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Are We Betting on the Wrong Horse? Insignificant Archaeological Leather Fragments Provide the First Evidence for the Exploitation of Horsehide in Renaissance Denmark

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Abstract: Large archaeological, organic materials can be difficult to preserve, conserve, and store in their entirety, which is why prioritisation is often necessary. Priority is generally given to recognisable objects rather than smaller fragments. Nevertheless, for archaeological leather, exactly such insignificant fragments can provide new information on the diversity of species exploited. In this pilot study, we use a Citizen Science approach for the first time to identify archaeological leather fragments using the protein-based method Zooarchaeology by Mass Spectrometry (ZooMS). By inviting the public to participate in archaeological research, the project's first 52 samples, including both recognisable and unidentifiable objects, were analysed. We show that the participants not only generated good data, but also contributed to current knowledge by identifying two hitherto undescribed animal species for leather in medieval and Renaissance Copenhagen. The finding of deer suggests that Copenhagen citizens now and then had access to game through the nobility and the finding of horse suggests that the unclean status of horses was sometimes overlooked to exploit its hide. Our findings are promising for more identifications and the new knowledge the project will generate. The study calls into question how we prioritise and assign value to cultural heritage materials.

Keywords: ZooMS; citizen science; archaeological leather; resource exploitation; cultural heritage

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1. Introduction

The study of archaeological cultural heritage is conditional on the preservation and recovery of material [1], but also by the options, including costs, to preserve, conserve and analyse it. The prioritisation of what to preserve and what to discard has, over the past two decades, been based on criteria for national or global values, as well as the cultural significance of objects (e.g., [2,3]).

In Denmark, such prioritizations have, for instance, been necessary for the enormous amounts of materials recovered from the underground of its capital, Copenhagen, following the intensive construction of the city´s most recent metro line [4]. The waterlogged stratigraphy of the medieval and Renaissance city has preserved surprisingly large amounts of organic archaeological materials such as leather. Throughout history, leather has been used for clothing, footwear, and accessories, but also many of the functions for which we today use modern fabrics, such as transportation and shelter. Leather therefore provides a close insight into the lives of people in the past and their everyday lives, but also animal exploitation, crafts, choices of materials, taste, fashion and aspects as gender, religion, trade, and climate [5]. Unfortunately, modern-day archaeological working conditions make the study of leather difficult, and this has resulted in an unexplored potential for material

culture studies. Due to economical limitations, priority on preserving and conserving leather from largescale excavations has been given to immediately recognisable objects such as shoes, book bindings, purses, and gloves, whereas offcuts and fragments have been given lower priority. Often, this on site prioritisation is made by untrained staff, as leather experts are often not present at archaeological excavation sites. This study showcases a new approach for the study of cultural heritage and archaeological leather, combining a Citizen Science-based approach and a new scientific method, ZooMS (Zooarchaeology by Mass Spectrometry) to expediate the identification of material.

Taxonomic identification of the animal species of the skin is key to exploring the lives of people though leather. This is traditionally performed using microscopy to examine the species-specific grain surface of the leather. However, the method is challenged in archaeological objects with worn, soiled, and incomplete surfaces as well as through methodological problems such as the experience required to perform the method, the access to suitable reference databases, and variation in and between species [6]. This is further complicated as waterlogged leather from excavations requires storage in waterfilled zip bags before conservation in order not to dry out. A wet leather surface is dark and reflective, which makes it difficult or even impossible to observe the grain pattern on its surface. An alternative and promising new method for species identification is ZooMS, which identifies the animal species of collagenous tissues, such as leather, based on small differences in the protein collagen that differentiates animal species [7]. This method has already proven very useful for archaeological leather [8–10]. The method has, however, not yet been applied to as large volumes of leather material as it has to bone [11–13] as it is still relatively labour intensive in terms of laboratory work and downstream analysis.

Studies of medieval (~AD1050–1536) leather in Denmark and in Copenhagen in particular have so far demonstrated the use of the skins of cattle, sheep, and goat as well as a few instances of deer (in Svendborg and Hedeby) [8,14–16]. These previous analyses have focused on complete objects or recognisable fragments of such. Recent studies from Poland have, however, demonstrated that by including fragments and offcuts for analysis, the variety of identified species increases [17,18]. In this article, we therefore hypothesise that a largescale ZooMS analysis of a potentially wider variety of leather would provide new information on animal exploitation for leather. Such a venture, however, requires massive amounts of laboratory work.

Analysis of Largescale Leather Materials Using a Citizen Science Approach

Citizen Science—involving members of the public in the scientific process—is a rapidly growing method across scientific disciplines [19,20]. Within archaeology, volunteers and amateur specialists have been involved, to varying degrees, in the scientific process for decades (e.g., [21]). New approaches have been developed, such as asking the public to help identify archaeological sites using satellite imagery [22]. Other recent approaches involve the public in projects with idea development through co-creation projects [23] and, further, the establishment of physical co-creational labs where volunteers work together with professionals. Both function as very successful platforms for archaeological Citizen Science projects [24]. In a recent review, archaeology came in seventh across scientific disciplines in Europe, but only contributing with less than 2% of Citizen Science projects [25]. In Denmark, organised Citizen Science-based archaeology projects are even less common [26]. Smith (2014) [27] pointed towards four main areas where Citizen Science can benefit archaeological research: fieldwork, searches of large satellite image collections, crowdfunding, and crowdsourced computer entry of heritage data. Here, we apply an additional Citizen Science approach in archaeology.

