Detection of claw lesions in dairy cows based on acoustic analyses

Kumulative Dissertation
zur Erlangung des
Doktorgrades der Agrarwissenschaften (Dr. agr.)

der

Naturwissenschaftlichen Fakultät III
Agrar- und Ernährungswissenschaften,
Geowissenschaften und Informatik
der Martin-Luther-Universität Halle-Wittenberg

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Tag der Verteidigung: 20. Februar 2023

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INTRODUCTION

Lameness in dairy cows

Besides reduced fertility and mastitis, lameness is considered to be one of the most important health problem in dairy cows and a major welfare issue on dairy farms (Bennett et al., 1999; Huxley, 2013). Lameness impairs the movement of the cow and has detrimental consequences on reproduction, production and longevity (Bareille et al., 2003; Langford and Stott, 2012; Whay et al., 2017). The main causes of lameness are claw lesions which are caused multifactorial, contributing factors being metabolic disorders, trauma and infection (Leach et al., 2010). As lame cows suffer from discomfort and pain, the observation of lameness is the most representative animal-based indicator of welfare in dairy cattle (Whay et al., 2003). Generally, lameness management on-farm consists of both: prevention and treatment. Prevention includes managing factors associated with lameness such as genetics, nutrition and the improvement of walking surfaces (O'Leary et al., 2020). Furthermore, claw trimming is a common practice as a preventive as well as treatment procedure for clinically lame animals (Sadiq et al., 2020). However, claw trimming respectively treatment of a lame cow first of all requires that cows' changed gait pattern is recognized, i.e. lameness is detected. Therefore, an early and easy detection of lameness continues to be the current aim of several research projects.

Locomotion scoring

A common practice to detect lameness is to reveal changes in the gait and posture of cows (Van Nuffel et al., 2015). Generally, the strength of abnormality is measured using a locomotion score. Presently, several different score systems exist, these varying in gait and posture traits observed, as well as in type of scale and number of scoring levels (Schlageter-Tello et al., 2014; Van Nuffel et al., 2015). Moreover, most studies performed their locomotion scoring in varying practical settings, for instance, they

differed in the timing of scoring (before/after milking, O' Driscoll et al., 2010; O'Callaghan et al., 2003) or on which walking surface the scoring was perfomed (rubber floor/solid or slatted concrete, O'Driscoll et al., 2009; O'Callaghan et al., 2003). However, these settings can have great impact on the scoring as for example the walking surface respectively the type and amount of moisture on the flooring can cause a careful gait (Phillips and Morris, 2000). Furthermore, locomotion scores raise problems, as they are uncertain due to lacking objectivity and missing agreement between different observers (Engel et al., 2003). Cows can show an impaired locomotion in different ways and they do not always demonstrate all traits described in the different locomotion scores (Bach et al., 2007; Thomsen et al., 2008; Chapinal et al., 2009). This could obviously complicate a consistent assessment in locomotion scoring.
Although visual locomotion scoring can be implemented on any farm at any given time, daily monitoring by a trained observer practically is not feasible (Van Nuffel et al., 2015). Therefore, with the ever increasing size of dairy farms and the reduced time available for observing the cows, detecting lameness by only visual observation is complicated, time-consuming and thus very expensive (Poursaberi et al., 2010).

Automated lameness detection

As an early detection of mild and moderately lame cows and an automatic drafting could reduce the time from onset to treatment, an automated lameness detection could prevent cases becoming severe, could speed up cows' recovery and, therefore, could substantially improve animal welfare (O'Leary et al., 2020). In addition to the benefits for animal health and welfare, there is also growing interest by dairy farmers being supported with the identification of lame cows in the herd. Therefore, several authors have addressed the question of detecting lameness automatically on-farm. There are several approaches to detect lameness automatically using potential technologies such as accelerometers (Pastell et al., 2009; Alsaaod et al., 2012), load cells

(Rajkondawar et al., 2006; Thorup et al., 2014), pressure-sensitive mats (Maertens et al., 2011; Van Nuffel et al., 2013) and computer vision techniques (Poursaberi et al., 2010; Viazzi et al., 2013; Van Hertem et al., 2014). Thereof, the only techniques already being used on-farm are accelerometers, which have the advantage that they can be applied for heat detection purposes also. However, a current review on lameness and accelerometer practice reported only small and moderate associations with lameness (O'Leary et al., 2020).

Gathering data continuously on a daily basis with no need for herding the cows for the purpose of measurement but e.g. recording during a normal routine, are particular advantages with such automatic systems for lameness detection. Van Nuffel et al. (2015) stated that, in practice, no free space is available in dairy barns to install any further apparatus. Therefore, those automated systems with sensor technologies that need e.g. a special alley set-up where measurements are performed (load cells or pressure-sensitive mats) or where a video can be recorded (vision techniques), are finally complicated for the use on-farm (Van Nuffel et al., 2015). Finally, a good cow traffic has to be ensured, particularly if a system is installed after a milking robot or a milking parlour, so not to affect the milking routine negatively. Currently, no practical system is available which can be used on-farm.

