

Microtrauma at the humeral medial epicondyle: Quantifying lacunar lesions to reconstruct activity patterns in past populations

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ARTICLE INFO

Keywords:

Enthesal change
Medial ulnar collateral ligament
Avulsion fracture
3D Surface Analysis
Activity-related skeletal change

ABSTRACT

Objective: Lacunar lesions at the anterior medial collateral ligament (MCL) bundle attachment on the humeral medial epicondyle may represent partial avulsion fractures. This study developed and validated a quantitative approach to assess their morphology.

Materials: Two Neolithic samples were studied: Parisian Basin (France, N = 45) and Meuse Valley (Belgium, N = 25).

Methods: Lesions were extracted using a 3D protocol with ambient occlusion and curvature filters, then screened and analyzed using size, shape and surface metrics. Reproducibility was assessed using Lin's concordance correlation coefficient.

Results: The protocol was successfully validated with excellent intra-observer agreement. Lesions occurred exclusively on right humeri at the anterior MCL bundle footprint, while showing uniform shape but variable size, flattening and surface characteristics.

Conclusions: The protocol provides an objective, reproducible method for lesion characterization and, when applied, revealed cortical-confined depths and surface areas smaller than the anterior MCL bundle footprint, suggesting specific fiber involvement. Right-side bias indicates a potential link with handedness, while morphological patterns align with clinical descriptions of proximal MCL partial avulsion fractures common in youth throwing athletes.

Significance: Findings support an activity-related etiology and demonstrate potential for reconstructing past behaviors from skeletal remains while complementing clinical studies on long-term injury outcomes.

Limitations: Limitations include small sample size, reliance on absolute measurements, dependence on imaging resolution, and lack of direct clinical validation.

Suggestions for Further Research: Studies should apply this protocol to larger, diverse samples, confirm the clinical association, and adapt it to additional imaging modalities for broader archaeological and clinical applications.

1. Introduction

Avulsion fractures are a type of traction injury that occurs when the pull of a tendon or ligament detaches a bone fragment from its attachment site (Resnick et al., 2024). These fractures most frequently affect the apophyses (non-articular epiphyses) of the pelvis and hip (e.g., iliac crest) but may occur throughout the skeleton, including at the medial epicondyle of the humerus (Abdelgawad et al., 2021; Resnick et al., 2024). The medial epicondyle serves as a key structure anchoring the common flexor muscles, pronator teres, and medial collateral ligament

(MCL), which together enable wrist and finger flexion and forearm pronation, while maintaining elbow stability.

The prevalence of medial epicondylar avulsion fractures varies markedly with skeletal maturity. In adults, isolated fractures are rarely encountered (Antonacci and Alberta, 2021). In contrast, in the immature skeleton, the presence of open physes (growth plates) creates a structural weak point, making avulsion fractures considerably more frequent (Resnick et al., 2024). These fractures often result from falls onto outstretched hands, sports activities such as baseball and arm-wrestling, or elbow dislocation, which accounts for approximately 50% of cases

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<https://doi.org/10.1016/j.ijpp.2026.05.002>

Received 19 January 2026; Received in revised form 31 March 2026; Accepted 27 May 2026

Available online 12 June 2026

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(Flynn et al., 2015; Gottschalk et al., 2012; Ogawa et al., 2022; Zheng et al., 2025). In throwing athletes, valgus forces during the late cocking and acceleration phases place significant stress on the apophysis. Chronic overuse may lead to medial epicondylar apophysitis, and in severe cases, to acute avulsion of the medial epicondylar apophysis (Zheng et al., 2025). In adults, similar stresses typically result in ligamentous injury rather than bony avulsion (Andelman et al., 2018).

Avulsion in the immature skeleton can involve either the entire apophysis, or a fragment of it (i.e., a partial avulsion, which may manifest as apophyseal fragmentation or as a subcortical defect (Sugimoto and Ohsawa, 1994). Partial avulsions can affect the area where the anterior bundle of the MCL attaches, a so-called “proximal MCL avulsion fracture”, or may include the attachment site of the flexor-pronator mass, resulting in a “cortical sleeve avulsion” (Lee et al., 2025). These injuries represent a substantial proportion of medial epicondylar fractures, accounting for approximately 16% (N = 113/709) of cases in a large pediatric series (Lee et al., 2025), though higher rates have been reported in athletes (Sinha et al., 2024; Tariq et al., 2023). Lee and colleagues (2025) found the proximal MCL avulsion fracture, the most common subtype (69%, N = 78/113), to be predominantly associated with the throwing mechanism, whereas cortical sleeve avulsions were predominantly traumatic. These injuries occur mostly between 9 and 14 years of age, with fracture patterns varying with age (Lee et al., 2025; Syed et al., 2025b; Woods and Tullos, 1977).

In archaeological collections, complete avulsion fractures of the medial epicondyle have been documented in both adult (Knüsel et al., 2000; Glencross and Stuart-Macadam, 2000, 2001; Rhodes, 2004; Knüsel, 2011; Dittmar et al., 2021; Ducher et al., 2023) and non-adult individuals (Verlinden and Lewis, 2015). These studies generally consider both a traumatic origin and a link to throwing activity, with interpretations favoring one or the other based on contextual evidence. Among these studies, Knüsel (2011) stands out for using of medial epicondylar avulsion fractures to explore social patterns in late mediaeval England. This author interpreted the presence and distribution of these injuries as a means of gaining insight into masculine social identities.

Beyond complete avulsions, a distinct line of studies has examined more subtle osseous changes affecting the medial epicondyle. Dutour (1986, p. 222) described the presence of an “osteophyte descending vertically from the lower part of the epicondyle” in two Neolithic individuals from the Sahara (Mali). He associated this feature with hyperactivity of the common flexor muscles, interpreting it as evidence for medial epicondylitis (Dutour, 2000). Drawing on sports medicine data from javelin throwers, he linked these changes to throwing-related activities, notably the use of assegais. Following Dutour’s interpretation, Capasso et al. (1998, 2004) reported an additional case from Herculaneum (79 AD), referring to the lesion as “epicondylar exostosis”.