In a new project, Next Generation Lab [28], we involve the public directly in archaeological research. By inviting high school students to take part in research at the University of Copenhagen and performing ZooMS, we (1) identify large amounts of discarded leather from the Museum of Copenhagen that would otherwise not be analysed, (2) provide the students with a hands-on research experience in an authentic museum setting at the Nat-

ural History Museum of Denmark (Figure 1). This feeds into the students' high school curriculum, lets them meet role models, and makes them an active part of creating new knowledge about their own past. Through this approach, we test the hypothesis that, by analysing sample material that is generally not prioritized for archaeological study, we will obtain new and valuable information on the history of Copenhagen and other Danish cities. This article presents the ZooMS identifications of the initial selection of leather processed by the first two high school visits and serves as a pilot study.



Figure 1. Students working in the lab, species-identifying archaeological leather using the ZooMS method (Zooarchaeology by Mass Spectrometry). Photo: Frederik Wolff Nisbeth Teglhus, the Natural History Museum of Denmark.

2. Materials and Methods

2.1. Sample Selection for the Pilot Study

Next Generation Lab will operate for at least three years, and the project's pilot study, therefore, had several purposes in terms of finetuning methods and defining a future strategy. First of all, we wanted to make sure that students were able to perform the ZooMS protocol. Second, we were interested in finding out if the archaeological sites had relatively good preservation conditions, enabling a fairly good success rate for the ZooMS approach. Third, we wanted to explore methods for the selection of material from the very large amount of material made available for the project by the Museum of Copenhagen. Several ideas were put forward, including focusing on certain object groups, on specific sites, on a diachronic analysis of objects, or on offcuts. To get an initial idea of the prospect of these different strategies, we chose material from two different sites in Copenhagen: Gammel Strand and Krøyers Plads (Figure 2), which represented different datings, as outlined below. We also chose recognisable objects (shoes and belts) as well as unidentifiable objects and offcuts.



Figure 2. City map of Copenhagen showing the location of the two included archaeological sites: Gammel Strand and at Krøyers Plads. *Photo: kbhbilleder.dk*.

2.2. The Archaeological Material

To get an idea of the contexts from which the leather objects derive, the two archaeological excavations in question are briefly addressed here.

In connection to building development at Krøyers Plads, situated at the harbour in central Copenhagen, the Museum of Copenhagen carried out two preliminary surveys at the site in 2012 [29,30], as well as an actual excavation in 2013 [31] (Figure 3). Both the surveys and the main excavation revealed extensive deposits of cultural layers from the first half of the 18th century and remains of well-preserved wooden structures from a former shipyard and port facilities dating from the 1740s and onwards. The thick and moist waste deposits between the bulwarks provided exceptionally good conditions for the preservation of organic materials such as leather, textiles, and wood. Leather objects were collected from

the first preliminary survey and from the main excavation. A total of 734 fragments were registered from the site itself, as well as from the sieving of 18 large bags, each containing 8.81 cubic metres of soil. The majority of the leather objects were characterised as personal objects, including 375 fragments of shoes, as well as multiple fragments of gloves, book binds, scabbards, etc. Additionally, 333 fragments of production waste were registered, of which many were from shoe production. The leather was generally well-preserved and had retained its strength due to the favourable conditions. The objects were generally very fragmented, but some intact specimens, e.g., shoes and book bindings, were very well-preserved (Figure 4). The vast majority of finds in this category were dated to the first half of the 18th century and were probably locally produced as both the material and the craftsmanship existed in Copenhagen at the time. There may be exceptions, and some of the objects could have been produced abroad, but this can neither be confirmed or refuted on the basis of the material found [32].



Figure 3. The archaeological excavation at Krøyers Plads. Photo: Museum of Copenhagen.

The archaeological excavation at Gammel Strand, which is situated on the historical coastline but is currently part of the Copenhagen canal system, was undertaken by the Museum of Copenhagen from 2012–2014 prior to the construction of a Metro station as part of the Metro Cityring Project [4] (Figure 5). Following a watching brief in 2010, the archaeological work comprised a set of watching briefs in 2012, an actual excavation in 2012–2013, a set of more watching briefs in 2013, and finally, the main excavation in 2014. The excavation revealed remains of multiple wooden bulwarks as well as the foundations of several administrative buildings from the 14th century onwards, along with extensive deposits of cultural layers containing a large collection of well-preserved objects. A total of 1706 leather fragments were collected from a range of prioritised contexts. The majority of the fragments were characterised as personal items, including 1483 fragments of shoes (Figure 6). Production waste amounted to 197 fragments. The leather objects were generally well-preserved due to the favourable wet soil conditions, and 63.3% of the objects were accounted for as fragmented, whilst 36.4% were complete and 0.3% intact. The objects were largely identified as either medieval or postmedieval, the majority being postmedieval, and the larger part of these apparently from the Early Renaissance and the 17th century. The

objects dated to the medieval period were mainly high/late medieval (13th to early 16th centuries). Theoretically, the larger part of the objects were made by craftsmen situated in Copenhagen, but not necessarily by local craftsmen alone, as the leather shoes showed trend connections to Western and Southern Europe [33].



Figure 4. Leather shoe from the excavation at Krøyers Plads. Originally a closed shoe, but later reused and redesigned. Early 18th century. Museum number X1081A. Photo: Museum of Copenhagen.

