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Computerized identification and classification of stance phases as made by front or hind feet of walking cows based on 3-dimensional ground reaction forces

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ABSTRACT

Lameness is a frequent disorder in dairy cows and in large dairy herds manual lameness detection is a time-consuming task. This study describes a method for automatic identification of stance phases in walking cows, and their classification as made by a front or a hind foot based on ground reaction force information. Features were derived from measurements made using two parallel 3-dimensional force plates. The approach presented is based on clustering of Centre of Pressure (COP) trace points over space and time, combined with logical sequencing of stance phases based on the dynamics of quadrupedal walking. The clusters were identified as full or truncated (incomplete) stance phases furthermore the stance phases were classified as originating from a front or hind foot. Data from 370 walking trials made by 9 cows on 5 experiment days were used to test the method. Four cows were moderately lame at experimental onset. On average 5.1 stance phases per cow per trial were obtained of which 3.2 were classified as full stance phases and therefore appropriate for further gait analysis (the latter not being the scope of this study). Of the 2617 identified clusters 1844 were classified as stance phases, of these 1146 (62%) were automatically identified as full stance phases and classified as made by a front or hind foot. As intended, the procedures did not favour identification of stance phases of healthy cows over lame cows. In addition, a human observer evaluated the stance phases by visual inspection, revealing a very low discrepancy (3.5%) between manual and automated approaches. Further, a sensitivity test indicated large robustness in the automatic procedures. In conclusion, the experimental setup combined with the computerized procedures described in the present study resulted in a high number of stance phases obtained per trial. It is thus a combination which has the potential to enable unsupervised gait analysis based on data collected automatically on-farm.

1. Introduction

Lameness is known to affect several gait parameters in quadrupeds. Thus, lame cows walk slower, exhibit shorter stride length and more negative overlap (negative overlap meaning that the hind foot does not reach the imprint of the ipsilateral front foot) compared to normally walking cows (Telezhenko and Bergsten, 2005). Furthermore, lameness in cows decreases vertical peak forces, average forces, stance time, and vertical impulse (Rajkondawar et al., 2006), and modifies the horizontal forces on the affected leg (Scott, 1989). Additionally, 3-dimensional (3D) studies in horses have shown that lame horses exhibit reduced vertical forces and altered horizontal forces on the affected leg (Clayton et al., 2000), but also contralateral and ipsilateral legs may show compensatory changes in experimentally induced lame horses (Merkens and Schamhardt, 1988).

The steadily increasing herd sizes in dairy production make manual surveillance more and more difficult, thus increasing the demand for automated monitoring of livestock health. Moreover, lameness is a costly and highly frequent disorder in dairy cows (Barker et al., 2010; Espejo et al., 2006; Ettema and Østergaard, 2006) with significant welfare issues (Bruijnis et al., 2012), and has been the focus of several recent studies attempting to detect lameness (semi-) automatically. For instance, lameness detection has been attempted using vertical ground reaction forces from walking cows (Rajkondawar et al., 2002b), from cows standing in a milking robot (Pastell et al., 2008) or in a trimming chute (Ghotoorlar et al., 2012), from dynamic and static ground pressure

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profiles (Almeida et al., 2007; Maertens et al., 2011), and using image-based methods (Pluk et al., 2012; Poursaberi et al., 2010; Song et al., 2008). Furthermore, Walker et al. (2010) used kinetic features derived from 3D ground reaction forces to automatically analyze the influence of speed on gait features of healthy cows. A similar approach may be employed as a novel method for automatic detection of lameness in walking cows.

As part of a system for automatic lameness detection in dairy cows, the present study aimed to develop a method that identifies and classifies (front or hind) the stance phases of walking cows based on features extracted from 3D ground reaction forces and moments. Lame cows were included in the present study with the aim to determine classification criteria that would not favour the stance phases of healthy cows over the stance phases of lame cows.

2. Materials and methods

2.1. Animals

Nine Danish Holsteins were included in the study: four first lactation cows (580 ± 22 kg) and five third or fourth lactation cows (616 ± 29 kg). The cows were 36 ± 13 days (range 10–54 days) post calving with an average energy corrected milk yield of 39 ± 5 kg (range 31–47 kg) that represented a typical high-yielding Danish dairy herd. Prior to the study the cows were lameness assessed visually on a 5-point scale (Sprecher et al., 1997) by a veterinarian, four of the cows were moderately lame (score 3), and five cows walked without showing signs of lameness (score 1). The cows were housed at the research facility at Foulum, Aarhus University.

All procedures involving animals were evaluated and approved by the Danish Animal Experiments Inspectorate and complied with the Danish Laws concerning experimentation and care of experimentation animals.