Villotte et al. (2010) reported two individuals with “excavated lesions” at the anterior bundle of the MCL attachment site in a European Upper Palaeolithic sample. They interpreted these as healed partial avulsion fractures in adults. Based on the archaeological context, the authors proposed that such lesions might relate to spear-throwing activity. Building on these observations, Polet et al. (2019) proposed a more comprehensive interpretative framework, suggesting that both bony outgrowths (i.e., distinct protrusions extending from the enthesal surface) and lacunae (i.e., large surface discontinuities) at the anterior MCL bundle attachment site may both represent partial avulsion fractures, reflecting different healing outcomes depending on bony union. When compared with current clinical descriptions, the lesions identified by Polet et al. (2019) correspond closely to what orthopedic literature terms proximal MCL partial avulsions fractures (e.g., Lee et al. 2025; Kim et al. 2013; Furushima et al. 2016; Sinha et al. 2024; Syed et al., 2025a; Zellner and May, 2013). The “exostoses” identified by Dutour (1986, 2000) and Capasso et al. (1998, 2004) likely reflect the same process, as their location corresponds more closely to the attachment site of the anterior bundle of the MCL than to that of the common flexor tendon (Buck et al., 2010; Camp et al., 2018; Fuss, 1991; Omoumi et al.,

2021).

As avulsion fractures in adults are rare today, it is plausible the same was true in the past. Consequently, most avulsions identified in archaeological material likely originated during childhood or adolescence. The strong association between these injuries, particularly proximal MCL partial avulsion, and throwing movements in young individuals underscores their potential as indicators of activity. Beyond providing evidence for habitual activity patterns in past populations, either alone or in combination with other evidence, e.g., cross-sectional geometry (Rhodes, 2004; Varalli et al., 2020), these lesions may shed light on broader socio-cultural dimensions such as youthful behaviors, the social contexts of skill acquisition, and sexual division of labor (Knüsel, 2011; Polet et al., 2019; Villotte et al., 2010).

Despite their potential for reconstructing past activity patterns, the systematic study of (partial) avulsion fractures in archaeological material remains limited (Knüsel, 2011; Polet et al., 2019; Rhodes, 2004; Varalli et al., 2020; Villotte et al., 2010). This may reflect their apparent rarity or the possibility that they have often gone unrecognized. Furthermore, previous research has relied solely on qualitative assessments, recording lesions as simply present or absent. While valuable for establishing their occurrence, this binary approach precludes systematic analysis of lesion morphology and variability. The absence of quantitative data limits the ability to compare lesions across studies, assess relationships between lesion characteristics and activity patterns, and develop standardized protocols. Quantitative characterization is essential to ensure reproducibility and move beyond documentation toward a more robust understanding of these injuries and their behavioral significance, potentially contributing to clinical knowledge through comparative data on lesion morphology and long-term skeletal responses.

The lacunar variant is particularly well-suited for quantitative analysis due to its distinct morphology and potential association with throwing activities. Building on this premise, this study aimed to: (1) develop and validate a quantitative approach to assess lesion morphology and variability, and (2) conduct a systematic analysis of lesions from both a previously published collection and newly examined osteological assemblages. This study provides the first quantitative characterization of this pathology and contributes to refining its interpretation within the broader framework of activity reconstruction in past populations.

2. Materials and methods

2.1. Materials

Lacunar lesions seem to be relatively rare in osteological collections, posing a considerable challenge for detailed analysis. Nonetheless, several cases have been found in Neolithic skeletal assemblages from the Paris Basin (France) and the Meuse Valley (Belgium) (Polet et al., 2019), providing the basis for developing a quantitative approach to analyze them. This study sample was subsequently divided into developmental and validation groups.

The developmental group was drawn from two large, commingled Neolithic collections from the Paris Basin (France): L’Isle-Adam (Pariat and Boursier, 2022) and Petit Morin (Baye, 1874) (Table 1). Excavated during the late 19th and early 20th centuries and curated at the Musée de l’Homme (Museum national d’Histoire naturelle) in Paris (France), these collections were chosen because they contain a relatively high number of lesion-bearing specimens. Pooling these collections ensured a sufficiently large sample for protocol development.

The validation group consisted of commingled Neolithic remains from the Meuse Valley (Belgium), where Polet et al. (2019) previously identified lacunar lesions. For three of these collections, 3D data were available: Grotte de Sclaigneaux in Sclaigneaux (Paeppe and Polet, 2007), Bois Madame in Burnot (Dumbrich, 2007), and Grotte de la Cave in Maurenne (Vanderveken, 1997) (Table 1). These collections, all curated

Table 1
Composition of the studied assemblages.

Collection	Site	Minimal number of individuals		Number of humeri*		
		Total	Adult individuals	Left	Right	Total
Paris Basin	Isle-Adam	112	96	25	18	43
	Petit Morin	-	-	78	94	172
	Total	-	-	103	112	215
Meuse Valley	Grotte de Sclaigneaux	58	45	26	21	47
	Grotte de la Cave	59	44	18	16	34
	Bois Madame	57	38	7	10	17
	Total	174	127	51	47	98

* Adult humeri with well-preserved MCL attachment sites.

at the Royal Belgian Institute of Natural Sciences in Brussels (Belgium), were excavated in the late 19th and early 20th centuries.

Following Polet et al. (2019), lesions were characterized as “large surface discontinuities affecting the cortical bone and underlying trabecular bone” at the attachment site of the anterior band of the MCL (Fig. 1). Among the 215 adult humeri with well-preserved MCL attachment sites in the Paris Basin collections, fourteen cases were identified, and nine of these were available as 3D models. For the Meuse Valley collections, five previously documented cases (Polet et al., 2019) were available based on existing 3D data.

To enhance statistical power and account for morphological variability, each lesion sample was supplemented with unaffected specimens at a 4:1 ratio. This approach is borrowed from case-control study design in epidemiology, where increasing the ratio of controls to cases

improves statistical power when the number of cases is limited, with diminishing returns beyond this ratio (Rothman et al., 2008). The selection of unaffected specimens was based on medial epicondyle fusion and preservation. Equal numbers of left and right humeri were included to control for side-related variation. This resulted in a developmental sample (Paris Basin group) of 45 humeri (9 with lesions, 36 without) and a validation sample (Meuse Valley group) of 25 humeri (5 with lesions, 20 without).

2.2. Protocol

3D surface models of these humeri were created using the Artec Space Spider (Artec 3D Inc., Luxembourg) in combination with Artec Studio 15 Professional (see Supplemental Information: Appendix A.1 for full description). A digital extraction and classification protocol were created to enable the quantitative study of lacunar lesions. This protocol was developed on the development sample and subsequently evaluated using the validation sample (see Supplemental Information: Appendix A.2 for full description). The medial epicondyle of the humerus and, in particular, the attachment site of the MCL, was defined as the main region of interest. To ensure that the entire enthesal surface was included, the cropping method proposed by Liagre et al. (2025) was applied using 3D Slicer (v5.6.2, 3D Slicer, 2024; Fedorov et al. 2012) (Fig. 2.1).