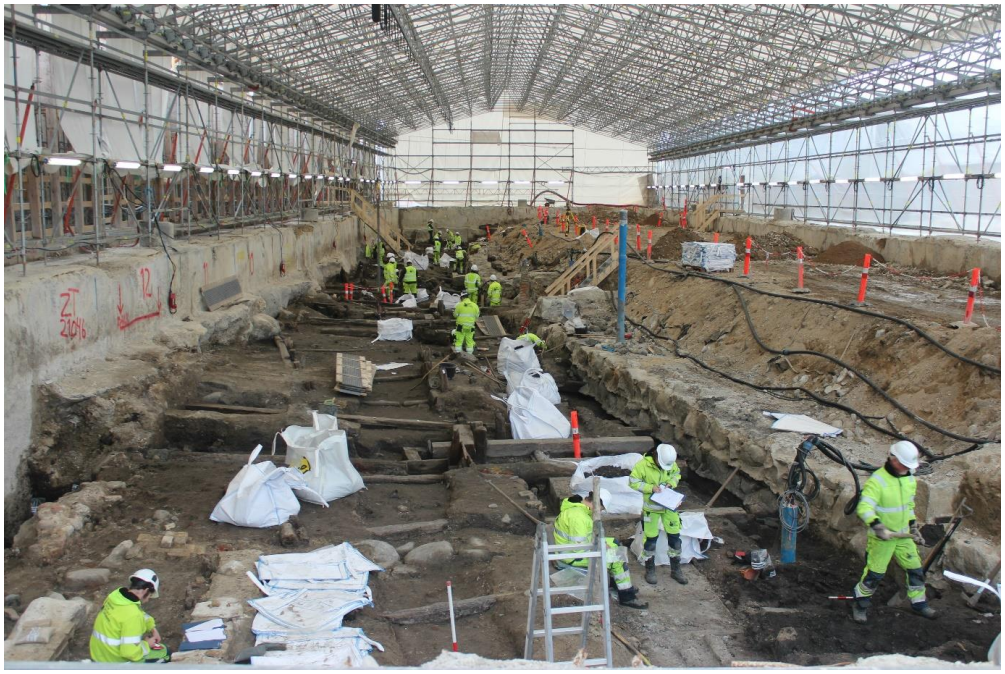


Figure 5. The archaeological excavation at Gammel Strand. Photo: Museum of Copenhagen.



Figure 6. Leather shoe from the excavation at Gammel Strand. Mule with wooden heel and decorative vamp. Late 16th/early 17th century. Museum number FU210379. Photo: Museum of Copenhagen.

The archaeological material from both Krøyers Plads and Gammel Strand is made up of waste from across the city rather than from specific neighbourhoods. The material, therefore, cannot be connected to specific groups of the city's inhabitants. On the other hand, the material shows the diversity of the city and its inhabitants and, thereby, also a diversity in the use of resources at the time and the society's demographics and status range, where every waste-producing individual is represented.

The physical material included in the Next Generation Lab project and presented here had already been discarded from the Museum of Copenhagen compared to more complete objects, under the assumption that conservation was not possible or relevant. Therefore, the objects either had not been given or no longer had museum identification numbers, for which reason internal numbers were provided to the individual objects. The first number describes the object number and following numbers refer to an element (an object could consist of more than one element) and a subsample number.

2.3. Species Identification by Protein Analysis

ZooMS is a material identification method which identifies animal species based on small differences in amino acid substitutions between animal species detected in the protein collagen. Collagen is abundant in the organic materials that are typically found in archaeological excavations, such as bone, antler, teeth, and processed animal skin, i.e., leather. Collagen has, moreover, been shown to survive archaeological degradation better than DNA (e.g., [34]), which makes it possible to analyse materials that are more degraded and older compared to ancient DNA analyses.

Samples were prepared following a previously published ZooMS protocol for archaeological leather [35], but also integrating a one-hour gelatinisation at 65 °C in 50 µL Ambic before trypsin digestion. After extraction, digestion, and purification, the final, short amino acid chains, peptides, were pipetted onto a Bruker steel plate for analysis using a MALDI-TOF MS instrument. Mass spectra were generated over the m/z range of

800–4000. Spectral analysis was undertaken using the opensource, cross-platform software mMass (www.mmass.org) [36]. The three spectra generated for each sample were averaged, and the average spectrum was manually inspected for the presence of peptide markers, designated A–G (Buckley et al., 2009), and P1 and P2 (Buckley et al., 2014), which have recently been renamed by Brown et al. [37]. We use both nomenclatures here. These peptide markers were compared to lists of markers for mammals [7,38]. Although the reference list does not include all possible species, the species that have so far been demonstrated to be most commonly used for leather in medieval Northern Europe are represented: cattle, sheep, goat, as well as pig, horse, and Northern European species such as fallow/red/roe deer and various carnivores. Taxonomic identifications were at the most conservative level (genus or family), based on the presence of unambiguous markers.

2.4. Citizen Science Approach Involving High School Students

The participating high school students took part in a full-day program at the Natural History Museum of Denmark, University of Copenhagen, where they were introduced to the theoretical background of the biological, chemical, historical, and archaeological aspects of the applied methods, materials, and research questions. As part of the teaching program, all students went through a pipette training session. The students used the exact research protocol described above, with only a few minor changes: TFA was added in concentration (2.5%) to a pH below 2, and trypsin was also added in lower concentration and higher volume, equaling the same total amount of substance in order to avoid students working with concentrated substances, as well as to minimise pipetting errors caused by pipetting small volumes.

As a pilot study, one to two subsamples of each object were analysed by the students to enable the study and discussion of variations between subsamples. Analysis was carried out by two different high schools from the Copenhagen area, hereafter presented as high school 1 (visit on 21 May 2021) and high school 2 (visit on 2 June 2021). The structure of the day and the dissemination of the academic content was developed and optimised between the two visits based on experiences and interviews with teachers and students with regard to the student's learning perspective as well as the accuracy of their work and thus the quality of the data produced.

3. Results

The results of the ZooMS analysis in this study can be placed into four categories: (1) a secure species identification based on the presence of unambiguous markers, (2) a probable species identification followed by '?', indicating that markers were present at low S/N threshold (which is here considered an S/N threshold of under 3), (3) identification to a lower taxonomic level caused by either the presence of only more general markers shared between several species or lacking resolution in markers between closely related species, and (4) No ID, caused by either very poor spectra or recovery of only single and very general markers shared, for instance, amongst all mammals.

