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RESEARCH ARTICLE

Comparison of occlusal dental wear and degenerative alterations of the temporomandibular joint in two medieval populations from Central Europe

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Abstract

Osteoarthritis (OA) is a degenerative joint disease commonly identified in archaeological human remains. This condition primarily affects stress-bearing joints, which include the temporomandibular joints (TMJs). Comparing dental status and degenerative alterations of the TMJs of individuals is crucial for understanding the role of the former in increasing predisposition to temporomandibular OA. The combination of visual and radiologic observations allows for a more in-depth assessment of TMJ-OA in archaeological specimens. A comparative study between tooth wear and the extent of degenerative signs on mandibular condylar surfaces was conducted on individuals from two medieval cemeteries in central Europe (Früebergstrasse in Baar and Dalheim). OA, tooth wear, and AMTL were evaluated in 41 individuals comprising both adult specimens as well as those of a more advanced age. Condylar OA was diagnosed in 14 individuals (Baar, $n = 7$; Dalheim, $n = 7$). No specific sex predisposition for OA in TMJs was found in the study's sample. Tooth wear was more severe in individuals with condyles affected by OA than in individuals whose condyles showed no degenerative signs. Although dental occlusion could not be evaluated, tooth wear values seem to point to diverse mastication patterns when there is unilateral or bilateral manifestation of mandibular OA in the two medieval populations under study.

KEYWORDS
computed tomography (CT), Middle Ages, osteoarthritis, temporomandibular joint (TMJ), tooth wear, X-rays

1 | INTRODUCTION

The documentation of degenerative diseases in archaeological human remains can provide valuable insight into the lifestyles of past populations. Existing research in bioanthropology has focused predominantly on the analysis of joints within the postcranial skeleton, as degenerative signs here can help reconstruct the overall impact of loading forces applied to the limbs, thus allowing the general workload over the lifetime of an individual to be assessed and, consequently, the associated social status to be inferred.

The temporomandibular joint (TMJ), a synovial joint that articulates the mandible with the temporal bone, has not frequently been

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studied in ancient human remains, possibly due to preservation issues. Data on this particular joint cannot be used to assess the overall bodily workloads of individuals; however, the TMJ can be affected by a number of disorders, collectively called temporomandibular disorders (TMDs) (Poveda Roda et al., 2007). Bell (1989) proposed using TMD as a universal term to define a subtype of musculoskeletal pain conditions affecting the masticatory system. Since then, several classifications have been proposed and published (Stegenga et al., 1989; Truelove et al., 1992). The TMJ is an anatomically and biomechanically complex structure whose growth and development affect that of the mandible. It is composed of the glenoid or mandibular fossa, the articular eminence of the temporal bone, and the condyloid process of the mandible. Interposed between the condyle and the temporal bone is the articular disk, which consists of dense collagenous connective tissue. The TMJ is enclosed in a capsule that is attached to the mandibular fossa and to the neck of the mandible (Alomar et al., 2007; Wheeler, 1974). The TMJ is a unique joint in the human body because it is involved in the performance of multiple functions such as mastication, speech, swallowing, and the manifestation of certain facial expressions. For applications in paleopathology, especially when soft tissues are not present, a relatively simple and schematic classification is to be followed. TMDs are generally divided into three groups: muscle disorders (myalgia and myofascial pain), internal joint alteration (disc displacement—the main cause of the development of OA—capsulitis/synovitis, and disc perforation), and degenerative disorders (i.e., arthritides) (Manfredini et al., 2007; Truelove et al., 1992).

Osteoarthritis (OA) is a degenerative joint condition that affects millions of people worldwide. It is the most common type of arthritis and is caused by the breakdown of articular cartilage that covers the ends of bones in the joints (Abramoff & Caldera, 2020; Buchanan et al., 2023). Symptoms of OA can include pain, stiffness, swelling, and difficulty in moving the affected joint. The etiology of TMDs, and by extension OA of TMJs, is complex and multifactorial (Okeson, 2020; Wright, 2009). Individual adaptability, among other factors, can determine the onset of the symptoms, as well as the extent to which these symptoms can develop into the chronic conditions evident in ancient and historical specimens. One of the most accepted initiating factors of OA is an excessive mechanical loading of the joints. For OA of the TMJ, at times, this can be related to changes in dental occlusion (Okeson, 2020). Antemortem tooth loss (AMTL) is defined as the shedding of one or multiple teeth in living individuals. When a significant number of posterior teeth are lost, the anterior teeth become the functional stops for mandibular closure. The vertical dimension decreases, which has been defined as posterior bite collapse and associated with functional disturbances (Okeson, 2020). The result is an uneven distribution of the forces involved in the masticatory activity. For example, when occlusal contacts are present on only the right side of the mouth, the elevator muscles of the mandible (i.e., masseter, pterygoid muscles, temporalis) tend to pivot the mandible using the tooth contacts as a fulcrum. This results in an increase in the joint force applied to the left TMJ and a decrease in the force to the right TMJ.

Changes in biomechanical stress may be also due to the types of food ingested and the associated loading forces received from chewing (Komino & Shiga, 2017). The TMJ is in fact responsible for the lower jaw movements during mastication: elevation (adduction), depression (abduction), anteroposterior translation (protrusion and retraction of the mandible), and mediolateral translation (side-to-side movements of the mandible) (Basit et al., 2023). The mastication of raw foods (such as roots, tubers, and raw meat) requires strong, repetitive bite forces that throughout time can damage the bone microstructure of TMJs (Piancino et al., 2008; Ratnasari et al., 2011); however, chewing hard foods can also stimulate bone growth (Inoue et al., 2019), counteracting the effects of this. Therefore, any remaining damage likely results from the combination of chewing hard foods and age. The extent of dental wear experienced is also dependent on the types of foods ingested, as well as being an indicator of food preparation practices (Mahajan, 2019). Additionally, the association between tooth wear and TMDs has been extensively documented (Fathima et al., 2020; Mickeviciute et al., 2017), although the exact underlying mechanisms are not yet fully explained.

The prevalence of TMJ-OA in ancient skeletal remains ranges between 2.4% and 38.5%, as reported by Rando et al. (2012). Although studies investigating TMJs in preindustrial populations focused mostly on Aboriginal populations (Richards, 1990; Webb, 1995), research on prehistoric hunter–gatherer populations has also been conducted (Stone et al., 2020; Suby & Giberto, 2019; Tanaka et al., 2004; Visser, 1994). Because the hardness and toughness of food can impact the development of TMJ-OA (Chen et al., 2013; Komino & Shiga, 2017; Liu et al., 2014; Peyron et al., 1997; Tran et al., 2023), it is important to identify the types of food ingested by the populations under study. In the Middle Ages, the amount of raw foods eaten was certainly lower compared with ancient hunter–gatherers, so this might not have had such a strong impact on the development of TMJ-OA as it had in earlier populations. However, most of the food consumed was still both harder and tougher than the processed food items available in modern societies (Kahn & Ehrlich, 2018).

It has been shown that food preparation techniques can significantly decrease both the hardness and toughness of raw foods (Zink et al., 2014). A number of food preparation techniques were used in the Middle Ages, from cereal milling and cooking/boiling to cheese production (Adamson, 2004). In particular, milling had an effect on tooth wear, as lithic particles from the mortars used in the process were transferred to the flours and subsequently entrapped in the breads. In addition, paramasticatory activities can also have an impact on TMJ-OA (Molnar, 2008). For example, activities such as processing of fibrous and collagenous material in the past are thought to contribute to the development of TMJ-OA (Stone et al., 2020). In fact, such activities are generally prolonged in duration and involve the entire masticatory apparatus; thus, the stress they apply to the TMJs can be very significant.

Medieval collections can be particularly rich in terms of skeletal remains, because they are usually retrieved from cemeteries and thus allow the acquisition of data on a significant part of a population. This, in turn, allows for better epidemiological reconstructions of certain diseases in the past (de Souza et al., 2003). This study aims to investigate the relationships between degenerative signs on TMJs, tooth wear, and AMTL in two medieval populations. Additionally, an evaluation of the role of differential imaging techniques (X-rays and computed tomography [CT]) in documenting degenerative signs on archaeological mandibular condylar eminences will be provided.

