Locomotor mechanics of the tölt in Icelandic horses

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Objective—To evaluate the locomotor mechanics of the tölt in Icelandic horses.

Animals—10 adult Icelandic horses with no history of lameness.

Procedures—Force platform data were captured for 27 trials for horses ridden at a tölt in a lateral sequence single-foot gait at a steady speed from 0.89 to 5.98 m/s. Simultaneous kinematic data were obtained by tracking retroreflective markers overlying the right fore- and hind limbs. These kinetic and kinematic data were combined to evaluate 3 mechanical approaches, duty factor, Froude number, and center of mass (COM) mechanics, and to evaluate the capacity to recover mechanical energies during töltting via inverse pendulum and spring-mass (bouncing) mechanics.

Results—Töltting horses had in-phase fluctuations of gravitational potential and kinetic energies of their COM and a capacity to recover mechanical energy through elastic recoil of spring elements in their limbs. These characteristics, along with Froude numbers exceeding values expected for the walk-run transition, are indicative of bouncing mechanics and, hence, most strongly ally töltting with running. Only the footfall pattern of a lateral sequence single-foot gait and low vertical excursions of the COM are more commonly associated with walking.

Conclusions and Clinical Relevance—At the tölt, horses have unique mechanical characteristics that should be understood for veterinary care. Differences in interlimb coordination between töltting and trotting mask the overall similarities in most other aspects of their locomotor dynamics. (Am J Vet Res 2006;67:1505–1510)

Walking horses commonly use a lateral sequence single-foot gait.1 This gait is defined by a limb phase centering on 0.25 (range, 0.19 to 0.31); limb phase (also known as lateral advanced placement) is the elapsed time between the footfalls of a hind limb and its ipsilateral fore-limb normalized to stride duration.1,2 At higher speeds, most horse breeds transition to a trot (limb phase of 0.5).2006;67:1505–1510)

Many gaited horses, however, use a symmetric 4-beat stepping gait consistent with the lateral sequence single-foot footfall pattern.3 These include familiar breeds such as the Paso Fino horse (classic fino, paso largo) and Icelandic horse (tölt). The popularity of ambling horses is on the rise among recreational riders, yet our understanding of the locomotor mechanics of gaited horses is limited. Further research is required to assess whether these gaits should be best considered walking gaits6 or running gaits. This distinction may influence susceptibility to lameness and rehabilitation protocols.

In the literature, mechanical descriptions are typically used to classify a walk from a run and numerous approaches exist.4 One approach uses stride kinematics described by duty factor (ratio of stance duration to stride duration) and gait. A duty factor of ≥ 0.5 and < 0.5 distinguishes a walk from a run, respectively.5 Furthermore, the walk-run transition in most horses is distinguished by an abrupt shift in gait from a 4-beat gait to a 2-beat gait (usually a trot),6 and running typically includes a period of suspension.7 A second approach evaluates the movements of the body’s COM to determine whether a horse is moving with inverted pendulum mechanics (walking) or spring-mass or bouncing mechanics (running).8,9 When walking, the limbs function as semirigid struts so that the COM is lifted to its highest position near midstance, while forward velocity of the COM is highest at hoof touchdown and liftoff and is lowest at midstance. Consequently, Ek cycles out of phase with Ek-tot, and the phase shift between minima of Ek and Ek-tot is near 180°. This pendulumlike exchange of energies provides an opportunity to recover external mechanical energy with every step (up to 70% in quadrupeds3,10), thereby reducing muscular effort during locomotion at slow speeds. At faster speeds, the limbs function with greater compliance during stance phase so that the COM no longer rises during the first half of stance but...
rather drops to its lowest position near midstance. Accordingly, $E_k$ and $E_{k-tot}$ fluctuate in phase with each other (phase shift near 0°). As much as 40% of the muscular work of trotting is recovered via bouncing mechanics by the storage and return of elastic strain energy in ligaments, tendons, and muscles of the limbs with every step. A third approach for distinguishing a walk from a run relies on Fr, a parameter that is related to the ratio of kinetic energy to $E_p$. Horses moving with similar dynamics are expected to move at comparable Frs, with cursorial mammals switching from a walk to a trot at an Fr of approximately 0.5 and from a trot to a gallop at an Fr of 2 to 3.

The purpose of the study reported here was to evaluate the locomotor mechanics of the tölt in Icelandic horses to assess whether the gait conforms more closely to walking or running. This breed and gait were selected because stride characteristics are well established and individual limb GRFs have been analyzed. Understanding the mechanics of the tölt has implications for performance, injury, and treatment of gaited horses.

Materials and Methods

Animals—Ten Icelandic horses (362 to 470 kg, including rider and tack) with no recent history of lameness or other gait defects were used. All procedures complied with a Michigan State University Institutional Animal Care and Use protocol.

