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Horse riding and the shape of the acetabulum: Insights from the bioarchaeological analysis of early Hungarian mounted archers (10th century)

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Abstract

Horse riding is a human activity that has particularly interested bioanthropologists and paleopathologists working on the reconstruction of activities from skeletal changes in ancient populations. However, various sample and methodological limitations, such as the absence of direct evidence connecting the individuals and the activity, result in a lack of confidence regarding what changes should be included in the so-called horse riding syndrome. Focusing on the ovalization of the acetabulum, regularly mentioned in literature, we analyzed comparative samples of presumed riders and non-riders to evaluate its reliability for the identification of horse riding.

We relied on a Hungarian Conquest period collection (10th century CE), including several individuals associated with horse riding equipment or horse bones in the graves. Direct and easily repeatable measurements were used to calculate an index of ovalization of the acetabulum (IOA). The index values were compared according to the presence or absence of archaeological deposit. An extra-group of presumed non-riders from the documented Luís Lopes Skeletal Collection (Lisbon) was used for comparison. Early Hungarians buried with horse-related grave goods exhibited a higher overall IOA compared with the ones without and those known not to ride ($p = 0.049$ in the latter case, with left and right values combined).

Our results suggest that the ovalization of the acetabulum may indeed be a promising indicator to be included in a set of markers for horse riding. The analysis of further different types of pathological and nonpathological skeletal changes (e.g., joint and entheseal changes) will contribute to a more reliable identification of horse riders in anthropological collections.

KEYWORDS

activity-related skeletal changes, anthropometrics, bioarchaeology, equestrian, hip, Hungarian Conquest period, morphology

1 | INTRODUCTION

Bone changes of different types have been interpreted for decades as activity, occupational, or stress markers, with an important step forward from the 1980s (e.g., Capasso, Kennedy, & Wilczak, 1999; Dutour, 1986; Hawkey & Merbs, 1995; Henderson & Alves Cardoso, 2013; Jurmain, 1999; Kennedy, 1989; Knüsel, 2000; Mariotti, Facchini, & Belcastro, 2004; Milella, Alves, Assis, Perréard Lopreno, & Speith, 2015; Niinimäki, 2012; Pálfi & Dutour, 1996; Perréard Lopreno, 2007; Villotte et al., 2010). Among all human activities, horse riding brought profound and lasting changes in the history of human cultural evolution concerning major aspects such as trade, settlement, warfare, subsistence, social organisation, and political ideology (Anthony, 2007). Archaeological evidence suggests that horse domestication likely started in the Botai culture, in the Kazakh steppe, around 3,500 years BCE (Outram et al., 2009).

Analyses of horse skeletal remains identified promising markers of equestrian activity (Bulatović, Bulatović, & Marković, 2014; Pluskowski, Seetah, & Maltby, 2010; Taylor, Bayarsaikhan, & Tuvshinjargal, 2015), bit wear being even often considered as a direct and unmistakable sign of riding (Anthony, 2007). Unfortunately, the existence of such a direct link between specific skeletal changes and the practice of horse riding has not been yet unarguably demonstrated regarding humans. Bioarchaeological research on horse riding has developed strongly, with a growing interest from the beginning of the 1990s especially and the early contributions of Miller on historic Native American Omaha and Ponca skeletal remains (Miller, 1992; Miller & Reinhard, 1991; Reinhard, Tiezen, Sandness, Beiningen, & Miller, 1994) and Pálfi on a Hungarian cemetery of the 10th century CE (Pálfi, 1992, 1997; Pálfi & Dutour, 1996).

