



Molograph 4.0: A demonstration of a non-invasive, automated system for evaluating aspects of the masticatory process in the horse

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ABSTRACT

We outlined a monitoring system as a demonstration of the Internet of Medical Things (IoMT) in horses that provided the ability to record aspects of the equine chewing process. Here we take up the idea of a Molograph, which was already proposed in the mechanical form in 1941 by Leue and transferred into today's world. As a substantial practical advantage, the system now involved a non-invasive measurement that was taken in the horse's familiar environment. All patients were fed roughage. In terms of the examination scenario, we focused on the determination of the direction of chewing. The system relieves the strain of the examination by automating an otherwise time-consuming and tedious observation, while the results were comparable to those of a human observer. Firstly, examining the horse with the Molograph 4.0 may provide indications like predominant unilateral chewing that justify a more detailed dental inspection by a veterinarian. The expert may identify the root cause and thus prevent pathologies like diagonal incisor malocclusion or shear mouth. All observed changes in chewing direction occurred in connection with chewing breaks, while the relationship is not bijective.

1. Introduction

The process of breaking down food by mastication is an essential part of equine digestion. Unlike carnivores, which swallow large pieces of food unchewed, horses, which are herbivores and monogastric, require a functional masticatory apparatus to prepare the mostly cellulose-containing food for further digestion by crushing and enzymatic breakdown.

There is often a striking discrepancy in the diet of horses in husbandry compared to their wild counterparts (Mac Fadden, 2005; Orlando, 2015). Significant differences exist, above all, in the abrasiveness of the food, the duration of the daily chewing activity, and the limited diversity of plant species in today's pastures. For this reason, diseases of the masticatory apparatus are not uncommon and regular veterinary check-ups are recommended.

Here, it is assumed that the equine mastication process is understood in its essential aspects (Carmalt et al., 2005; Collinson, 1994; Easley et al., 2022; Huthmann et al., 2009; Staszuk et al., 2006). Observing or measuring aspects of this chewing process and comparing it to the physiological process can therefore provide clues to the presence of a

pathology.

Numerous investigations have been conducted to measure the movement of the lower jaw relative to the upper jaw during mastication. One of the first and widely cited experiments was carried out by Leue (1941). A mechanical construction was attached to the horse's head, which recorded the movements using a mechanical recorder. This device was named "Molograph" and the recorded diagrams were called "Mologrames" (Fig. 1). Baker and Easley (2005) performed two-dimensional video observations of horses during the chewing process and developed a chewing curve. Simhofer et al. (2011), Niederl (2007), Bonin (2001), Anen (2008) leveraged arrays of optical cameras to observe optical markers, attached to the skin of the horse's head, and recorded three-dimensional chewing curves. Wagner (2020) described an experimental setup with x-ray markers fixed inside the mandibula and maxilla, monitored by XROMM (Brainerd et al., 2010).

Variations in the chewing curve from horse to horse were documented (Anen, 2008) and the dependency on the types of food was analyzed (Bonin et al., 2007). The chewing cycle is described as unilateral movement Collinson (1994), that is, chewing with a lateral excursion "to the right" or "to the left", where these directions are

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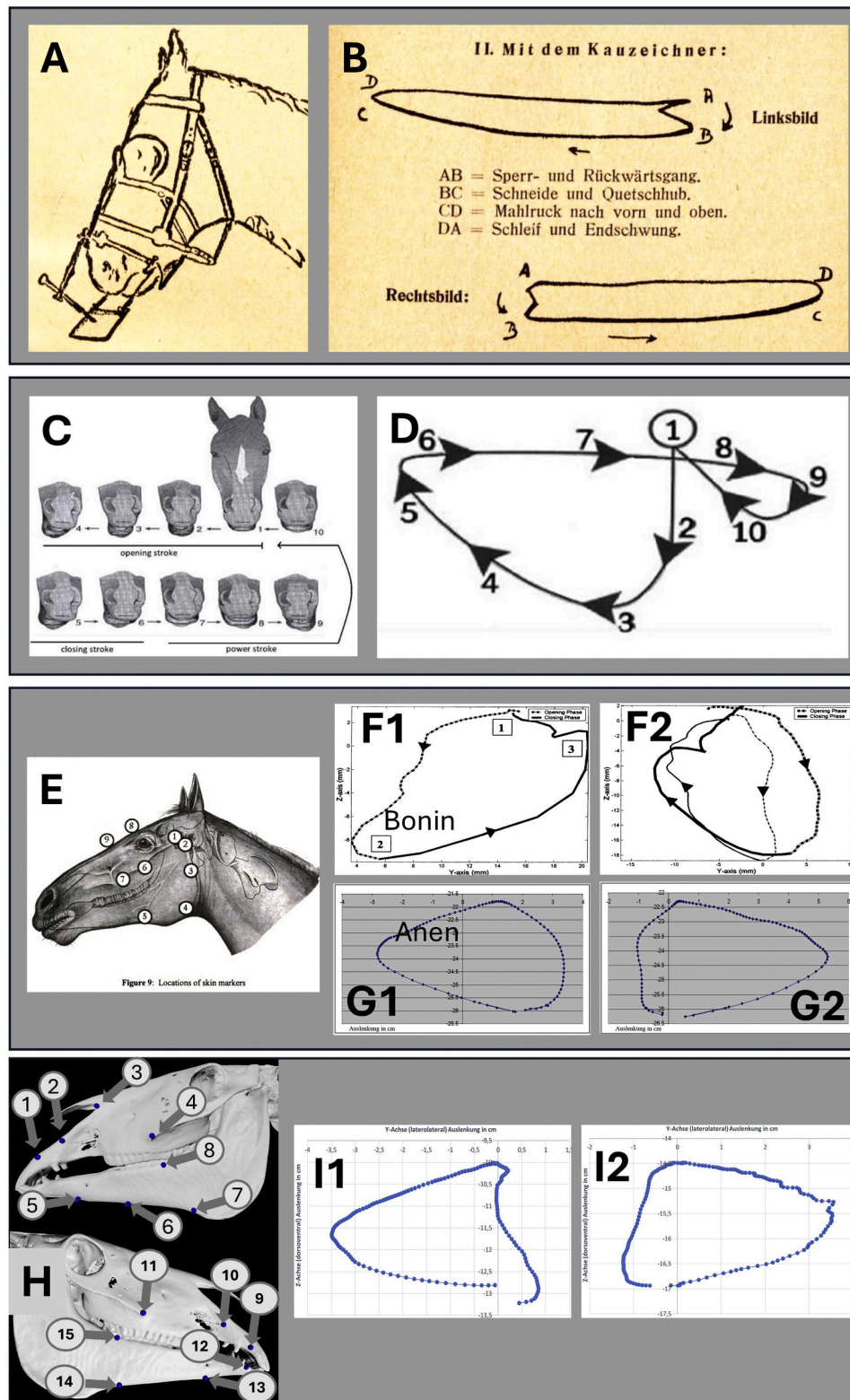