Eighteen of fifty-two samples (~35%) provided an identification of family, genus, or species level (Tables 1, 2, A1 and A2 for observed markers), which is similar to the success rates of ZooMS on archaeological leather reported previously [8]. The success varied between the two high schools (~19% for high school 1 to 46% for high school 2). For objects with two subsamples analysed, the results were consistent, i.e., either identifying the same species in both subsamples or showing lower level taxonomic identification in one subsample in accordance with the species identification from the other subsample.

Table 1. Results of ZooMS identifications of leather from the Gammel Strand site (KBM 3828). * Theoretically, bison, aurochs, and yak are also possible, but would be exceptional in this context. ** Theoretically, gazelle (as marker A, also known as α2(I) 988–1000, is missing), bison, aurochs, and yak are also possible, but would be exceptional in this context. Internal sample numbers with '?' indicate that students have labelled tubes unclearly, but this is the most probable sample no.

Object	High School	Internal Sample No.	Species ID
Shoe element	2	40, 1_5	No ID
Shoe element	1	40, 2_3	No ID
	2	40, 2_5	Bovidae/cervidae?
Sole from shoe	1	42, 1_4	No ID
Sole from shoe	2	43, 1_2	Cattle *
	1	43, 1_4	No ID
Unknown	1	45?, ?	No ID
	2	45, 1_4?	No ID
Heel from shoe	1	46, 1_3	No ID
Unknown	1	107?, 1_2	Bovidae
Heel from Shoe	1	120, 1_3	No ID
	2	120, 1_5	No ID
Unknown	1	123, 1_3	No ID
	2	123, 1_5	No iD
Sole from shoe	1	166, ?	No ID
	2	166, 1_5	Cattle *
Heel from shoe	1	171, 1_3	Cattle **
	2	171, 1_5	Cattle *
Unknown	1	173, 1_3	No ID
	2	173, 1_5	No ID

Table 2. Results of ZooMS identifications of leather from the site Krøyers Plads (KBM 3967). * Theoretically, bison, aurochs, and yak are also possible, but would be exceptional in this context. ** Theoretically, gazelle (as marker A, also known as α2(I) 988–1000, is missing), bison, aurochs, and yak are also possible, but would be exceptional in this context. † Several African bovids are possible but unlikely in this cultural historical context. Internal sample numbers with '?' indicate that students have labelled tubes unclearly, but this is the most probable sample no.

Object	High School	Internal Sample No.	Species ID
Belt	2	5, 1_3	Cattle **
	1	5, 1_4	No ID
Offcut	2	26, 1_3	Cattle **
	1	26, 1_4	No ID
Unknown	2	27, 1_3	Cattle *
	1	27, 1_4	Cattle **
Unknown	2	28, 2_3	Cattle **
Unknown	2	28, 1_3	No ID
	1	28, 1_4	Bovidae/cervidae
Unknown	2	29, 1_3	No ID
	1	29, 1_4	No ID
Unknown	2	30, 2_3?	No ID
	1	30, 2_4	No ID
Belt	2	101, 1_5	Bovidae/cervidae
Belt	2	102, 1_4?	Bovidae/cervidae
Belt	2	103, 1_4	Equidae
Belt	2	104, 1_3	Bovidae/cervidae
	1	104, 1_4	No ID

Table 2. *Cont.*

Object	High School	Internal Sample No.	Species ID
Sole from shoe	1	126, 1_2	No ID
	2	126, 1_3	No ID
Sole from shoe	1	127, 1_3?	No ID
	2	127?, 1_4	No ID
Sole from shoe	1	128?, 2_4	No ID
Heel from shoe	1	129?, 1_2	No ID
	2	129, 1_5	No ID
Sole from shoe	1	130, 1_2	No ID
Belt	2	131, 1_4	Cattle **
Sole from shoe	1	132, 1_3	No ID
	2	132, 1_5	No ID
Unknown	1	134, 1_3	No ID
	2	134, 1_5	Cervidae †
Unknown	1	136, 1_2	No ID

All samples securely identified to species level were from domesticated animals except for one. Sample 134 was identified as the family Cervidae (deer) based on a combination of markers (1180, 1427, 1550, 2883, 3017) [7,38] (Figure 7, panel d). Another sample (103) was particularly surprising (see later discussion) as it was identified as the family Equidae (horses and horse-like animals) based on a combination of markers (1427, 2145, 2820, 2883) [7,38] (Figure 7, panel c). These two samples were verified by an experienced researcher (LØB) and found to be valid (Table A3).

