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Walk–run classification of symmetrical gaits in the horse: a multidimensional approach

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Walking and running are two mechanisms for minimizing energy expenditure during terrestrial locomotion. Duty factor, dimensionless speed, existence of an aerial phase, percentage recovery (PR) or phase shift of mechanical energy and shape of the vertical ground reaction force profile have been used to discriminate between walking and running. Although these criteria work well for the classification of most quadrupedal gaits, they result in conflicting evidence for some gaits, such as the tölt (a symmetrical, four-beat gait used by Icelandic horses).

We use established pattern recognition methods to test the hypothesis that the tölt is a running gait based on an *automated and optimized decision drawn from four features* (dimensionless speed, duty factor, length of aerial phase and PR for over 6000 strides from four symmetrical gaits in seven Icelandic horses) simultaneously. We compare this decision with the use of each of these features in isolation.

Sensitivity and specificity values were used to determine optimal thresholds for classifying tölt strides based on each feature separately. Duty factor and dimensionless speed indicate that tölt is more similar to running, while aerial phase and PR indicate that it is more similar to walking.

Then, two multidimensional pattern recognition approaches, multivariate Gaussian densities and linear discriminant analysis, were used and it was shown that, in terms of stochastic multidimensional discrimination, tölt is more similar to 'running'. The approaches presented here have potential to be extended to studies on similar 'ambling' gaits in other quadrupeds.

Keywords: walk–run; quadrupedal gait; symmetrical gait; pattern recognition; horse

1. INTRODUCTION

Two distinct mechanisms have been described for minimizing energy expenditure during locomotion in bipeds (Cavagna *et al.* 1977). In 'walking', gravitational potential energy of the centre of mass is converted into kinetic energy and vice versa in a pendulum-like manner and up to 70 per cent of the energy can be recovered through this mechanism (Cavagna *et al.* 1977; Griffin *et al.* 2004*a*). At higher speeds 'running' gaits are chosen, where energy is conserved during elastic bounces of the body (Cavagna *et al.* 1977).

In quadrupeds, gaits are typically categorized into walking and running (Hildebrand 1968, 1989; Cavagna *et al.* 1977) as well as into symmetrical and asymmetrical gaits (Hildebrand 1968, 1989). Walking and running types of gaits have been distinguished using one or several of the following features:

(i) duty factor (Hildebrand 1965, 1968, 1989; Hoyt *et al.* 2006),
(ii) presence of a whole-body aerial phase (Hildebrand 1985),
(iii) Froude number (Alexander & Jayes 1983) or dimensionless speed (Gatesy & Biewener 1991),
(iv) phase relationship between kinetic and potential energies (Cavagna *et al.* 1976, 1977), which has been quantified in two different ways: as a phase shift or using the amount (percentage) of energy recovery of mechanical energy (Cavagna *et al.* 1977), and
(v) shape of vertical ground reaction force profile (Pratt & O'Connor 1976; Merkens *et al.* 1985, 1993*a*,*b*; Biknevicius *et al.* 2004).

Duty factors above 0.5 have been used to indicate walking and those equal to 0.5 or below to indicate running (Hildebrand 1965, 1989; Hoyt *et al.* 2006). In bipeds, this definition is equivalent to using the presence or absence of a whole-body aerial phase (when no limb is in contact with the ground) as an indicator. However, in quadrupeds, the limb phase between front and hind limb pairs can allow duty factors below 0.5 without a whole-body aerial phase (Hildebrand 1965).

Dimensionless speed has also been used as an indicator of gait transition with the walk–run gait transition typically occurring at Froude numbers between 0.3 and 0.5 (a consistent gait transition was observed for horses

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of different sizes at a Froude number of 0.35 (Griffin *et al.* 2004*b*)). Since Froude number ($Fr = v^2/gl$; v, speed; g, 9.81 m s^{-2}; l, characteristic leg length) and dimensionless speed ($\hat{u} = \sqrt{v^2/gl} = \sqrt{Fr}$) are based on the ratio of kinetic ($E_{\text{kin}} = mv^2/2$; m, mass of animal) to potential ($E_{\text{pot}} = mgl$) energy, Froude numbers ultimately relate to the two basic locomotor mechanisms described by Cavagna *et al.* (1977).