Fig. 1. A short history of chewing motion measurement in horses. The schematic drawing of the Molograph was proposed in 1941 by Leue (A). Exemplary chewing curves (B). Illustration of the chewing cycle (C) and the chewing curve (D) according to Baker and Easley (1999). Horse head with marker positions (E) on the skin according to Niederl (2007). Related exemplary chewing curves, were recorded by Bonin (F1, F2) and Anen (G1, G2). Potential marker positions in the bone (numbered) ^{a=} (H) and descriptive kinematic first description of the related chewing curves (I1, I2). ^{a=} Picture H: Own illustration aligned to Wagner (2020).

viewed from the perspective of the horse. If chewing occurs "to the right", the right side is named the "working side", while the left side is named the "balancing side" [Sterkenburgh et al. \(2022\)](#) and vice versa. Starting in a neutral position of the lower jaw with the mouth closed and the incisors in contact, the chewing process is described in 3 phases: The first phase is called an "opening stroke", where the mouth is opening and a lateral excursion of the lower jaw to the "working side" is initiated. During the second phase, named the "closing stroke", the mouth closes, while the lateral excursion slows down but continues. The end of this second phase is characterized by contact of the cheek teeth on the working side. In the third phase, named "power stroke", the lateral movement is finally reversed, while the lower jaw slides back into the starting position, maintaining contact of the cheek teeth on the working side. Mechanical feed shredding occurs during the power stroke. It is known that physiological horses change the direction of chewing from time to time and alternate between a lateral excursion to the right and an excursion to the left ([Baker & Easley, 2007](#)).

The transportation of food in the mouth is described as a process that begins with the actual food intake with lips and incisors and then continues with the ongoing mechanical grinding process by the cheek teeth and under the effect of saliva. The effects of both processes intensify as the food moves towards the esophagus ([Easley et al., 2022](#)).

Pathologies and anomalies such as shear mouth ([Moore, 2016](#)), diagonal incisor malocclusion (DIM) ([Kunz et al., 2020](#); [Sterkenburgh et al., 2023](#)), and differences in shape and distance between the right and left molar arcades are assumed to develop or at least be promoted due to one-sided chewing. One-sided chewing is either believed to be caused by painful pathologies ([Smyth et al., 2016](#)) of the masticatory apparatus and an assumed reliever posture. Or it is caused by mechanical blockages of the chewing apparatus or due to asymmetric deformations in the mandibula or/and maxilla ([DeLorey, 2007](#)). Early detection of unilateral chewing and appropriate treatment of the causes can thus reduce the severity of the possible development of such pathologies. This is particularly the case if the diagnosis is easy to make and does not cause the animal any stress.

The Internet of (Medical) Things (IoMT) is driving many improvements in health care and monitoring. The medical data of the patient, captured by sensors, is typically forwarded to databases on cloud servers, analyzed, and then reported back to the attending physician. Here, it is incorporated into the assessment and diagnosis. With a suitable IoMT sensor system for monitoring aspects of the chewing process, it should be possible to continuously observe the horse chewing over longer periods, with high reliability, and without the need for a laboratory environment and the presence of an experimenter. At the same time, the horse can be observed in its familiar environment and, apart from wearing a mask, virtually undisturbed.

Due to the relatively complex setups, all of the observation methods for the chewing process, presented in [Fig. 1](#), allow recording of the chewing motion under an experimenter's control and laboratory conditions, i.e., while restricting the horse's mobility. Beyond these methods, we propose a non-invasive setup to determine the chewing direction. Here, we chose the chewing direction as the observation intent, as, for comparison, this can also be determined without equipment by simply observing the horse. However, this observation is time-consuming, requires focused observation, and might be perceived as boring, making up a typical field for automation. This non-invasive setup has no negative impact on the horse's well-being apart from wearing a head mask. The effect on the horse when putting on the mask is likely to be similar to the effect of putting on a halter and therefore has minor relevance under animal welfare or ethical law. With suitable further development of measurement technology and evaluation, it should also be possible for people without medical training to carry out measurements to provide indications of anomalies from automated evaluation.