Measuring dairy cows footfall sound

Walking on a solid surface - as it can be found in most dairy cow housings - produces sound signals which can be measured using acoustic sensors. Previously, acoustic sensors have been implemented in livestock farming, mainly to measure animals' vocalization (Manteuffel et al., 2004; Chung et al., 2013). The challenge with sound recordings on-farm is to measure only the relevant sound signals without any disturbing background noises, which are usual in common barn environments. However, by constructive measures, respectively decoupling the measurement system, erroneous sound signals can be eliminated (Feldmann, 2009) and the footfall sound - caused by movement on the floor or solid surface - can be measured with piezo-electric sensors. Therefore, an undisturbed recording of cows' footfall sound with an acoustically decoupled plate should be possible. Taken into account results from previous studies using kinematic measures (Flower et al., 2005) or measures of weight distribution (Neveux et al., 2006), which showed gait differences of lame and non-lame cows, it was also expected to be able to measure these differences by analyzing cows' footfall sound. Thus, developing a system to record and analyze different properties of the footfall sound of dairy cows should enable to detect animals affected by claw lesions.

SCOPE OF THE THESIS

One of the most important health issues in dairy production is lameness. Despite different approaches there is no valid possibility yet to detect lameness automatically. This doctoral thesis addresses this system by detecting claw lesions in dairy cows based on the footsteps of individual animals i.e. their recorded walking respectively footfall sound.

The first aim of the thesis was to validate an existing gait scoring system in terms of an objective assessment. This validated locomotion scoring system should serve as the matching system in the further approaches to distinguish the lame from the mildly lame and non-lame animals (Paper 1).

It was hypothesized that the footfall sound produced by dairy cows walking on solid surface differs between those animals affected by claw lesions and those not affected. Therefore, the second aim was to investigate the recordings of cows' footfall sound on slatted floor and to analyse different parameters of these recordings in terms of lameness detection (Paper 2).

The third approach focused on a practical acoustic method to use on-farm and a stochastic model for detecting claw lesions analysing the properties of cows' footfall sound (Paper 3).

PUBLICATIONS

Paper 1:

Evaluation of a gait scoring system for cattle by using cluster analysis and Krippendorff's α reliability

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Veterinary Record 184, 7, 2018

http://dx.doi.org/ 10.1136/vr.105059

https://veterinaryrecord.bmj.com/content/184/7/220/full

Abstract:

The aim of the presented study was to validate a three-point locomotion score (LS) classifying lameness in dairy cows. Therefore, locomotion of 144 cows was scored and data on claw lesions were collected during hoof trimming. Based on latter data a cluster analysis was performed to objectively classify cows into three groups (Cluster 1–3). Finally, the congruence between scoring system and clustering was tested using Krippendorff's reliability. In total, 63 cows (43.7 %) were classified as non-lame (LS1), 38 (26.4 %) were rated as LS2 with an uneven gait and 43 (29.9 %) cows were ranked as clearly lame (LS3). In comparison, hoof-trimming data revealed 64 cows (44.4 %) to show no diagnosis, 37 (25.7 %) one diagnosis, 33 animals (22.9 %) two diagnoses and 10 (7.0 %) more than two. Comparing the respective categorisation received by either

the cluster analysis or LS in between groups, a high correspondence (79.4 % and 83.7 %) could be found for LS1 and cluster 1 as well as for LS3 and cluster 3. Only LS2 had partial agreement (21.1 %) to cluster 2. However, Krippendorff's α was 0.75 (95 %, CI 0.68 - 0.81), indicating a good degree of reliability. Therefore, the results of this study suggested that the presented LS is suitable for classifying the cows' state of lameness representing their claw diseases.

Paper 2:

Using the Footfall Sound of Dairy Cows for Detecting Claw Lesions

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Animals, 9, 78, 2019

http://dx.doi.org/ 10.3390/ani9030078

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6466211/

Abstract:

An important factor for animal welfare in cattle farming is the detection of lameness. The presented study is part of a project aiming to develop a system that is capable of an automated diagnosis of claw lesions by analyzing the footfall sound. Data were generated from cows walking along a measurement zone where piezoelectric sensors recorded their footfall sounds. Locomotion of the animals was scored and they were graded according to a three-scale scoring system (LS1 = non-lame; LS2 = uneven gait; LS3 = lame). Subsequently, the cows were examined by a hoof trimmer. The walking speed across the test track was significantly higher in cows with LS1 compared to those with LS2 and LS3 and thus, they were showing a smoother gait pattern. The standard deviation of volume (SDV) in the recorded footfall sound signal was considered as a factor for the force of a cow’s footsteps. Cows with non-infectious claw lesions showed

lower SDV than healthy cows and those with infectious claw diseases. This outcome confirmed the hypothesis that the evaluated cows affected by non-infectious claw lesions have a greater sensitivity to pain and demonstrate a less forceful gait pattern. These first results clearly show the potential of using footfall sound analysis for detecting claw lesions.

Paper 3:

On-farm detection of claw lesions in dairy cows based on acoustic analyses and machine learning

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Journal of Dairy Science, 104, 5, 5921-5931,

https://doi.org/10.3168/jds.2020-19206

https://www.sciencedirect.com/science/article/pii/S0022030221001983?via%3Dihub

Abstract:

Claw lesions are a serious problem on dairy farms, affecting both the health and welfare of the cow. Automated detection of lameness with a practical, on-farm application would support the early detection and treatment of lame cows, therefore, potentially reduce the number and severity of claw lesions. Thus, in this study, a method was proposed for the detection of claw lesions based on the acoustic analysis of cows' gait. A panel was constructed to measure the impact sound of animals' walking over it. The recorded impact sound was edited, and 640 sound files from 64 cows were analyzed.