In a similar way, phase shift between potential and kinetic energies or percentage recovery (PR) of mechanical energy (Cavagna *et al.* 1976, 1977; Griffin *et al.* 1999, 2004*a*) has been described as features to distinguish between walking and running. These are related to the timing and the amount of energy interchange, which occur in the two basic locomotor mechanisms (Cavagna *et al.* 1977).

Finally, a change in the shape of the vertical ground reaction force curve of a single footfall from double to single humped can be observed when changing from walking to running (Pratt & O'Connor 1976; Merkens *et al.* 1985, 1993*a*,*b*; Biknevicius *et al.* 2004).

In cursorial quadrupeds (e.g. horses or dogs), the two main symmetrical gaits (walk and trot) can be consistently categorized using the above features. We use the term 'walk' here for a lateral sequence gait in the Icelandic horse (see Robilliard *et al.* 2007) typically falling into the area of a lateral sequence single foot or a lateral sequence lateral couplet gait as defined by Hildebrand (1968). Whereas during walk the feet are on the ground for more than half the stride cycle (duty factor >0.5; Hildebrand 1968, 1989), in trotting (apart from very low speeds) the limbs are in contact with the ground for 50 per cent or less of the stride cycle (duty factor ≤ 0.5). This results in the presence of an aerial phase since diagonal pairs (one front limb and the contralateral hind limb) of limbs are in contact with the ground simultaneously during the trot (Hildebrand 1989). At the walk–trot transition, a sudden drop in duty factor has been described from approximately 0.6 to approximately 0.5 in horses on the treadmill (Hoyt *et al.* 2006). Also in horses, the shift in the phase relationship between kinetic and potential energies allows more energy conversion between these two types of energy in walking compared with trotting (Minetti *et al.* 1999).

Apart from walk and trot, horses (and other quadrupeds) are able to use other symmetrical gaits like the pace and a variety of four-beat gaits (Nicodemus & Clayton 2003). A particular variety of four-beat gait is the tölt that is observed in the Icelandic horse (Zips *et al.* 2001; Biknevicius *et al.* 2004, 2006; Robilliard *et al.* 2007), a gait pattern very similar to that used by elephants at higher speeds (Hutchinson *et al.* 2003, 2006; Ren & Hutchinson 2007) or primates at intermediate speeds (Schmitt *et al.* 2006). This gait is particularly interesting since it is typically displayed over a large range of speeds (Zips *et al.* 2001; Robilliard *et al.* 2007) and thus allows for a direct comparison with the other three symmetrical gaits (walk, trot and pace) seen in these horses (Robilliard *et al.* 2007). Some Icelandic horses show all four symmetrical gaits, whereas others exhibit a reduced gait repertoire.

A categorization into walking and running appears less straightforward for this particular gait: whereas duty factor values tend to be below 0.5 (Robilliard *et al.* 2007), the particular footfall pattern for this gait means that even at duty factors below 0.5, there might not be a whole-body aerial phase (Hildebrand 1965; Robilliard *et al.* 2007). As a result of the range of speeds seen in tölt (Zips *et al.* 2001; Biknevicius *et al.* 2006; Robilliard *et al.* 2007), dimensionless speeds predominantly fall into the running category; however, some values for dimensionless speed fall into the walking category (Biknevicius *et al.* 2004, 2006; Robilliard *et al.* 2007). Biknevicius *et al.* (2006) also reported comparatively low values for PR (mean 7.9%) consistent with spring-mass mechanics. Finally, the shape of the vertical ground reaction force has been reported to be 'single peaked' thus typical for running (Biknevicius *et al.* 2004). In both studies, Biknevicius *et al.* (2004, 2006) concluded that despite conflicting evidence the tölt must be considered more similar to running. However, to the authors' knowledge no multidimensional (e.g. pattern recognition) approach has been presented combining more than one feature to find a *common decision* as to whether the tölt should be considered more similar to walking or to running.