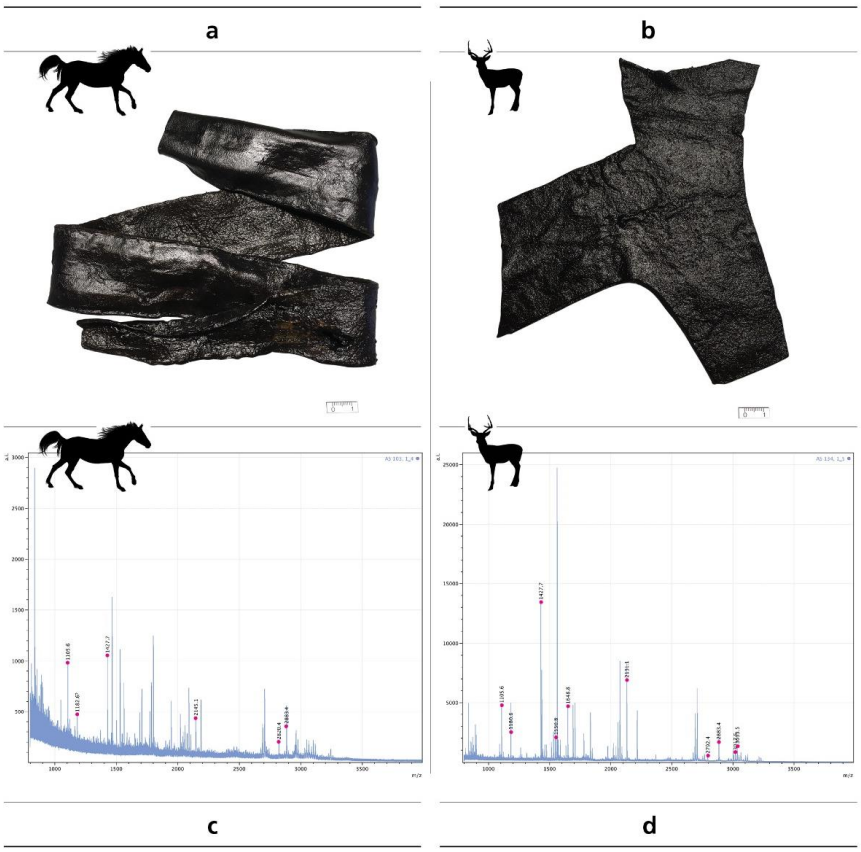


Figure 7. The two leather objects identified as horse (**a**) and deer (**b**) and spectra showing peaks identifying them to these species, (**c**) horse and (**d**) deer. Photos: Jannie Amsgaard Ebsen, Odense City Museums. Graphics: Søren Splidsboel Hansen, Natural History Museum of Denmark.

4. Discussion

The results of our pilot study demonstrate that high school students are able to perform the ZooMS protocol. Several analyses yielded very good spectra, comparable to spectra produced on archaeological leather by experienced professionals (Figure 8). This is encouraging for the project and for future perspectives on involving the public in ZooMS analysis of archaeological material using a Citizen Science approach. Moreover, the two sites incorporated here on first note seem to have environmental conditions which at least partially favour preservation of collagen in leather.

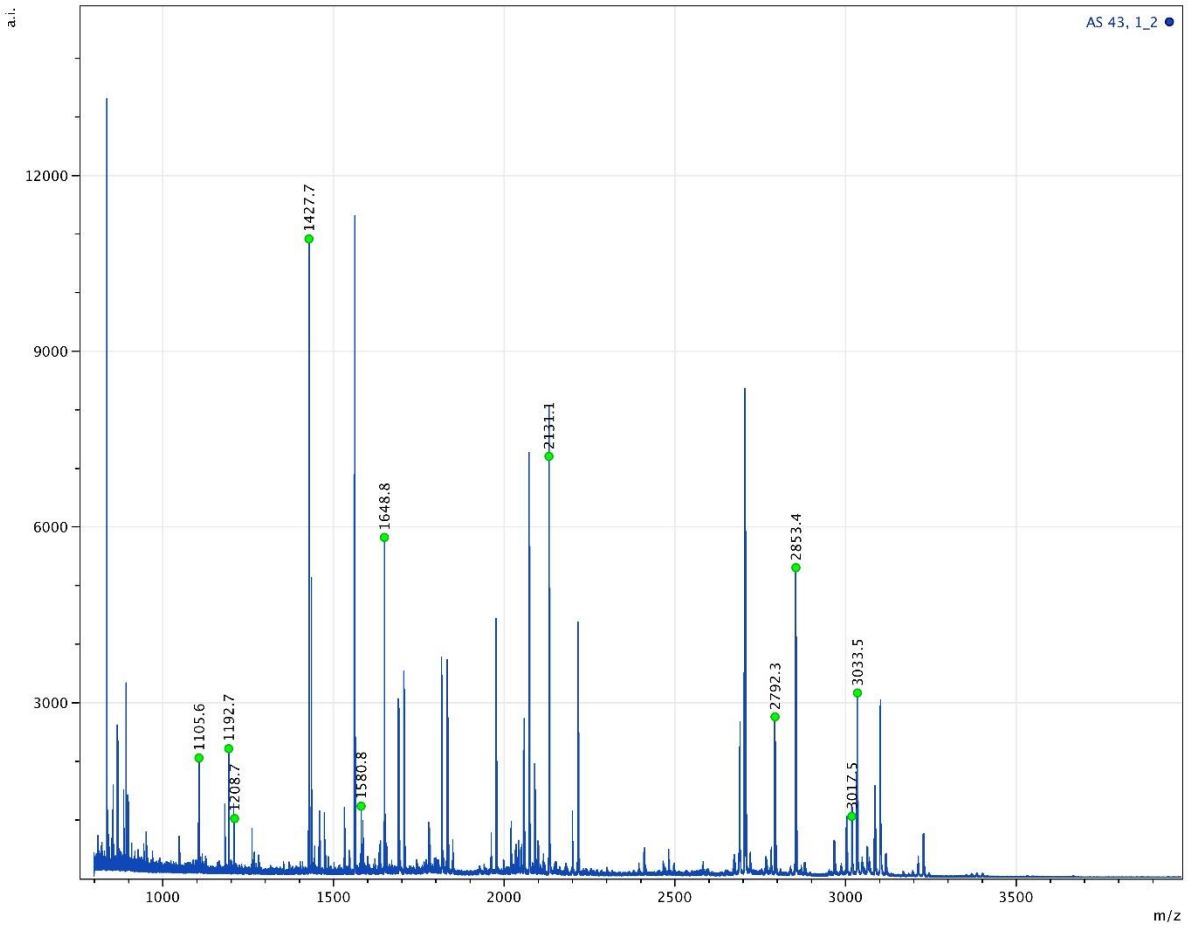


Figure 8. ZooMS spectrum of sample from a leather sole (internal no. 43, 1_2) from the site Gammel Strand produced by a high school student. The presence of all markers and their high intensity allows us to identify the sole as cattle (or calf) skin.