1.1 | Differential imaging techniques in the study of TMJ changes

Although TMJ-OA in archaeological specimens can be identified by visual observation (e.g., Rando & Waldron, 2012), radiological finds provide additional useful information. On clinical radiographs, OA of a TMJ can be seen as a narrowing of the joint space, erosion of the joint surfaces, and sclerosis of the bones around the joint (Boeddinghaus & Whyte, 2013). The eburnation parameter, described in Rando and Waldron, is the visual manifestation of the internal generalized sclerosis observed through imaging (Rando & Waldron, 2012). This should be considered when the two methods (i.e., visual and radiology-based diagnosis) are used to inspect TMJs.

The narrowing of the joint space on archaeological specimens can only be seen in mummified individuals that still bear all components of the TMJs in situ. Erosion is mainly observed on joints affected by inflammatory diseases (i.e., rheumatoid arthritis) (Panagopoulos & Lambrou, 2018), but it can also be observed on joints affected by OA. Additionally, there may be cysts or bony outgrowths (i.e., osteophytes) around the joint affected by OA. Osteophytes can cause changes to the shape of the joint (Ahmad et al., 2009; Kalladka et al., 2014; Song et al., 2020) that can be macroscopically visible. Although gross articular changes are visible to the naked eye (Rando & Waldron, 2012), radiology can reveal features that are not visually perceptible. Internal bone changes, cysts, and incipient osteophytes are all features that can be observed with various imaging techniques. Planar radiography is the simplest and least expensive imaging technique available for examining ancient human remains (Seiler et al., 2018; Wanek et al., 2011). A major advantage of planar radiographs is the existence of portable machines that can be used in the field when specimens cannot be transported to the laboratory (Seiler et al., 2018).

During a CT scan, the X-ray tube rotates around the object, detecting data from different angles, thus allowing for the reconstruction of a 3D dataset instead of just radiographic projection images. The main advantage of CT scans over 2D plain radiographs is that any of the observed anomalies can be precisely located within the specimen being examined. Another advantage of CT scans that was not utilized in this study is the ability to segment the data and create 3D models or 3D prints.

2 | MATERIALS AND METHODS

2.1 | The studied human remains

Two medieval anthropological collections were included in this study, which were retrieved from the excavation of two cemeteries in rural areas. No ethical review board approval was necessary for this study. Nevertheless, authorization to study the material was granted by the competent institutions (Institute of Evolutionary Medicine of the University of Zurich, IEM-UZH and *Museum für Urgeschichte[n]* of Zug). Additionally, this research project is strictly committed to the code of ethics of the IEM-UZH, which demands a careful judgment of the appropriateness of any research involving ancient human remains (IEM-UZH, 2014).

The Dalheim medieval cemetery (Figure 1), near the city of Lichtenau (North-Rhine Westphalia, Germany), was excavated in the 1990s (Pieper, 2003). The cemetery was in use from ca. 950 to1200 CE, and the remains of 151 individuals were retrieved from 110 burials (32 females, 44 males, and 75 indeterminate individuals) (Butz, 1991; Hofmann et al., 2008). The osteological collection is presently curated by the Institute of Evolutionary Medicine (University of Zurich, Switzerland). The cemetery at Früebergstrasse in Baar (Zug, Switzerland) dates back to the seventh-century CE and was excavated in 2000 by the Archaeology Department of Canton Zug (Figure 1). The excavation yielded 208 burials (101 males, 89 females, and 18 indeterminate individuals) (Müller, 2010).

FIGURE 1 Geographical location of the two archaeological sites under study.

A total of 41 individuals from both sites (Baar, 16; Dalheim, 25) were included in this study (Table 1). The selection criteria were (1) good preservation of mandibular condylar eminences (i.e., no postdepositional changes) and (2) adequate preservation of teeth (i.e., at least 10 alveolar loci). The glenoid fossae were preserved in only five individuals within one of the studied collections, making it

TABLE 1 List of the individuals included in this study and related information: archaeological site, burial ID, sex, age category, age at death, AMTL (number of mandibular teeth lost antemortem), and present teeth. Demographic information was previously reported by Butz (1991) and Lohrke et al. (2010).

No.	Site	Burial ID	Sex	Age category	Age	Teeth present	AMTL	Socioeconomic status
1	Dalheim	G48	Female	Senile	> 50	9	6	NA
2	Dalheim	B79	Female	Senile	> 50	12	2	NA
3	Dalheim	B52	Female	Adult	40–50	15	0	NA
4	Dalheim	B13	Indeterminate	Adult	18–20	14	0	NA
5	Dalheim	B16	Male	Adult	25–35	13	0	NA
6	Dalheim	B89	Female	Adult	40–50	9	4	NA
7	Dalheim	B59	Male	Senile	> 50	10	0	NA
8	Dalheim	B85 a2	Female	Senile	> 50	8	1	NA
9	Dalheim	G6	Female	Adult	40–50	9	3	NA
10	Dalheim	B36	Male	Adult	25–35	12	0	NA
11	Dalheim	296	Male	Adult	30–40	7	3	NA
12	Dalheim	G11	Male	Adult	20–30	16	0	NA
13	Dalheim	B50	Male	Adult	18–20	15	0	NA
14	Dalheim	314	Male	Adult	25–35	13	0	NA
15	Dalheim	B41	Male	Adult	30–40	12	0	NA
16	Dalheim	B27 a	Male	Adult	25–35	5	0	NA
17	Dalheim	B10	Female	Adult	40–50	6	2	NA
18	Dalheim	B60	Indeterminate	Senile	> 50	2	14	NA
19	Dalheim	B61	Male	Adult	40–50	8	3	NA
20	Dalheim	B15	Male	Adult	40–50	3	2	NA
21	Dalheim	B39	Male	Adult	40–50	9	2	NA
22	Dalheim	B56 a	Male	Senile	> 50	3	3	NA
23	Dalheim	G16	Female	Adult	30–40	11	0	NA
24	Dalheim	B94	Male	Senile	> 50	1	9	NA
25	Dalheim	B78	Female	Senile	> 50	7	4	NA
26	Baar	Z16	Male	Senile	> 50	9	5	Standard
27	Baar	Z17	Female	Adult	35–40	12	0	Standard
28	Baar	Z19	Male	Senile	> 50	11	2	Standard
29	Baar	Z25	Female	Adult	39–44	13	0	Standard
30	Baar	Z37	Male	Senile	> 50	6	3	Standard
31	Baar	Z47	Male	Senile	> 50	9	6	Standard
32	Baar	Z61	Male	Adult	45–50	10	1	Standard
33	Baar	Z88	Female	Adult	34–43	12	2	Wealthy
34	Baar	Z98	Female	Adult	20–29	16	0	Standard
35	Baar	Z124	Male	Senile	> 50	8	0	Standard
36	Baar	Z130	Male	Senile	> 50	11	2	Standard
37	Baar	Z134	Female	Adult	34–40	9	0	Standard
38	Baar	Z147	Male	Adult	27–32	15	0	Standard
39	Baar	Z166	Female	Adult	18–21	6	0	Standard
40	Baar	Z189	Female	Adult	42–47	10	5	Wealthy
41	Baar	Z190	Male	Adult	28–35	13	1	Wealthy

statistically unsuitable for analysis (Figure 2). Both anthropological collections were studied in the past, and individuals were sexed and aged following standard methods in the field, including the examination of morphological characteristics in the pelvis, skull, and long bones (Butz, 1991; Lohrke et al., 2010).