Automated pattern recognition techniques have been used for decades; automated speech recognition is a typical example (Young 1996; Cole *et al.* 1997) in which spoken language is transformed (by a computer) into a readable string of words. This essentially represents a mapping of a signal (digitized wave form) into discrete categories (words or series of words). The first step in this process usually is to derive a set of features from the original data, e.g. from a series of power spectra. These features are then combined into a series of multidimensional feature vectors (Young 1996; Cole *et al.* 1997). Then, a classifier is trained, which makes a decision based on information from a multidimensional feature space. This is achieved through a mapping (or classification) of the feature vectors into discrete categories (classes) based on either distances (geometrical classifiers) or probabilities (statistical classifiers), thus taking into account multiple features simultaneously. A variety of feature extraction methods and classification algorithms are commonly used including principal component analysis or linear discriminant analysis (LDA) in the feature extraction stage and multidimensional Gaussian densities for statistical classifiers based on continuous probability density functions (for a more detailed survey of traditional speech recognition methods, please refer to Cole *et al.* (1997)).

The aim of this study was to present an automated and optimized decision commonly drawn from four established features (which can be robustly and automatically calculated for a large number of strides to test the hypothesis) to determine whether the tölt is more similar to running than walking. The features used are dimensionless speed, duty factor, aerial phase and PR. We compare this decision with the use of each of these features in isolation to show how well established uni- and multidimensional automated pattern recognition methods can be applied to a database of kinematic features of Icelandic horses collected during overground locomotion to find an optimal (in the sense of multidimensional automated classification of specific features) decision. We were also interested to find out which of the proposed features is best suited for this decision.

The specific objectives were to evaluate the following:

(i) the discriminative power of four previously identified features (which can be robustly and automatically calculated for a large number of strides) for classifying tölt strides into either walking or running using receiver operating curves and to compare the determined optimized thresholds with biological values (*unidimensional approach*), and

(ii) simple multidimensional pattern recognition approaches for the task of classifying tölt strides into walking or running and to identify the importance of the four features in this decision (*multidimensional approach*) and to draw a common conclusion.

2. MATERIAL AND METHODS

2.1. Data collection and feature extraction

We have collected a dataset comprising speed (from global positioning system, GPS), limb-timing information (from hoof-mounted accelerometers) and trunk movement (from an inertial sensor) of seven Icelandic horses (see Robilliard *et al.* (2007) for more details). The horses used were naturally five gaited and were ridden in the four symmetrical gaits (walk, trot, pace and tölt) and in the asymmetrical gait of canter/gallop (see Robilliard *et al.* (2007) for more detail). For the study presented here, 6138 strides corresponding to the symmetrical gaits were used. Strides were manually assigned to a gait category based on a set of criteria including the order of footfalls and the number of limbs in contact with the ground at any time (Robilliard *et al.* 2007). The number of strides per gait and horse ranged from 19 to 456 (see table 1 for details).

In addition to speed and limb-timing information (Robilliard *et al.* 2007), the horses were equipped with a small inertial sensor (modified MT9, Xsens, Enschede, The Netherlands) attached underneath the most cranial edge of the saddle over the withers using a custom-made harness (Pfau *et al.* 2005, 2006). This sensor gives accurate six degrees of freedom movement information for the withers of the horse (Pfau *et al.* 2005) and allows estimation of the centre of mass movement (Pfau *et al.* 2006; Parsons *et al.* 2008) and thus calculation of potential and kinetic energy fluctuations (Pfau *et al.* 2006). From these data, the following features were calculated.

(i) Duty factor was calculated from the stance (time between foot on and foot off) and stride times (time between foot on and next foot on of the same limb) for the front left leg.

(ii) The presence of an aerial phase was determined by assessing whether all four limbs were simultaneously not in contact with the ground (termed 'air time'). This was done on the basis of the hoof-mounted accelerometer data of all four legs.

Table 1. The number of data points per horse and gait for symmetrical gaits.

	gait			
horse	walk	trot	pace	tölt
1	140	149	107	308
2	129	347	57	346
3	171	145	68	304
4	347	241	85	342
5	192	327	105	329
6	315	456	101	339
7	181	198	19	290
total	1475	1863	542	2258

(iii) Dimensionless speed ($\hat{u}$) was calculated from GPS speed using the following equation (Gatesy & Biewener 1991):

$$\hat{u} = \sqrt{\frac{v^2}{g \cdot l}} \tag{2.1}$$

with v=stride speed; g=9.81 m s^{-2}; and l= withers height.