Potential lesion areas were first identified using Ambient Occlusion (AO) techniques in PyMeshLab (v2023.12; Muntoni and Cignoni, 2025), which highlight concave surfaces such as lacunar lesions. Vertex colors were smoothed and adjusted to enhance lesion margins (Fig. 2.2). Curvature-based filtering was then applied to refine the extracted regions by removing border vertices within a defined curvature range, potentially trimming or splitting surfaces, while preserving internal



Fig. 1. Example of a lacunar lesion at the medial epicondyle in a right humerus from the Paris Basin, Neolithic-period France (Petit Morin n°21220), derived from MNHN images (crédit image MNHN – réutilisation interdite [image credit MNHN – reuse prohibited]). The inset shows the lesion in detail, within the approximate attachment site of the anterior bundle of the medial collateral ligament (dashed line), after Buck et al. (2010).

irregularities (Fig. 2.3). This step was necessary as morphological variation occasionally caused the extracted regions to extend beyond the lesion area. Surfaces containing fewer than 10 faces were also removed, as curvature-based filters are unstable for very small meshes.

Extracted surfaces located in areas with evident taphonomic surface damage were excluded based on visual assessment of the 3D models and detailed images, supplemented where available by pre-existing examination notes. Taphonomic damage was distinguished from other surfaces by its irregular breakage margins, undulating outlines, and color changes (Knüsel and Robb, 2016). The remaining surfaces were then screened to distinguish true lesions from unrelated surface features (e.g., foramina, deep depressions) using R (v4.3.2; R Core Team, 2023) and RStudio (v2024.04.1.748; Posit team, 2024), with the packages Rvcg (v0.25.0; Schlager, 2017; Schlager et al., 2025), geometry (v0.5.2; Habel et al., 2025), and pracma (v2.4.4; Borchers, 2023). Surfaces were retained if their centroid fell within the spatial extent defined by the distribution of lesion surfaces in the development sample and exceeded a minimum depth threshold (see Fig. 2.3 for depth calculation). These decision rules were formulated based on the development sample and evaluated on the validation sample (Fig. 2.4; see Supplemental information: Appendix A.2 for full details). Only surfaces identified as true lesions were used for subsequent quantitative analysis of lesion morphology (Fig. 2).

2.3. Analysis

Lesion morphology was analyzed using size, shape, and surface metrics. These were selected based on established radiomics standards (Zwanenburg et al., 2016), and supplemented with an additional surface metric to capture relevant textural features, particularly those relating to surface irregularities (e.g., trabecular bone exposure).

Size metrics included maximum depth, 2D surface area, and volume. Before measurement, each mesh was aligned so that a best-fit plane through the boundary vertices coincided with the xy-plane, with the z-axis perpendicular to the lesion opening. Depth was defined as the maximum perpendicular distance from this plane to the deepest point (i.e., the maximal negative z-coordinate). Surface area was measured as the 2D footprint projected onto the xy-plane, rather than 3D surface area, to isolate changes in lesion extent from surface texture. Volume was calculated as the volume of the extracted lesion, capped by its convex hull.

Shape metrics included sphericity, as a measure of compactness, and axis ratios to describe directional shape. The sphericity index was

calculated as $\Psi = \pi^{1/3}(6V)^{2/3}/A$, where V is lesion volume and A is surface area (Wadell, 1935). Values closer to 1 indicate a more spherical (compact) shape. To quantify directional shape, meshes were oriented as described above, with the depth axis defined as a_3 (z-axis). For the in-plane axes, the longest axis (a_1) was defined as the maximum Euclidean distance between any two boundary points in the xy-projection. A second axis (a_2) was defined as the extent of the lesion along the direction perpendicular to a_1 . Elongation was calculated as a_2/a_1 and flatness as a_3/a_1 , with values closer to 1 indicating a more equidimensional shape.

Surface metrics included solidity and local roughness, capturing complementary spatial scales of surface variation. Solidity, defined as the ratio of lesion volume to the volume of its convex hull, quantifies the global concavity, i.e., the degree to which the surface deviates inward from a smooth boundary. Values closer to 1 indicate less deviation. Local roughness was quantified as the median absolute deviation (MAD) of mean curvature (Liang et al., 2021; Patton et al., 2018). The dispersion of curvature values, rather than mean curvature, captures local-scale surface variability independent of the characteristic concave shape of lesions. MAD was preferred over standard deviation as a more robust measure, being less sensitive to localized extreme values. Curvature MAD captures local-scale variability in surface bending, with higher values indicating greater roughness. Curvature was calculated on the cropped surface, and then mapped onto the extracted surfaces, thereby avoiding artifacts associated with unstable vertex normal and curvature estimates at boundary vertices (Pampush et al., 2016).

As most variables showed skewed distributions, metrics were summarized using median, interquartile range (IQR), and a robust, median absolute deviation-based coefficient of variation (rCV) (Arachchige et al., 2022). Associations between metrics were assessed using Spearman's rank correlation coefficient (r_s), which ranges from -1 (perfect negative correlation) to 1 (perfect positive correlation). Correlation strength was interpreted according to convention: $0.00 - 0.10$ = negligible, $0.10 - 0.39$ = weak, $0.40 - 0.69$ = moderate, $0.70 - 0.89$ = strong, $0.90 - 1.00$ = very strong (Schober et al., 2018). To account for multiple comparisons, a Bonferroni correction was applied, yielding a corrected significance threshold of $p < 0.0018$.

As the cropping method retains a limited degree of subjectivity (Liagre et al., 2025), protocol reproducibility was assessed by cropping the sample twice by the same observer (E.L.) at a four-month interval. The resulting surfaces were extracted following the protocol, and correspondence between paired surfaces was manually verified. Differences in 3D surface area were summarized using median and IQR due to the