The individuals who complied with the selection criteria comprise 27 younger and middle-aged adults (Baar, 10; Dalheim, 17) and 14 older adults (Baar, 6; Dalheim, 8) (Table 1). Individuals aged above 50 were considered to be senile or older adults. Juvenile individuals were not included, as they are unlikely to present osteoarthritic changes. In particular, 69 condyles (Baar, 24; Dalheim, 45) were available for study (Tables S1–S2). Since the upper dentition was severely damaged or missing, only mandibular teeth (Data S1) were included ($n = 396$). Information about the socioeconomic status of the individuals is only available for the site at Baar (Table 1). Social status was determined based on the grave goods associated with each individual in previous studies (Müller, 2010). Early medieval graves reveal gender-specific offerings, shedding light on clothing, equipment, and burial practices. Baar-Früebergstrasse cemetery's female graves include necklaces, belts, and chatelaines, along with earrings. Male

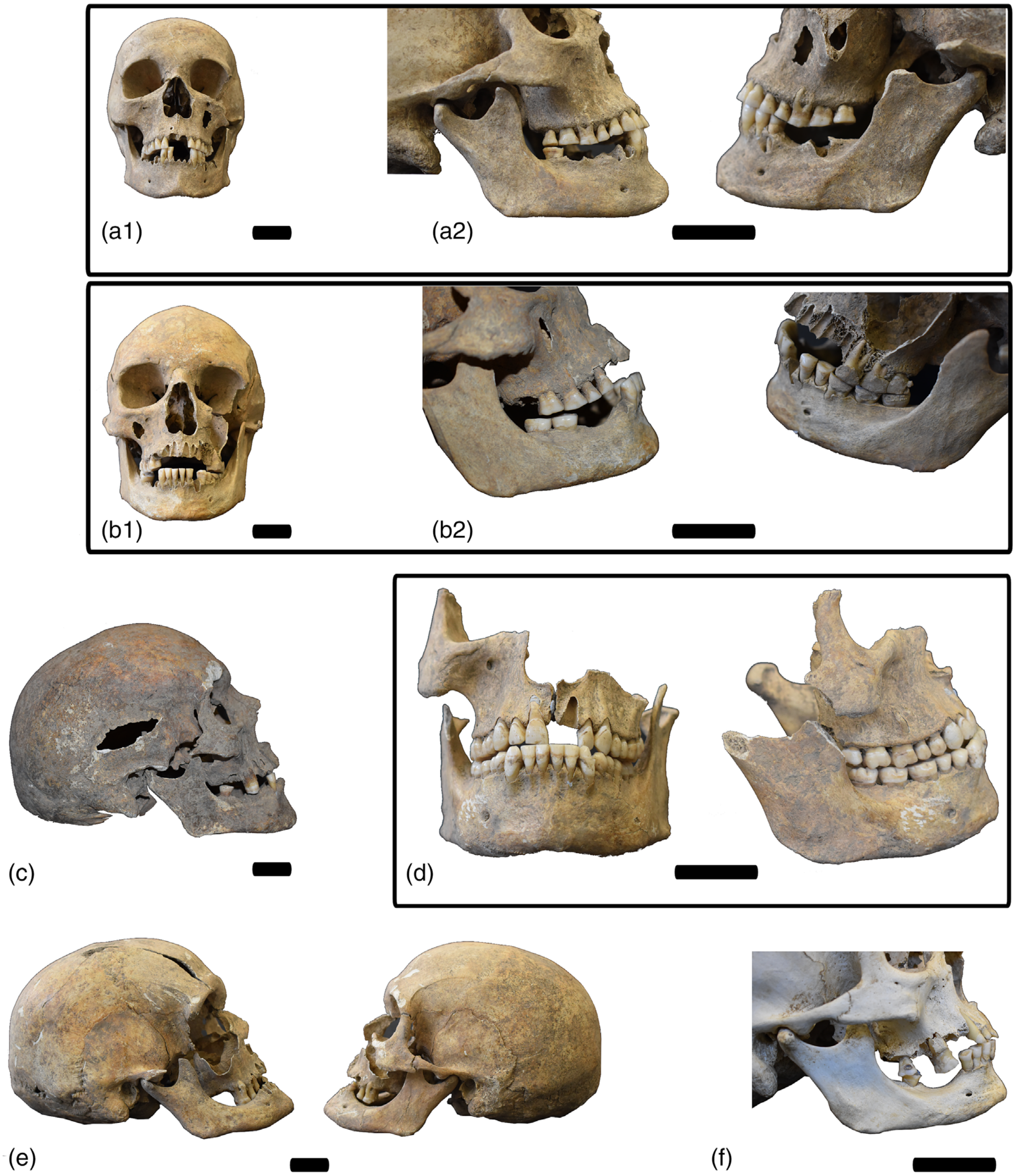

FIGURE 2 *Cranial elements of the Dalheim collection.* (a1–a2) B10: frontal and lateral views; (b1–b2) B79: frontal and lateral views; (c) B61a: right lateral view; (d) G11: frontal and left lateral views; (e) B94: lateral views; and (f) G48: right lateral view. Scale bars 3 cm. [Colour figure can be viewed at wileyonlinelibrary.com]

graves feature tripartite belts, tool-containing pouches, and weapons such as saxes. Arrows and quivers are common, and higher social status is suggested by rare items such as multipart belt fittings, shields, lances, spathas, horse harnesses, and spurs (Müller, 2010). At Dalheim, the buried individuals were most likely of lower class, although the presence of a small community of nuns from the 11th century onward has been documented (Pieper, 2003).

2.2 | Radiological inspection

The human remains were documented through photography and radiology (Figure 3c). A clinical CT scanner (SOMATOM Definition Flash, Siemens Healthineers, Erlangen, Germany) located at the Institute of Forensic Medicine of the University of Zurich (UZH) was used to image the mandibles of the Dalheim individuals (Figure 3a). The CT scanning settings were a tube voltage of 120 kV and a tube current ranging from 200 to 300 mAs. The field of view was adjusted to mandible anatomy with a reconstruction matrix of 512 × 512. The Ur68 sharp kernel was used, and the slice thickness was set to 0.4 mm. CT data were visualized with Horos software (version 3.3.6) using multiplanar reconstructions for axial, sagittal, and coronal alignments, as well as volume renderings to create projections of the three-dimensional datasets.

A portable dental X-ray unit (Kavo Nomad-Pro) with fixed voltage of 60 kV and exposure time of 0.12 s and a dental X-ray detector (RVG6500 DR-Sensor G2; 27 × 36 mm) with a spatial resolution of 1440 × 1920 pixels and 20 lp/mm were used to image all 69 condyles (Figure 3b). The imaging sessions were conducted at laboratories of the IEM-UZH, for the Dalheim specimens and at the Museum of Prehistory (*Museum für Urgeschichte(n)*) of Zug for the Baar specimens.

2.3 | Diagnostic criteria for OA of TMJ on skeletal remains

Diagnosis was made based on both visual and radiological inspections. Signs for eburnation, porosity, and visible osteophytes were firstly documented following Rando and Waldron (2012) (Data S2). The condylar coronal morphology was also recorded for all condyles analyzed (Derwich et al., 2020; Rando & Waldron, 2012; Yale et al., 1963). The condyles were classified as having minimum, moderate, and florid expression of OA (Rando & Waldron, 2012). Subsequently, following Ahmad et al. (2009), a grading system was used when inspecting radiological finds (Table 2). The diagnosis of OA was proposed when at least two of the parameters associated with grade 3 (i.e., osteophyte formation, subcortical cysts, generalized sclerosis) were observed

