumps is highlighted (dashed line). The different phases of the jump (vertical dashed lines) were determined for this specific jump.

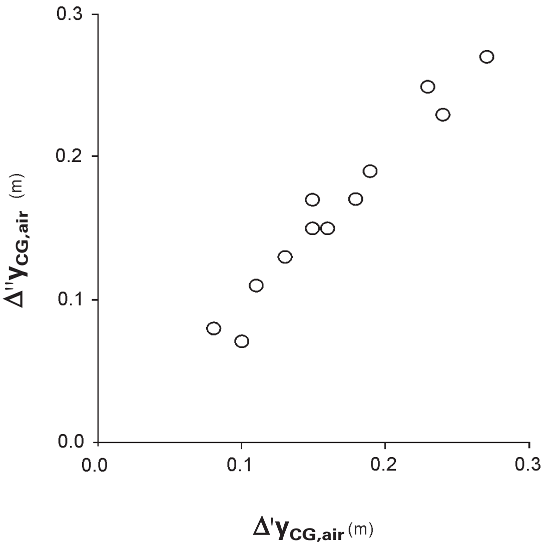

Figure 3—Correlation (*r*, 0.98) between 2 estimates of the vertical displacement of the CG from takeoff to the apex of the jump. The $\Delta' y_{CG,air}$ is the y_{CG} at the apex of the jump relative to y_{CG} at takeoff, and $\Delta'' y_{CG,air}$ is calculated from $\dot{y}_{CG}$ at takeoff.

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Table 1—Mean ± SD values for kinetic and kinematic variables calculated for 12 horses during free jumping over a fence.