"Horse(back) riding syndrome" commonly refers to a combination of skeletal changes repeatedly observed and interpreted as signs of riding. It covers various types of pathological and nonpathological changes, which were previously reviewed (Baillif-Ducros, Truc, Paresys, & Villotte, 2012; McGrath, 2015). To summarise, they can be categorised in different groups of indicators: (a) spinal changes: osteoarthritis, Schmorl's nodes, and thoracic and lumbar wedging (e.g., Baillif-Ducros et al., 2012; Blondiaux, 1994; Karstens, Littleton, Frohlich, Amgaluntugs, & Pearlstein, 2017; Reinhard et al., 1994; Üstündağ & Deveci, 2011; Wentz & de Grummond, 2009); (b) extraspinal joint changes: coxarthrosis and gonarthrosis (e.g., Baillif-Ducros & McGlynn, 2013; Fornaciari et al., 2014); (c) entheseal changes: adductor, gluteal, quadriceps, hamstring, external obturator, and soleus muscles (e.g., Belcastro, Facchini, Neri, & Mariotti, 2001; Blondiaux, 1994; Djukic, Miladinovic-Radmilovic, Draskovic, & Djuric, 2018; Miller, 1992; Pálfi, 1992; Tichnell, 2012); (d) morphological variations: femoral head–neck junction changes (Poirier's facet, plaque, and cervical fossa of Allen) and elongated acetabula (e.g., Baillif-Ducros et al., 2012; Courtaud & Rajev, 1998; Dutour & Buzhilova, 2014; Erickson, Lee, & Bertram, 2000; Molleson & Blondiaux, 1994; Pálfi, 1992); and (e) traumatic lesions resulting from riding accidents, at the clavicula, radius/ulna, carpal bones, skull, tibia/fibula, and ribs (e.g., Anđelinović, Anterić, Škorić, & Bašić, 2015; Khudaverdyan, Khachatryan, & Eganyan, 2016; Ki et al., 2018).

The lack of specificity of the markers and problems of equivalence between contemporary references and historical cases are among the many limitations to the use of skeletal changes as activity markers in archaeological samples (e.g., Dutour, 1992; Jurmain, Alves, Henderson, & Villotte, 2012). Although clinical and sport medicine data may provide valuable information and guide the bioarchaeological analyses, the existence of a clear archaeological, historical, or ethnographic context is crucial to support the link between skeletal changes and a specific activity. Unfortunately, the contextual data provided in the studies are often insufficient. Although it must not be considered as absolute evidence, only the presence of archaeological goods related to equestrian activity in the grave may represent a robust indicator that one individual among others might be a rider. Furthermore, the studies relying on direct archaeological evidence rarely concern more than a handful of subjects (when not only one), which prevents from performing systematic observations and identifying reliable specific changes. With these aspects in mind, we aim to contribute to improving the recognition of horse riding-related skeletal changes to identify more reliably the presence of riders in anthropological collections.

Among all skeletal changes related to horse riding, we focused here on the modification of the shape of the acetabulum, indicator which is quite consensual (Baillif-Ducros & McGlynn, 2013; Baillif-Ducros et al., 2012; Courtaud & Rajev, 1998; Erickson et al., 2000; Fornaciari et al., 2014; Larentis, 2017; Miller, 1992; Miller & Reinhard, 1991; Pálfi, 1992; Pálfi & Dutour, 1996; Reinhard et al., 1994; Üstündağ & Deveci, 2011). Changes consist in an ovalization of the acetabulum or an expansion/elongation of the rim, which can be anterior-superior or superior. The results of a visual examination greatly depend on the experience of the observer, thereby limiting the reliability and reproducibility of the observations. Therefore, different methodologies have been experimented to identify precise, reliable, and repeatable criteria to describe the acetabular shape changes. Erickson et al. (2000) performed a Fourier analysis on adult males from two Native American Arikara populations, respectively, presumed riders (24 acetabula) and non-riders (37 acetabula). They observed significant differences (set level of $\alpha = 0.1$) between both groups, with expanded anterior-superior acetabular rims in the presumed riders group. Later on, a morphometric analysis of the acetabular rim shape performed with the use of 3D scans on samples of ancient Mongolian pastoralists (34 coxae) revealed significant differences between the Scythians and the other Mongolian samples, but not with a reference collection (Eng, Baker, Tang, Thompson, & Gomez, 2012). According to the authors, these results could be related to the riding style or sample and methodological limitations. Finally, through direct measurements and the calculation of an index, one probable Merovingian horse rider revealed very elongated acetabula compared with a reference collection (Baillif-Ducros et al., 2012), whereas, with the same method, Sarry, Courtaud, and Cabezuelo (2016) did not observe particularly elongated acetabula in a La Tène period mass burial associating eight horses and eight human individuals. However, bone preservation was a limiting factor. This last methodological approach was the one adopted in this paper.

The position that is privileged by riders is characterised by a pelvis in retroversion (tilted backward) and a diminished lumbar lordosis that allows a better absorption of vertical stresses (Auvinet, 1999; Humbert, 2000). Baillif-Ducros et al. (2012) explain how changes in the acetabular shape can result from pressure of femoral head on the superior and anterior-superior parts of the acetabula when the hip is in a rider position (Figure 1).