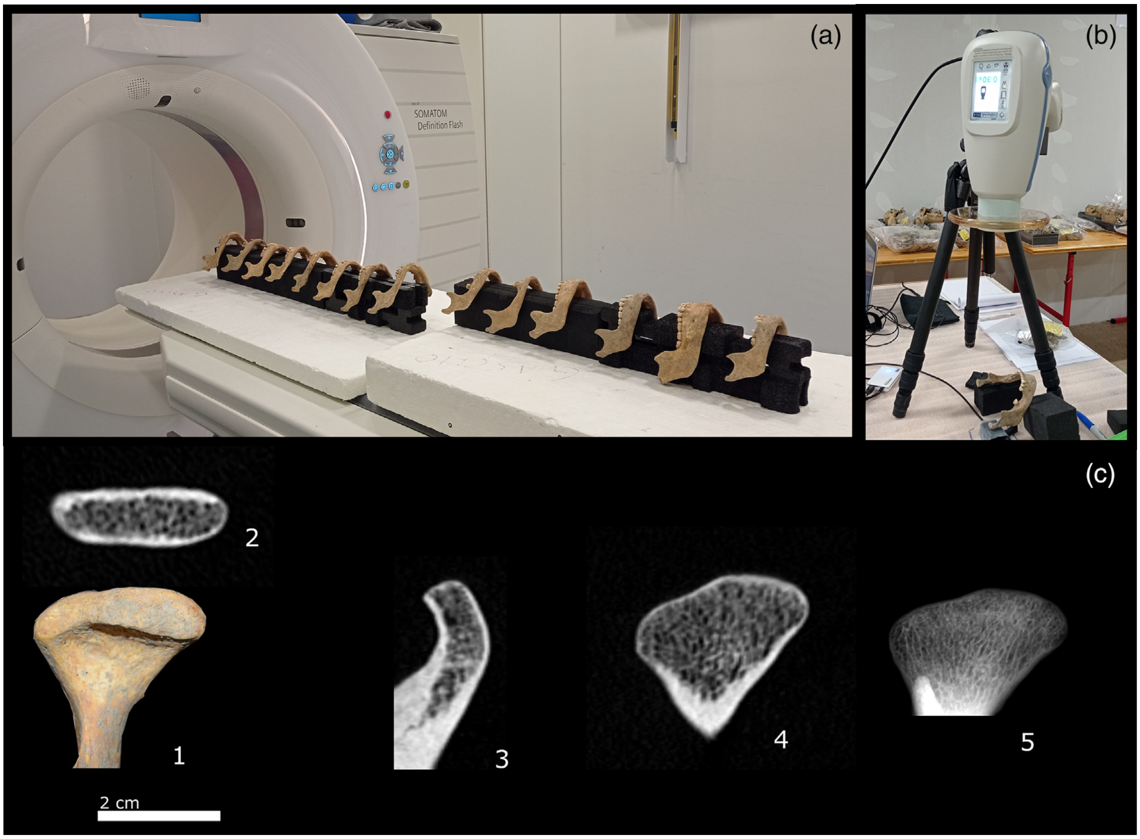

FIGURE 3 (a) A selection of the mandibles studied during CT scanning. (b) the portable X-ray dental machine (Kavo nomad-pro) used to image the mandibular condyles. (c) an example of the data acquired on a right condyle (1, individual B36). CT reconstructions (2 = axial plane, 3 = sagittal plane, 4 = coronal plane) of the condyle analyzed and a radiograph of its coronal plane (5). [Colour figure can be viewed at wileyonlinelibrary.com]

(Ahmad et al., 2009; Derwich et al., 2020; dos Anjos Pontual et al., 2012). When joint modifications other than these (i.e., sclerosis, erosion, articular flattening) were present, the condyle was categorized as indeterminate for OA. When no modifications were present on condyles, they were considered to be nonosteoarthritic (i.e., unaffected).

Tooth wear was scored for all individuals (Pedergnana et al., 2024) following a modified system from Smith and Knight (1984) (Table 3). Antemortem tooth loss (AMTL) was also recorded for all individuals.

Statistical analysis was applied using the free R software (version 4.0.5) (R Core Team, n.d.) to compare tooth wear in individuals diagnosed with OA and individuals with no osteoarthritic joints. The Mann–Whitney *U* test ($p < 0.05$) was used for comparing tooth wear values. Statistical significance of frequencies was calculated using a *G* test ($p < 0.05$) or maximum likelihood chi-squared, which is ideal for small sample size (< 50 samples) (Klaus & Tam, 2010). Raw data are available as Supporting Information and Data S1-S2, and all CT scans and radiographs of the condyles can be found at 10.5281/zenodo.7789000

3 | RESULTS

3.1 | OA of TMJs

OA was diagnosed in 14 individuals (34.1%) (Table 4). Specifically, 18 out of the 41 condyles analyzed were found bearing OA signs.

TABLE 2 Diagnostic criteria for OA in TMJs used in this study, following Ahmad et al. (2009).

Radiological criteria	
Score	**Description**
1	*No change*: No OA
2	*Indeterminate for OA*: Subcortical sclerosis, articular flattening, erosion
3	*OA*: Joint deformation, osteophyte formation, subcortical cysts, generalized sclerosis

TABLE 3 The tooth wear score system used in this study. Comparison with the scores found in Smith (1984) is provided.

Tooth wear score	Description	Equivalent scores found in the Smith (1984)
0	*No enamel loss*	1
1	*Minimal enamel loss*	2
2	*Loss of enamel exposing dentine (less than one third of surface)*	3/4
3	*Loss of enamel exposing dentine (more than one third of surface)*	5/6
4	*Complete loss of enamel*	7/8

The Dalheim specimens affected by OA were four adults (3 males, 1 female) and three older adults (1 male, 1 female, 1 indeterminate) (Figure 4a). Three individuals had both condyles affected, whereas on four specimens, only one joint showed degenerative signs. Regarding Baar, OA was diagnosed in five adults (1 male, 4 females) and two senile (2 males) individuals (Table 4; Figure 4a,c). Only one case of bilateral condylar degeneration was documented in this subsample. In all other cases, only one condyle per individual showed clear signs of OA. Visual inspection was consistent with the diagnoses made based on imaging data, with only two exceptions (Table S3).

Exemplary cases of unilateral and bilateral condylar OA are described below. The adult male individual B15 showed a left condyle affected by OA, which is linked to a compromised molar support (Figure 5a). On both radiographs and CT scans, signs of OA are visible, mainly generalized sclerosis, osteophyte formation, and subchondral cysts (Figure 5c–f). The older adult male B56a showed osseous degenerations on the right condyloid extremity (Figure 5g). Articular flattening, sclerosis, and osteophyte formation can be observed on both radiographs and CT scans (Figure 5i–l). In other cases, evidence of bilateral OA of the TMJ's condyles was observed (Figure 6), such as in the female adult individual G6 (Figure 6a). On the right condylar eminence, articular flattening, generalized sclerosis, osteophyte formation, and a subchondral cyst are visible (Figure 6b–d), whereas on the left condyle, there is evidence of a sclerotic spot and an osteophyte (Figure 6e–g). The older adult female individual B85 had both mandibular condyles affected by OA. The right condyle displays evidence of flattening, generalized sclerosis, incipient marginal osteophytes, and a subchondral cyst (Figure 6i–k). The left condyle showed evidence of articular flattening, generalized sclerosis, and minor osteophytes (Figure 6l–n).

OA frequencies do not show significantly different values both in sex ($G = 0.43435$, $df = 2$, $p = 0.8$) and age categories ($G = 0.023165$, $df = 1$, $p = 0.88$) (Table S4).

3.2 | Tooth wear

Tooth wear values from individuals with mandibular condylar OA and from unaffected individuals are significantly different ($W = 14{,}417$, p value < 0.05) (Table S4). Similar values for tooth wear were observed in individuals with unaffected condyles and those with damage only on the right condyle (mean values: unaffected group = 1.77; right condyle affected = 1.75) (Tables 5 and S4; Figure 7).

When OA affects only the left condyle, severely high values for tooth wear of the right dentition (mean = 3.14) (Table 5; Figure 7a) were observed. However, relatively high values of the left dentition's wear are also observed in the group showing bilateral condylar OA (Figure 7b). When the sample size is enlarged comprising individuals with compromised condyles of the two collections under study, tooth wear has been found to increase with age (Pedergnana et al., 2024).

TABLE 4 Individuals that were diagnosed with unilateral or bilateral OA of the mandibular condyles.

No.	Burial	Site	Sex	Age	Right condyle—OA score	Left condyle—OA score
1	B16	Dalheim	Male	Adult	3	2
2	B85	Dalheim	Female	Senile	3	3
3	G6	Dalheim	Female	Adult	3	3
4	B60	Dalheim	Indet.	Senile	3	3
5	B15	Dalheim	Male	Adult	1	3
6	B39	Dalheim	Male	Adult	3	2
7	B56	Dalheim	Male	Senile	3	2
8	Z61	Baar	Male	Adult	1	3
9	Z88	Baar	Female	Adult	3	n/a
10	Z98	Baar	Female	Adult	3	2
11	Z124	Baar	Male	Senile	3	3
12	Z130	Baar	Male	Senile	n/a	3
13	Z166	Baar	Female	Adult	3	2
14	Z189	Baar	Female	Adult	3	2