Data acquisition—Six experienced riders rode horses at a tölt across a 40-m-long track into which a 1.2-m-long force platform was embedded. Fore- and hind limb GRFs were captured at 1,200 Hz in each trial and were smoothed by use of a fourth-order, low-pass Butterworth filter with a cutoff frequency of 40 Hz. Simultaneous kinematic data were captured across a 5-m data capture volume at 120 Hz by tracking reflective markers overlaying major joints of the right fore- and hind limbs and all 4 hooves with an infrared camera system. Icelandic horses prompted to tölt can use a variety of footfall patterns, but trials were limited to a lateral sequence single-foot gait with a limb phase of 0.25 ± 0.13%, which is the most common footfall pattern observed.

Locomotor mechanics—The following 3 methods were used to assess whether tolering conforms more closely to walking or running mechanics: duty factor, Fr, and COM mechanics. Duty factor was computed as hind limb stance duration divided by stride duration, and a kinematic walk and run were identified with duty factors ≥ 0.5 and < 0.5, respectively. Froude number was calculated as $u^2/gl$, where $u$ is forward speed (mean forward velocity of the lateral tubercle and greater trochanter, respectively), and l is hip height at midstance (vertical distance from the ground to the greater trochanter). Cursorial mammals are expected to switch from a walk to a tölt at an Fr of approximately 0.5. Center of mass mechanics and external mechanical energy calculations generally followed that of Cavagna et al, except whole-body GRFs were estimated from fore- and sequential hind limb GRFs that were summed by use of footfall timing data because the force platform was too short for capturing whole-body GRFs. It was assumed that GRFs obtained when the limbs struck the force platform were representative of proceeding and succeeding footfalls, and the left- and right-limb GRFs were symmetric as is typical in sound horses. An acceptable trial possessed a steady forward speed of <15% difference between the first and second half of the 5-m capture volume, and braking and propulsive components of the whole-body cranio-caudal impulse that differed by < 15%.

Only 27 trials of the original 62 trials qualified in their limb phase and steady speed requirements for further analysis. The $F_x$, $F_y$, and $F_z$ GRFs during a step were integrated to derive velocities ($v_x$, $v_y$, or $v_z$) and thereby compute kinetic energies of the COM in each direction (ie, $E_k = \frac{1}{2}mv^2$, where m is mass and v is velocity). These kinetic energies were then summed to obtain the $E_{k-tot}$. Vertical velocity was further integrated to obtain the vertical fluctuations of the COM and, thus, changes in $E_p$ ($E_p = mgh$, where m is mass, g is gravitational acceleration, and h is vertical displacement of the COM). The integration constant for the cranio-caudal direction was set as mean forward speed; the constants for the vertical and mediolateral directions were estimated as the mean value for velocity and vertical displacement profiles. The phase shift between $E_{k-tot}$ and $E_p$ was calculated as the time difference for reaching minimum values in the $E_{k-tot}$ and $E_p$ profiles relative to the duration of the stride multiplied by 360°. Trials conforming more to pendulumlike mechanics are expected to have phase shifts closer to a 180° phase shift ($E_{k-tot}$ is at its minimum when $E_p$ is maximum; out-of-phase fluctuations), whereas bouncing mechanics should show phase shifts closer to 0° (in-phase $E_{k-tot}$ and $E_p$ fluctuations). Intermediate mechanics occur at 45° to 90°.

Recovery of external mechanical energy—The capacity of tolering Icelandic horses to recover external mechanical energy by use of inverted pendulum mechanics was calculated as follows:

$$\%R = \left( \frac{\Delta E_{k-tot} + \Delta E_p}{\Delta E_{tot}} \right) \times 100$$

where %R is percent energy recovery; $E_{k-tot}$ is $E_{k-tot} + E_p$; and $E_{tot}$ is $E_{k-tot} + E_p$ and $E_{tot}$ are the sum of the positive increments of the $E_{k-tot}$, $E_p$, and $E_{tot}$ profiles, respectively. A positive increment is the portion of an energy profile during which there is a net gain during a step. Leg-spring stiffness was used to estimate the potential for elastic strain energy recovery during the stance phase. Because limbs overlap in their support phases during the tölt, kleg does not reflect the stiffness of an individual limb but rather the overall stiffness of a single imaginary spring representing the efforts of all limbs during the step. It was computed as follows:

$$k_{leg} = \frac{F_{max-COM}}{\Delta L}$$

where $F_{max-COM}$ is peak vertical force for the whole body, and $\Delta L$ is the change in leg length from hoofstrike to the middle of the stance phase. The latter parameter was calculated as follows:

$$\Delta L = \Delta y + L_o (1 - \cos \theta)$$

where $\Delta y$ is the vertical displacement of the COM (calculated by twice integrating vertical acceleration), $L_o$ is the length of the leg spring at touchdown (the mean of the fore- and hind limb lengths, measured as the linear distance from the hoof to the lateral tubercle and greater trochanter, respectively), and $\theta$ is half of the angle swept by the leg spring during its stance phase (computed as $\sin^{-1}(|uLt|/2L_o)$, where $uLt$ is stance duration and u is forward speed). To facilitate comparison of stiffness values in published data on trotting horses of different sizes, $k_{vel}$ was also computed ($k_{vel} = k_{leg}/(mg)$).