In the following section, we present a corresponding system, which we refer to as "Molograph 4.0" in reference to the term "Industry 4.0".

We hypothesize that this system will be able to determine the direction of a horse's chewing over a feeding period.

Next, we introduce the components of the Molograph 4.0 system, describe the data and information flow, and provide information about the patients involved.

2. Material and methods

2.1. Components of the Molograph 4.0 system

A non-invasive IoMT device that allows long-term observation with little disturbance to the horse was described as desirable. Here, we present a concept that largely fulfills this requirement and might contribute to a better understanding of aspects of the equine mastication process.

We refer to Molograph 4.0 as a technical system that consists of the following components:

1. A tight-fitting mask, which is pulled over the horse's head. The mask is made of an elastic stretch textile and covers the head, reaching from rostrally just behind the jaw angles to caudally behind the ears. Thus it covers the whole area but has openings for the eyes and ears. As the size of the horse's head varies greatly from individual to individual, we used three different sizes, each of which was selected to match the shape of the horse's head in such a way that the fabric was properly sticking to the animal's skin and we could no longer detect any slippage between skin and mask during chewing movements. We used commercially available masks ([Catago Equestrian Corporation, 2024](#)), which we equipped with small pockets for the sensors in our own tailor work. The first of these two pockets was placed on the bridge of the horse's nose. The second pocket was located on the skin between the two branches of the lower jawbone. The rostro-caudal position was chosen approximately at the level of the anterior premolar teeth (306 and 406). For the chewing direction experiments, we limited ourselves to a setup with two sensor devices that allow us to independently determine the attitude of the upper and lower jaw, thus allowing us to determine the direction of the chewing. This is in difference to the Rumiwatch system (ITIN + HOCH [GmbH, 2023](#)), which uses one IMU sensor and an additional pressure sensor to count the chewing strokes of ruminants.
2. Two 9-axis inertial measurement units (IMU) ([TDK Corporation, 2017](#)), in modules with power supply and radio transmission of measurement results, were placed in the pockets described above. 9-axis IMU sensors measure linear accelerations along the x-, y- and z-axis, as well as angular velocities from the rotation around the x-, y- and z-axis and the x-, y- and z-component of the magnetic field. The measurement frequency was selected at 10 measurements per sensor and per second with a maximum value of the recorded linear acceleration of 16 times the acceleration of gravity (16 g), and a measurement range of the recorded angular velocity of max. 2000° per second. The acceleration sensor accuracy was specified as 0.01 times the acceleration of gravity (0.01 g), and the angular velocity sensor accuracy was 0.2 ° / s.
3. By analyzing the gravitational acceleration and the magnetic field of the earth, the attitude (i.e. the angular orientation of the sensors in space) was determined, leveraging the respective angles of the sensor to the gravitational force and the earth's magnetic field ([Wang & Rajamani, 2016](#)).
4. A 4-th generation RaspberryPi computer system ([Raspberry Pi Foundation, 2024](#)) with a 7-inch touchscreen and a keyboard with an integrated mousepad powered by a power bank was used to record measurement data, calculate the attitude of each sensor from the transmitted orientational raw data, as well as for rudimentary visualization, (measurement duration, data rate, battery level), and subsequent storage of measurement data via a mobile tethering into cloud storage.

2.2. Data analysis

As the measurement data describe the angular orientation of the sensors in space, the sensor on the bridge of the nose allowed us to determine the orientation of the horse's head. When the mouth is at rest and closed, the sensor on the lower jaw is in a fixed orientation relationship to the sensor on the bridge of the nose. During the chewing process, this relationship changes over time, allowing us to describe the change in attitude of the lower jaw relative to the upper jaw, and thus to record aspects of the chewing movement.

Here, the movement of the lower jaw relative to the upper jaw can be seen as a motion around a rostro-caudal axis (Simhofer et al., 2011). The chewing direction can be determined by analyzing the phase shift between the dorso-ventral and latero-lateral movements, as shown in Fig. 4. Due to the hardware used, we were able to record 10 attitudes per sensor and second. The sensors were not synchronised in time. Therefore, before calculating the attitude variance, the data from one sensor was interpolated over time in a way that for each sensor reading, a time-interpolated value from the second sensor was calculated. This procedure leads to 20 values per sensor and second, and half of them are created by interpolation. Sensor data was initially acquired at the head of the horse, then transmitted to the robust measuring computer, and finally stored in cloud storage (Microsoft Corporation, 2024) via mobile communications (i.e., tethering of the smartphone). The data scientist then analyzed the data, as presented in Fig. 2. This data path essentially corresponds to the data path of IoMT applications, with sensors connected to the internet through a hub, data storage in cloud databases, and subsequent fully or partially automated data analysis. In the example set-up presented here, data analysis was performed offline after measurement and cloud storage. In the first step, data from both sensors were interpolated on the time axis to compensate for the different

measurement times of the two sensors. In the second step, the orientation of the lower jaw relative to the upper jaw was determined from the variance in the attitude data. The chewing direction was then calculated from the phase shift in the time course between dorso-ventral and latero-lateral movements, as presented in Fig. 3. The latero-lateral excursion was taken as "positive to the right", and the dorso-ventral excursion was "positive to dorsal".