Variable	Exact moment	All horses	Within-horse SD*	Subgroup L†	Subgroup R†	Subgroup H†	*r*‡
y_{CG}							
	Standing horse (m)	1.43 ± 0.05	NA	1.45 ± 0.02	1.43 ± 0.06	1.42 ± 0.05	–0.46
	Transition (m)	1.46 ± 0.06	0.02§	1.49 ± 0.03	1.47 ± 0.06	1.41 ± 0.06	–0.68
	Takeoff (m)	1.73 ± 0.05	0.02§	1.71 ± 0.01	1.74 ± 0.05	1.72 ± 0.08	–0.10
	Forelimb clearance (m)	1.76 ± 0.08	0.04§	1.67 ± 0.04	1.75 ± 0.05	1.87 ± 0.05	0.77‖
	Apex of jump (m)	1.89 ± 0.07	0.04§	1.81 ± 0.01	1.90 ± 0.03	1.97 ± 0.06	0.78‖
	Hind limb clearance (m)	1.86 ± 0.08	0.04§	1.74 ± 0.02	1.87 ± 0.02	1.95 ± 0.05	0.87‖
	Landing (m)	1.71 ± 0.05	0.03§	1.71 ± 0.01	1.71 ± 0.06	1.71 ± 0.05	–0.11
$\Delta'y_{CG,air}$							
	Apex of jump (m)	0.17 ± 0.06	0.03§	0.10 ± 0.02	0.16 ± 0.02	0.25 ± 0.02	0.97‖
$\dot{y}_{CG}$							
	Transition (m/s)	1.08 ± 0.21	0.12§	0.83 ± 0.09	1.08 ± 0.14	1.32 ± 0.08	0.88‖
	Takeoff (m/s)	1.75 ± 0.35	0.16§	1.29 ± 0.17	1.76 ± 0.11	2.20 ± 0.08	NA
$\ddot{y}_{CG}$							
	Peak during forelimb push (m/s^2)	14.2 ± 3.1	2.2§	11.7 ± 2.9	14.7 ± 2.6	15.7 ± 3.8	0.34
	Transition (m/s^2)	–5.3 ± 1.8	1.5§	–6.6 ± 0.4	–5.9 ± 1.6	–3.0 ± 0.7	0.77‖
	Peak during hind limb push (m/s^2)	13.0 ± 2.2	1.1§	11.0 ± 1.8	12.9 ± 1.6	15.3 ± 1.7	0.79‖
$\dot{E}_{eff}$							
	Peak during forelimb push (W/kg)	21.3 ± 4.1	2.9§	18.1 ± 3.0	21.2 ± 4.3	24.5 ± 2.0	0.47
	Peak during hind limb push (W/kg)	36.5 ± 9.5	4.1§	25.0 ± 3.9	35.9 ± 3.5	49.0 ± 4.4	0.98‖
x_{CG}							
	Transition (m)	–1.65 ± 0.19	0.11§	–1.58 ± 0.05	–1.57 ± 0.17	–1.89 ± 0.06	–0.66
	Takeoff (m)	–0.50 ± 0.22	0.10§	–0.32 ± 0.08	–0.45 ± 0.17	–0.77 ± 0.09	–0.83‖
	Apex of jump (m)	0.72 ± 0.11	0.12¶	0.63 ± 0.01	0.74 ± 0.13	0.80 ± 0.06	0.57
	Landing (m)	1.86 ± 0.31	0.17§	1.45 ± 0.09	1.88 ± 0.17	2.22 ± 0.04	0.93‖
$\dot{x}_{CG}$							
	Initial (m/s)	7.69 ± 0.26	0.30¶	7.59 ± 0.18	7.66 ± 0.29	7.86 ± 0.26	0.44
	Takeoff (m/s)	6.83 ± 0.28	0.25§	6.73 ± 0.11	6.77 ± 0.35	7.05 ± 0.14	0.51
Forelimb ($y_F – y_0$)	Forelimb clearance (m)	0.14 ± 0.05	0.06¶	0.11 ± 0.05	0.15 ± 0.06	0.17 ± 0.01	0.38
Hind limb ($y_F – y_0$)	Hind limb clearance (m)	0.17 ± 0.06	0.08¶	0.14 ± 0.08	0.16 ± 0.05	0.21 ± 0.03	0.43
Forelimb length	Forelimb clearance (m)	0.62 ± 0.08	0.05§	0.58 ± 0.06	0.60 ± 0.08	0.70 ± 0.04	0.47
Hind limb length	Hind limb clearance (m)	0.78 ± 0.10	0.06§	0.81 ± 0.04	0.76 ± 0.13	0.80 ± 0.05	–0.18
Duration of forelimb push (s)	—	0.20 ± 0.04	0.02§	0.24 ± 0.02	0.21 ± 0.02	0.16 ± 0.03	–0.78‖
Duration of hind limb push (s)	—	0.18 ± 0.02	0.01§	0.20 ± 0.01	0.18 ± 0.01	0.17 ± 0.01	–0.78‖
Duration of airborne phase (s)	—	0.37 ± 0.07	0.03§	0.28 ± 0.02	0.37 ± 0.03	0.46 ± 0.02	0.95‖

*Represents the mean within-horse SD for all 12 horses. †Subgroups L, R, and H represent the 3 horses with the lowest vertical velocity of the center of gravity ($\dot{y}_{CG}$) at takeoff, the 6 horses with intermediate $\dot{y}_{CG}$ at takeoff, and the 3 horses with the highest $\dot{y}_{CG}$ at takeoff, respectively. ‡Pearson correlation coefficient between each variable and $\dot{y}_{CG}$ at takeoff. §Within-horse variance is significantly ($P < 0.001$) less than the variance among horses. ¶Within-horse variance is significantly ($P < 0.05$) less than variance among horses. ‖Correlation is significant ($P = 0.01$; 2-tailed test).