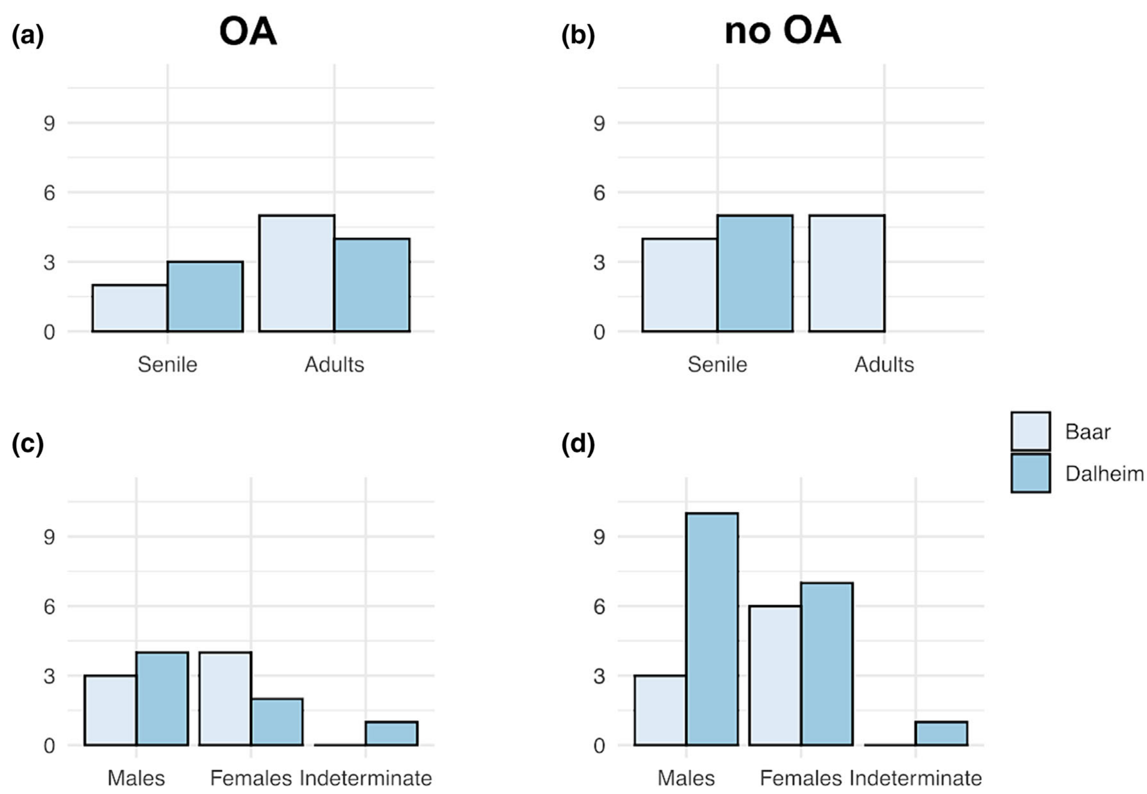

FIGURE 4 The studied individuals with osteoarthritic (a, c) and unaffected (b, d) condyles sorted by age and sex categories. [Colour figure can be viewed at wileyonlinelibrary.com]

The teeth that have been lost antemortem in the analyzed sample are mainly molars and premolars (Figure S2). There is no visual correlation between the location of the teeth lost antemortem and the condyle affected (left, right, or both) (Figure 8). The number of teeth lost antemortem (Table 1) does not seem to correlate with the presence of condylar OA ($G = 8.9138$, $df = 8$, $p = 0.35$) (Table S4).

4 | DISCUSSION

In this study, 69 condylar eminences of 41 medieval individuals were analyzed in order to find degenerative signs, resulting in the diagnosis of OA in 14 (34.1%) individuals (Baar, $n = 7$; Dalheim, $n = 7$) (Table 4). These diagnoses on our sample comprised both bilateral ($n = 4$) and

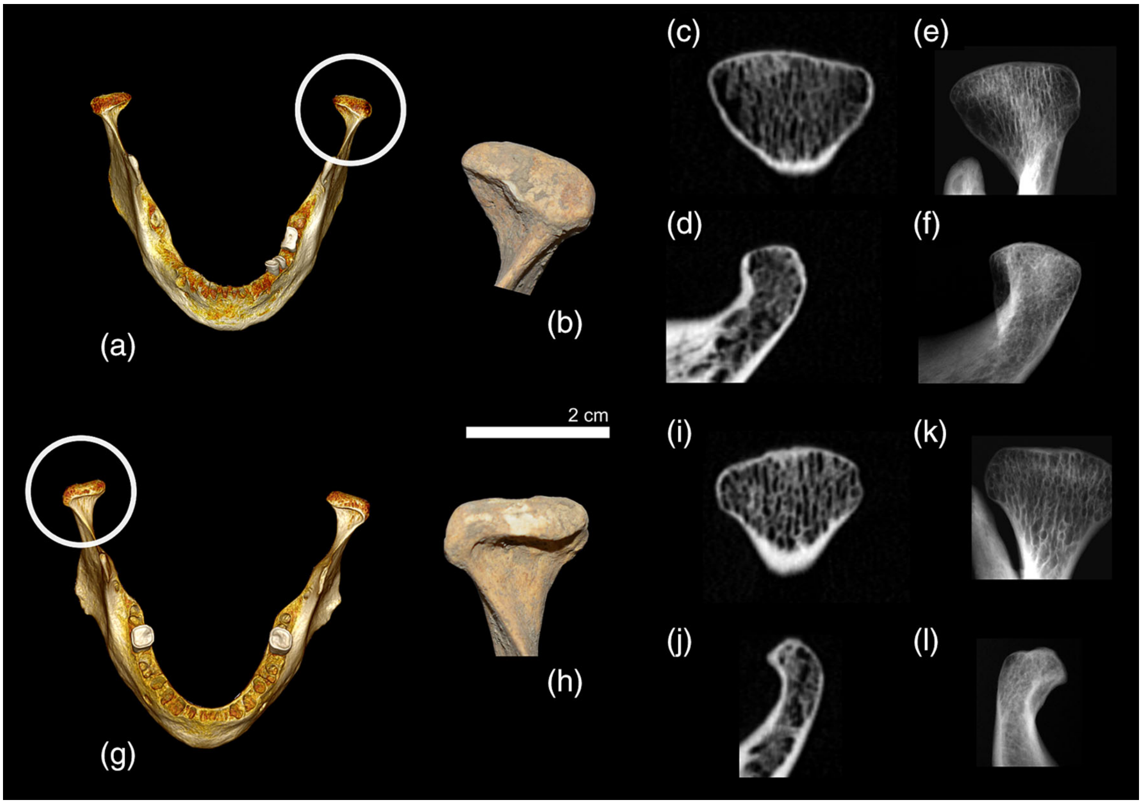

FIGURE 5 Unilateral OA in an adult (a, volume rendering, B15) and an older adult (g, volume rendering, B56a) from the Dalheim collection. Closeups of the affected left (b) and right (h) condyles (frontal views). Coronal (c, e, i, k) and sagittal (d, f, j, l) views of the condyles. The condyles show typical OA changes, namely flattening of the superior surface, generalized sclerosis of the articular surfaces, osteophyte formation, and subcortical cysts. Multiplanar reconstructions from CT data (a, g), CT scans (c, d, i, j), and radiographs (e, f, k, l). The 3D illustrations are not to scale. [Colour figure can be viewed at wileyonlinelibrary.com]

unilateral ($n = 10$) cases of OA in both older adults ($n = 5$) and adults ($n = 9$). Similar to findings published elsewhere (Griffin et al., 1979; Hodges, 1991; Richards & Brown, 1981), our study reveals significantly different values in tooth wear between individuals affected by OA and those who were unaffected. However, in other studies, no correlations between tooth wear and the occurrence of OA were observed (Eversole et al., 1985; Nancy, 2014; Sheridan et al., 1991). A correlation between the two variables is generally to be expected, because severely worn and especially differentially abraded dentition may cause more stress on the mandibular articulation during mastication (Liu et al., 2023; Seligman et al., 1988).

At the same time, the onset of (especially unilateral) OA could have an impact on the way chewing movements are performed (e.g., side preference) (Su et al., 2018) thus affecting the development of tooth wear and potentially causing variable degrees of discomfort during chewing (Kalladka et al., 2014; Su et al., 2018). In the diseased individuals, tooth wear surprisingly shows higher values in those whose left condyle was affected by OA than in those whose right condyle was compromised (Figure 7). In addition, tooth wear values from the right-sided dentition are higher in the group where both condyles were affected by OA, compared with all the other groups (Figure 7a; Table 5). Based on these observations, although a significant correlation between tooth wear and OA is confirmed, highly variable values for tooth wear are observed in individuals with affected versus unaffected condyles.