2.3. Patients

In total, 8 horses were examined, including four mares and four geldings. Breeds were presented as follows: Four German riding ponies, one Hanoverian, one Westphalian, one Thoroughbred Chestnut, and one Holstein. The age distribution ranges from one 6-year-old and two 8-year-old, over two 12-year-old and one 18-year-old up to one 20-year-old and one 25-year-old. The horses were chosen according to the opportunities that presented themselves. The 20-year-old Hanoverian horse exhibited a striking chewing behavior, in that the chewing movement had a large dorso-ventral component, while the lateral component was only detectable with very careful observation. All other horses exhibited ordinary chewing motions. One of the horses had an extreme diagonal incisor malocclusion (DIM) and only chewed on one side during the observation period. This unilateral chewing was also confirmed by horse owner. A total of 9 hours of measurements were performed. The chewing direction was recorded by the Molograph 4.0 as described above, as well as through observation by the experimenter.

The patients studied were in stables and were all fed roughage. Except for one horse that suffered from laminitis, all the others were in a straw-lined box. The study period began at the start of feeding and lasted one hour. Only for horse No. 5, we extended the observation and measurement period to two hours, with the effect that feed intake slowed

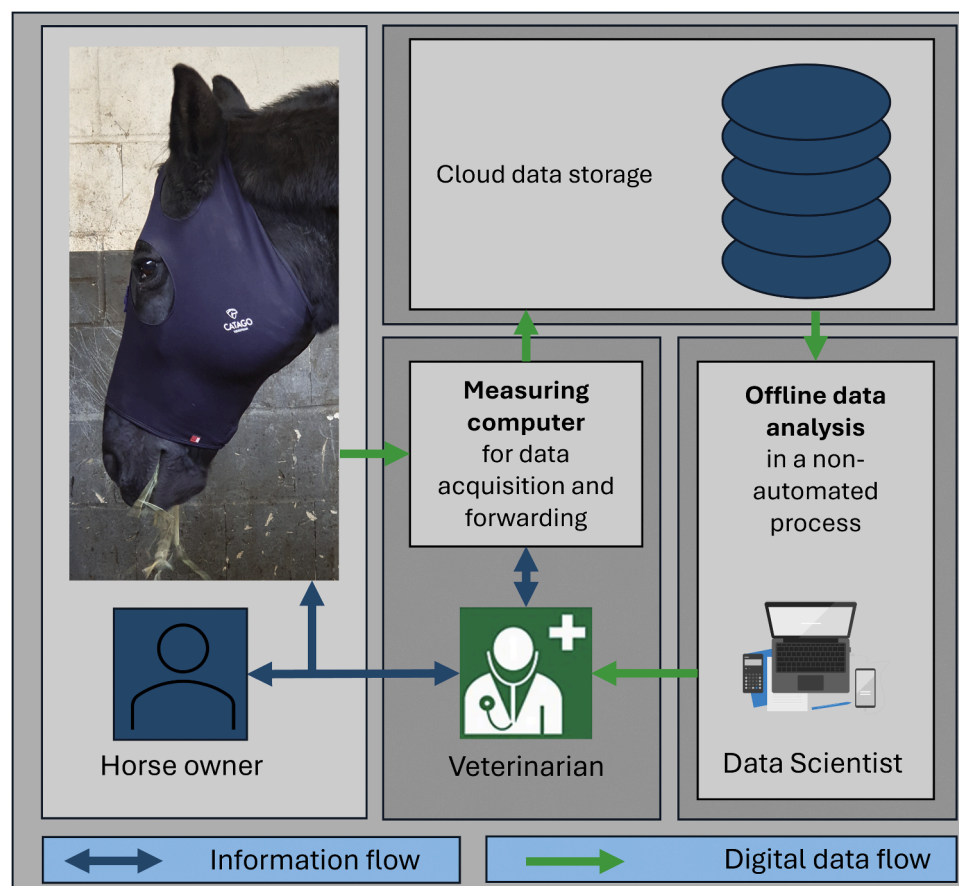


Fig. 2. Measurement setup and data path.