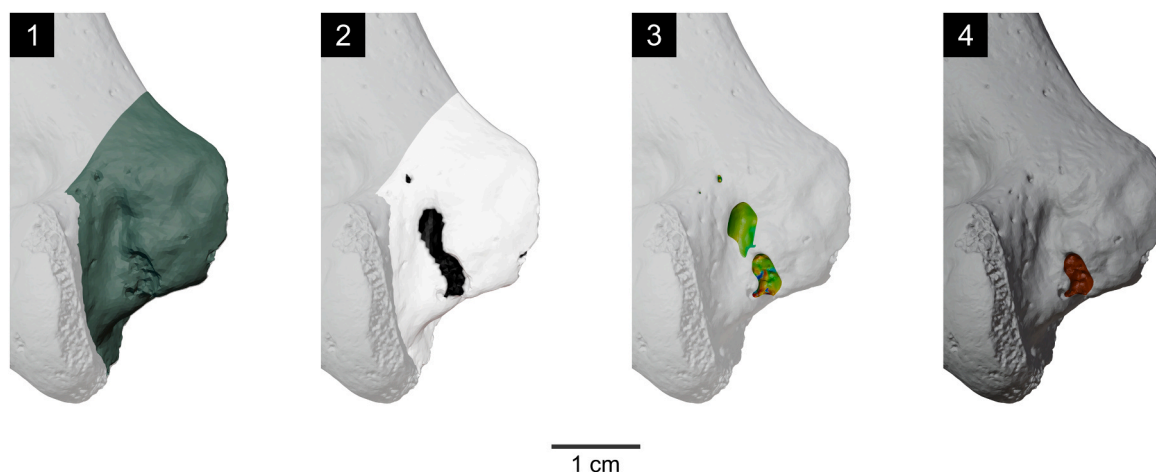


Fig. 2. Protocol for lacunar lesion identification and extraction, illustrated with the right humerus n°21203 from the Petit Morin collection (Paris Basin, France). The workflow includes (1) cropping of the region of interest (i.e., the enthesal surface of the medial epicondyle), (2) application of ambient occlusion techniques to identify concave surface areas, (3) application of curvature-based filters to refine lesion margins, (4) the identified lesion surface after the screening protocol to exclude non-lesion features. (Derived from MNHN data; crédit image MNHN – réutilisation interdite [image credit MNHN – reuse prohibited]).

skewed distribution of the data. Overall agreement was quantified using Lin's concordance correlation coefficient (CCC) (Lin, 1989), which ranges from -1 (complete disagreement) to 1 (complete agreement). While thresholds vary across fields, McBride (2005) suggested that CCC values below 0.90 indicate poor agreement.

Metrics were calculated and statistical analyses were performed in R and RStudio using the packages “Rvcg” (v0.25.0; Schlager, 2017; Schlager et al., 2025), “doolkit” (v1.42.2; Thiery et al. 2023), “DescTools” (v0.99.57; Signorell, 2024) and “Hmisc” (v5.2–4; Harrell, 2025). Volume was calculated in PyMeshLab (“Compute geometric measures”).

3. Results

The protocol successfully extracted all lesion surfaces in both samples (Fig. 3; and see Supplemental information: Appendix A.3). In total, 456 surfaces were extracted from 70 humeri (median: 5 surfaces per

humerus, range: 0–27), of which 185 were of taphonomic origin. The remaining 271 surfaces (median: 3.5 surfaces per humerus, range: 0–10) included true lesion surfaces as well as other features (e.g., foramina, depressions). Surfaces outside the region of interest or below the depth-threshold of 0.58 were removed (see Supplemental Information: Appendix A.2). All lesion surfaces were retained, as were several non-lesion surfaces (three in the development sample, eight in the validation sample). Four of these (one in the development sample, three in the validation sample) occurred in humeri with lesions, and represented remnants of the extracted surfaces after refinement (Fig. 2.3), possibly reflecting effects of lesions on nearby topography or minor methodological artifacts. The remaining false positives corresponded to a foramen and pronounced depressions without surface discontinuity. A full performance evaluation of the screening protocol is provided in Supplemental information: Appendix A.2.

The intra-observer test showed excellent agreement between the two sets of cropped surfaces, with a Lin's CCC of 0.94 (95% CI: 0.93–0.95).