The classification of the animals' lameness status was performed using a machine learning process with a random forest algorithm. The gold standard was a two-point scale of hoof-trimming results (healthy vs. affected), and 38 properties of the recorded sound-files were used as influencing factors. A prediction model for classifying the cows' lameness was built using a random forest algorithm. This was validated by comparing the reference output from hoof-trimming with the model output concerning the impact sound. Altering the likelihood settings and changing the cutoff value to predict lame animals improved the prediction model. At a cutoff at 0.4, a decreased false-negative-rate was generated, while the false-positive-rate only increased slightly. This model obtained a sensitivity of 0.81 and a specificity of 0.97. With this procedure, Cohen's Kappa value of 0.80 showed good agreement between model classification and diagnoses from hoof-trimming. In summary, the prediction model enabled the detection of cows with claw lesions. This study shows that lameness can be detected by machine learning from the impact sound of hoofs in dairy cows.

GENERAL DISCUSSION

Lameness is a big issue in dairy farming as it is a current major animal health and welfare problem. This prominent role is spurred on by the increasing prevalence and the fact, that no other common dairy disease is associated with such visible symptoms of pain when becoming severe (Bicalho and Oikonomou, 2013; Langova et al., 2020). One possibility to avoid an unnoticed increase of lame animals in the herd is the continuous measurement of their locomotion (Grandin, 2018). But, since such continuous measurement on an individual animal basis is manually not feasible in todays' large dairy farms, currently, various efforts have been made to provide an automatic lameness detection. For example, O'Leary et al. (2020) stated that such an automatic detection and drafting could reduce the time from onset to treatment simultaneously prevent cases becoming severe, speed up recovery, increase production and finally improve welfare. Therefore, precision livestock farming (PLF) technologies, using some kind of sensor system, could be applied to monitor dairy cows' locomotion respectively detecting their lameness. For instance, several traits like animal behaviour, gait or posture were measured by PLF technologies (accelerometers, load cells, cameras) and used to detect lameness. However, these PLF solutions, mostly developed in a lab environment, are not available as a commercial product to be implemented on a dairy farm. This could be for different reasons: For example, because they are (still) too expensive for the commercial market or they only perform in an experimental setting, where the sample size is small and the conditions are controlled (Stygar et al., 2021). Therefore, the main objective of this study was to develop an automatic system for lameness detection and to apply it on-farm.

Discussion of the results of publications within the study

Evaluation of a locomotion score system

Locomotion scores are imprecise due to a lack of objectivity and missing agreement between different observers (Engel et al., 2003). Thomsen et al. (2008) showed that even some training of experienced observers in locomotion scoring had only a limited effect on intra- and inter-observer agreement. As cows can show an impaired locomotion in different ways and do not always demonstrate all traits described in the different scores, a consistent assessment by the observers is always difficult and subjective (Thomsen et al., 2008; Chapinal et al., 2009). Nevertheless, numerous previous studies used a locomotion scoring system to identify lame cows (e.g. Espejo et al., 2006; Rouha-Mülleder et al., 2009), although the used score had not previously been validated. For this reason, it raises the question of the extent to which a locomotion score can be used as a kind of 'gold standard' to estimate lameness in dairy cows in a research study.

Therefore, the aim of the first study was to evaluate a visual and practical on-farm locomotion scoring system in terms of such an objective assessment. Taking the diagnostic findings of hoof trimming into account, the purpose of this study was to provide groups of animals with the same condition of claw health using a cluster analysis. Subsequently, the reliability between the clustered groups and the scales from locomotion were compared to validate the scoring. The obtained $\alpha = 0.7460$ was considered to be a reliable congruence between clustering and the locomotion scoring and, therefore, the validated locomotion score was suitable to detect claw lesions which were currently present. For this reason, the score could be recommended for the scoring in the barn and also as a matching system for further investigation regarding lameness, even if it is not possible to do hoof-trimming to record and use the diagnosed claw lesion as verification. Consequently, the evaluated locomotion score was also used in the following examinations within this thesis.

Recording cows' footfall sound for gait analysis

As claw lesions cause pain to the cows, they tend to change their natural behaviour and especially their normal gait to reduce arising discomfort (Scott, 1989; O'Callaghan et al., 2003; Ito et al., 2010). The animals normally try to relieve the affected and painful limb due to altered weight distribution and they take shorter and more tentative steps. These changes in the normal movement were used in previous studies to develop various tools to detect cows' lameness by for instance measuring weight shifting with force sensors (Kujala et al., 2008; Maertens et al., 2011) or evaluating specific movement pattern like hoof positions using computer vision concepts (Song et al., 2008; Haladjian et al., 2018). Since the changes in cows movement (for example in the intensity of weight bearing on the leg) should also produce steps with different acoustic patterns on a solid surface, the aim of the second study within the thesis was to record these sound signals, respectively cows' footfall sound, and to evaluate them with regard to other gait parameters in terms of lameness detection.

Summarising the results, the study could show that the recording of the footfall sound of cows is potentially possible. Each cow left an individual gait pattern on the solid surface which could be measured and examined. It was possible to decouple the recording of possible acoustic disturbances from any disturbing noises from the environment. Therefore, variations in the walking speed as well as differences in the maximum volume representing the weight loaded on each leg to differentiate non-lame and lame cows were found. Nonetheless, the study revealed deficiencies in the system and various suggestions for further improvement. Particularly, the installation of the test track outside the stable proved not to be a practical solution for an undisturbed experimental procedure. Despite previous training, walking over the installed test track in the unfamiliar environment did not become normal for the cows as the error rate in the data showed. Therefore, the previous targeted habituation was possibly not sufficient, although in another study two days were found to be enough for an adaption phase (Flower et al., 2007). However, other studies propose using the way from the milking parlour back to the stable or to pasture for measurements if that way offers a straight plan section (Telezhenko and Bergsten, 2005; Espejo et al., 2006; Zillner et al., 2018).