4.1 | Dental factors and TMJs

Tooth wear is a ubiquitous phenomenon in (pre)historic dentitions and should therefore be considered as a physiological process. Accordingly, the loss of the dental crown's height is compensated by the continuous eruption of the teeth to achieve a stable occlusal height (Wheeler, 1974) that largely protects the TMJ from overloading during physiological loading (e.g., during mastication). When tooth wear shows extreme values, the reducing height of dental crowns can no longer be compensated for, resulting in a reduced occlusal height. Moreover, overloading of the joint components and pathological changes may occur in the case of trauma, parafunction, or disturbed occlusion caused by the loss of molar support. Molar support has been shown to be a reliable predictor for OA in ancient individuals (Levartovsky et al., 2012), although we could not evaluate molar support within our sample due to the poor conditions of the upper dentitions. However, when only one dental arcade is present, molar support can be inferred from the number of AMTLs (Figure S2). As reported in Hodges (1991), we also did not observe any clear

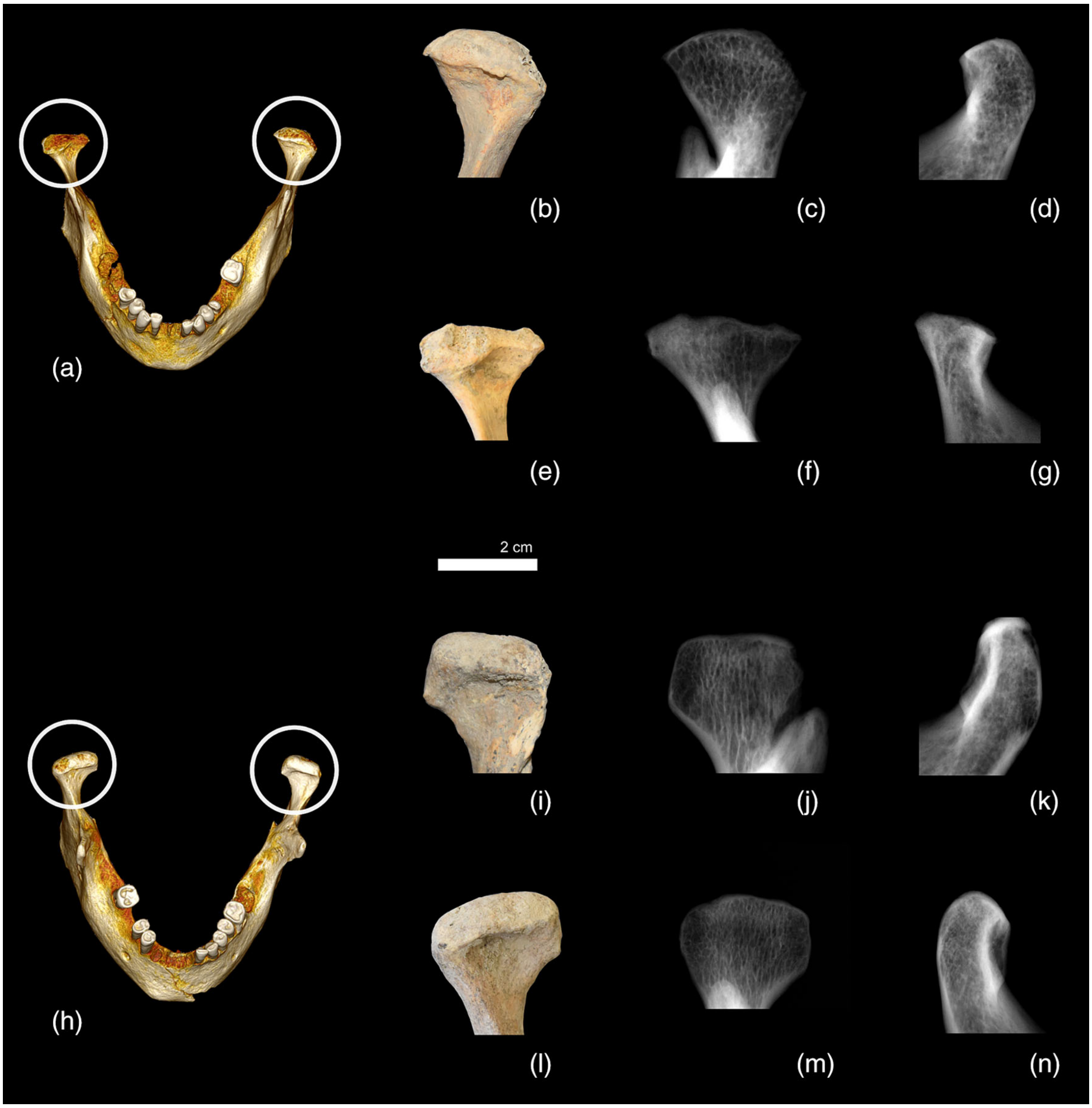

FIGURE 6 Bilateral condylar OA in an adult (a, G6) and an older adult (h, B85) from the Dalheim collection. Coronal (c, f, j, m) and sagittal (d, g, k, n) views of the condyles. The condyles show typical OA changes, namely flattening of the superior surface, generalized sclerosis of the articular surfaces, osteophyte formation, and subcortical cysts. Multiplanar reconstructions from CT data (a, h), closeups of the affected condyles (b, e, i, l), and radiographs (c, d, f, g, j, k, m, n). The 3D illustrations are not to scale. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Mean, standard deviation (SD), and median values for tooth wear calculated for all the available lower teeth (right and left), and for the right and left teeth taken separately. The groups refer to the status of the condyles (no condyle affected, both condyles affected, right or left condyle affected).

	Condyle status											
	None affected			Both affected			Right side affected			Left side affected		
Parameter	*Mean*	*SD*	*Median*	*Mean*	*SD*	*Median*	*Mean*	*SD*	*Median*	*Mean*	*SD*	*Median*
Right and left dentitions	1.77	1.08	2.0	2.41	1.22	2.0	1.75	1.01	2.0	3.08	1.06	3.0
Right dentition	1.77	1.07	2.0	2.0	1.24	1.	1.8	0.99	2.0	3.14	1.09	3.5
Left dentition	1.77	1.09	2.0	2.85	1.07	3.0	1.76	1.04	2.0	3.0	1.05	3.0

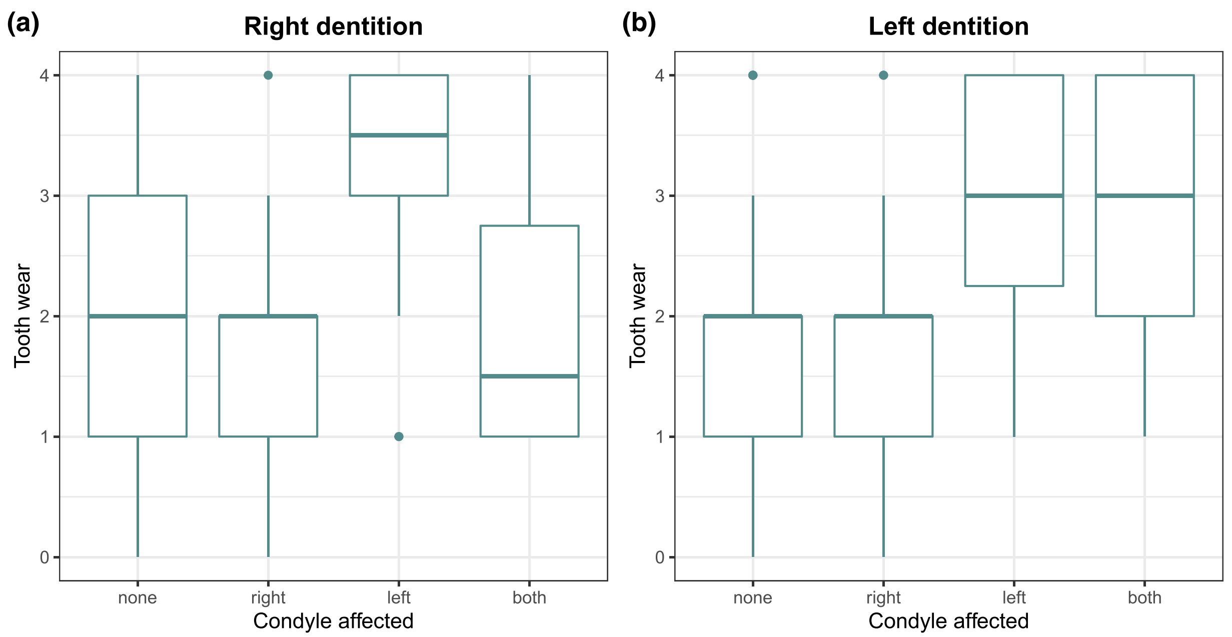

FIGURE 7 Tooth wear values of the right lower dentition (a) and the left lower dentition (b) plotted considering the level of damage of the mandibular condyles (none = both unaffected condyles; right = right condyle affected by OA; left = left condyle affected by OA; both = bilateral OA). [Colour figure can be viewed at wileyonlinelibrary.com]