2.2. Measurement system

The cows walked individually and freely, followed by a technician, over the force plates several times on 5 experiment days within a period of 10 days. Our measurement system consisted of a narrow aisle with two parallel 3D strain gauge force plates that were custom designed, each measuring 0.46 m × 2.07 m (Bertec Corporation, Columbus, OH), built into a wooden ramp and covered by a 13 mm rubber mat to provide walking friction. From each force plate the anterior–posterior (F_y), mediolateral (F_x) and vertical (F_z) ground reaction forces and their corresponding torques (M_y, M_x, and M_z) were sampled at 2 kHz using a custom-made data acquisition system (Mr. Kick, Knud Larsen, Aalborg University, Denmark, based on National Instruments technology). The maximum capacity and resolution of the force plate signals were 15 kN and 58.6 N/bit vertically (F_z), and 7.5 kN and 29.3 N/bit in both horizontal planes (F_x and F_y), respectively. Maximum capacity and resolution of the moment signals were 15 kNm and 58.6 Nm/bit for M_x, 7.5 kNm and 29.3 Nm/bit for M_z, and 3.5 kNm and 13.7 Nm/bit for M_y, respectively. A cow was identified by its transponder ID (Nedap transponder, Groenlo, The Netherlands, and Allflex PNL4060 antenna, Allflex dan-mark Aps, Lemvig, Denmark) upon entering the system. A data sequence was initiated and finished by the cow passing photocells placed 7.3 m apart in the aisle, both instances were time-stamped, and the walking velocity was derived. Such a data sequence was denoted a trial. The cows were weighed on a regular scale initially on each experiment day.

The data were preprocessed using software custom written in MATLAB (The Mathworks Inc., Natick, MA, USA), including a low pass filtering at a cut-off frequency of 5 Hz using a fourth order zero lag Butterworth filter. R (R Development Core Team, 2011) was used for the remaining stance phase identification, feature extraction and analysis.

2.3. Stance phase identification and sequencing

The length of the force plates allowed a cow to make 2–4 stance phases on each plate during a trial, depending mainly on walking speed. A representative trial is illustrated in Fig. 1 during which the cow generated two stance phases on the left force plate and four on the right force plate.

The footfall sequence of the same trial is shown in Fig. 2, where each snapshot illustrates how many feet have ground contact when the cow passes the force plates, however, it should be noted that the snapshots do not represent the same amount of time. All stance phases, including truncated ones, had to be identified to enable correct footfall sequencing and eventually allow calculation of spatio-temporal features between and within all stance phases for further gait analysis (not the scope of the present paper).

However, when a cow slid its foot or placed a foot on both plates simultaneously, that particular footfall generated several clusters, thus complicating identification and classification procedures. An illustration of a trial, where one foot is placed simultaneously on both plates, is given in Fig. 3.

The force plates did not register stance phases *per se*, but from the forces and torques the trace of the Centre of Pressure (COP) were derived for each force plate as follows:

$$\mathrm{COP}_i = ((-M_{yi} - \delta F_{xi})/F_{zi} + \mathrm{offset}_{xi}; (-M_{xi} - \delta F_{yi})/F_{zi} + \mathrm{offset}_{yi}), \tag{1}$$

where $(\mathrm{offset}_x, \mathrm{offset}_y)_i$, force plate $i = (1,2)$ was the offset of plate centre relative to the global coordinate centre, and δ is the vertical distance from the centre to the surface of the mat. Each of the two force plates generates forces and torques, such that F_x, F_y and F_z represent the mediolateral, anterior–posterior, and vertical forces, respectively. M_x, M_y and M_z represent the torques about the corresponding axes.

Fig. 4. 'COP filter': To establish the footfall sequence the procedure presented below and schematically represented in Fig. 4 was developed to analyze the complete COP data material after the cow has passed the force plates. A COP trace may represent several distinct positions over the force plate, as illustrated in Figs. 1 and 3, where the COP was stable for several periods forming clusters of trace points being separated in time and space. A cluster was identified plate-wise as a collection of COP points within a period with high vertical force ($F_z > F_{z0}$) and within short inter-COP distance ($|\mathrm{COP}_{i+1} - \mathrm{COP}_i| < d_0$), see Fig. 5A. The used thresholds were F_{z0} = 10% body weight (BW) and d_0 = 0.5 mm, the latter corresponds to a COP velocity of 1 m/s at a sample rate of 2 kHz. A relatively high force level was required to ensure that the identified COP trace was likely to represent a footfall. In practice, BW is unknown or must be obtained e.g. during milking (Thorup et al., 2012), but BW may also be estimated from the force data (Walker et al., 2010). All sample points not fulfilling the criteria above (F_{z0}, d_0) were then removed. Still however, two footfalls on the same position could not be separated unless time was considered. Thus, clusters were required to be well separated by a small time-gap (t_0), see Fig. 5A, of at least 0.075 s or 150 sample points. These thresholds (F_{z0}, d_0, t_0) were identified by inspection of time trajectories of COP velocity, position and vertical force. Fig. 4. 'Cluster 5-tuple': At this point the clusters identified on a plate were represented by the 5-tuple $(t_0, t_1, x, y, F_{z\max})_i$, $i = 1,\ldots,n_j$, $j = \{L,R\}$ giving start and end time, average position coordinates, and maximum vertical force, respectively. A summary of interpretation and