The variable which was found to be essential to describe the footfall sound was the standard deviation in volume (SDV) which was considered as a factor for the force of cows' single footsteps. The measured SDV value decreased with increasing locomotion score and as well with the presence of non-infectious claw diseases. These findings support previous results showing the effect of claw lesions and how cows distribute their weight on the affected respectively healthy leg (Pastell and Kujala, 2007; Rushen et al., 2007). Passos et al., (2017) stated that especially non-infectious claw diseases (like sole ulcers) have clear impacts on the strain on limbs. Furthermore, lame cows have a greater sensitivity to pain, particularly those with non-infectious claw diseases and demonstrate a less forceful gait pattern (Passos et al., 2017). The findings from this study confirmed that lame cows adopt the best compensatory movements to minimize pain and, therefore, show less variation in their movement (Blackie et. al., 2013) as shown in the decreased SDV. With SDV in the recorded signal of footfall sound interpreted as a variable for the loudness or the weight load of cows' footstep the results showed the potential of footfall sound analysis for lameness detection. However, the performance of the system had to be validated with more cows and on another farm where such a system could be installed inside the stable, for instance on the way back from the milking parlour to the stable.

On-farm detection of claw lesions using a prediction model

In this study, the first attempt was implemented to detect lame cows on-farm by recording their footfall sound and using it for a machine-learning model. By means of a constructed panel on the way back from the milking parlour, the footfall sound of the animals was measured, and a prediction model was used to distinguish between cows affected by claw lesions and healthy ones.

A concordance of 64 % between the observations from locomotion scoring and the diagnostic findings from hoof-trimming was found in this study. Thus, this could not match the results reported in the first study within this thesis, which had a consistency of 95 %. Therefore, it was decided to use the results from hoof-trimming as a 'gold standard' and target value of the prediction model instead of results from locomotion scoring. This procedure could also be biased as there was a possibility that animals had lesions that did not affect their gait nor, consequently, the recorded footfall sound. Or animals were lame by inference in pain but yet did not have a visible lesion, which would be a drawback to prevention and early detection. Nonetheless, taking the results of hoof-trimming as a gold standard was the method most appropriate for this attempt.

To adjust the misclassification weights, the cutoffs for the class of affected cows in this third approach of the study were changed from 0.5 to 0.4 and 0.3, respectively. Changing the cutoff threshold influenced the machine-learning models' sensitivity and specificity and, likewise, the false-negative and false-positive rates. Besides the potential costs for a lameness detection system, for farmers the most important characteristics of a lameness detection system would be the percentage of missed lame cows (false negatives) and the percentage of false alarms (false positives) (Van De Gucht et al., 2017). With a cutoff at 0.4, the achieved values for false-positive (2.5 %) and false-negative rate (5.1 %) would possibly still be tolerated by farmers. Hitherto, the accuracy of this prediction model remained at Cohen's Kappa value κ = 0.80, which did not achieve better results than a manual-visual rating (Schlageter-Tello et al., 2014). Nevertheless, the automatic detection would be an advantage for lameness detection on-farm, as it is not as susceptible to subjective variation as human observers (Babatunde et al., 2019) and can be applied in dairy farms of increasing size without increasing time for observing (Pastell et al., 2010).

The main restriction of the prediction model used in this study was the reduced data set. This data set was limited as the aim was to verify the accuracy of the model outcomes, and thus only the footfall sound recordings of cows was used which were hoof-trimmed. Furthermore, the sound recordings were based on Holstein cows from only one farm; therefore, they are not transferable to other breeds, herds, and farm conditions. Currently, the system is not able to analyse the footfall sound left by a single leg. As the ability to indicate which leg is lame is an integral part of a lameness-detection system (Van De Gucht et al., 2017), it would be desirable to provide such information in the future. It would also be worth considering the analysis of the footfall sound of each individual cow and to calculate a healthy reference, as well as an individual threshold in the footfall sound which could be defined to detect the individual with only a slight deviation or in an early stage of disease. Such a procedure is known to improve the discriminatory power of monitoring systems (Tambuyzer, 2018).

Although a sensor attached to the cows would be preferred by farmers (Van De Gucht et al., 2017), it was decided to develop a walkover system. This has the advantage that the costs for the system do not scale with herd size. Moreover, no further sensor needs to be attached to the animals. However, in addition to the panel construction, the walkover system still requires some improvements. For example, the cows do not always cross the plate one at a time. This lead to problems with assigning signals in the sound files to individual cows. Furthermore, it happened that there were two animals on the plate simultaneously. This aspect might have had negative effects on the statistical modeling. However, due to the architectural conditions on the studied farm and because the observations should not disrupt the normal procedure at milking, for example by adjusting the parlor speed, no better solution could yet be implemented.

Implications and further research

Lameness is a significant multifactorial disorder that is widespread on both conventional and organic dairy farms (Richert et al., 2013; Pinedo et al., 2017). Risk factors which impact claw diseases include nutrition and environment (e.g. Hedges et al., 2001; Swalve et al., 2014; Oehm et al., 2019), genetics (e.g. Heringstad et al., 2018) as well as various breeding conditions and technologies (e.g. Moreira et al., 2019; Oehm et al., 2019; Sun et al., 2019). Concrete and slatted floors are common in current animal husbandry. However, as for instance Venegas et al. (2006) and Fjeldaas et al. (2011) showed, these housing conditions are associated with adverse claw health. Thus, the detection of possible claw lesions on-farm will also play a major role in the future.