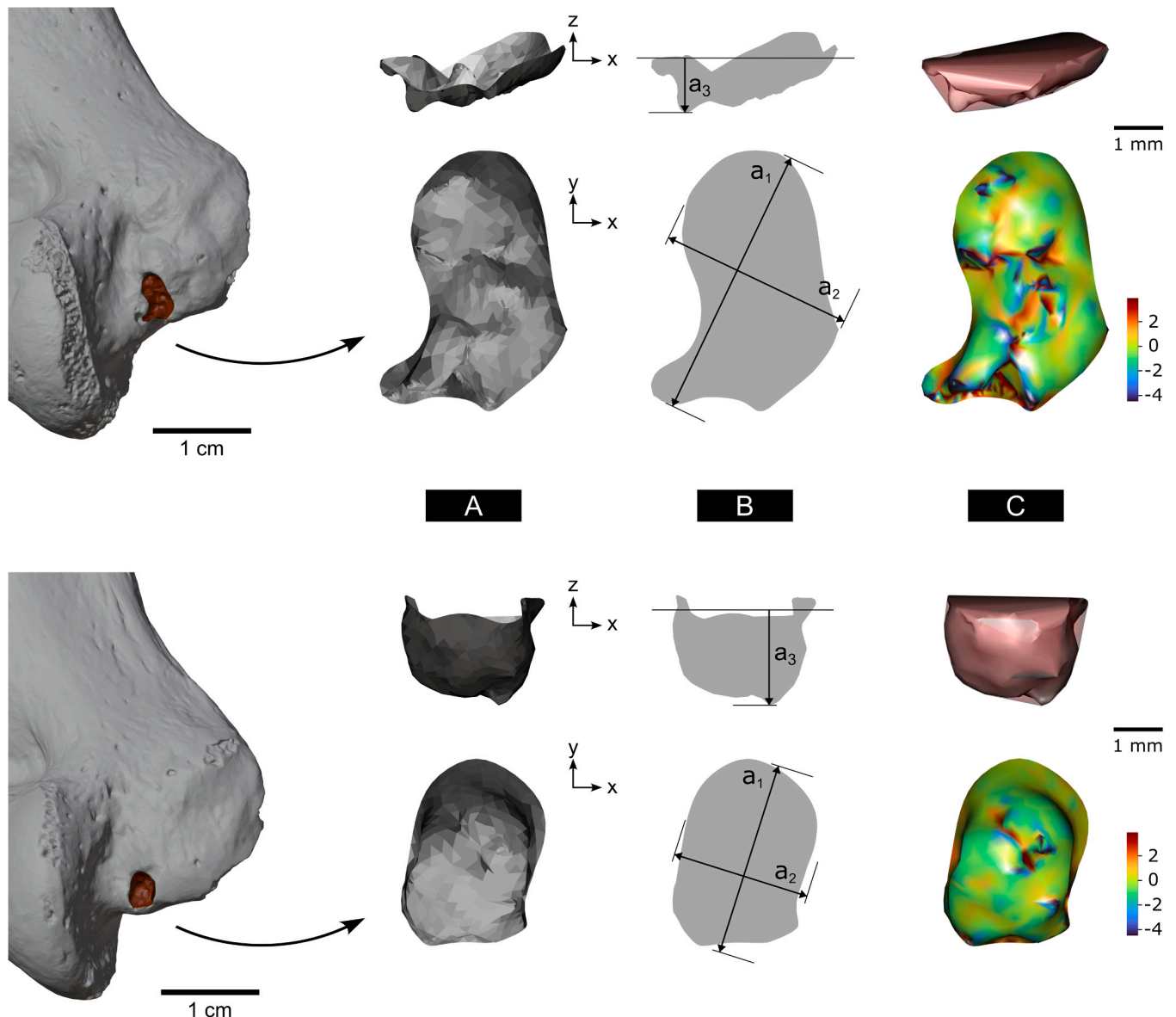


Fig. 3. Comparison of surface extraction and analysis for Petit Morin n°21203 (upper panel) and n°21220 (lower panel). (A) Extracted surfaces aligned based on the best-fit plane through boundary vertices, shown in side and top views. (B) Size metrics: maximal depth from the plane (a_3) (top row), the longitudinal (a_1) and perpendicular axes (a_2) measured on the xy-plane projection (bottom row). The footprint projection is used to calculate the 2D surface area. (C) Surface metrics: capped surface with convex hull (grey surface enclosed by the semi-transparent red hull) (top row), and mean curvature distribution (bottom row). Scale bars: 1 cm (full specimen), 1 mm (extracted surfaces). (Derived from MNHN data; crédit image MNHN – réutilisation interdite [image credit MNHN – reuse prohibited]).

Absolute differences in extracted areas (in mm²) were generally small (N = 493, median = 0.014, IQR: 0.000–0.076), although a few large outliers were observed (max = 43.96). Because subjectivity in the cropping protocol primarily affected the margins, surfaces located along these margins in either set were excluded. This adjustment led to almost complete agreement between sets (CCC = 0.99, 95% CI: 0.99–0.99) and removed the largest outliers (N = 440, median = 0.011, IQR: 0.000–0.045, max = 10.157).

All identified lesions were located on the right humerus, consistently appearing along the lateral border of the antero-inferior tubercle of the medial epicondyle (Fig. 3; and see [Supplemental information](#): Appendix A.3). Quantitative metrics were calculated for each surface (Table 2, and see [Supplemental information](#): Appendix A.4), and correlations between lesion metrics are presented in Fig. 4.

Lesion size showed considerable variability across the sample (rCV > 30%). Maximum depth was the most consistent (≈ 1–2 mm; Table 2). The distribution showed a potential bimodal pattern with clustering around 1 mm (range 0.89–1.35 mm) and 2 mm (1.95–2.12 mm), and one notable outlier at 3.63 mm (Petit Morin n°21229). In contrast, 2D surface area was nearly twice as variable as maximum depth (rCV = 64.59% vs. 34.42%). The moderate but non-significant correlation between the two metrics ($r_s = 0.49$, $p = 0.078$) suggests that lesions do not deepen proportionally as they expand laterally. Lesion volume was very strongly correlated with 2D surface area ($r_s = 0.96$, $p < 0.001$) and moderately with maximum depth ($r_s = 0.64$, $p = 0.015$), suggesting that lateral expansion is the primary contributor to overall lesion volume.

Lesion morphology showed moderate sphericity with low variability (rCV 7.72%), reflecting a consistent overall shape. Lesions were moderately elongated and fairly flat. Among the shape descriptors, flatness showed the greatest variability (rCV 56.27%), suggesting greater heterogeneity in this aspect of shape. Maximum depth showed moderate correlations with sphericity ($r_s = 0.62$, $p = 0.018$) and flatness ($r_s = 0.52$, $p = 0.056$), while flatness and sphericity were also moderately, but non-significantly correlated ($r_s = 0.51$, $p = 0.061$), suggesting that deeper lesions tended to be somewhat more spherical and less flat. In contrast, 2D area and volume were only weakly, non-significantly correlated with sphericity, which indicates that overall size is largely independent of shape.

Lesion surfaces exhibited varying surface irregularities (Table 2). Global irregularity (solidity) showed moderate to high values and was relatively consistent (rCV 14.55%), whereas local surface characteristics showed greater heterogeneity (curvature MAD rCV 50.57%). Solidity and curvature MAD showed a strong negative correlation ($r_s = -0.80$, $p < 0.001$), indicating that surfaces with greater global irregularity

also display increased local roughness. Solidity correlated moderately with sphericity ($r_s = 0.56$, $p = 0.035$), indicating that more spherical lesions tend to have smoother surfaces (higher solidity). In contrast, correlations between elongation and surface metrics were weak and non-significant, while flatness showed a moderate, non-significant correlation with curvature MAD ($r_s = 0.48$, $p = 0.081$), suggesting that flatter lesions tend to have somewhat rougher surfaces.

4. Discussion

4.1. Protocol

The protocol developed in this study successfully identified and virtually extracted lacunar lesions in the validation sample. The intra-observer test further demonstrated that the protocol is highly reproducible, with almost perfect agreement once surfaces affected by cropping-margin subjectivity were excluded. This provides a robust approach that can be applied to other collections for consistent comparisons. The screening protocol offers an objective way to flag candidate lesions, though these include both lesion and non-lesion surfaces. Macroscopic verification of the bone surface is required to confirm the presence of surface discontinuity and to distinguish biological lesions from taphonomic alterations. While this verification step introduces an element of subjectivity, the systematic screening approach is particularly valuable in ambiguous cases or large-scale comparative studies where reducing observer bias is critical.

The use of 3D imaging, while requiring initial investment of time and resources, provides several methodological advantages. It is a non-invasive approach that minimizes handling of fragile human remains, while allowing more accurate and reproducible measurements. For example, depth measurements using calipers may introduce substantial error due to uncertainty in defining the reference plane, and to the difficulty of consistently identifying the deepest point within these lacunae. The 3D-based protocol addresses both issues through standardized virtual measurements. Moreover, 3D approaches facilitate future integration with clinical imaging data (e.g., CT scans) and enable sharing of models through online repositories, opening avenues for broader comparative research.

4.2. Lesion characteristics

Even with a modest sample size of fourteen lesions, several consistent patterns emerge that provide insight into the nature and origin of these lesions. The lesions show a high degree of spatial consistency, with their location falling entirely within the region described in anatomical literature as the origin of the anterior bundle of the MCL (Berg and DeHoll, 1997; Buck et al., 2010; Camp et al., 2018; Dugas et al., 2007; Fuss, 1991; Ikezu et al., 2020). A similar localization has been reported in previous bioarchaeological studies (Polet et al., 2019; Villotte, 2009; Villotte et al., 2010).