(iv) Phase relationship between kinetic and potential energies is expressed by PR using the following equation (Cavagna *et al.* 1976, 1977):

$$\mathrm{PR} = \frac{\Delta\mathrm{KE} + \Delta\mathrm{PE} - \Delta E\mathrm{tot}}{\Delta\mathrm{KE} + \Delta\mathrm{PE}} \times 100, \tag{2.2}$$

where ΔKE, ΔPE, ΔEtot are positive increments in kinetic, potential and total (sum of potential and kinetic) energies, respectively. These were calculated from a combination of GPS speed (forwards velocity), inertial sensor velocity and vertical displacement data (see Pfau *et al.* (2006) and Parsons *et al.* (2008) for more details).

2.2. Automated classification

2.2.1. Unidimensional classification. Initially, each of the four individual features was used to determine a threshold value to discriminate between walking and running. This was achieved using all the walk strides (see Robilliard *et al.* (2007) for details about gait classification) for the walking category and all the trot and pace strides for the running category. The thresholds were selected based on the sensitivity and specificity achieved for the individual features. Here, sensitivity was defined as the percentage of correctly detected running strides and specificity as the percentage of correctly detected walking strides, thus substituting 'positive' by running and 'negative' by walking in a common definition for sensitivity and specificity,

$$\text{sensitivity} = \frac{\text{true positive}}{(\text{true positive} + \text{false negative})} = \frac{\text{true 'running'}}{(\text{true 'running'} + \text{false 'walking'})}, \tag{2.3}$$

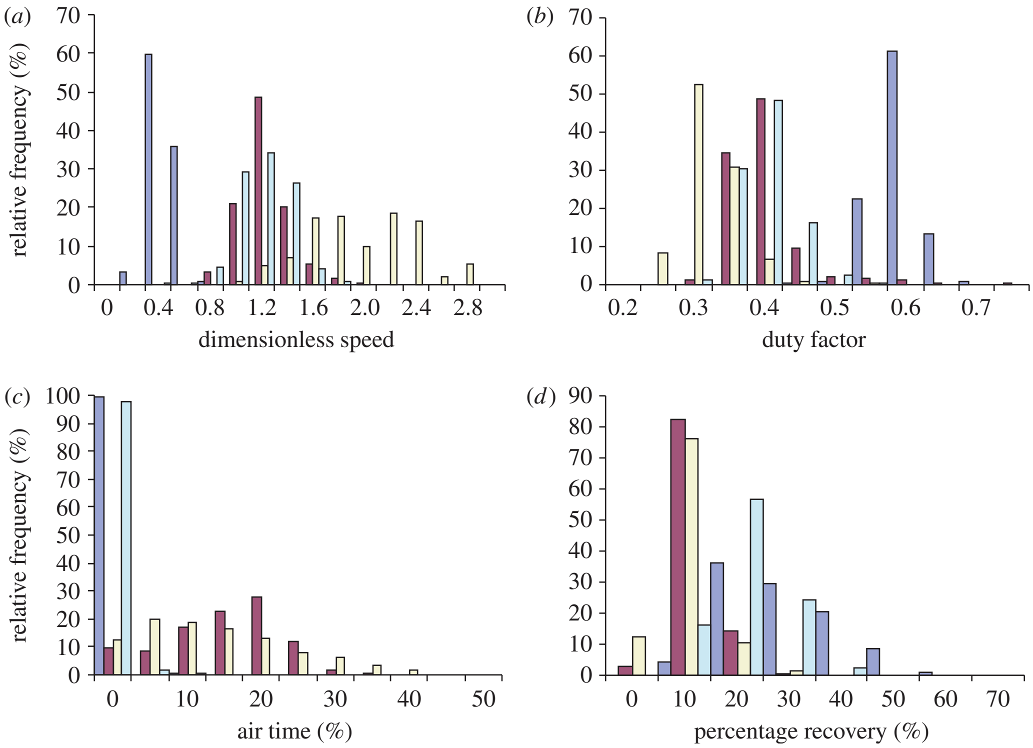

Figure 1. Histograms for (*a*) dimensionless speed, (*b*) duty factor, (*c*) air time and (*d*) PR for all walk (light blue), trot (dark red), pace (yellow) and tölt (cyan) strides of the dataset. Relative frequency values (%) of strides falling into the categories are given for each gait to account for the varying number of strides per gait category (table 1).

$$\text{specificity} = \frac{\text{true negative}}{(\text{true negative} + \text{false positive})} = \frac{\text{true 'walking'}}{(\text{true 'walking'} + \text{false 'running'})}. \tag{2.4}$$

For dimensionless speed and air time, strides with values below the determined thresholds were assigned to the walking category, whereas for duty factor and PR, strides with values above the threshold were assigned to the walking category.