Frequently, farmers tend to underestimate the number of animals in their herd which are actually affected by claw lesions (Leach et al., 2010), which could lead to bias in lameness scoring and the monitoring of health in the herd. An automatic and objective system which is capable of detecting claw lesions, therefore could help the farmer to identify any problem and to deal with it accordingly. Thus, one important goal in dairy research should remain to develop a system that supports lameness detection on-farm.

Such a system should be able to be integrated into the daily routine, it should neither influence the work of the people nor the behaviour of the animals, it should be affordable and of course be able to reliably detect the lame animals. In spite of the many different approaches and new PLF technologies, such a system does not exist on the market yet. Also the system that was developed within this study has not reached market maturity. However, results of the thesis showed, that there is the possibility to apply the system in the farm environment which is an advantage compared to systems developed in controlled experimental setting only. Even if such on-farm research poses certain challenges as in the present study the location of the test track respectively the constructed panel for instance, it has benefits too. As Holinger (2018) stated, on-farm research reflects naturally occurring variation among farms or herds as well as that the results can be transferred to dissemination activities, advisory services and policymaking. In addition, only such on-farm research can provide information on how systems could be improved for practical use. With regard to the constructed measuring plate in the study, there have been difficulties with the material properties which would not have been visible in a test under laboratory conditions. For instance, for a redesign of the test track, a permanently non-slippery material must be selected. Also the decoupling layer has to be chosen more durable. Generally, the acoustic properties of the measuring section should be better and also less temperature dependent. For this it seems appropriate to use a "harder" or more rigid material for the measuring plate.

Another critical point to be improved was the signal-to-noise ratio, which was perfectible in the footfall sound files for three reasons. Firstly, it was due to the unfavourable properties of the measuring plate, which absorbed the sound much more at higher temperatures and showed material changes effecting the quality of the recorded footfall sound negatively. Secondly, it was due to the arrangement and number of footfall sound sensors, which create a volume gradient in the measurements, and thirdly, caused by the quality of the sensors in the processing section of the footfall sound files (primarily the USB sound card) which for reasons of cost, i.e. to create a financially viable system, were not used in a high-quality way. All three sources of error must be processed and improved in the further development of the test track.

Within the scope of the study, a further problem could be identified during the experiments on-farm. Unfortunately, due to the free cow traffic on the test track, the assignment to one individual animal could not be provided. To solve this limitation, the following approaches would be conceivable. The installation of the test track on another place in the stable, which offers the cows an incentive to walk quickly without stopping, could be considered. On farms with an automatic milking system (milking robots), the test track can be placed in the corridor which the cows pass after leaving the robot. The animals enter this passage only one by one and walk through it at a constant speed, as there is little distraction at this point in the barn. For structural reasons, no relocation of the test track at the investigated farm was realisable. But, this can be taken into account when redesigning a stable and intending to install such a test track. However, using the system as presented in this study, a second animal recognition could help to improve the individual recognition of animals. This could be located behind the measuring section, to record the point in time when a cow leaves the test track. Through the information about the recorded start and end time of the measurement process further filter and editing options for the footfall sound files could be developed.

To improve the prediction model used in the study, the sample size (of cows) for machine learning should be increased significantly. This could be done by using the locomotion score as a 'gold standard' by observing several successive milking times and cows' returns to the stable and not the hoof-trimming results only. Then, however, further points would have to be taken into account. For example an improvement of the test track, the use of locomotion scoring ratings from more than two observers and an increased number of repetitions of measurements for a combined judgment.

Analysing the footfall sound of dairy cows to detect lameness turned out to be a useful approach. Nevertheless, this research had several limitations which should be avoided in further studies in order to improve the study results. However, the measuring system developed and tested in this thesis for the automated detection of lameness by means of acoustic analysis of cows' footfall sound can contribute to a risk assessment model for lameness. An integration of the model found for the prediction of lameness in a herd management or a quality management system (QMS) seems possible. As the measuring system is currently not able to reliably identify lameness, synergies with other systems could be used. Previous studies for example described the correlation between udder health, body condition and lameness (Singh et al., 2018) as well as between feeding behaviour, locomotion and lameness in dairy cows (Beer et al., 2016).

Basically it seems promising to continue working on the methodology and the method of measurement. In future research attempts regarding analysing cows' footfall sound, it should also be determined with which sensitivity a disease can be detected in order to enable an early treatment of potential lesions. In addition, it would be desirable if the affected limb could be recognized at the same time as the detection.

Conclusion

Lameness is a serious issue in dairy cows and it still poses a problem in dairy production and in particular for animal welfare. Measuring and respectively detecting the percentages of lame cows on a farm could help farmers to prevent lameness from increasing without being noticed. Therefore, the aim of the thesis was to develop a system which is capable of detecting claw lesions in dairy cows by analyzing their footfall sound and to apply it on-farm.

Main limitations in the studies were the reduced sample size, the individual animal recognition and the unfavorable properties of the constructed measuring plate. Nevertheless, analyzing the footfall sound seems to be an appropriate method to detect claw lesions in dairy cows.