y_{CG} = Height of the center of gravity (CG). Transition = Transition between forelimb push and hind limb push; it is defined as the exact moment that vertical acceleration of the CG ($\ddot{y}_{CG}$) reaches a local minimum. Takeoff = Exact moment that $\ddot{y}_{CG}$ becomes –9.81 m/s^2. Forelimb clearance = Exact moment that the metacarpophalangeal (ie, fetlock) joint of the left forelimb is over the top of the fence. Apex of jump = Exact moment that y_{CG} is maximal. Hind limb clearance = Exact moment that the metatarsophalangeal (ie, fetlock) joint of the left hind limb is over the top of the fence. Landing = Exact moment that $\ddot{y}_{CG}$ stopped being –9.81 m/s^2 at the end of the airborne phase. $\Delta'y_{CG,air}$ = Vertical displacement of the CG in the airborne phase; this value was calculated by subtracting y_{CG} at takeoff from the maximal y_{CG}. $\dot{E}_{eff}$ = Rate of change of effective energy; it is calculated as the sum of potential energy and kinetic energy attributable to $\dot{y}_{CG}$. x_{CG} = Horizontal distance from the CG to the top of the fence; this distance has a negative value when a horse is approaching the fence. $\dot{x}_{CG}$ = Horizontal velocity of the CG. Initial = Exact moment that the right forelimb impacts the ground. Forelimb ($y_F – y_0$) = Vertical distance between the fetlock joint of the left forelimb and the top of the fence. Hind limb ($y_F – y_0$) = Vertical distance between the fetlock joint of the left hind limb and the top of the fence. Forelimb length = Linear distance between the left front fetlock and left shoulder. Hind limb length = Linear distance between the left hind fetlock and left hip. Duration of forelimb push = Interval from initial to transition. Duration of hind limb push = Interval from transition to takeoff. Duration of airborne phase = Interval from takeoff to landing. — = Not applicable.

$\Delta''y_{CG,air} = (0.5/9.81) \times (\dot{y}_{CG,takeoff})^2$. By definition, these 2 vertical displacements are not the same because changes in orientation and configuration of a horse and movement of the markers with respect to the underlying structures, especially close to the time of takeoff, could cause discrepancies between these 2 estimates of $\Delta y_{CG,air}$. However, a strong linear relationship (*r*, 0.98) existed between these 2 variables (**Figure 3**). Also, the E_{eff} of the CG after takeoff remained quite constant as expected. Therefore, we believed it was safe to assume that the method of calculating estimates of the CG position and its derivatives was sufficiently accurate.

Although some variation was evident in the height reached by the CG at the apex of the jump, each of the horses jumped quite consistently (Figure 2). This corresponded with results of the statistical analysis, which revealed that for each of the variables selected in this study, the variance within a horse was significantly smaller than that among horses (**Table 1**). Consistency of the jumping technique of each horse and variation among horses were further illustrated when the exact moments of forelimb clearance and hind limb clearance were plotted (**Figure 4**). Some horses had less variation in their jumps than other horses. For example, at the apex of the jump, mean within-horse variation was 4 cm for the y_{CG} and 12 cm for the horizontal distance from the CG to the fence. Moreover, mean within-horse variation in the amount of clearance by the forelimbs and hind limbs was 6 and 8 cm, respectively.

When comparing mean y_{CG} at the apex of the jump among horses, we detected large variation, with values

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ranging from 1.80 to 2.01 m. Variation in this height seemed to be primarily attributable (*r*, 0.78) to variation in $\dot{y}_{CG}$ at takeoff, which ranged from 1.18 to 2.28 m/s (**Figure 5**). There was 1 horse with a high $\dot{y}_{CG}$ at takeoff that did not attain a large y_{CG} at the apex of the jump. On closer inspection, this horse was the smallest horse in the entire group, which obviously had to achieve greater $\dot{y}_{CG}$ at takeoff to reach the same absolute y_{CG}.