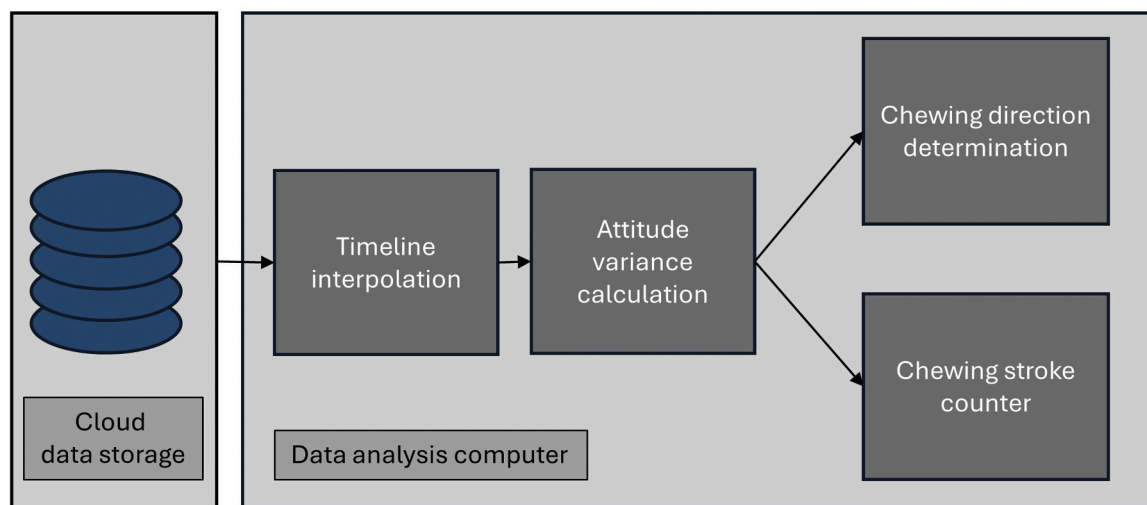


Fig. 3. Components of the Molograph 4.0 system including data flow and information flow in between.

down in the last 20 min of observation, and breaks became longer. For the entire study period, the experimenter was in front of the box, observing the chewing direction. The timeline and additional occurrences were recorded in writing (e.g., unrest in the stable corridor, noise, or distribution of concentrated feed to horses in neighboring boxes).

Next, we present the results of our investigation. Based on the individual chewing curve, we describe the temporal course of the chewing direction, dive into the similarities and differences between the results of the Molograph 4.0 system and the observations of the human observer, and present the results of the analysis for the 8 patients examined.

3. Results

As presented in the Introduction, mastication in horses is a unilateral process and may be performed over the right or the left cheek teeth arcades. For both directions, a single chewing curve can be determined, as presented in Fig. 4D and E. In contrast to the chewing curves in Fig. 1, we have indicated the deflection of the mandible in the dorso-ventral and latero-lateral directions by the deflection angle, with positive dorso-ventral angles indicating a deflection of the lower jaw to dorsal, corresponding to a more closed mouth, while the negative ventral direction equaled a wider opened mouth. Positive latero-lateral angles correspond to a deflection to the right, observed from the patient's perspective. With suitable assumptions about the axes of rotation of the mandible during dorso-ventral and latero-lateral movement relative to the maxilla, the length data from Fig. 1 can be converted to the adopted angles.

The curves shown for individual chewing cycles in Fig. 4D and E each start on the marker line connected by the dotted line to the earlier time in diagrams B and C and end correspondingly with the marker line representing the later time. While in diagrams A to C the latero-lateral and dorso-ventral chewing deflection is plotted over the time axis, curves D and E show the corresponding chewing deflections on the two diagram axes. The progression over time is indicated here by the red arrows.

Fig. 4 A presents the course of a measurement period of 3600 s for patient 1. Individual chewing strokes can hardly be identified in this representation (A); however, longer chewing pauses are recognizable as marked. During this measurement, a total of 3 chewing pauses were identified, the first and third of which were accompanied by a change in the direction of chewing, initially from right to left, and in the third from left to right. After the second pause, the patient maintained the chewing direction to the left. For this specific patient 1, it can also be seen that the

dorso-ventral chewing stroke angle (black) often exceeds the latero-lateral chewing stroke angle (red). This situation was identified as specific to the individual horse. By spreading the time axis to a 40-second interval (B, C), the individual chewing deflections became visible. B and C present different chewing directions, which can be recognized by the leading of the latero-lateral (red) curve in B and the lagging in C.

To provide a first indication of the quality of this experimental chewing direction measurement, the chewing direction was independently determined by the experimenter via visual observation. He observed the horse as closely as possible, determined the direction of chewing, and recorded it. Both, these records and the results of the Molograph 4.0 provide the chronological course of the chewing direction as presented by the bar graphs in Fig. 5. The total observation period as a sum of all patients lasts 9 h., equaling 32.400 s. Over 28.906 s, both methods provided the same results, while differences occurred over 3494 s. From our results, we can calculate Cohen's Kappa (Byrt et al., 1993; Cohen, 1960; Krippendorff, 2019) as a measure for inter-rater reliability from the confusion matrix in Table 1.

The calculation of Cohen's Kappa results in $\kappa = (P_o - P_e)/(1 - P_e) = 0.82$ with $P_o = 0.892$ as observed match and $P_e = 0.385$ as expected match on the three states. Thus, it can be concluded that the observer and Molograph

4.0 provide substantial inter-rater reliability in determining the chewing direction. Different measurement results from the observer and Molograph 4.0 can be found in the matrix outside the center diagonal. While a counterdirectional chewing motion was only rarely measured (Molograph 4.0 "right" to observer "left" and vice versa: 9 s. respectively 96 s.), deviations concerning chewing pauses occur much more frequently (526 up to 1108 s.). In particular, breaks, not detected by human observers will be a matter of discussion. In addition, the observer and Molograph 4.0 system detected the same number of changes in the chewing direction. A break accompanied all observed changes in chewing directions, while conversely, not every break leads to a change in chewing direction. Due to the given sample size limitation we evaluate these results as promising, but with the need for validation on larger scale.