SUMMARY

Nina Volkmann (2021)

"Detection of claw lesions in dairy cows based on acoustic analyses"

Lameness is a widespread health problem in dairy production. An early detection and treatment of cows suffering from claw lesions is an important factor for animals' welfare. The visual scoring of locomotion is the most common method to detect lame cows, although this visual observation is complicated as well as time consuming with the ever increasing size of dairy farms and, furthermore, a subjective assessment method. For this reason, there is growing interest in supporting automated methods to detect lame animals on-farm.

The aim of the thesis was to develop a system for the automated diagnosis of lameness in dairy cows by analysing their footfall sound. To reach this aim, first, a three-point locomotion score (LS) was validated. Locomotion of 144 cows was scored and data on claw lesions were collected during hoof-trimming. Based on latter data a cluster analysis was performed to objectively classify cows into three groups (Cluster 1-3). Finally, the congruence between scoring system and clustering was tested using Krippendorff's α reliability. Comparing the respective categorization received by either the cluster analysis or LS in between groups, a high correspondence could be found for LS1 and cluster 1 (79.4 %) as well as for LS3 and cluster 3 (83.7 %). Only LS2 had partial agreement to cluster 2 (21.1 %). However, Krippendorff's α was 0.75, indicating a good degree of reliability. The used LS was suitable for classifying the cows' state of lameness representing their claw diseases and, therefore, also suitable as a matching system to distinguish the lame from non-lame cows for further approaches.

As a first step to implement a system which is capable to determine the health status of cows' claws by analysing their footfall found, data was generated from 144 cows

walking along a test track situated outside the stable. On this test track eight piezoelectric sensors recorded their walking speed and the footfall sound of their steps. Locomotion of the animals was scored and they were graded using the validated three-point scoring system. Additionally, the cows were examined by a hoof trimmer. The mean walking speed at the test track was significantly higher in cows with LS1 (0.96 m/s) compared to animals with LS2 (0.76 m/s) and LS3 (0.82 m/s). The measured standard deviation of volume (SDV) in the recorded footfall sound signal was considered as a factor for the force of cows' footsteps. Therefore, a higher value of SDV describes an increased difference between a sound signal and no sound signal. Actually, cows with non-infectious diseases showed lower SDV (0.017 dB) than healthy ones and those affected by infectious diseases (both = 0.021 dB). This result confirmed the assumption, that especially cows with non-infectious diseases have a greater sensitivity to pain and demonstrate a less forceful gait pattern. This attempt showed that the used measurement system could record cows' individual footfall sound without any noise interference. But, installing the test track outside the stable resulted in an increased agility of the cows, even though they had been habituated to the test track in advance.

The third study of the thesis was performed at another farm where the experimental set-up was placed on the way back from the milking parlour to the stable. Now, the test track was a constructed panel equipped with a piezoelectric sensor recording the footfall sound and an antenna to allow animal identification. The footfall sound from 64 cows was recorded and edited, and 640 sound files from these animals were analysed. The classification of animal-lameness status was performed using a machine-learning process with a random forest algorithm. The gold standard was a 2-point scale of hoof-trimming results (healthy vs. affected), and 38 properties of the recorded sound files were used as influencing factors. A prediction model for classifying cows' lameness was built using a random forest algorithm. This was validated by comparing the

reference output from hoof-trimming with the model output concerning the footfall sound. Dealing with the likelihood settings and changing the cutoff value to predict lame animals improved the prediction model. At a cutoff at 0.4, a decreased false-negative rate was generated, and the false-positive rate only increased slightly. This model obtained a sensitivity of 0.81 and a specificity of 0.97. With this procedure, Cohen's Kappa value of κ = 0.80 showed good agreement between model classification and diagnoses from hoof-trimming. Thus, the prediction model enabled the detection of cows with claw lesions.

In summary, the developed system could be integrated in the stable and in the normal practice, in other words on the way back from milking, on this farm without disturbing the normal process in the stable. But, as the rates for missing lame cows (false-negatives) or false alarms (false-positives) and the misclassification rate remained high, further research is required on this system. Furthermore, the current version of the constructed panel was neither ready for a continuous usage on-farm nor for series production. Nevertheless, our results showed the potential of the system, and that it is worth investing more effort in further research concerning the detection of lame cows on-farm by analysing their footfall sound.

ZUSAMMENFASSUNG

Nina Volkmann (2021)

"Detektion von Klauenerkrankungen bei Milchkühen mittels akustischer Analysen"

In der Milchviehhaltung sind Klauenerkrankungen sind ein weit verbreitetes Gesundheitsproblem. Ihre frühe Erkennung und Behandlung ist ein wichtiger Tierwohlaspekt. In der Praxis ist die Durchführung eines „Locomotion Scorings" die gebräuchlichste Methode, um lahme Kühe im Bestand zu erkennen, obwohl diese visuelle Begutachtung aufgrund der immer größer werdenden Herden sowohl kompliziert als auch zeitaufwendig und eine subjektive Methode ist. Aus diesem Grund gibt es ein stetig wachsendes Interesse an unterstützenden, automatischen Systemen, um lahme Kühe im Betrieb zu erkennen.