Several studies have documented the humeral footprint of the anterior bundle of the MCL, but reported surface areas vary widely, ranging from 14.9 to 59.4 mm² (Camp et al., 2018; Dugas et al., 2007; Frangiamore et al., 2018; Ikezu et al., 2020). In comparison with these published values, most 2D surface areas in the present sample are substantially smaller (median = 9.29 mm², IQR = 7.34–14.73 mm²), with only three specimens falling within the previously published range (Petit Morin n°21186 and n°21229 and Maurenne 111). While methodological differences in boundary delineation and measurement techniques may contribute to this discrepancy, the marked difference suggests that additional factors are likely at play.

Maximum depth is relatively consistent, with almost all observed depths falling within the range of 1–2 mm. This range corresponds to the thickness of cortical bone in this region (1–2.5 mm; Diederichs et al., 2009), suggesting that lesions are largely confined to this outer cortical layer. This idea is further reinforced by their overall flatness.

Table 2
Descriptive statistics for lesion size, shape, and surface metrics (N = 14).

Metrics		Median [IQR]	Minimum	Maximum	Robust CV (%)
Size	Depth (mm)	1.23 [1.04–1.96]	0.89	3.63	34.42
	2D Area (mm ²)	9.29 [7.34–14.73]	1.88	31.84	64.59
	Volume (mm ³)	9.79 [5.29–13.21]	0.91	65.28	60.61
Shape	Sphericity	0.67 [0.65–0.74]	0.58	0.83	7.72
	Elongation	0.74 [0.71–0.84]	0.50	0.89	14.97
	Flatness	0.31 [0.24–0.45]	0.16	0.68	56.27
Surface	Solidity	0.84 [0.73–0.90]	0.69	0.93	14.55
	MAD of mean curvature (mm ⁻¹)	0.84 [0.65–2.05]	0.54	2.52	50.57

Abbreviations: IQR = Interquartile Range, CV = Coefficient of Variation, MAD = Median Absolute Deviation.



Fig. 4. Correlation matrix showing relationships between lesion size, shape, and surface metrics (N = 14). The lower triangle displays Spearman correlation coefficients (r_s), with asterisks indicating significance after Bonferroni correction (* $p < 0.002$). The upper triangle shows the corresponding p-values.

The lesions are slightly elongated, and visual inspection shows that they are generally aligned along the proximo-distal axis, with slight deviations toward the medial or lateral side. This consistent orientation suggests that lesion morphology may be influenced by the fiber arrangement of the anterior bundle of the MCL at its enthesis. Low variability in sphericity further suggests that lesions maintain a consistent overall shape, unlike erosive processes, which typically produce irregular, non-uniform shapes.

Surface metrics (MAD of mean curvature and solidity) appears to vary independently of lesion size. Despite capturing different spatial scales, the metrics were strongly correlated, suggesting coupled patterns of surface variation. Based on visual comparisons, they correspond closely to trabecular bone exposure. High curvature MAD values (and low solidity values) reflect surfaces where individual trabeculae are recognizable, whereas low values (and high solidity values) indicate more uniform, remodeled surfaces. Given that bone remodeling tends toward surface regularization (Martin et al., 2015), this spectrum is consistent with a temporal progression from early-stage lesions with preserved trabecular structure to later stages with extensively remodeled surfaces. Some lesions deviated slightly from this general trend, which may reflect variation in remodeling dynamics.

Perhaps the most notable observation is the exclusive right-sided occurrence of all fourteen lacunar lesions in this study. Moreover, this pattern extends to other cases reported in the literature, including the complete sample studied by Polet et al. (2019), two individuals with unilateral lesions examined by Villotte et al. (2010), and a humerus of uncertain association described by Villotte (2009). A similar right-sided lesion was observed in the Mary Rose individual FCS No. 7 (Knüsel, pers. obs.), alongside a complete medial epicondylar avulsion on the left side (Knüsel, 2011).

Due to the commingled context of the Neolithic samples, laterality could not be assessed at the individual level. Both assemblages show a roughly equal distribution of left and right humeri (Table 1), but the

number of humeri by side is generally lower than the minimum number of individuals. Therefore, it is likely that not all individuals are represented by both sides, which may introduce some preservation bias. Despite this caveat, the exclusive presence of lesions on right humeri remains striking.

4.3. Etiology

The morphology, consistent location, and laterality of these lesions provide important clues to their etiology. The fact that lesions are consistently found at the anterior bundle of the MCL origin indicates that their formation is likely related to local mechanical or biological factors rather than random bone changes. The uniformity in shape and orientation likewise points to a specific, localized mechanism rather than a heterogeneous degenerative process. Furthermore, their appearance differs from the characteristic changes seen in degenerative, age-related change (Milz et al., 2004; Resnick and Niwayama, 1983) and in diffuse idiopathic skeletal hyperostosis (Resnick et al., 1975), thereby ruling out the “bone formers” hypothesis (Rogers et al., 1997).

The directional patterning of the lesions further supports a behaviorally driven mechanism. Approximately 90% of the population is estimated to be right-handed (Fitch and Braccini, 2013; Papadatou-Pastou et al., 2020), a proportion that appears to have been rather stable in past human populations (Uomini and Ruck, 2018). In the Neolithic period, for example, this is reflected in humeral diaphysis asymmetry (Sládek et al., 2018) and tool production patterns (Dominguez-Ballesteros and Arrizabalaga, 2015). Handedness therefore provides a plausible explanation for the highly asymmetrical occurrence of lacunar lesions. When combined, these patterns make an activity-related etiology the most likely explanation for these lesions.

4.4. The partial avulsion hypothesis

In this context, the partial avulsion hypothesis, proposed by Villotte (2009), and elaborated on by Villotte et al. (2010) and Polet et al. (2019), is compelling. The location and morphology of the lesions correspond well with clinical descriptions (Fig. 5), and their close association with the throwing mechanism is consistent with the behavioral pattern observed.

Several lesion characteristics support this interpretation. The comparatively small surface areas observed may indicate that only specific fibers, rather than the entire anterior MCL bundle, were involved. The anterior bundle is commonly subdivided into functional anterior and posterior bands (Callaway et al., 1997; Floris et al., 1998; Schwab et al., 1980), with the anterior band serving as the primary restraint to valgus stress (Hotchkiss and Weiland, 1987; Morrey et al., 1991; Morrey and An, 1983).