The threshold values corresponding to the highest average value of sensitivity and specificity (for each feature separately) were then applied to the tölt data to determine the percentage of tölt strides that would be classified into the two categories.

2.3. Multidimensional classification

2.3.1. Multivariate Gaussians. A four-dimensional feature vector $\boldsymbol{x}$ was created for each stride of the dataset consisting of dimensionless speed, duty factor, air time and PR,

$$\boldsymbol{x} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = \begin{pmatrix} \text{dimensionless speed} \\ \text{duty factor} \\ \text{air time} \\ \text{percentage recovery} \end{pmatrix}. \tag{2.5}$$

These feature vectors were then used to estimate the means $\boldsymbol{m_k}$ and covariance $\boldsymbol{C_k}$ matrices of the walking (k=1, i.e. walk) and running (k=2, i.e. 'trot' and 'pace') strides, in effect using Gaussian distributions $\boldsymbol{N_k}$ to represent the class-specific probability density function $p(\boldsymbol{x}|k)$'

$$p(\boldsymbol{x}|k) = \boldsymbol{N_k}(\boldsymbol{x}) = \frac{1}{\sqrt{(2\pi)^M |\boldsymbol{C_k}|}} \times \exp\left(-\frac{1}{2}\left((\boldsymbol{x}-\boldsymbol{m_k})' \boldsymbol{C_k}^{-1} (\boldsymbol{x}-\boldsymbol{m_k})\right)\right) \quad \text{with} \quad M = 4. \tag{2.6}$$

We then estimated the posterior probability $p(k|\boldsymbol{x})$ of each tölt stride for each of the two classes based on the class-specific probability density function $p(\boldsymbol{x}|k)$ and the *a priori* likelihood $p(k)$ for each class following Bayes' theorem,

$$p(k|\boldsymbol{x}) = \frac{p(k) \times p(\boldsymbol{x}|k)}{p(\boldsymbol{x})}. \tag{2.7}$$

For the comparison of the posterior probabilities (e.g. $p(1|\boldsymbol{x})$ and $p(2|\boldsymbol{x})$), the probability $p(\boldsymbol{x})$ is not relevant and can thus be neglected. The *a priori* probabilities of the different classes $p(k)$ were estimated at 0.38 for walking (from the number of walk strides) and 0.62 for running (from the trot and pace strides; table 1). In the classification process, each tölt stride was then assigned to the class with the highest posterior probability.

2.4. Linear discriminant analysis

LDA was used as an alternative classification method (see Fukunaga 1990; Duda *et al.* 2000). Walk, trot and pace data were used in order to calculate an LDA matrix that combined the original four features (duty factor, air time, PR and dimensionless speed) into one single feature that provides an optimum discrimination between walking and running based on a linear combination of the original features. Briefly, the LDA

Table 2. The combination of sensitivity and specificity yielding the highest average value of sensitivity and specificity. The table also gives the threshold used to classify the tölt data into 'walking' and 'running' (table 3).

	sensitivity	specificity	average	threshold
dimensionless speed	0.996	0.997	0.996	0.774
duty factor	0.969	0.986	0.977	0.518
air time	0.993	0.941	0.967	0.5%
percentage recovery	0.906	0.932	0.919	16.7%

Table 3. The number of tölt strides classified as walking or running using individual features and thresholds from table 2.

	class	
feature	walking	running
dimensionless speed	31 (1.4%)	2227 (98.6%)
duty factor	29 (1.2%)	2229 (98.8%)
air time	2137 (94.6%)	121 (5.4%)
percentage recovery	1698 (75.2%)	560 (24.8%)
average	973.75 (43.1%)	1284.25 (56.9%)

Table 4. The means of walking, running and tölt for the four features. The means of the walking category have been calculated using the walk strides, the means of the running category have been calculated using the trot and pace strides.

	dimensionless speed	duty factor	air time (%)	percentage recovery (%)
walking	0.48	0.59	0.05	29
running	1.39	0.38	14	10
tölt	1.19	0.40	0.2	21

aims to find a linear combination of features that maximize the Fisher criterion J,

$$J = \frac{|m_1 - m_2|^2}{s_1^2 + s_2^2}, \tag{2.8}$$

where m_1 and m_2 represent the mean and s_1 and s_2 represent the variance for each class (intra-class variance). Thus, the optimal linear combination will show a large difference between class means and a small variation around class means.