4. Discussion

In contrast to the Molograph 4.0, the observer could not analyze individual chewing strokes. The experimenter's recordings are therefore always to be understood as a summary of an observation lasting a few tens of seconds. The chronological sequence was then recorded to the minute. Deviations of more than one minute between the time sequences

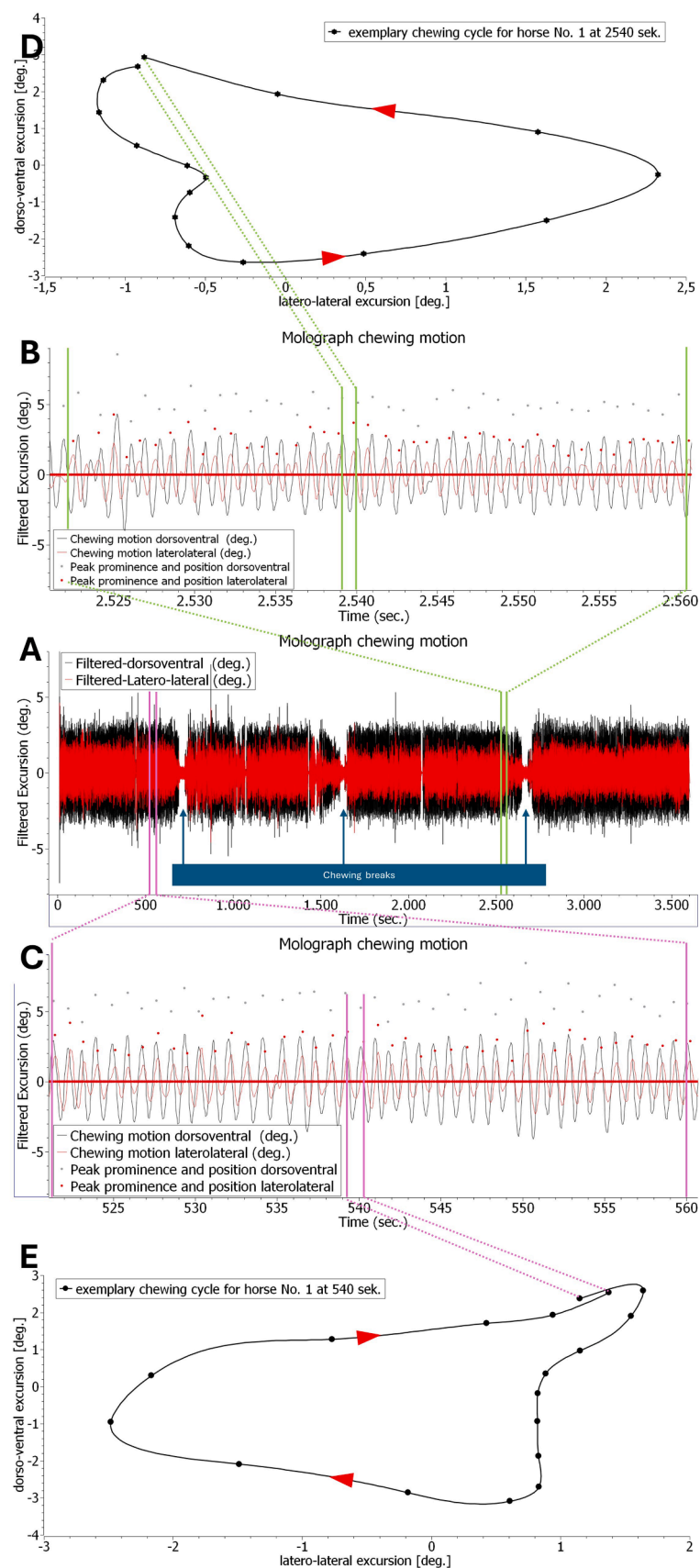


Fig. 4. Dorsoventral and latero-lateral chewing motion component for patient No 1: One hour of recording (A) detail for chewing over left (B) and over right (C). Peak prominences and positions are marked in the detailed views. Chewing cycle over left (D) and over right (E). ((A) to (C): bandpass-filtered).