Historical and archaeological sources attest that Hungarian, or Magyar, tribes conquered the Carpathian Basin at the end of the 9th and the beginning of the 10th century with powerful armies of mounted archers, resulting in the foundation of the Kingdom of Hungary by Stephen I in the year 1000 or 1001 (Engel, 2001). In many cemeteries from that period, pieces of archery and horse riding equipment, as well as horse bones, were deposited in the graves (Révész, 2003). The close association between these items and the skeletons, together with the

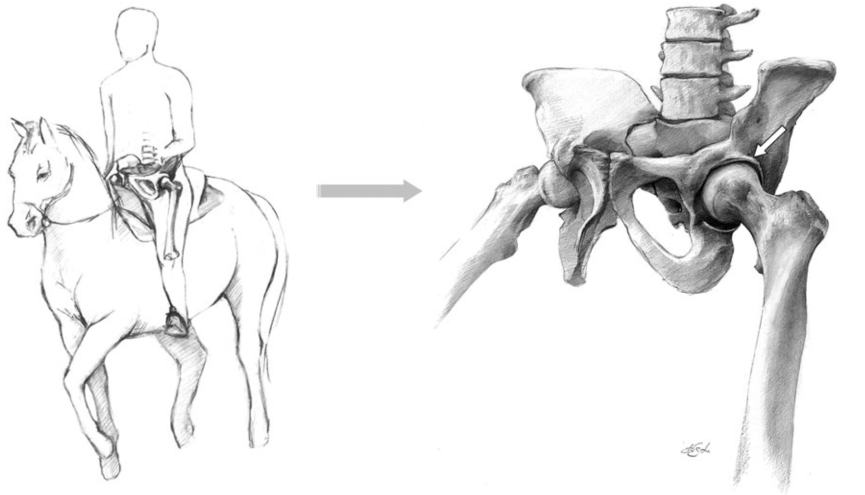

FIGURE 1 Reconstruction illustrating the possible contact between the femoral head and the superior part of the acetabulum (white arrow) in the riding position, with the pelvis in retroversion. Drawing by Luca Kis

well-known historical context, allows postulating that the concerned individuals were riders. This population is, therefore, one of the most relevant for methodological investigations of activity-related skeletal changes, especially those regarding horse riding, already identified in skeletal remains of medieval Hungarians (Józsa, Pap, & Fóthi, 1991; Pálfi, 1992; Pálfi & Dutour, 1996; Pap, 1985).

We followed an approach previously applied in studies about skeletal changes related to archery and horse riding in particular (Belcastro et al., 2007; Belcastro & Facchini, 2001; Thomas, 2014; Tihanyi et al., 2015), which provided promising results in an exploratory investigation (Berthon et al., 2016). The objective is to analyse the acetabular shape according to the presence or absence of archaeological deposits related to the investigated activity in the graves. Specifically, through a comparison between two subgroups of Hungarians, those with and without a horse-related deposit, as well as with an extra-group of non-riders, we test the hypothesis that the skeletons associated with a funeral deposit present a stronger ovalization of the acetabulum, indicating a horse riding practice.

2 | MATERIALS AND METHODS

2.1 | A unique cemetery from the Conquest period

The cemetery of Sárrétudvari-Hízóföld, located in the Northern Great Plain region of eastern Hungary, was excavated by Ibolya M. Nepper between 1983 and 1985. The graves delivered a large number of archaeological goods, such as jewels, elements of clothing, or weapons (Nepper, 2002). Those included, in particular, pieces of archery (antler bow plates, quivers, and arrowheads) and horse riding equipment (stirrups, bits, girth buckles, and saddles). Several graves also contained horse bones (skull and extremities) that were, in some cases, folded inside the horsehide before being deposited in association with the individuals (Révész, 2003; Figure 2a,b). Sárrétudvari-Hízóföld was exhaustively excavated, well documented and published, and yielded a large number of archaeological remains that can be related to mounted archery. The signs of riding were originally identified in several individuals in a comprehensive paleopathological study (Pálfi, 1992, 1997; Pálfi & Dutour, 1996).