We decided to analyze in more detail the effect of these variations in $\dot{y}_{CG}$ at takeoff by studying correlations with other variables. Needless to say, correlation analysis is hazardous when researchers have not systematically manipulated 1 variable and studied the effect on other variables; high correlations can theoretically result because of a single outlier. To support the validity of our analysis, we discerned 3 subgroups of horses (3 horses with the lowest $\dot{y}_{CG}$ at takeoff [subgroup L], 3 horses with the highest $\dot{y}_{CG}$ at takeoff [subgroup H], and the remaining 6 horses with intermediate $\dot{y}_{CG}$ at takeoff [subgroup R]). For each of these subgroups, mean ± SD results for several variables were calculated in addition to the correlations between these variables and $\dot{y}_{CG}$ at takeoff; these correlations were not dependent on the formation of subgroups (Table 1). For all variables in which the correlation coefficient between the variable and $\dot{y}_{CG}$ at takeoff was > 0.7, subgroups H and L differed significantly (ie, the values of horses of subgroup L did not overlap with the values of horses of subgroup H). On the basis of these data, we determined that because of a higher $\dot{y}_{CG}$ at takeoff (70% higher), horses in subgroup H achieved greater y_{CG} at forelimb clearance (ie, 20 cm higher), greater y_{CG} at the apex of the jump (ie, 16 cm higher), and greater y_{CG} at hind limb clearance (ie, 21 cm higher), compared with corresponding values for the horses in subgroup L. Interestingly, despite the greater y_{CG} at forelimb clearance, horses in subgroup H did not achieve greater clearance of the forelimbs because they flexed their forelimbs a lesser amount at clearance (12 cm less). By virtue of their higher $\dot{y}_{CG}$ at takeoff, horses in subgroup H were airborne for a longer duration. Because the $\dot{x}_{CG}$ at takeoff was not different, the longer airborne phase corresponded to a greater jump distance in subgroup H (1.22 m greater), consisting of a takeoff 0.45 m farther before the fence and a landing 0.77 m farther after the fence (**Figure 6**).

The question remained as to how the difference of 70% in $\dot{y}_{CG}$ at takeoff developed between subgroups H and L. A greater increase of the $\dot{y}_{CG}$ during the push-off phase implies a greater integral of $\ddot{y}_{CG}(t)$. In turn, this can be the result of a higher $\ddot{y}_{CG}$, a longer duration of the push (which then requires greater vertical displacement of the CG during the push), or a combination of both. On the basis of analysis of the data, it can be concluded that the horses in subgroup H had a shorter duration of the push-off phase and achieved higher values for $\ddot{y}_{CG}$ (ie, they generated greater vertical push-off forces; Table 1). These differences were illustrated by comparison of values for horses in subgroups L and H (Figure 2). A further subdivision of the push-off phase into forelimb push and hind limb push revealed that differences were primarily during hind