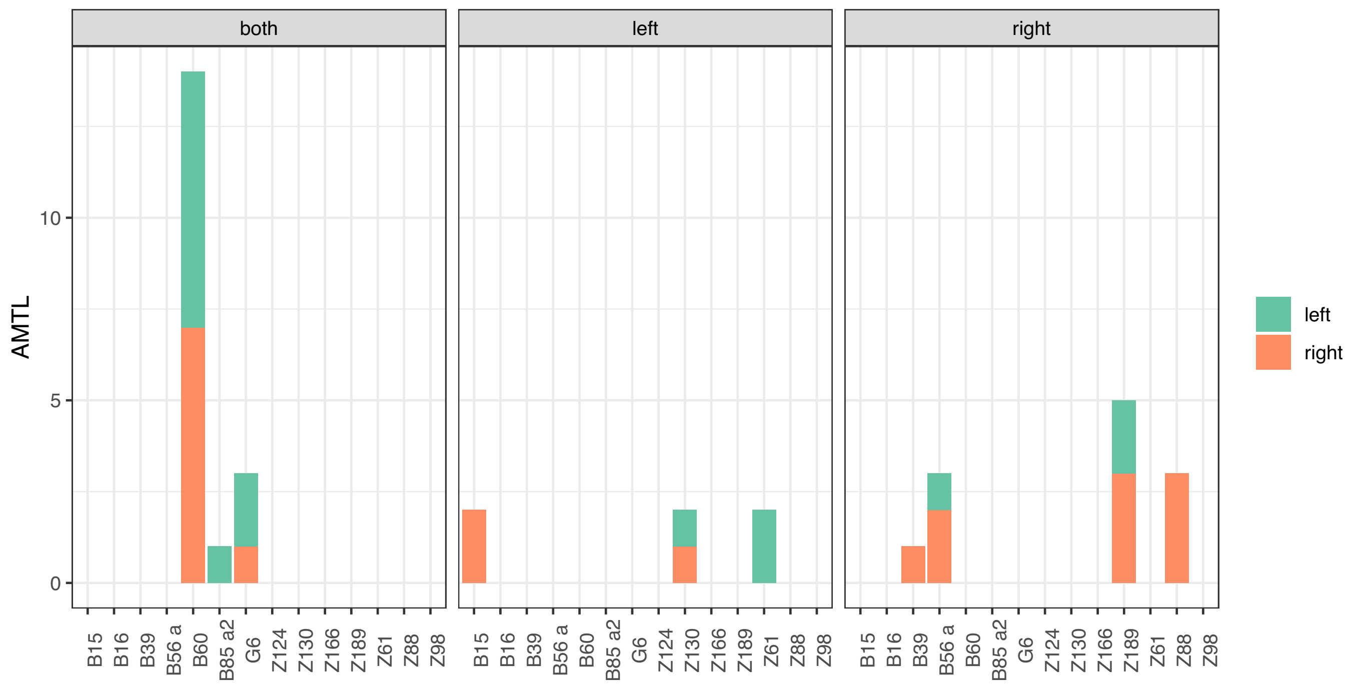

FIGURE 8 AMTL distribution and dental quadrant affected (lower right or left) in individuals with OA (with both condyles affected, left, right, or both condyles affected). [Colour figure can be viewed at wileyonlinelibrary.com]

association between the teeth lost antemortem and the manifestation of OA signs in the mandibular condyles. This may suggest that, despite the increasing number of AMTLs in older adults, the overall molar support of the studied individuals may have been well preserved and therefore may not have contributed significantly to any overload of the TMJs in our sample. Nevertheless, a correlation between TMJ-OA and AMTL has been reported in other contexts (e.g., Suby & Giberto, 2019).

Different frequencies of TMJ-OA are reported depending on the archaeological context (e.g., Stone et al., 2020; Suby & Giberto, 2019) with frequencies ranging from between 2.4% and 38.5% (Rando et al., 2012). However, it is difficult to draw direct comparisons between studies for several reasons. In the past, human populations used dentition to perform diverse paramasticatory activities (Molnar, 2008; Stone et al., 2020), dietary habits differed greatly (Alt et al., 2022; Veile, 2018), and the current methods used to collect data may slightly vary. The mandibular glenoid fossae, the counterpart of the condyles in the TMJ, were not available for this study. If preservation of the finds is favorable, visual inspection (Rando & Waldron, 2012) and radiological measurement of the thickness of the fossae (Ejima et al., 2013) would provide complementary data, although it is not necessary for a thorough diagnosis. In fact, the mandibular fossa is not a functionally stress-bearing part of the TMJ (Nayak et al., 2018). Furthermore, the bone thickness of such a delicate structure may also change due to taphonomic processes, so the inclusion of such measurements in the diagnostic features for OA could be misleading. Another important aspect in the diagnosis of degenerative TMJ signs on dry skulls is that a number of conditions affecting the articular disc and the surrounding capsule are not visible. Even when mandibles and maxillae are well preserved, evaluation of the dental occlusion is extremely challenging due to the absence of the articular disc. Finally, we must not forget that most TMDs (Truelove et al., 1992) cannot be diagnosed on dry skulls, and therefore, the picture we can obtain from archaeological finds is always limited.

4.2 | OA and demography

In addition to OA signs in TMJs, degenerative signs in the spine were also documented in the Dalheim collection, suggesting high spinal stress due to warfare or farming activities (Hofmann et al., 2008). Only two instances (2 older adults out of 37 individuals analyzed) of OA within the limbs were reported (Hofmann et al., 2008). The previous paleopathological analysis of the Dalheim individuals also did not reveal a clear prevalence of OA in female individuals, as the only two individuals with osteoarthritic signs were both males. However, degenerative vertebral signs in the cervical spine were more prevalent in females than in males (Hofmann et al., 2008). Degenerative signs in the spine were also found in the Baar individuals (19.1%), in addition to degeneration in the limbs, suggesting that these individuals were also exposed to a high average workload during their lifetime and therefore high physical stress (Lohrke et al., 2010). OA is a condition associated with age in both modern and ancient populations. In general, OA (articular and vertebral) occurs more frequently in the elderly, because they have likely been exposed to joint loads more frequently than adults (Jurmain & Kilgore, 1995); however, we did not find strong correlations with age in the studied individuals. In modern populations, women are more frequently affected by OA than men (e.g., Migliore & Picarelli, 2018; Szilagyi et al., 2022). However, our data did not show significantly different frequencies of mandibular OA between the sexes in both the Baar and Dalheim populations. It is possible that historically, OA of TMJs, unlike other skeletal components, did not manifest more frequently in females than in males.

4.3 | TMJs and medieval diet

The mechanical characteristics of the foods consumed, particularly their toughness and stiffness, have an impact on the biomechanical stress and load to which the dentition and TMJs are subjected. Different foods require the application of varying amounts of force during mastication, which in turn affects the load distribution on both TMJs. This has a number of evolutionary implications for the genus *Homo*, such as the progressive reduction of the size of teeth and occlusal surface, and more generally, the entire facial structure (Lieberman et al., 2004). Very intuitively, the TMJs, which are an integral part of the masticatory system (Alomar et al., 2007; Kuroda et al., 2009), were also affected. It follows that by decreasing the hardness, toughness, and stiffness of foods through processing methods such as tenderizing and cooking/boiling, less stress is applied to the entire masticatory system (Zink et al., 2014).