2.2 | Composition of the sample of early Hungarians

Two hundred sixty-two graves from the 10th century provided a total of 265 individuals. According to previous studies, the population is composed of 101 subadults (including three fetuses), 162 adults, and two undetermined subjects (Oláh, 1990; Pálfi, 1997). The reconstruction of activities in past populations involves numerous limitations (e.g., Dutour, 1992; Jurmain et al., 2012). We included in this study only adult males to limit the influence of nonmechanical factors such as hormonal and developmental changes. All adult age categories were included as a large number of subjects could not be categorised due to the state of preservation. Furthermore, age does not seem to be a bias factor for the changes of the acetabular shape as it is not related to degenerative processes (Baillif-Ducros et al., 2012). Erickson et al. (2000) found no significant correlation between the estimated age at death and the coefficients used in a Fourier analysis of the acetabular shape.

On the basis of a reassessed sex diagnosis (Bruzek, 2002; Bruzek, Santos, Dutailly, Murail, & Cunha, 2017; Murail, Bruzek, Houët, & Cunha, 2005) and age estimation (Bruzek, Schmitt, & Murail, 2005; Scheuer & Black, 2004), we identified a total of 67 adult male individuals in the population. In Sárrétudvari-Hízóföld, 32 graves presented an archaeological deposit that can be related to horse riding (equipment, horse bones, or both). There are at least 16 adult males in this group (RD$\oplus$ = "riding deposit"). The other subjects, not included in the study, are one adult female, seven adults with indeterminate sex, seven subadults, and one nonidentified subject. On the other hand, 51 adult males did not have any horse riding equipment or horse bones in their graves (RD$\ominus$ = "no riding deposit").

2.3 | Out-group comparison

The Hungarian samples were also compared with an extra-group for which the intensive and regular practice of horse riding was highly improbable. As the use of horses was very widespread in medieval Hungary, we used, among the limited possibilities available, a European documented skeletal collection with a known sociocultural context. Bearing in mind the potential limits that this might involve,