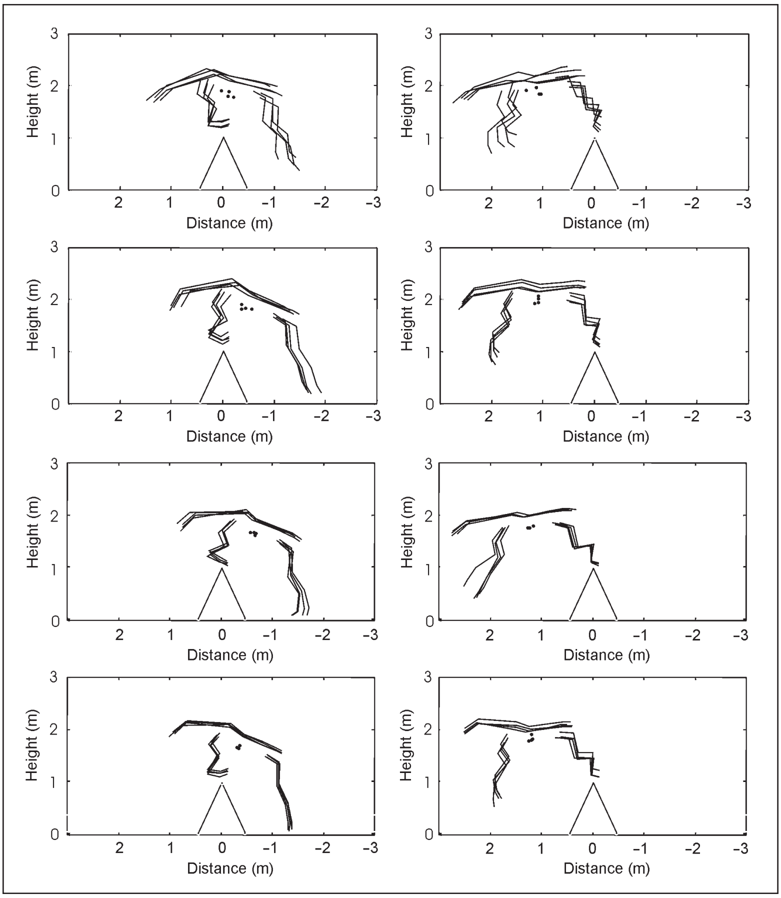

Figure 4—Representative illustrations of 4 jumps by each of 4 horses plotted at the exact moment of clearance by the left forelimb (left) and exact moment of clearance by the left hind limb (right). The CG of each horse is indicated (dot).

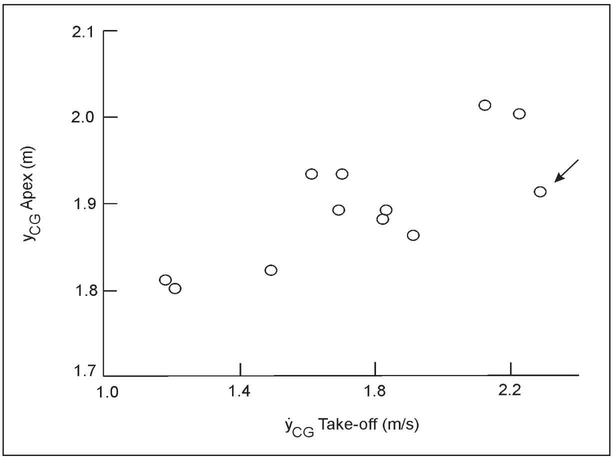

Figure 5—Correlation (*r*, 0.78) between the y_{CG} at the apex of the jump and $\dot{y}_{CG}$ at takeoff for 12 horses. The value for the smallest horse in the group is indicated (arrow).

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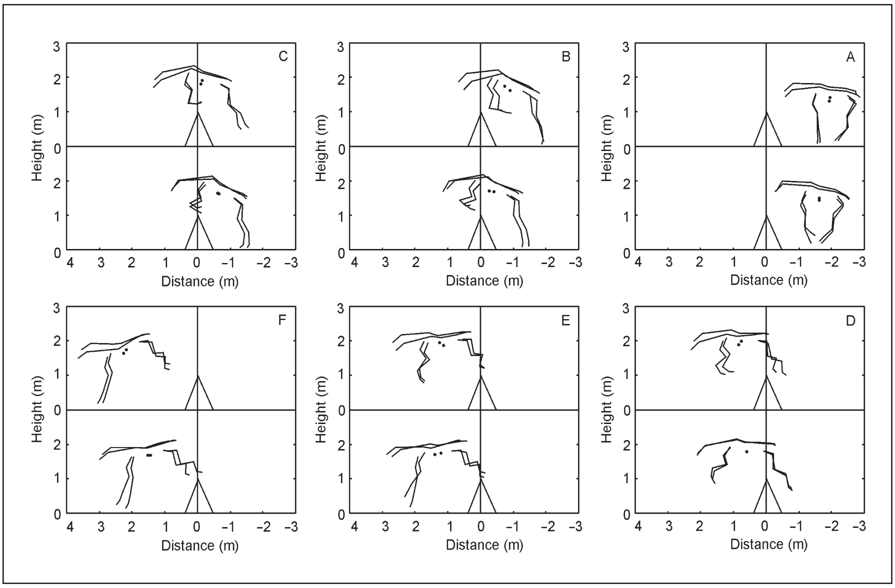

Figure 6—Illustrations of typical jumps for 2 representative horses with the highest $\dot{y}_{CG}$ at takeoff (subgroup H; top of each panel) and 2 representative horses with the lowest $\dot{y}_{CG}$ at takeoff (subgroup L; bottom of each panel) plotted at the exact moment of the transition (A), takeoff (B), forelimb clearance (C), apex (D), hind limb clearance (E), and landing (F) during a jump. Notice for the horses with the lowest $\dot{y}_{CG}$ at takeoff that the exact moment of forelimb clearance preceded the exact moment of takeoff. The CG of each horse is indicated (dot).