Das Ziel der Studien der Dissertation war es, ein System zu entwickeln, welches Klauenerkrankungen bei Milchkühen mittels der Analyse ihres Trittschalls automatisiert detektiert. Um dieses Ziel zu erreichen, wurde zunächst ein 3-Punkte Locomotion Score (LS) validiert. Dafür wurde mittels eines LS (LS1 – LS3) der Bewegungsablauf von 144 Kühen bewertet und ihre Klauenerkrankungen wurden bei einer anschließenden professionellen Klauenpflege erfasst und dokumentiert. Basierend auf den Daten dieser Klauenpflege wurde eine Clusteranalyse durchgeführt, um Kühe objektiv in drei Gruppen (Cluster 1-3) einzuteilen. Schließlich wurde die Kongruenz zwischen der Einteilung mittels LS-System und Clustering mit Krippendorffs α-Reliabilität getestet.

Beim Vergleich der Klassifizierung, die durch die Clusteranalyse beziehungsweise durch den LS zwischen den Gruppen vorgenommen wurde, konnte eine hohe Übereinstimmung für LS1 und Cluster 1 (79,4 %) sowie für LS3 und Cluster 3 (83,7 %)

gefunden werden. Nur LS2 stimmte lediglich teilweise mit Cluster 2 überein (21,1 %). Insgesamt betrug Krippendorffs α 0,75, was auf eine gute Reliabilität hindeutet.

Dementsprechend konnte festgehalten werden, dass der verwendete LS geeignet war, um den Lahmheitszustand der Kühe entsprechend ihrer Klauenkrankheiten zu klassifizieren und daher auch für folgende Versuche als Abgleichsystem geeignet war, um lahme von nicht lahmen Kühen zu unterscheiden.

Als erster Schritt zur Implementierung eines Systems, das in der Lage ist, vorhandene Klauenerkrankungen bei Milchkühen mittels einer Analyse des Trittschalls zu detektieren, wurden in der zweiten Studie die Daten von 144 Kühen erfasst, die über eine Teststrecke außerhalb des Stalls liefen. Auf dieser Teststrecke zeichneten acht piezoelektrische Sensoren das Trittgeräusch ihrer Schritte auf und ihre Laufgeschwindigkeit wurde gemessen. Außerdem wurde der Bewegungsablauf der Tiere mittels des validierten LS (LS1 – LS3) bewertet und eventuelle Klauenerkrankungen bei einer professionellen Klauenpflege dokumentiert.

Die mittlere Laufgeschwindigkeit auf der Teststrecke war bei Kühen mit LS1 (0,96 m/s) signifikant höher als bei Tieren mit LS2 (0,76 m/s) und LS3 (0,82 m/s). Die gemessene Standardabweichung der Lautstärke (SDV) im aufgezeichneten Trittschallsignal wurde als Faktor für die Auftrittskraft der Kuh gewertet, da ein höherer SDV Wert einen größeren Unterschied zwischen einem vorhandenen Tonsignal und keinem Tonsignal darstellte. Insgesamt zeigten Kühe mit nicht infektiösen Krankheiten einen niedrigeren SDV Wert (0,017 dB) als gesunde Kühe und solche mit infektiösen Klauenerkrankungen (beide = 0,021 dB). Dieses Ergebnis bestätigte die Annahme, dass insbesondere Kühe mit nicht infektiösen Klauenerkrankungen eine höhere Schmerzempfindlichkeit und ein weniger kraftvolles Auftreten aufweisen.

Dieser Versuchsansatz zeigte, dass die eingesetzte Teststrecke das individuelle Trittgeräusch der Kühe ohne Störgeräusche aufzeichnen konnte. Die Installation der

Teststrecke außerhalb des Stalls führte jedoch zu einer erhöhten Agilität der Kühe, obwohl sie sich zuvor an die Teststrecke gewöhnen konnten. Diese Agilität führte letztlich dazu, dass Messschwierigkeiten auftraten beziehungsweise viele Messdaten nicht für die Analyse genutzt werden konnten.

Die dritte Studie der Dissertation wurden auf einem weiteren Versuchsbetrieb durchgeführt, auf dem die Messstrecke auf dem Rückweg vom Melkstand zum Stall installiert wurde. Diese Teststrecke bestand aus einer konstruierten Platte, die mit einem piezoelektrischen Sensor zur Erfassung des Trittschalls und einer Antenne zur Tieridentifikation ausgestattet war. Damit wurde der Trittschall von 64 Kühen aufgezeichnet sowie bearbeitet und 640 Sound-Dateien dieser Tiere wurden analysiert. Die Klassifizierung des Lahmheitsstatus der Tiere wurde mithilfe eines maschinellen Lernverfahrens durchgeführt. Der „Goldstandard" war eine 2-stufige-Skala (ohne Klauenerkrankung/gesund vs. mit Klauenerkrankung/erkrankt) basierend auf den Ergebnissen einer professionellen Klauenpflege. Als Einflussfaktoren wurden 38 Eigenschaften der aufgenommenen Sound-Dateien herangezogen. Ein Prädikationsmodell zur Klassifizierung des Klauenerkrankungs-Status wurde unter Verwendung eines Random-Forest-Algorithmus erstellt. Dieser wurde durch den Vergleich der Ergebnisse von der Klauenpflege (Referenz) mit der Ausgabe des Modells bezüglich des Trittschalls validiert. Das Prädikationsmodell, welches Tiere mit Klauenerkrankungen vorhersagen sollte, wurde daraufhin durch Veränderungen des Cutoff-Wertes versucht zu verbessern. Bei einem Cutoff von 0,4 wurde eine verringerte Falsch-Negativ-Rate generiert und die Falsch-Positiv-Rate nur geringfügig erhöht. Das Modell mit einem Cutoff von 0,4 erreichte eine Sensitivität von 0,81 und eine Spezifität von 0,97. Der errechnete Cohens-Kappa-Wert von $\kappa = 0{,}80$ erzielte schließlich eine gute Übereinstimmung zwischen der Klassifikation durch das genutzte Modell und den

Ergebnissen der Klauenpflege. Insgesamt bot das aufgestellte Prädikationsmodell somit die Möglichkeit, Kühen mit Klauenerkrankungen grundsätzlich zu erkennen.