4.1. Intra-Sample Variation

When comparing results of the 20 cases where two subsamples of the same object were analysed, 40% of the cases yielded a different level of identification between subsamples and students: one subsample yielded No ID, whereas the other was identified to a taxonomic level. In 50% of the cases, the two subsamples both failed to provide any identification. In the last 10% of the cases, two subsamples both yielded identifications to a taxonomic level that were not contradictory. The observation that results vary between samples from the same object can be explained by either intra-student or intra-day variation. The demonstrated higher success rate of the second high school compared to the first could point to intra-student variation either caused by adjustments to the teaching program between the two school visits that prepared the second high school more thoroughly, thus preparing them better to complete the protocol successfully. Alternatively, the students in the second class may have simply been more skilled. Another possibility explaining these results could be

the use of a different and better batch of reagents on the day of the second visit, which could have led to a higher success rate. To test this further, a new experiment will be set up, letting different students make a total of four replicates of the same sample with a fifth sample being verified by an experienced professional using the same batch of reagents. In this way, we will obtain a better understanding of subsample variation and reproducibility.

4.2. Screening of Archaeological Environments, Object Groups, and Species Range

The pilot study provided us with new knowledge on the material, its potentials and how to continue in the future. A previous study showed a considerable variation in the success rate of ZooMS on leather between sites [8], highlighting that waterlogged stratigraphy does not necessarily promote collagen preservation. Nevertheless, material from both included sites provided taxonomic identifications (30% at Gammel Strand and ~63% at Krøyers Plads), suggesting that neither the environments at Gammel Strand nor at Krøyers Plads entirely hampered collagen preservation. For the samples that provided No ID in two cases, this result can be explained by the poor preservation of collagen in those particular objects or, alternatively, two failures to the protocol. It is worth mentioning that in eight of the ten cases in which two subsamples provided No ID, very similar markers or lack of markers were observed (Tables A1 and A2). This could suggest that the analyses were in fact valid, and that the failure was in fact due to poor collagen preservation.

With regard to the objects and their identifications, this pilot study also provided novel archaeological findings. All objects that could be identified as either soles or heels, and could also be identified to species, were identified as cattle. This is unsurprising, as it confirms a previous study identifying parts of medieval Danish leather shoes [8]. In this study, all shoe soles were made of cattle skin, and the authors argue that this choice of species was made based on the properties of cattle skin and its excellent fit with a shoe part that was heavily worn and needed to be sturdy. These identifications, therefore, confirm previous knowledge and suggest that this trend also extends to the Renaissance. However, the most surprising results come from an unidentifiable object and from another group of objects: belts.

4.3. The Use of Horsehide in the Renaissance

Six objects identified as belts, but with varying appearances, were analysed here, providing at least two different species (Equus, cattle, and bovid/cervid (including cattle but with many other possibilities)). The identification of Equidae is of particular interest (103, 1_4). Currently, the ZooMS database includes six species within this family: domestic horse (*Equus ferus caballus*), wild horse (*Equus ferus*), zebra (*Equus quagga*), Asiatic and European wild ass (*Equus hemionus* and *Equus hemionus hydruntinus),* and donkey (*Equus asinus*). Unfortunately, these species cannot currently be distinguished using the ZooMS approach, but based on the cultural historical context, it seems fair to exclude zebras. Donkeys and asses have, so far, not been recorded in Renaissance Copenhagen, and thus, horse is the most likely identification for this object.

The hide of a horse has properties equivalent to mature cattle hide and is suitable for objects that need to be durable and strong [39], for example, objects that are exposed to great wear and repeated friction. The original function of the object identified to horsehide is not completely clear, but it was most likely part of a belt or a strap. Objects of this type may be linked to horse equipment, such as harnesses or saddles. We know from excavations in Copenhagen in general that bones from cattle appear far more frequently than bones from horses. The zoological analysis of the animal bones shows a wide variety of species, with an expected majority of domesticated animals such as cattle, sheep, goat, and pig. For example, at the Copenhagen City Hall Square (Rådhuspladsen), 5.092 cattle bones were identified compared to 2.832 bones from sheep or goat and 2.420 bones from pig. In comparison, only 129 bones could be identified as originating from horse [40]. Inhabitants of Copenhagen owning a horse were a minority, and horses were first and foremost used for transporting goods or people. The problem of identifying horses may

thus be methodological; identifying large, nondiagnostic mammal bones as cattle because of the prevalence of this species, as well as the previously mentioned difficulties with examining wet leather in the excavation and sorting phases, may have led to limited knowledge of the use of horsehide.

While meat from cattle was indeed part of the Copenhagen diet, as recipes from the time period mention meat from cattle, these recipes do not mention horses [41]. It is believed and assumed that horse meat was not eaten in medieval times. It is often suggested that this was due to a Christian prohibition against an old pagan custom, though this theory cannot be accounted for [42]. In medieval times, the skinning of horses was described as being carried out by the so-called 'dishonest people' [43], indicating that this was an unclean job. Likewise, horsehide is mentioned as a banned material for shoe leather by the shoemakers' guild in Stockholm [44]. Horsehide may have been regarded as inferior because of the variation in its properties over the body [45], which made it difficult to tan [46], or it was excluded for cultural or religious reasons. Nevertheless, our finding of horse leather shows that some citizens may have acted against these norms and regulations. This is also seen in zooarchaeological material, as bones from horses have been found in refuse layers in areas where butchers worked [47], indicating that they were in fact eaten.

4.4. Evidence of Hunted Game in Copenhagen

The results of the first 52 samples showed that most identifiable samples could be identified as domesticated species, while at least one could be identified as a wild species. Leather from an object of unknown purpose was identified as stemming from deer (134, 1_5). Several African bovids were also possible based on the markers [48], but these were excluded based on the context of the samples. Of the five matching species in the ZooMS database, Pere David's deer (*Elaphurus davidianus*), chital deer (*Axis axis*), fallow deer (*Dama dama*), red deer (*Cervus elaphus*), and elk (*Alces alces*), only the last two are native to Europe after the last Ice Age. While elk had disappeared by the Bronze Age [49], fallow deer were introduced during the medieval period. Another local species, roe deer (*Capreolus capreolus*), can be excluded based on the marker COL1 α2 757–789 (formerly known as marker G) [37]. If local, the skin would therefore have come from either fallow deer or red deer.