Certain fibers of this bundle have been described as remaining taut throughout the full range of motion (Callaway et al., 1997; Fuss, 1991; Jackson et al., 2016; Ochi et al., 1999; Regan et al., 1991), with Armstrong et al. (2004) identifying a near-isometric region on the lateral aspect of the attachment site of the anterior bundle, close to the anatomic axis of rotation. A similar region was identified *in vivo* by Kholinne et al. (2018), who noted its correspondence to Fuss's (1991) “guiding bundle”. The lesion locations observed in the current sample correspond closely to this near-isometric region. This pattern suggests that the smaller lesions may involve primarily near-isometric fibers, whereas the larger lesions may involve the entire bundle. Because near-isometric fibers remain taut throughout the full range of motion and would experience the greatest cumulative stress, they are likely the

most susceptible to microtrauma, and, ultimately, avulsion.

An important consideration is whether size comparisons with adult data remain valid for the immature medial epicondyle. Although the location of the anterior bundle attachment site remains constant relative to the physis (Larsen et al., 2013; Zell et al., 2013), the underlying substrate differs in growing individuals and growth-related changes must be considered. Before ossification, the medial epicondyle consists of unossified hyaline cartilage, with a secondary ossification center (SOC) appearing around 4–8 years (Miyazaki et al., 2017; Patel et al., 2009; Schaefer et al., 2009). The SOC gradually enlarges by replacing the surrounding layer of vascularized unossified growth cartilage (Nguyen and Caine, 2024). By skeletal maturation, typically reached between 13 and 18 years, this cartilage is fully replaced by bone. Proximal MCL partial avulsion fractures occur during this window, after the appearance of the SOC but before complete maturation (Lee et al., 2025).

While healing outcomes of complete avulsion have been described (e.g., Farsetti et al. 2001), there appears to be no literature addressing partial avulsions or fragmented medial epicondyles. This raises several questions regarding how these injuries might evolve during development. When avulsion involves bone, the fragment would include both developing bone and overlying growth cartilage (Dwek, 2016; Sugimoto and Ohsawa, 1994). Because cartilage has limited inherent repair capacity (Green, 2020; Martin et al., 2015), nonunion could result in a persistent defect, while the remainder of the SOC continues ossification. Within this framework, one possible explanation for the observed variability in lesion size is the timing of injury. As ossification progresses, the relative proportion of the epicondyle occupied by the defect may alter, such that injuries that occur earlier in life ultimately occupy a smaller proportion of the mature epicondyle due to subsequent growth. However, the presence of lesions with extremely small surface areas, e.g., Petit Morin 21212 (1.88 mm²), raises the possibility that variation in the extent of fiber involvement could also play a role. In that case, variability may relate to differences in injury mechanism, such as elbow position during valgus stress (Safran and Baillargeon, 2005), or acute versus chronic loading, as well as age-related factors, including heterogeneity in enthesis maturation at the time of injury.

The observed depth values align with the thickness of the cartilaginous layer surrounding the SOC. Yoshizawa et al. (2018) found mean values ranging from 3.25 mm to 0.61 mm in 9- to 14-year old baseball players, with cartilage thinning progressively with age. Lesion depth may therefore reflect not only the size of the avulsed bone fragment, but also the thickness of the overlying cartilage removed with it. Given cartilage's limited repair capacity, a thicker cartilaginous layer at the time of injury would result in a deeper persistent defect. Variation in lesion depth may thus reflect the age at which the fracture occurred, with deeper lesions corresponding to earlier injuries when the cartilaginous layer was thicker.

The observed elongation may reflect the variable shapes of the enthesal footprints, which have been reported as round, elongated, or even triangular (Berg and DeHoll, 1997; Buck et al., 2010; Camp et al., 2018; Dugas et al., 2007; Frangiamore et al., 2018; Fuss, 1991; Ikezu et al., 2020). Alternatively, if lesions primarily involve fibers, their directionality could represent shearing along the fiber orientation of the anterior bundle of the MCL, potentially linked to valgus stress applied at specific elbow angles. However, the independence of size and elongation would imply this is less likely.

The right-sided bias observed in the archaeological samples is consistent with the partial avulsion hypothesis. By the age at which these fractures typically occur, handedness in children is considered to be ‘adult-like’ (Scharoun and Bryden, 2014), and throwing is one of the most consistent expressions of handedness (Loffing et al., 2014). This supports the idea that use of the dominant limb in throwing activities during childhood may account for the right-sided lacunar lesions observed in the sample.



Fig. 5. Anterior-posterior radiograph of the elbow in a 15-year-old male baseball pitcher showing a proximal medial collateral ligament (MCL) avulsion fracture at the time of injury. Arrowhead indicates the proximal MCL avulsion fragment.

(Adapted from Lee et al., 2025, Fig. 1A).

4.5. Broader patterns

These lesions are relatively rare, occurring in 7% of Paris Basin humeri ($N = 14/215$). Polet et al. (2019) and Villotte et al. (2010) reported similar prevalence rates (5%) in their Neolithic ($N = 9/196$) and Upper Palaeolithic ($N = 2/38$) samples, respectively. This consistency across studies suggests that such lesions, while rare, may represent a recurring phenomenon rather than isolated cases.

In the general pediatric population, medial epicondylar avulsion fractures are also relatively rare, with annual incidence of 3–5 per 100 000 children (7–15 years old) in Finland for complete avulsions (Grahm et al., 2021). Partial avulsions are even less common, accounting for only four cases among 116 medial epicondyle injuries in that cohort. In contrast, higher frequencies have been documented in populations with repetitive valgus loading, such as youth baseball players. Fragmented medial epicondyles were identified in 8.4% of pitchers in the United States ($N = 50/595$) and 19.2% of players in Taiwan ($N = 66/343$) (Gugenheim et al., 1976; Hang et al., 2004). These data indicate that while partial avulsions are uncommon in the general pediatric population, they can be markedly more frequent in activity groups experiencing repeated stress from throwing.

In the archaeological samples, an approximate individual-level frequency can be estimated by restricting analysis to right humeri, as all identified lesions occur on that side. Using this approach, frequencies range from 10% to 13% (this study; Polet et al. 2019; Villotte et al. 2010). Although these samples are not directly comparable with the clinical data, these values fall within the range documented for modern high-load groups. Moreover, these estimates are conservative, as nonunion represents one possible outcome of such injuries. This underscores that the concentration of such lesions within single assemblages is unlikely to be incidental if they reflect partial avulsion injuries.