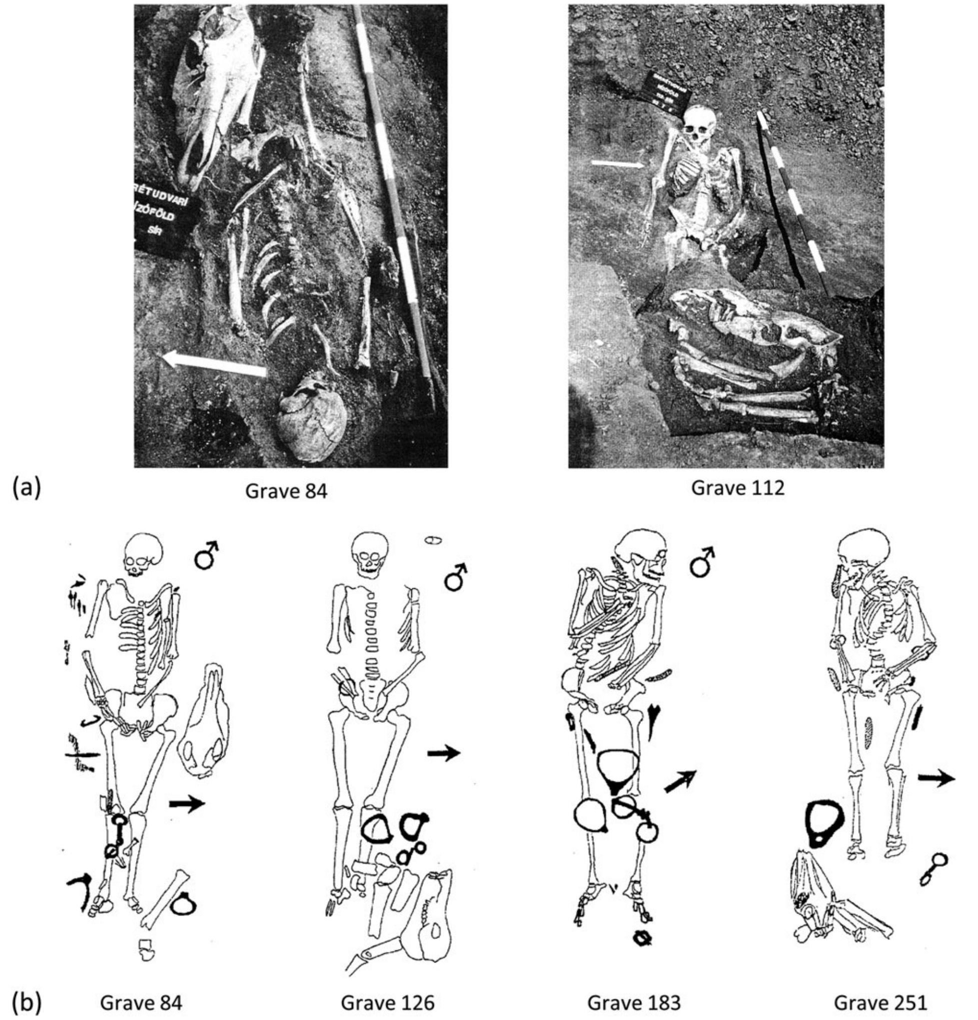

FIGURE 2 Examples of graves from the Hungarian Conquest period cemetery of Sárrétudvari-Hízóföld (10th century) with deposits of horse riding equipment (stirrups, girth buckles, and bits), sometimes associated with horse bones: (a) field photographs and (b) archaeological drawings of graves. From Nepper (2002)

we believed that it represents a valid alternative to provide input to discuss the link between bone changes and horse riding.

We used the Luís Lopes Skeletal Collection, curated in the National Museum of Natural History and Science (MUHNAC), in Lisbon, Portugal. It is composed of 1,692 skeletons with information regarding the sex, age at death, occupation, the cause of death, and so forth (Alves Cardoso & Henderson, 2013; Cardoso, 2006). Our sample was composed of Portuguese people who mainly lived during the first half of the 20th century, in the urban area of Lisbon, with electricity and modern means of transport. It is therefore very unlikely that they were practicing horse riding intensively and on a daily basis. The sample selected in the collection is composed of 47 adult males, aged 20 and older.

2.4 | Metric acquisition

The analysis of the acetabular shape relied on direct measurements of the vertical and horizontal diameters of the acetabulum and the calculation of an index, following the approach taken by Baillif-Ducros et al. (2012) and Sarry et al. (2016) that we also previously experimented (Berthon et al., 2016). Although the Fourier analysis used by Erickson et al. (2000) seems particularly relevant to capture the changes of the shape of the entire acetabular rim, several portions of the acetabular rim are frequently not preserved in ancient materials. Second, the vertical and horizontal diameters allow assessing the anterior-superior rim expansion previously described (Baillif-Ducros et al., 2012; Erickson et al., 2000). Finally, we applied a methodology that does not raise technical and time issues in broad studies of large samples as our results aim to be combined with those of a more comprehensive analysis including the scoring of various other types of observations.

The metrics are well-defined measurements that can be easily taken: VEAC (M22) corresponds to the maximum vertical diameter of the acetabulum, measured as a prolongation of the longitudinal axis of the ischium, and HOAC (M22) is the maximum horizontal diameter, measured perpendicularly to VEAC (Baillif-Ducros et al., 2012; Bräuer, 1988; Bruzek et al., 2017; Murail et al., 2005). The measurements are neither external nor internal but taken precisely on the rim of the acetabulum (Figure 3a).[1] They were used to calculate a vertical/horizontal diameter index (VEAC/HOAC) that allows comparing the acetabular

[1] Bruzek et al. (2017) also provide an illustration of the technique to measure the vertical diameter of the acetabulum in the DSP2 software.