Only 75 of the 54,763 identified bones from the Copenhagen City Hall Square (Rådhuspladsen) could be referred to deer [40]. To eat meat from deer species was exclusive and reserved for the nobility, but especially the king, who had the right to hunt [41,50]. Nevertheless, the king and the nobility could donate this exclusive meat to ordinary citizens or sell the surplus if a hunt had resulted in more meat than the elite would be able to consume. Recipes from that time with deer as the main ingredient are known, but we know very little about how hide from deer was used. Given that Copenhagen was the capital of Denmark, and that the king, the court, and members of the nobility lived or stayed there for longer periods of time, it is not entirely surprising to find traces of deer skin in the archaeological material, but this is the first time that it has been proven. Deerskin has properties well suited for clothing, being soft and stretchy [39,51], and it is thus not surprising that its skin would have been utilised if access to it was gained.

4.5. Cultural Historical Value and the Opportunity for Analyses

Needless to say, the opportunity to analyse large volumes of materials and materials that are not immediately found to be of great value is rare. The grant that supported this study has made this possible by not solely focusing on research, but also on teaching. This opportunity has provided sensational pilot results based on just the first 52 samples. Our study thus demonstrates that research focusing on identifiable objects misses out on important historical knowledge. We therefore encourage a new discussion on *value* in cultural heritage.

5. Conclusions

The results of our pilot study were very promising in demonstrating that high school students are able to perform the ZooMS protocol, yielding, in some cases, very impressive results both in terms of spectrum quality and new knowledge generated on animal exploitation. This is encouraging for the project and for the future perspectives involving the public in ZooMS analysis of archaeological material and marks out a completely new direction for Citizen Science in archaeology. The success rate was within hitherto demonstrated success rates of waterlogged, medieval leather, and the two sites incorporated here on first note seem to have environmental conditions which at least partially favour preservation of collagen in leather.

Some variation between subsamples of the same objects was observed. This may be caused by either intra-student variation, changes in the teaching day, or the use of different batches of reagents. This aspect will be the focus of future research.

Our pilot data suggests that the leather used in medieval and Renaissance Copenhagen mainly came from domesticated animals. An exception to this was the finding of deerskin, which adds new knowledge to the history of Copenhagen, as this species has never previously been documented in archaeological leather assemblages of the city. The presence of deerskin can probably be explained by the presence of the king, the court, and the nobility in Copenhagen, who had access to the hunt. Another surprising finding was the exploitation of horsehide, which has hitherto been believed to be unclean or even banned. The finding of horsehide in our material suggests that some citizens acted against such cultural norms. Through this initial pilot study, high school students identified two surprising species, which provided new knowledge about the students' own historical background. Based on their initial results, it seems promising to focus our attention on unidentifiable objects and object groups which are less frequently studied, such as belts, in order to gain new information on medieval and Renaissance Copenhagen. The project calls into question the way we attribute value to cultural heritage objects and encourages a reconsideration of the selection of archaeological objects for preservation, conservation, and analysis.

Based on the first 52 samples, we believe that we have yet only seen the tip of the iceberg of new findings of surprising animal species and the new knowledge these identifications will generate through this four-year project.

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Appendix A

Table A1. Observed markers on ZooMS spectra from the site Gammel Strand (KBM 3828). * Theoretically, bison, aurochs, and yak are also possible, but would be exceptional in this context. ** Theoretically, gazelle (as marker A, also known as α2(I) 988–1000, is missing), bison, aurochs, and yak are also possible, but would be exceptional in this context. Internal sample numbers with '?' indicate that students have labelled tubes unclearly, but this is the most probable sample no.

Internal Sample No.	(P1)	α2(I) 988–1000 (A)	α2(I) 494–508 (B)	α2(I) 512–529 (C)	(P2)	α2(I) 803–826 (D)	E	α1(I) 602–634 (F)	α2(I) 767–799 (G)	ZooMS ID
40, 1_5	-	-	-	-	-	-	-	-	-	No ID
40, 2_3	-	-	-	-	-	-	-	-	-	No ID
40, 2_5	1105.6	-	1427.7	1580.8?	1648.8	2131.1?	-	2853.4?	-	Bovidae/cervidae?
42, 1_4	-	-	-	-	-	-	-	-	-	No ID
43, 1_2	1105.6	1192.7 + 1208.7	1427.7	1580.8	1648.8	2131.1	2792.3	2853.4	3017.5 + 3033.5	Cattle *
43, 1_4	-	-	-	-	-	-	-	2853.4	3033.5?	No ID
45?, ?	1105.6?	-	-	-	-	-	-	-	-	No ID
45, 1_4?	1105.6?	-	-	-	-	-	-	-	-	No ID
46, 1_3	1105.6?	-	1427.7?	-	1648.8?	-	-	-	-	No ID
107?, 1_2	-	-	-	-	1648.8?	2131.1	2792.3	2853.4?	3017.5? + 3033.5?	Bovidae
120, 1_3	-	-	-	-	-	-	-	-	-	No ID
120, 1_5	1105.6	-	-	-	-	-	-	-	-	No ID
123, 1_3	-	-	-	-	-	-	-	-	-	No ID
123, 1_5	1105.6	-	-	-	-	-	-	-	-	No ID
166, ?	-	-	-	-	-	-	-	-	-	No ID
166, 1_5	1105.6	-	1427.7	1580.8	1648.8	2131.1	2792.3	2853.4	3017.5	Cattle *
171, 1_3	1105.6	-	1427.7?	-	1648.8?	-	-	2853.4	3017.5? + 3033.5	Cattle **
171, 1_5	1105.6	1192.7 + 1208.7	1427.7	1580.8	1648.8	2131.1	2792.3	2853.4	3017.5 + 3033.5	Cattle *
173, 1_3	-	-	-	-	-	-	-	-	-	No ID
173, 1_5	1105.6	-	1427.7	-	1648.8	-	-	-	-	No ID

Table A2. Observed markers on ZooMS spectra from the site Krøyers Plads (KBM 3967). * Theoretically, bison, aurochs, and yak are also possible, but would be exceptional in this context. ** Theoretically, gazelle (as marker A, also known as α2(I) 988–1000, is missing), bison, aurochs, and yak are also possible, but would be exceptional in this context. † Several African bovids are possible but unlikely in this cultural historical context. Internal sample numbers with '?' indicate that students have labelled tubes unclearly, but this is the most probable sample no.