Finally, $C_{app}$ for the fore- and hind limbs was calculated as follows:

$$C_{app} = \Delta L/F_{max-COM}$$
where $F_{z_{\text{max-limb}}}$ is the peak vertical force of an individual limb and $\Delta t$ is the change in hip height from touchdown to the time of $F_{z_{\text{max-limb}}}$. Inability to track both hip and shoulder markers in 3 trials decreased the sample number for leg stiffness to 22 horses.

**Results**

**Speed and duty factor**—Speeds ranged from 0.89 to 5.98 m/s in the 27 trials in which the Icelandic horses trotted with a lateral sequence single-foot gait. These values correspond to duty factors of 0.66 to 0.41, in which approximately 40% of the trials qualified kinematically as a run (duty factor < 0.5). None of the trotting horses had aerial phases in their gait.

Fr—At the tölt, Icelandic horses had Fr values ranging from 0.21 to 3.13. Thus, horses remained within the lateral sequence single-foot gait through the typical walk-trot (Fr of approx 0.5) and trot-gallop (Fr of 2 to 3) transitions. Most trials fell within the Fr range of a trot (0.5 to 3), with only 2 trials below and 2 trials above this range. Extensions into the walking and galloping Fr ranges may have been attributed to rider encouragement.

**Whole-body forces**—Values of $F_{z}$ fluctuated around body weight (Figure 1). The $F_{z}$ profiles had a long ascending portion, reflecting the loading of the forelimb followed by the loading of the contralateral hind limb and the unloading of the ipsilateral hind limb. Because individual fore- and hind limb $F_{z}$ records are single peaked and because $F_{z}$ values of the forelimbs reach their maximum values later in the stance phase than do the hind limbs, $F_{z}$ values were also invariably single peaked. Both horizontal forces were much smaller in magnitude than the $F_{z}$ value. The $F_{z}$ profiles typically changed sense multiple times during the step because braking and propulsive phases of each sequential limb overlapped each other for approximately 25% of stride duration. The $F_{x}$ values were small in magnitude and fluctuated around zero with no consistent pattern. Impact spikes caused irregular spiking on the 3 force profiles at the beginning of each limb’s stance phase.

**External energies**—Magnitudes of $E_{p}$ and $E_{k-tot}$ were high initially in the step then fell to their minima during midstance only to rise again during the second portion of the step (Figure 1). As a result, the tölt gait was closer to the phase shift for spring-mass mechanics (phase shift of < 90°). Most trials (70.3%) had an undisputed pattern of mechanical energy fluctuations of the spring-mass model (0° to 45° phase shift between minima of $E_{p}$ and $E_{k-tot}$); the remaining trials may be considered to operate under intermediate mechanics, albeit with a strong tendency toward spring-mass mechanics (< 90° phase shift).

**Energy recovery**—The capacity to recover external mechanical energy during trotting via inverted pen-
that of forelimbs (0.095 m/kN), resulting in a hind limb-to-forelimb compliance ratio of 64:36.

Vertical displacements—The COM of tölting Icelandic horses fluctuated vertically by 12 ± 1 mm, reaching its lowest position at midstance (Figure 3). The shoulder and hip landmarks were highest at each limb’s touchdown, descended to their lowest position at midstance, and ascended again during the second half of stance phase. The shoulder and hip markers depressed by, on average, 70 and 66 mm, respectively. Only the 4 slowest trials had a different kinematic pattern in which the hips ascended to their highest position at mid stance so that the hind limbs acted more as struts even as the forelimbs continued to compress throughout stance phase (trials 1 to 4). Nevertheless, even these slow trials had vertical excursions of the COM consistent with spring-mass mechanics (Figure 2). For all trials, the COM fluctuates more in phase with the shoulder than with the hip.

Discussion
The tölt is allied with the trot, a running gait in horses, in most of the biodynamic parameters assessed in our study. The walk-trot transition of small horses (110 to 170 kg) moving on a treadmill occurs at an Fr of approximately 0.5, and tölt ing Icelandic horses virtually always move with an Fr of > 0.5. Furthermore, the COM of trotting mammals decreases to its lowest position at mid stance because the limbs are more compliant during the stance phase of trotting than they are during walking, and a similar pattern of COM movement and limb compliance is observed during the tölt. It follows that Ep and Ek-tot fluctuate in phase with each other in trotting mammals and tölt ing Icelandic horses alike. Consequently, during neither trotting nor tölt ing are appreciable amounts of external mechanical energy recovered via pendul umlike mechanisms. Rather, the elastic elements in the limbs stretch and recoil during the stance phase as a means for recovering elastic strain energy with every step during the tölt and tölt. Indeed, the hind limbs in running non-gaited horses provide approximately two thirds of overall elastic energy storage, a value similar to the 64:36 compliance ratio found in our study for tölt ing Icelandic horses.