3. RESULTS

3.1. Data collection and feature extraction

The distribution of duty factor, air time, PR and dimensionless speed for the different symmetrical gaits can be found in figure 1. Figure 1*a* shows the speed ranges for each gait: walk is exhibited at the slowest speeds (up to dimensionless speed of 0.8); trot and tölt at intermediate speeds (up to dimensionless speed of 2, respectively, 1.8); and pace at the highest speeds (up to dimensionless speed of 2.8). This is consistent with the findings for duty factors: the highest duty factors occurred for walk (0.47–0.68); intermediate values for trot (0.33–0.46) and tölt (0.29–0.41); and the lowest values for pace (0.28–0.45). Most walk and tölt strides were associated with no aerial phase; however, some strides of the remaining gaits had considerable air time (air times for trot and pace ranged from 0 to approx. 45% of the stride time). The PR values were the highest for walk (between 10 and 60%), intermediate for tölt (between 4 and 50%) and the lowest for pace (between 2 and 33%) and trot (between 2 and 30%).

Table 5. The number of tölt strides classified into walking or running using the log probabilities calculated using the four-dimensional feature vector and the LDA.

	walking	running
four-dimensional feature vector	26 (1.2%)	2232 (98.8%)
LDA	104 (4.6%)	2154 (95.4%)

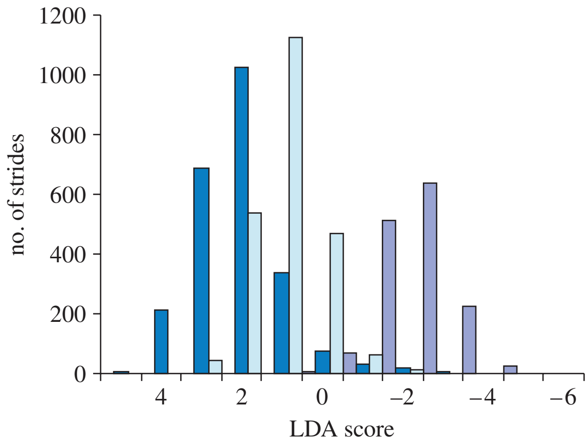

Figure 2. Histogram of the LDA score for 'walking' (light blue), 'running' (blue) and tölt (cyan) strides for a LDA trained for walking (i.e. walk) and running (i.e. trot and pace). A clear overlap between tölt and running and only a small area of overlap between tölt and walking are shown.

3.2. Automated classification

3.2.1. Unidimensional classification. The feature resulting in the best discrimination between walking and running gaits using this dataset was dimensionless speed with a sensitivity of 99.6 per cent and a specificity of 99.7 per cent (table 2). This combination can be found using a threshold value of 0.774 for dimensionless speed. Duty factor, air time and PR resulted in average values of sensitivity and specificity of 97.7, 96.7 and 91.9 per cent, respectively, resulting in threshold values of 0.518 for duty factor, 0.5 per cent for air time and 16.7 per cent for PR.

Applying the determined thresholds to the tölt strides results in contradictory classifications depending on the individual feature used (table 3). Whereas the majority of tölt strides were categorized as running using dimensionless speed (98.6%) and duty factor (98.8%), the majority of tölt strides were classified as walking using air time (94.6%) and PR (75.2%).

3.3. Multidimensional classification

3.3.1. Multivariate Gaussian densities. Class means for each of the four features for the two categories (walking and running) can be found in table 4. These were calculated using walk strides for walking and trot and pace strides for running. The use of multivariate Gaussian densities to classify tölt strides into either walking or running categories resulted in the majority (98.8%) of the strides assigned to running (table 5).

3.4. Linear discriminant analysis

The histograms of the LDA scores (values of the calculated LDA feature) for walking, running and tölt are shown in figure 2. There was virtually no overlap between walking and running, some overlap between walking and tölt and a large amount of overlap between tölt and running. Therefore, the vast majority of tölt strides (95.4%) were classified as running (table 5).