Zusammenfassend lässt sich sagen, dass das entwickelte System im normalen Stallaufbau eines Praxisbetriebes respektive auf dem Rückweg vom Melken integriert werden konnte, ohne die üblichen Arbeitsabläufe im Stall zu stören. Da jedoch der Anteil an nicht detektierten aber klauenkranken Kühen (falsch-negative) sowie an Fehlalarmen (falsch-positive) und die Missklassifikationsrate hoch blieben, sind noch weitere Forschungen zu diesem System erforderlich. Darüber hinaus war die aktuelle Version der konstruierten Messplatte weder für den dauerhaften Einsatz in der Praxis noch für eine marktreife Produktion geeignet. Dennoch zeigten unsere Ergebnisse insgesamt das Potenzial des Systems auf und, dass es sich lohnt, weitere Untersuchungen zur Erkennung lahmer Kühe im Betrieb durch die Analyse ihres Trittschalls durchzuführen.

LIST OF PUBLICATIONS

Besides the publications included, the following ones have been published in connection with this thesis:

VOLKMANN, N., RICHTER, U., HÖLSCHER, R., KEMPER, N. (2018): Sound hooves: detection of lameness in dairy cows by acoustic analysis. In: Book of abstracts No.24, EAAP-69th Annual Meeting, Dubrovnik, Croatia, 27.-31.08.2018, 388

VOLKMANN, N., KEMPER, N. (2018): Evaluation of a gait scoring system for dairy cows by using cluster analysis. Poster: Book of abstracts No.24, EAAP-69th Annual Meeting, Dubrovnik, Croatia, 27.-31.08.2018, 29

VOLKMANN, N., KULIG, B., KEMPER, N. (2018): „Sound Hooves": Klauenerkrankungen mittels akustischer Analyse des Trittgeräusches detektieren. In: Tagungsband der Vortragstagung der DGfZ und Gff, Bonn, 12.-13.09.2018, D23

VOLKMANN, N., KULIG, B., HOPPE, S., HENSEL, O., KEMPER, N. (2019): Acoustic of dairy cows' gait: Detecting claw lesions by analyzing the footfall sound. In: Book of abstracts S.78, 17th International. Conference on Production Diseases in Farm Animals, Bern, Switzerland, 27. – 29.06.2019

VOLKMANN, N., KULIG, B., KEMPER, N. (2019): The sound of claw lesions: Detection of lameness by acoustic analysis. In: Book of abstracts S. 22, UFAW International Symposium 2019, Bruges, Belgium, 03. – 04.07.2019

VOLKMANN, N., KULIG, B., KEMPER, N. (2019): Is it possible to detect lame cows by analysing their footfall sounds? In: Book of abstracts, The European Conference on Precision Livestock Farming; Cork, Ireland, 26. – 29.08.2019, 397-402

ACKNOWLEDGEMENTS

I want to express my deepest gratitude to Prof. Dr. Nicole Kemper for inspiring, reliable supervision, for continuous guidance, and for valuable feedback throughout my research.
I am very grateful to Prof. Dr. Hermann H. Swalve for taking on my supervision from the Martin Luther University Halle-Wittenberg and for the pleasant cooperation.
Furthermore, I am thankful to the whole staff of the research farm "Ruthe" of the University of Veterinary Medicine Hannover, Foundation, and to the colleagues of the Agricultural Research and Training Center „Haus Riswick", of the Agricultural Chamber of North Rhine-Westphalia. I would also like to thank all the project partners who, despite all the difficulties, contested the project with me.

In addition, I want to thank the Federal Ministry of Food and Agriculture (BMEL) based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE) under the innovation support programme for founding this research.
I also want to acknowledge all my former and present colleagues of the Institute for Animal Hygiene, Animal Welfare and Farm Animal Behaviour. The helpfulness, the continuous exchange of expertise and the friendly manner of all colleagues created the kindest working atmosphere. Very special thanks go to my (former) colleagues and really good friends Jenny Stracke and Sally Rauterberg aka 'PadB' as well as Katja Kulke, Eyke Lühken and Rafael Hernán Mateus Vargas for so many great (working hard) memories!

Finally, I would like to thank my whole beloved family.
Dearest Burbest and Frietzen, thanks for your constant support and love. I really treasure that!
Additionally, I am thankful to my parents-in-law for their assistance in every respect.

Most of all I would like to thank my very best friend and my dear Basti for continuously supporting the implementation of our *Masterplan*$^{+++}$. It would be vain to try to explain how much your support and love mattered to me and how it made all this possible.
My beloved ones, Anton and Moritz, thanks that also you had a lot of understanding and interest in my work. You are the best that could have happened to me, you make me so happy and proud.

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DECLERATION UNDER OATH / EIDESSTATTLICHE ERKLÄRUNG

I declare under penalty of perjury that this thesis is my own work entirely and has been written without any help from other people. I used only the sources mentioned and included all the citations correctly both in word or content.

Ich erkläre an Eides statt, dass ich die Arbeit selbstständig und ohne fremde Hilfe verfasst, keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

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