limb push. It should be mentioned that an additional increase of 10% in $\dot{y}_{CG}$ during hind limb push is not negligible because vertical displacement varies with the square of $\dot{y}_{CG}$; thus, the gain in jump height attributable solely to the increase in $\dot{y}_{CG}$ during the hind limb push was 15 cm in subgroup H and only 5 cm in subgroup L. During hind limb push, the horses in subgroup H generated higher peak $\ddot{y}_{CG}$ and, hence, a higher peak vertical ground reaction force; not surprisingly, they also generated a greater peak rate of change of E_{eff}.

Discussion

In the study reported here, kinematic data were analyzed for naïve 4-year-old show jumpers during free jumps over a fence 1.05 m in height that was approached by a cantering horse leading with the left forelimb. The collection of kinematic data was limited to 1 side of the horses for a practical reason: the horses needed to be constrained to the jumping track. Jumps in which a horse led with its right forelimb were excluded because the inclusion of those data could have caused large variance in the results. Analysis of our results allowed us to state that in jumps performed with the left forelimb in the lead, the variation within a horse for the variables studied was smaller than the variation among horses. As a matter of fact, quite a large variation was found among the horses in the way they cleared the fence.

In the study reported here, y_{CG} at the apex of the jump varied substantially among the horses, and this variation could be explained to a large extent by the variation in $\dot{y}_{CG}$ at takeoff. Horses with greater $\dot{y}_{CG}$ at takeoff took off farther before the fence and landed farther after the fence. Variation among horses for these variables was not related to dimensions of the horses (ie, y_{CG} of the standing horses was not correlated to $\dot{y}_{CG}$ at takeoff). It was important to establish this fact because we did not adapt the distances between the fences in the jumping track to the dimensions of the horses. Moreover, to achieve a given absolute height, a smaller (ie, shorter) horse needs to achieve a greater $\dot{y}_{CG}$ at takeoff than does a larger (ie, taller) horse. Therefore, it seems safe to state that horses used differing jumping techniques to clear the fence. Researchers in another study[9] arrived at a similar conclusion. Interestingly, the differences in y_{CG} at the apex of the jump did not result in greater clearance of the forelimbs or hind limbs because the horses that jumped higher tended to flex their limbs less. This means that they spent more energy in clearing the fence and therefore were less economical. The jump over a fence at a height of 1.05 m was not a maximal jump for the horses; thus, it is not possible to say whether the horses with a greater increase in their y_{CG} simply made no effort to flex their limbs or whether they were not good at flexing their limbs and therefore had to increase their y_{CG} to allow them to clear the fence.

In our analysis of how the differences in $\dot{y}_{CG}$ at takeoff developed, we found that they resulted from differences in forelimb push and hind limb push. The higher $\dot{y}_{CG}$ at the end of the forelimb push was not related to initial $\dot{x}_{CG}$ at the start of forelimb push or initial configuration of the body. Therefore, in line with the conclusion reached in another study,[10] there seems to be no indication that a higher $\dot{y}_{CG}$ at the end of the forelimb push is attributable to a more effective use of the pole-vaulting mechanism (ie, transformation of kinetic energy resulting from $\dot{x}_{CG}$ in E_{eff} by use of the forelimbs as poles); it simply resulted from a higher vertical push-off force and higher mean power output (rate of change of E_{eff} of the forelimbs). The same was true for the contribution of the hind limbs; a higher $\dot{y}_{CG}$ at takeoff was associated with a higher peak $\ddot{y}_{CG}$ and higher peak vertical power output. Interestingly, higher $\dot{y}_{CG}$ at takeoff was also associated with a less pronounced dip in $\ddot{y}_{CG}$ at the transition from forelimb push to hind limb push, meaning that the hind limb push started earlier relative to the end of the forelimb push so that the whole push-off was seemingly continuous (Figure 2). Apparently, these differences in the transition varied with the vertical force and power of the forelimb push and hind limb push.