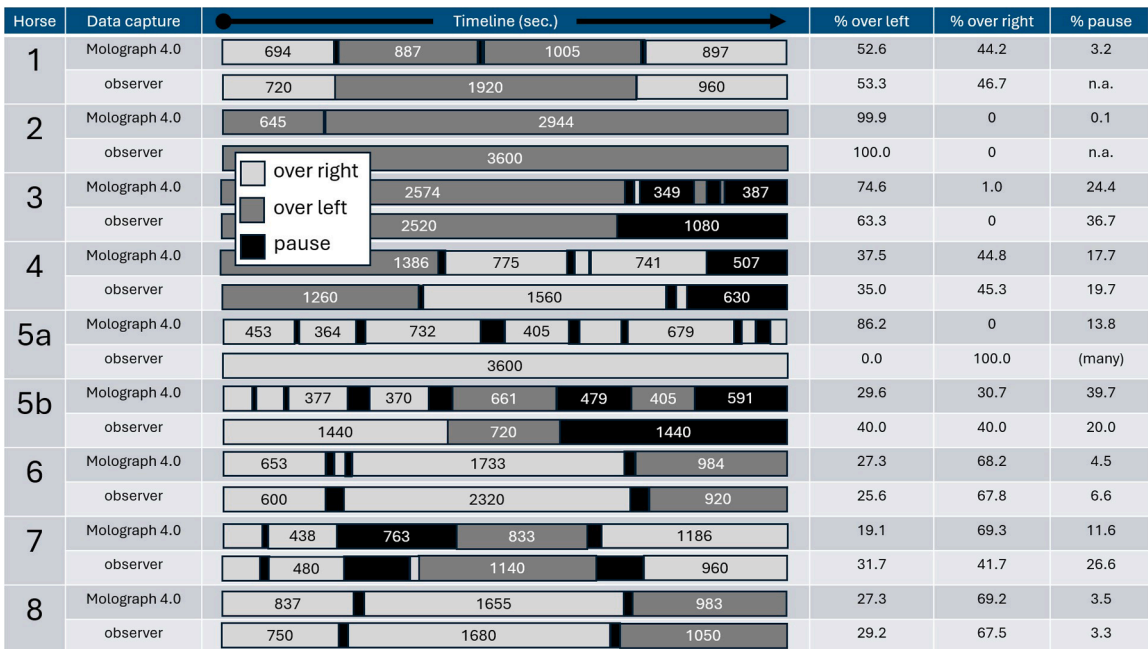


Fig. 5. Recorded time course of the determined chewing direction for 8 patients in the comparison of Molograph 4.0 and human observer, together with percentages for chewing over the right, chewing over the left, and the determined pauses. In patient 5, two consecutive measurements were carried out.

Table 1
Confusion matrix, summarizing the results from Molograph 4.0 and a human observer over the entire duration of the 32,400 s of the experiments regarding combinations of the occurrences of chewing over “left”, over “right”, and “breaks”. All values in seconds.

Human Observer	Molograph 4.0			
	right	break	Left	sum rows
right	13,406	1108	96	14,610
break	851	3105	904	4860
left	9	526	12,395	12,930
sum cols.	14,266	4739	13,395	32,400

are, therefore, system-related. Diving into the details, the differences between the two recording methods regarding the observed length and position of the individual periods become visible: Molograph 4.0 recorded short pauses that were not recorded by the observer. This may uncover major weaknesses of the human observer:

- Distractibility or temporary loss of focus: When there are distracting events, such as unfamiliar occurrences, noise, or movement in the barn corridor, humans and horses seem to fare similarly: While the human observer loses focus and gives in to the unfamiliar stimulus, the horse might do the same. However, if humans and horses lose focus at the same time, chewing pauses can easily be overlooked.
- The determination of the direction of the chewing process by the human observer is subject to a significant training effect. While the determination in the initial phase of the investigation was still not very routine, a significant learning effect was achieved over the test period. Different levels of experience among different observers can thus influence the result.

However, Cohen’s kappa of $\kappa = 0.82$ can be considered a good agreement between the human observer and the Molograph 4.0 system. We interpret the result to mean that the Molograph 4.0 measurement is at least approximately equivalent to that of the human observer, while the use of the technical system supports humans in terms of the effort required for observation. By providing consistent, automated observations, Molograph 4.0 could reduce the potential for human error or

observer fatigue, common issues in lengthy or repetitive monitoring tasks. The accuracy reflected in the matrix suggests that Molograph 4.0 could offer a reliable alternative to manual observation, making it especially valuable in routine settings where continuous monitoring by a trained individual is impractical. This data supports the idea that Molograph 4.0 could be trusted by veterinarians, who sometimes require detailed, longitudinal insights into chewing behavior to diagnose potential issues early. Additionally, the system’s automated nature and straightforward setup mean it could also be used by laypersons, such as horse owners, without the need for specialized training. By delivering accessible, consistent data, the Molograph 4.0 enables owners to proactively monitor their horses’ chewing patterns and detect potential issues early, informing a veterinarian if necessary. This can reduce stress for the horse by minimizing invasive checkups and provide peace of mind to owners who want to support their animal’s health on a more routine basis. In sum, the confusion matrix demonstrates that Molograph 4.0 is not only a powerful tool for specialized research but also holds practical utility for various users in equine care, making it versatile enough to be used reliably in both professional and casual settings.

The Molograph 4.0, presented here, is a concept that allows the collection of new types of data relating to the horse’s chewing process. In this paper, we have limited ourselves to recording the direction of chewing but see great potential for further analyses. For future investigations, we see a multitude of other parameters that may allow conclusions to be drawn about various aspects of the chewing process. Beyond others, these include:

- The chewing frequency (number of chewing strokes per second) and its dependence on the type of food and teeth status (e.g. level of occlusion, lateral excursion to separation (LETS),
- The degree of dorso-ventral and latero-lateral chewing deflection and correlation with pathologies like sharp enamel points or cheek teeth malocclusion.
- Duration of feed intake and monitoring of adequate tooth abrasion.
- Analysis of jaw movement during grazing for a better understanding of differences between natural food intake and food intake in husbandry.

- Clue of the temporomandibular joint (TMJ) movement and dysfunctions.
- Can excessive transverse ridges (ETR) be diagnosed based on characteristic movement patterns?

We have also limited ourselves to a sample size of 8 horses in this report. Although we tried to achieve a wide range of sexes, breeds, and ages, the number of test subjects is not nearly sufficient, to conduct a study based on these factors. It will also be necessary to study larger groups with statistical relevance for further analyses using artificial intelligence, to determine differences due to variations in feeding or to detect anomalies. Corresponding studies are planned for the future.

The process of food intake in horses is complex. It is not only divided into chewing to the right and left and pauses, but includes other components like sorting and rummaging through the roughage, shaking the head, e.g. to ward off insects, tearing movements such as when grazing, turning the entire body, which can make it much more difficult to observe the chewing process, drinking, making contact with the neighbor in the stall, and many other processes that overlap the chewing process.

The chewing process itself is also not a continuous process, but rather an interplay of the actual feed intake and a subsequent phase of chewing or feed crushing.