Internal Sample No.	(P1)	α2(I) 988–1000 (A)	α2(I) 494–508 (B)	α2(I) 512–529 (C)	(P2)	α2(I) 803–826 (D)	E	α1(I) 602–634 (F)	α2(I) 767–799 (G)	ZooMS ID
5, 1_3	1105.6?	1192.7? + 1208.7?	1427.7	-	1648.8	2131.1	2792.3?	2853.4	3017.5 + 3033.5	Cattle **
5, 1_4	-	-	-	-	-	-	-	-	-	No ID
26, 1_3	1105.6?	-	1427.7	1580.8?	1648.8	2131.1	2792.3	2853.4	3017.5 + 3033.5	Cattle **
26, 1_4	-	-	-	-	-	-	-	-	-	No ID
27, 1_3	1105.6	1192.7? + 1208.7	1427.7	-	1648.8	2131.1	-	2853.4	3017.5? + 3033.5	Cattle *
27, 1_4	1105.6?	1208.7?	1427.7?	-	1648.8?	2131.1?	-	2853.4	3017.5? + 3033.5	Cattle **

Table A2. *Cont.*

Internal Sample No.	(P1)	α2(I) 988–1000 (A)	α2(I) 494–508 (B)	α2(I) 512–529 (C)	(P2)	α2(I) 803–826 (D)	E	α1(I) 602–634 (F)	α2(I) 767–799 (G)	ZooMS ID
28, 1_3	-	-	-	-	-	-	-	2853.4	-	No ID
28, 1_4	1105.6	1192.7? + 1208.7?	1427.7	1580.8?	1648.8?	2131.1?	-	2853.4?	3017.5? + 3033.5	Bovidae/cervidae
28, 2_3	1105.6	-	1427.7?	-	1648.8	-	-	2853.4	3033.5	Cattle **
29, 1_3	1105.6?	-	1427.7?	-	1648.8?	-	-	-	-	No ID
29, 1_4	1105.6?	-	1427.7	-	1648.8?	-	-	-	-	No ID
30, 2_3?	-	-	-	-	-	-	-	-	-	No ID
30, 2_4	-	-	-	-	-	-	-	-	-	No ID
40, 2_3	-	-	-	-	-	-	-	-	-	No ID
42, 1_4	-	-	-	-	-	-	-	-	-	No ID
101, 1_5	1105.6?	-	1427.7	-	1648.8	2131.1	-	2853.4?	3017.5? + 3033.5	Bovidae/cervidae
102, 1_4?	1105.6?	1192.7? + 1208.7?	1427.7	-	1648.8?	2131.1	-	-	3033.5	Bovidae/cervidae
103, 1_4	1105.6	1182.6?	1427.7	-	-	2145.1	2820.4	2883.4	-	Equidae
104, 1_3	-	-	1427.7	-	1648.8?	2131.1	-	2853.4?	3017.5? + 3033.5	Bovidae/cervidae
104, 1_4	-	-	-	-	-	2131.1?	-	2853.4?	3017.5? + 3033.5	No ID
126, 1_2	1105.6	-	-	-	-	-	-	-	-	No ID
126, 1_3	1105.6	-	-	-	-	-	-	-	-	No ID
127, 1_3?	-	-	-	-	-	-	-	2853.4?	3017.5? + 3033.5	No ID
127? 1_4	-	-	-	-	-	-	-	2853.4?	3017.5?	No ID
128?, 2_4	-	-	-	-	-	-	-	-	-	No ID
129?, 1_2	-	-	-	-	-	-	-	-	-	No ID
129, 1_5	-	-	1427.7?	-	-	-	2792.3?	2853.4?	-	No ID
130, 1_2	1105.6	-	-	-	-	-	-	-	-	No ID
131, 1_4	1105.6	-	1427.7	-	1648.8	2131.1	2792.3	2853.4	3017.5 + 3033.5	Cattle **
132, 1_3	-	-	-	-	-	-	-	-	-	No ID
132, 1_5	-	-	-	-	-	-	-	-	-	No ID
134, 1_3	-	-	-	-	-	-	-	-	-	No ID
134, 1_5	1105.6	1180.6	1427.7	1550.8	1648.8	2131.1	2792.3	2883.4	3017.5 + 3033.5	Cervidae †
136, 1_2	-	-	-	-	-	-	-	-	-	No ID

Table A3. Verifications of two ZooMS identifications of leather produced by students on objects 134 and 103. † Several African bovids are possible but unlikely in this cultural historical context.

Internal Sample No.	(P1)	α2(I) 988–1000 (A)	α2(I) 494–508 (B)	α2(I) 512–529 (C)	(P2)	α2(I) 803–826 (D)	E	α1(I) 602–634 (F)	α2(I) 767–799 (G)	ZooMS ID
134_LØB	1105.6	1180.6	1427.7	1550.8	1648.8	2131.1	-	2883.4	3017.5? + 3033.5	Cervidae †
103_LØB	1105.6	1182.6	1427.7	-	-	-	2820.4?	2883.4	-	Equidae

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