As mentioned previously, judges evaluate the jumping ability of 3- to 4-year-old horses during free jumping to assess their potential as show jumpers. Some of the differences observed between the horses participating in the study reported here can easily be

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detected by observation, such as vertical displacement of the CG during the airborne phase, position of the limbs at clearance, and horizontal distance from the fence at takeoff. A possible relationship of this latter variable with show jumping performance has been addressed in the literature. For example, investigators in 1 study[11] evaluated takeoff kinematics of sixteen 3- to 4-year-old untrained horses during free jumping of a single square oxer fence (1 × 0.5 m). In that study, horses that were poor jumpers, which were included in that category because they consistently hit the fence, had their CG closer to the fence at takeoff. Researchers have also examined kinetic variables that cannot be detected directly by observation but are ultimately responsible for the differences in kinematics among horses. For example, the dorsoventral acceleration of the CG has been measured by use of an accelerometer on the sternum in 8 horses during jumping of 14 obstacles in a selective experimental show jumping course.[3] In that study, investigators reported that each horse had a unique technique for jumping (ie, selected a stride frequency, changed stride frequency toward the end of the approach, and generated acceleration impulses by the forelimbs and hind limbs that differed from those in other horses). They concluded that horses ranking higher in the selective course generated lower acceleration peaks with the forelimbs and higher acceleration peaks with the hind limbs than the lower ranking horses. In another study,[1] investigators measured the dorsoventral accelerations of two hundred 3-year-old horses during free jumping in selection events. On the basis of the rankings in those selection events, good jumping ability was characterized by high acceleration during the hind limb push and high $\dot{y}_{CG}$ at takeoff.

It is generally acknowledged that $\dot{y}_{CG}$ at takeoff is an important variable for the jumping performance in long and high jumps.[5,9] Moreover, findings reported in the literature indicate that good jumpers tend to generate greater acceleration with their hind limbs and leave the ground farther from the fence than poor jumpers. It is tempting to combine all this information and presume that on the basis of results for the group of horses participating in our study, horses that achieved the highest $\dot{y}_{CG}$ at takeoff, which were also the horses that had the highest $\ddot{y}_{CG}$ and power peaks with their hind limbs and took off farthest from the fence, were the most talented show jumpers. However, it is too early for such a presumption. First, it should not be forgotten that all horses cleared the fence without difficulty. Perhaps the horses that did so with a low $\dot{y}_{CG}$ at takeoff were simply being economical and could have easily increased this velocity if the height of the fence had been increased. Also, they flexed their limbs more, and the ability to flex the limbs may be of decisive importance for the clearing of high fences. Furthermore, it is not currently clear whether the jumping technique observed in naïve 3- to 4-year-old horses is representative of the technique of those same horses as adults when performing as full-grown show jumpers. Perhaps the technique can easily be changed by training or affected by a rider. Another characteristic that may be an indicator of future jumping ability is the within-horse variability. When 2 horses have the same mean values for all variables but differences in within-horse variation, the horse with the lowest variation is likely to rank higher in competition. This factor may also be affected by training or a rider. Finally, the attitude of a horse may be so important that it will prevent a horse with good athletic ability from becoming a good show jumper.

In the study reported here, we concluded that within-horse variation for all variables studied was significantly less than the variation among horses, warranting the use of these variables for the selection of specific horses. Of the variables analyzed, $\dot{y}_{CG}$ at takeoff was related to many performance-determining variables and seemed to have good discriminative power. However, although this variable yielded promising results, its real value can be assessed only after establishing the relationship between jumping characteristics in a naïve horse at the age when selection takes place and the eventual athletic performance when the horse has been fully trained as a show jumper.

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[a] Pro Reflex, Qualisys Medical AB, Göteborg, Sweden.

[b] Loeffen C, Dutch Equine Training Center, Deurne, The Netherlands: Personal communication, 2002.

[c] SPSS 10.0 for Windows, SPSS Inc, Chicago, Ill.

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