4. DISCUSSION

4.1. Summary

In this study, we have gathered experimental evidence on whether tölt, a symmetrical four-beat gait most commonly found in Icelandic horses (Zips *et al.* 2001; Nicodemus & Clayton 2003; Biknevicius *et al.* 2004, 2006; Robilliard *et al.* 2007), is more similar to walking or to the other symmetrical running gaits (i.e. trot and pace). The use of individual features resulted in contradictory decisions. Air time and PR indicate that tölt is more similar to walking, while dimensionless speed and duty factor indicate similarity to running. Two different multidimensional pattern recognition approaches were used to find an automated and optimized decision that resulted in between 95 percent and approximately 99 per cent of the tölt strides being assigned to the running category. This, in combination with the findings of a previous study (Biknevicius *et al.* 2006), which reported conflicting evidence, confirms that tölt should be, in terms of a stochastic multidimensional discrimination, considered more similar to running than walking.

The multidimensional approaches presented here could be expanded to evaluate similar ambiguous gaits in other quadrupeds using a common stochastic pattern recognition framework. This would allow the objective analysis of the discriminative power of commonly used features for a number of quadrupeds. The same approaches could also be used to automatically find the most striking (discriminative) differences between particular ‘ambling’ gaits found in quadrupeds (e.g. horses, elephants and primates).

4.2. Automated classification

4.2.1. Walking versus running. It was important to collect data from a large number of consecutive strides to enable robust estimation of features. In this study, PR of mechanical energy rather than phase shift between potential and kinetic energies (e.g. Cavagna *et al.* 1977) was used. These two features are not strictly equivalent; PR assesses the amount of energy exchange and phase shift is the time shift between the two types of energy. The calculation of PR is simple to implement (sum of positive energy increments over a stride, Cavagna *et al.* 1977), which is an essential prerequisite for an automated decision based on over 6000 strides. Phase shift requires the exact localization of minima within the energy profiles over full strides potentially using sine waves (Audigié *et al.* 2002). This is more difficult to automate due to biphasic energy modulations seen in symmetrical gaits and is very sensitive to the exact timing used during stride cutting.

For training of the classification systems, trot and pace strides were attributed to the category running irrespective of the observed speed (i.e. duty factor). Other studies in bipeds and quadrupeds (Hildebrand 1968; Reilly & Biknevicius 2003; Rubenson *et al.* 2004; Hoyt *et al.* 2006) have observed strides with spring-like mechanics falling into both the walking and running categories (with a ‘walk–run’ categorization based on duty factor only). Although a previously published study (Robilliard *et al.* 2007) had shown that the LDA can be used to distinguish between different symmetrical and asymmetrical gaits, we did not include tölt strides into the training process in this study as we aimed to extract robust generalized features to classify this ‘previously unseen’ tölt data.

Using a single feature to attribute gaits to the walking and running categories would automatically bias the trained classification system. Thus, we relied on the observed gait patterns (Robilliard *et al.* 2007) to distinguish between the gaits.

4.2.2. Unidimensional classification. The use of the four features individually resulted in different conclusions. The time of the aerial phase and the PR suggested that tölt strides were similar to walking, whereas dimensionless speed and duty factor indicated similarity to running. While duty factor relates to the timing of limb movement, aerial phase and PR relate to whole-body movement. The observed phase shift between front and hind limb pairs in tölt (Zips *et al.* 2001; Robilliard *et al.* 2007) means that, even at duty factors considerably below 0.5, it is possible not to have a whole-body aerial phase (Hildebrand 1965) and that whole-body movement can be different from the movement of the limbs (Biknevicius *et al.* 2006). Effectively, while the front and hind ‘half’ of the animal are running, the body is always in contact with the ground.

4.3. Multidimensional classification

4.3.1. Multivariate Gaussians. Histograms for dimensionless speed and duty factor are different for walk than for the three other symmetrical gaits (figure 1) and these two features give high sensitivity and specificity values (table 2). Therefore, it is not surprising that approximately 99 per cent of the tölt strides are categorized as running using the multidimensional approach.