Less straightforward to interpret are the results for duty factor. Icelandic horses in a slow to moderate speed tölt move with a hind limb duty factor of ≥ 0.5, which qualifies them as a walk according to Hildebrand’s kinematic criterion. Yet, duty factor of a faster tölt fall to < 0.5, as expected for a run. A high (≥ 0.5) duty factor matched with in-phase fluctuations of Ep and E_k-tot has also been reported in the artificial crouched-limb human gait of “Groucho running” and observed naturally in trotting marsupials and lizards and striding birds. Furthermore, because suspension phases are commonly absent in these horses, grounded or nonaerial locomotion does not negate the possibility of running mechanics. In any case, a single-foot gait is at a mathematically disadvantage for obtaining a period of suspension. With a limb phase of approximately 25%, at least 1 limb is in contact with the ground dur-

Figure 3—Vertical movement of joints and COM during a tölt ing step. A—Maximum vertical displacement of proximal limb joints (closed circles, shoulder; open circles, hip) and COM (closed triangle s) plotted against speed in tölt ing Icelandic horses. Values indicate a change from the touchdown to midstep, where positive values indicate a vertical rise. Shoulder and hip markers moved out of phase in the slowest trials (trials 1 to 4). B—Vertical displacement profiles for the COM (solid line), right shoulder (dashed line), and right hip (dotted line) during a typical step (excluding trials 1 to 4; 4.67 m/s). Shoulder and hip profiles shown only during fore- and hind limb support phases, respectively.
ing a single-foot gait until duty factor decreases to < 0.25, much lower than the smallest duty factor value recorded for a trot of 0.41. Suspension phases reported for Icelandic horses primarily occurred when horses deviated toward a lower limb phase into a 4-beat pace (lateral sequence lateral couplet) at higher speeds.19

One notable walklike characteristic of the trot is the following most common footfall patterns: lateral sequence single-foot gait or, at higher speed, lateral sequence lateral couplet.19 Whereas these footfall patterns have been recorded at low walking speeds in a broad range of mammals including Rodentia, Carnivora, Artiodactyla, Perissodactyla, and Proboscidea, only the latter 2 orders retain the lateral sequence single-foot gait into higher speeds.10,17,27 Unfortunately, the locomotor biodynamics of a single-foot gait in elephants is mixed20 and thus uninformative for furthering our understanding of the trot. Thus, whereas the trot initially seemed like a walk-run chimera, only its footfall pattern is truly unusual for a run, so that the trot is best categorized as a run.

Riders of gaited horses commonly remark on how comfortable their breed’s special gait feels, compared with the trot.26 In Icelandic horses, this is primarily the result of an exceedingly small vertical excursion of the COM during the tölt (12 mm). By comparison, the COM of trotting horses is displaced 53 mm during each step.22 Indeed, the value for a trot is more similar to that of a flat walk (20 mm in 450- to 670-kg warm-bloods).23 The COM position is most strongly influenced by forelimb dynamics in at least the trot and walk,9 as evidenced by the closer phase relationship of vertical movements of the COM and shoulder. This is largely the result of forelimb dominance in body weight support (forelimb-to-hind limb peak Fz ratios of approx 57% in the tölt16 and walk20,31). Although the greater stiffness of forelimbs in töltting horses helps to stabilize the COM, perhaps more influential is footfall pattern. Individual limbs during single-foot gait land every 25% of the stride duration, compared with 50% for the diagonal couples in trots. While each limb of a töltting horse compresses as it accepts its role in body weight support, the COM cannot equivalently descend due to the smaller vertical excursion of the COM and shoulder. This is typically associated with slower gaits.

Because Icelandic horses are still a relatively rare breed, veterinarians may be conflicted on how to evaluate lameness at the tölt. Results of our study, together with those published earlier,14,16 provide some direction. A trot is walk-like in its footfall patterns with small vertical excursions of the COM and the low magnitudes of fore- and hind limb vertical GRFs. In all other aspects of locomotor biodynamics, töltting should be compared with trotting, as both gaits operate under spring-mass mechanics. However, töltting horses may be less effective at masking lameness than trotting horses because of frequent periods of single-limb support (45% to 65% of stride duration).13 Rehabilitation programs for injuries to the limb spring system should recognize that soft tissues stresses during töltting are similar to those during trotting.

References
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