As described in the introduction, the transport of food during the chewing process is one-sided, complex and involves increasing food comminution and salivation. We suspect that a change in chewing direction either requires the food to be shifted from one side of the mouth to the other or that it is easier for the horse to change once the mouth has been largely emptied. This may explain the relationship between chewing pauses and changes in direction.

The recording of 10 measured values per sensor and second was sufficient to determine the chewing direction. For further analysis, significantly higher recording rates can increase the level of detail.

The radio connection between the sensor and the recording computer has been shown to become unstable, especially if the horse is positioned unfavorably. For this reason, we took care that the roughage was positioned close to the measurement computer to provide a stable connection. Positioning the computer over the horse in the middle of the box could be an ideal setup, although more difficult to achieve. Already before starting the series of measurements described here, we stabilized the signal by the use of an external antenna on the measurement computer. Using a further optimized antenna with an even higher gain may support a stable reception in unfavorable conditions. Replacing the sensors with alternatives that have a better-optimized radio link is another option.

Measurement of the chewing process with the Molograph 4.0 system is similar to measurement using marker points on the skin and, unlike measurement using XROMM, has the weakness that it cannot be guaranteed that the lower jaw sensor, in particular, is in a rigid mechanical connection with the mandibular bone and thus with the teeth. Rather, it can be assumed that the sensor moves slightly with the skin within the clearance provided by the two branches of the mandible. In contrast to markers on the skin, which essentially describe the movement of the skin, we have attempted to closely couple the movement of the sensor to the movement of the lower jaw branches through appropriate embedding. However, the mechanical coupling will probably not reach the coupling quality of the XROMM markers. For the upper jaw, we see a very good mechanical coupling because on the one hand, the skin at the selected site is very thin and the sensor is located at a short distance from the maxilla, and on the other hand, the mask rests over a large area and undergoes little elastic deformation due to the chewing movement.

In this paper, we have shown one aspect of the parameters that can be determined using the sensor data, namely the determination of the chewing direction.

Comparative measurements between XROMM and Molograph 4.0 would be desirable to assess the measurement accuracy of the system

more accurately and, if necessary, to further optimize the sensor positions and embeddings.

Variations such as the use of different types of feed (roughage / concentrated feed) and variations in the environment (stable / pasture) also promise further interesting results.

5. Conclusions

We proposed an innovative, non-invasive IoMT-based system for monitoring aspects of masticatory activity in horses that can be used in the horse's usual environment over one or many feeding periods.

- The system was used to determine the chewing direction for a relatively small group of 8 patients over 9 h of measurement and the measurement was verified by a human observer.
- In two horses, there was no change in chewing direction during the observation period; Four horses showed one change and two horses underwent two changes during an observation period of one or two hours.
- Changes in chewing direction were accompanied by chewing pauses.
- Cohen's Kappa was calculated as $\kappa = 0.82$, which indicates a high interrater reliability of both measurements. Some of the deviations could be explained.
- Due to its non-invasive nature, ease of use, and potential to detect unilateral chewing and pauses automatically, we see benefit in adopting Molograph 4.0 systems in stables for routine monitoring.

Even in its current stage of development, the Molograph 4.0 can provide indications of possible pathologies, for example, if predominantly one-sided chewing is detected over a longer period. Obvious extensions of this system should also enable the veterinary layman in the stable to determine relevant parameters of the chewing process and to transmit these to the attending veterinarian for further analysis.

Ethical statement

The studies were conducted in accordance with local legislation and institutional requirements.

The responsible department 81 for Animal Experimental Matters of the State Office for Nature, Environment and Consumer Protection of North Rhine-Westphalia, Germany has confirmed under file number 2024-0015926 that the non-invasive procedure used here does not cause pain, suffering, or harm to the animal and does not result in any significant stress or fear. The research project therefore, does not meet the definition of an animal experiment and does not require a corresponding permit.

Informed consent was obtained from the owners for the participation of their animals in this study.

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Javier Villalba-Diez
Joaquin Ordieres-Mere

CRedit authorship contribution statement

Tomas Rudolf Sterkenburgh: Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joaquín Ordieres-Meré:** Writing – review & editing, Validation, Supervision, Methodology. **Javier Villalba-Diez:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Author contributions

TRS conceived the idea presented and designed the study. JVD and JOM supervised the work. TRS prepared the original draft. JVD, JOM, and TRS reviewed and edited the original draft. All authors have read and agreed to the published version of the manuscript.

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Appendix C. Data availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. Data inquiries can be directed to the corresponding author.

Appendix D. Acknowledgments

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Appendix E. Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix F. Ethics statement

The studies were conducted in accordance with local legislation and institutional requirements. The responsible department 81 for Animal Experimental Matters of the State Office for Nature, Environment and Consumer Protection of North Rhine-Westphalia, Germany has confirmed under file number 2024-0015926 that the non-invasive procedure used here does not cause pain, suffering, or harm to the animal and does not result in any significant stress or fear. The research project therefore does not meet the definition of an animal experiment and does not require a corresponding permit. Informed consent was obtained from the owners for the participation of their animals in this study.

Appendix G. Abbreviations

The following abbreviations are used in this manuscript:

IoMT Internet of Medical Things
TMJ Temporomandibular joint
XROMM X-ray Reconstruction of Moving Morphology
DIM Diagonal Incisor Malocclusion
IMU Inertial Measurement Unit

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