4.4. LDA

The majority of tölt strides would be classified as running using LDA (figure 2, table 5). During the LDA training, only strides of the three remaining symmetrical gaits (not tölt) were used. The tölt strides can therefore be considered an independent test set (although of course the data have been collected from the same horses). The combination of all four features together suggests that tölt is more similar to running than walking, and that air time and PR (which on their own indicate similarity to walking) contribute less to the discrimination between walking and running than duty factor and dimensionless speed (which on their own indicate similarity to running). Duty factor is essential in this classification process showing the highest absolute value of correlation with the LDA function (see Robilliard *et al.* 2007). When excluding duty factor from the analysis, the classification changes considerably; 53 per cent of the tölt strides are then classified as walking and 47 per cent as running. By contrast, when excluding dimensionless speed (the feature with the second highest absolute value of correlation with the LDA function) from this process, classification outcome changes only slightly to 94.5 per cent running and 5.5 per cent walking.

4.5. Comparison with previously published data

Dimensionless speeds (or absolute speeds) reported here and in the previous studies (Zips *et al.* 2001; Biknevicius *et al.* 2006) are similar. Duty factors observed here are slightly lower than reported elsewhere (Biknevicius *et al.* 2006). This can be partly explained by the longer hind limb stance phases (Robilliard *et al.* 2007) and the fact that Biknevicius *et al.* (2006) reported hind limb duty factors. Previous studies reported conflicting evidence with respect to the existence of an aerial phase during tölt. Whereas Biknevicius *et al.* (2006) reported that no aerial phase was observed, an earlier study showed that with increasing speed the likelihood of an observed aerial phase increases (Zips *et al.* 2001). In our study, we found that approximately 7 per cent of the tölt strides had an aerial phase; however, the threshold found for the aerial phase indicates that the aerial phases are shorter than 0.5 per cent of the stride time. The PR values (mean approx. 21%; see table 4) are slightly higher when compared with the results of Biknevicius *et al.* (2006) (mean value, 7.9%; maximum, 22.8%). Part of this discrepancy might be explained by the different technical set-ups, in particular the use of a single six degrees of freedom sensor to estimate centre of mass movement. The centre of mass movement has been shown to be similar to the movement of the withers (Buchner *et al.* 2000); however, our method still needs to be validated for less common gaits.

The experimentally determined threshold values (table 2) for duty factor (approx. 0.51) and air time (approx. 0.005) are close to what would be expected theoretically at the walk–run transition: 0.5 for duty factor (Hildebrand 1965, 1989) and 0 for air time (Hildebrand 1985). Dimensionless speed (approx. 0.77) is slightly higher than expected (Froude number of 0.5, dimensionless speed $\sqrt{0.5}=0.707$; Alexander & Jayes 1983; Gatesy & Biewener 1991) and reported elsewhere (e.g. Froude number 0.35, equating to a dimensionless speed of 0.59 reported in horses of various sizes; Griffin *et al.* 2004*b*). The mean value for PR reported here for walk of approximately 0.3 (30%) is lower than published values for walking (Cavagna *et al.* 1977). However, values of up to above 0.6 (60%) are achieved for some walk strides and others have found similar values. (Minetti *et al.* (1999) reported values ranging from below 20% to below 50%.) Discrepancies might be due to the experimental methods, in particular GPS speed (Witte & Wilson 2004, 2005) and the use of a six degrees of freedom inertial sensor (see Pfau *et al.* (2006) for more detail). Also, the horses in this study were ridden rather than manoeuvred ‘in hand’ or exercised on a treadmill. Ridden overground locomotion was essential to elicit a large range of speeds in all gaits to get a robust estimate of feature variation. Differences have been reported between treadmill and overground locomotion (Buchner *et al.* 1994), which might explain the discontinuity observed elsewhere for duty factor at the walk–trot transition (Hoyt *et al.* 2006).

5. CONCLUSION

Automated pattern recognition approaches have been applied to test the hypothesis that the tölt can be considered more similar to running than walking. We present, for the first time, a unified decision based on multidimensional features vectors rather than relying on each feature in isolation. Dimensionless speed, duty factor, length of aerial phase and PR of mechanical energy were automatically extracted from kinematic data collected during ridden overground locomotion (6138 strides of seven Icelandic horses). The use of two different multidimensional pattern recognition approaches concluded that the tölt is, in terms of a stochastic discrimination, more similar to running than walking. The approach presented here has the potential to be extended to investigate similarities and differences between other ambling gaits.

This work was approved by the Royal Veterinary College ethics committee.

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