During the Middle Ages, when the average diet consisted of coarse grains, tough meats, and fibrous vegetables, the biomechanical loading on the TMJs was likely higher because these food items were difficult to chew. These were certainly harder to chew than most industrialized, processed (and very soft) foods (Kahn & Ehrlich, 2018). It can be assumed that in the Middle Ages, vegetables were eaten both raw and cooked. Hence, the proportion of raw versus cooked foods might have had an impact on the development of TMJ-OA. An experiment described by Liebermann (Lieberman, 2011:274) focused on parsnip, a common vegetable in the medieval diet. Eating it raw required 40% more chewing force and 51% more biting movements than when it was cooked. However, parsnip is probably not the best example, as it was shown that, unlike other tubers and roots, roasting does not decrease its toughness (Zink et al., 2014). All other tubers included in the experiments of Zink et al. (2014) displayed significant textural changes after cooking. Other tubers and roots, such as turnips, beets, carrots, and kohlrabi, were commonly consumed in medieval times, especially by the poorest (Pearson, 1997). In addition to being eaten raw, they were added to beans or meat stews and then consumed cooked. Because cooked vegetables are in general much more tender and less stiff than their raw counterparts (Zink et al., 2014), the way food was prepared could have considerable implications in the study of TMJ-OA in human skeletons.

In the Middle Ages, the most used cooking methods were boiling and stewing for two main reasons. First, it was a very economical way of cooking, as no juices were lost during the process. Second, even the poorest could afford it, providing that they lived in a house. Even the most modest households had a fireplace, hearth, cooking stone, or a clay stove, usually placed in the center of the main room (Adamson, 2004; Charytonowicz & Latala, 2011). This central place had both cooking and heating purposes. Baking was far more challenging because ovens were not a usual commodity—they were expensive and only bakers or the wealthiest people owned one. Moreover, milling grains was also expensive, so only the wealthier classes could afford a constant supply of bread (Adamson, 2004; Qin, 2017). For this reason, the lower classes mostly consumed grains as pottage (i.e., creamy, thick soup), to which vegetables, meats, and legumes could be added (Qin, 2017). Unleavened bread was also a valid alternative when milling and baking were impractical (Adamson, 2004). The types of grains used to make bread also varied according to socioeconomic status. While the rich class had more access to white flour for both bread and pies, the poorest often had to consume low-quality grains such as rye, millet, and oats, which were also given to livestock animals. Moreover, mixtures of crops were also grown such as dredge, made of spring barley and oats, and maslin, which was composed of wheat and winter barley (Qin, 2017). Bread was also commonly consumed dry and, therefore, very hard. Rye bread, in particular, has the tendency to become very stiff after a few days—a property that facilitates preservation.

As for meat consumption, almost all fractions of the population could eat some portions of it, especially cattle and ovicaprids. Venison and other game meats were mostly a luxury reserved for the wealthier class (Qin, 2017). Although roasted meat is not characterized by a decrease in toughness compared with raw meat (Zink et al., 2014), when boiled, such as in stews, the collagen surrounding the meat fibrils soften significantly and partial denaturation of myoglobulin occurs. Hence, meat toughness is reduced, while an increase in tenderness is observed (Christensen et al., 2012). Since boiling and stewing occurred more frequently than roasting, it is plausible that roasted meat was not preponderant in the medieval cuisine.

It results that, in the Middle Ages, socioeconomic factors not only determined access to food resources but most likely also to cooking methods. As already seen, cooking/boiling renders food more tender, thus more chewable and digestible. In fact, the number of chews per food unit required to process items in the oral cavity decreases dramatically when these items are cooked (Lieberman, 2011). In addition, there is also a substantial decrease in the average force required for chewing when eating cooked foods (Zink et al., 2014).

Given the above, the ratio of raw versus cooked foods has likely always been a dominant factor in determining the stress and loads applied to TMJs. In medieval Europe, a fraction of the population might have had to resort more often than others to raw foods out of necessity. For example, those who lacked access to cooking stones or fireplaces could not procure tinder to light fires on a daily basis, or did not possess adequate cooking utensils, were likely to consume higher percentages of raw food. In these cases, this repetitive behavior most likely had a strong effect on the average (lifetime) stress on TMJs. Ultimately, this repetitive loading may have contributed to the development of TMJ-OA.

In this study, data on social status was only available for one of the two collections analyzed. The social status of the individuals from the site of Baar could be inferred from the goods that accompanied the graves (Müller, 2010). No significant differences regarding oral pathologies were observed in this population. Based on this evidence, it appears that individuals accompanied by wealthy and standard grave goods had similar oral habits and diets (Pedergnana & Huber, 2024). As for Dalheim, the cemetery was in use for several centuries, and the status of the individuals cannot be determined with certainty because grave goods were absent. It is very likely that the individuals buried were peasants, but among them, there could also be a small number of nuns (approximately 14) (Pieper, 2003; Radini et al., 2019). If so, the diet of these individuals probably differed from that of the peasant group. The question of how different it was remains open for now.

4.4 | TMJs and parafunctional activities

An additional aspect that may increase stress on the mandibular joints is the systematic exploitation of parafunctional dental activities. Knowing that these affect the articular disk differently, depending on the type of forces applied (Kuroda et al., 2009), a prolonged exploitation of nonalimentary dental habits may have been a contributing factor to the development of TMJ-OA in predisposed individuals in the past. The association between TMJ-OA and highly specialized parafunctional use of dentition has been already observed in past populations. An interesting example is the prehistoric population at Palau (Micronesia), which specialized in betel nut (*Areca catechu*) chewing to take advantage of its stimulant properties (Stone et al., 2020). This activity, if prolonged over time, has the ability to stain enamel surfaces and can be preserved in the archaeological record. This study demonstrated that nonalimentary activities performed with the dentition over long periods of time have the potential of affecting TMJ-OA in humans. In the Middle Ages, possible dental parafunctional activities were probably driven by professional occupations, such as leatherworkers, cordage or baskets makers, and sewers (Monaco et al., 2022; Rodrigues et al., 2021).

In the studied osteological collections, possible evidence of nonalimentary induced dental modifications was documented only in individuals from the cemetery of Baar. Only atypical wear patters on the anterior dentition were observed, and no evidence of chipping, notching, or "tooth picking" was visible. Some wealthy individuals showed the same patterns of severe occlusal wear, suggesting that the richest fraction of society was not exempt from such activities (Lohrke et al., 2010; Pedergnana & Huber, 2024).

5 | LIMITATIONS OF THE STUDY

The main limitation of this study is its sample size. It was not possible to inspect the totality of individuals from both cemeteries, which makes it difficult to comprehensively reconstruct the frequency of OA of the mandibular condyles in the two populations studied. In the future, it is of interest to enlarge the sample size of medieval individuals in central Europe and develop a more detailed model for the development of degenerative diseases of TMJs in this time period. An enlargement of the sample will allow a paleoepidemiological approach to the frequency of condylar (bilateral or unilateral) OA in the Middle Ages, and its impact on dietary habits and masticatory patterns. In this context, comparison of data on mandibular OA with dietary proxies (such as isotopic values, microdebris, and proteins in dental calculus) would also provide important insights.

6 | CONCLUSIONS

Data on tooth wear and TMJ degeneration in past populations can provide valuable information for understanding their lifestyles. OA has a strong effect on mastication, as it may hinder or impede proper jaw movements. The types of food ingested over one's lifetime may also influence the onset and development of TMJs disfunctions.

In our study, we succeeded in identifying OA on the mandibular condyles of 14 medieval individuals (out of the 41 individuals analyzed) based on visual and radiological observations. Tooth wear showed significantly different values in individuals in individuals who were affected or unaffected by OA, indicating a possible correlation between extreme tooth wear and occurrence of mandibular condylar OA. The combination of radiology and visual observation allows for a more comprehensive look at degenerative skeletal diseases, as demonstrated in this study. All the diagnostic features used in this study to identify OA in TMJs could be observed on both planar radiographs and CT reconstructions and perfectly complement macroscopic observation. CT scans were particularly useful in locating cystic lesions along the height of the condyles and assessing their extent.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at 10.5281/zenodo.7789000.

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