4.6. Potential for activity reconstruction

These lacunar lesions have considerable potential as activity-related skeletal changes. Their strong connection to the throwing motion offers insight into behaviors performed during youth, while their persistence after remodeling means they remain visible throughout life, independent of age-related onset. This feature is a major advantage over other entheses-based methods for activity reconstruction, where age-at-death has well-known effects (e.g. Shaibani et al. (1993), Villotte and Santos (2023)), that are further complicated by the challenges of age-at-death estimation. In addition, their specificity permits their use with commingled assemblages - where information on the individual is absent - to infer population-level patterns.

These lesions could also be explored in combination with other approaches (e.g., cross-sectional geometry, osteoarthritis, enthesal changes), providing a complementary perspective on activity during an individual's life, from youth into adulthood. Such analyses could, however, benefit from non-commingled samples in which age-at-death can be more reliably controlled.

These archaeological cases also provide data that could complement clinical studies. The specificity of lesion location indicates a distinct pattern in ligament involvement that could provide insights into the biomechanics of this pathological condition, and inform surgical planning. It also offers a basis for examining related structural features of the elbow, including internal bone architecture and localized biomechanical responses. Furthermore, these cases show long-term outcomes not typically documented in clinical follow-ups, and may reflect differential healing patterns.

4.7. Limitations

Nevertheless, several limitations must be acknowledged. The sample is small, which is unfortunately common when studying archaeological collections, particularly for rare features. Expanding the application of

the protocol to larger and more diverse samples is essential for further validation. The dependence on mesh resolution also necessitates caution when comparing data from different imaging modalities or scanning equipment. The equipment used in this study (Artec Space Spider) captures data at a 3D resolution of 0.1 mm, which could be considered a practical benchmark for this protocol. Coarser resolutions may still yield usable results, but, given the scale of the features measured, could introduce measurement error representing a substantial proportion of the values being quantified. Before applying this protocol to models acquired through different sources or techniques, the comparability of results should be verified. The exploratory nature of this study establishes a foundation that will require continued refinement as the approach is tested across varied preservation conditions, collections, and imaging modalities.

The metric analyses relied on absolute measurements rather than values scaled to individual bone or attachment site. Although this does not account for individual size differences, most lesions fall below the expected range, suggesting the main conclusions of this study remain valid. Future studies could explore these allometric relationships more systematically.

More fundamentally, direct clinical validation of the association between partial avulsion fractures and lacunar lesions is still lacking. Such confirmation is necessary to fully integrate this lesion into reconstructions of past activity. Nonetheless, the convergence of anatomical location, morphological characteristics, laterality patterns, and population-level frequencies provides compelling support for the partial avulsion hypothesis and its utility in activity reconstruction.

5. Conclusion

This study provides the first quantitative characterization of lacunar lesions at the medial epicondyle and introduces a reproducible, non-invasive protocol for extracting and analyzing their morphology. The lesions examined showed consistent location and overall form, but notable variation in size, flattening, and surface texture. Depth values generally fell within the range of cortical bone thickness, and surface areas were smaller than the full footprint of the anterior bundle of the MCL, suggesting involvement of specific ligament fiber regions. Surface characteristics ranged from exposed trabeculae to smoothly remodeled bone, suggesting different stages of healing. Their exclusive right-side occurrence further indicates a potential relationship with handedness and asymmetric loading.

The observed patterns align with clinical descriptions of proximal MCL partial avulsion fractures in youth throwing athletes, highlighting a plausible etiology for these lesions. Confirmation of this hypothesis in clinical cases would permit full integration of these lesions into activity reconstruction research, opening avenues for interpreting past behavior, social roles, and skill acquisition from skeletal remains. Testing the protocol across broader samples would further deepen our understanding of lesion variability, while adaptation to additional imaging modalities could enhance clinical and archaeological applicability.

Beyond archaeological applications, these features could complement clinical studies on long-term skeletal responses to such injuries and be examined within the broader context of elbow morphology and biomechanics to identify potential adaptive patterns. By bridging these perspectives, this approach can provide a more comprehensive understanding of medial epicondylar partial avulsion fractures as a distinct pathological and biomechanical phenomenon, with the potential to advance both fields.

CRediT authorship contribution statement

Elle B.K. Liagre: Data curation (lead), Formal analysis (lead), Funding acquisition (equal), Investigation (lead), Methodology (lead), Visualization (lead), Writing – original draft (lead), Writing – review and editing (lead). **Christopher J. Knüsel:** Formal analysis (supporting),

Funding acquisition (equal), Investigation (equal), Methodology (equal), Supervision (equal), Writing – original draft (equal), Writing – review and editing (equal). **Sébastien Villotte**: Conceptualization (lead), Formal analysis (supporting), Funding acquisition (equal), Investigation (equal), Methodology (equal), Supervision (equal), Writing – original draft (equal), Writing – review and editing (equal).

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT–4 (OpenAI) in order to edit language for clarity and conciseness, and assist with debugging code. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Funding statement

This study received financial support from the French government in the framework of the University of Bordeaux's IdEx "Investments for the Future" program/GPR "Human Past", and from the Département des Sciences archéologiques of the University of Bordeaux (AAP n°4, 2023) through the project "From fragments to behaviour". We also gratefully acknowledge the UMR5199 PACEA for additional financial support.

Declaration of Competing Interest

The authors have no known competing interests to declare.

Acknowledgements

We thank the teams who facilitated access to the collections and 3D data. At the Musée de l'Homme (MNHN), we are grateful to scientific curator Aline Thomas and to Liliana Huet and Véronique Laborde for their technical assistance. At the RBINS, we thank scientific curator Patrick Semal, Caroline Polet, and Eric Dewamme for their support. We also acknowledge the authors of [Polet et al. \(2019\)](#), in particular Merlin Leunda-Martiarena, for generously providing their data, and the authors of [Lee et al. \(2025\)](#) for kindly granting permission to reproduce their figure. We thank Sacha Kacki (UMR5199 PACEA), who commented upon an earlier version of this manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ijpp.2026.05.002](https://doi.org/10.1016/j.ijpp.2026.05.002).

Data availability

The 3D models analyzed in this study are property of the institutions housing the original remains, namely the Musée de l'Homme (MNHN) and the Royal Belgian Institute of Natural Sciences. Complete results of lesion extraction and associated metrics are provided in Appendix A (A.3 and A.4). The scripts for lesion extraction and for applying the screening protocol are available in Appendices B and C and on GitHub (<https://github.com/ElleLiagre/medial-epicondyle-lacunar-lesions>). Additional scripts used for data processing and statistical analysis are available in the same GitHub repository.

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