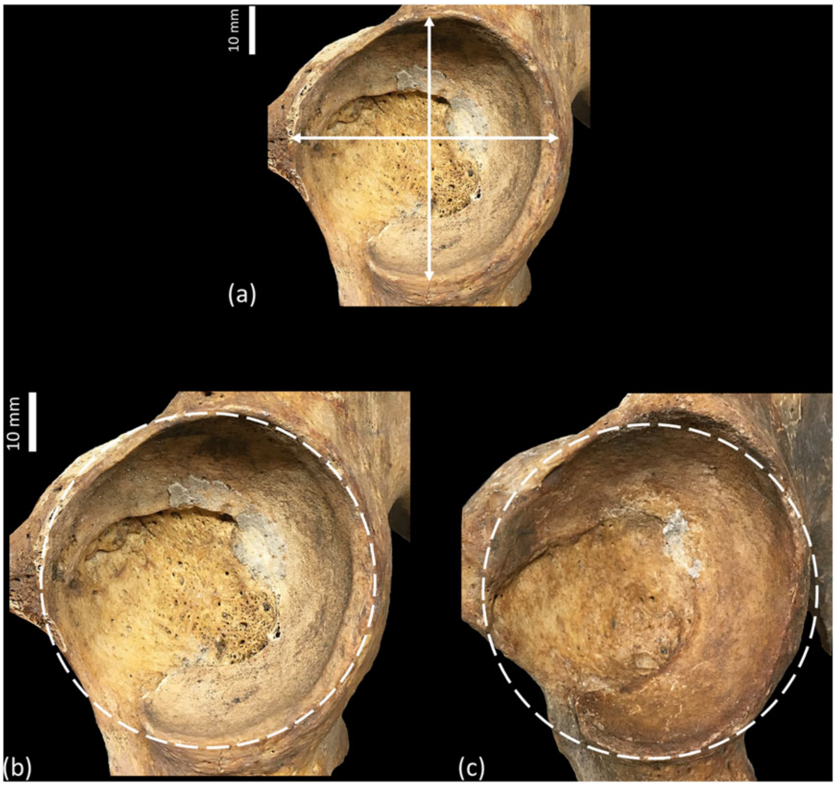

FIGURE 3 (a) Measurements of the maximum vertical and horizontal diameters of the acetabulum, and examples of (b) an acetabulum with a shape intermediate between circular and a horizontal ovalisation (index = 0.971), and (c) an acetabulum exhibiting a strong vertical ovalization (index = 1.082) [Colour figure can be viewed at wileyonlinelibrary.com]

shape between individuals, groups, and studies. This index of ovalization of the acetabulum (IOA) indicates a vertical ovalization when it is higher than 1 (VEAC > HOAC), whereas an IOA close to 1 corresponds to circular acetabula, and an IOA inferior to 1 indicates acetabula wider than their height (HOAC > VEAC; Figure 3b,c). The metrics were recorded with a digital sliding caliper with a precision of 0.1 mm. Both left and right acetabula were measured to address asymmetry questions. We excluded suspected cases of hip dysplasia, subluxation or dislocation, and acetabula showing strong osteophytosis at the rim.

The measurements were taken by one observer (A), without knowledge of the presence or absence of horse riding deposit in the graves, concerning the Hungarian samples. Additionally, a set of measurements was taken by a second observer (B), independently, to evaluate the reproducibility of the measurements. Observer A had more practical experience than Observer B in metrics of the coxal bone, but both observers are experienced in osteometry. The definitions and techniques of measurements were clarified before the test. Observer A also performed a second round of measurements (A2), with an interval of several months, to assess the intraobserver agreement. Observer B's measurements were compared with the A2 set. Thirty coxae from 15 individuals were measured for comparing the vertical and the horizontal diameters, respectively. The individuals were selected randomly among the Hungarian adults, provided that the acetabular rim was well preserved. The concordance between the series of measurements was evaluated using the concordance correlation coefficient that allows quantifying the agreement between two measures of the same variable (Lin, 1989). Values are ranged between −1 and 1, with ±1 denoting a perfect concordance or discordance and 0 denoting an absence of correlation.

2.5 | Statistical analyses

Boxplots were constructed to visually represent the distribution of the indices in each group. The non-parametric Mann–Whitney test was used to assess the differences between the groups. It was applied to the indices, both sides combined and taken independently. We used the non-parametric Wilcoxon test, applied on the paired indices in each group, to evaluate the asymmetry (Nikita, 2017). The difference between both sides' indices was also calculated (right index–left index) and compared between the groups. The set significance level was $\alpha = 0.05$. The analyses were performed using SPSS Statistics 25.

3 | RESULTS

3.1 | Interobserver and intraobserver agreement evaluation

There was a very good concordance between the series of measurements taken by Observer A and Observer B for the diameters of the acetabulum (Table 1). The mean absolute difference was indeed close to 1 mm in each case, and the concordance correlation coefficient was superior to 0.900, which is considered as very satisfying. Additionally, we observed an excellent concordance for both diameters between the two series of measurements taken by Observer A, with a mean absolute difference not higher than 0.5 mm and concordance correlation coefficients superior to 0.970 (Table 1). The concordance was almost perfect in the case of the horizontal diameter, with a coefficient of 0.993.

TABLE 1 Interobserver (A–B) and intraobserver (A1–A2) agreement in the measurement of the maximum diameters of the acetabulum (n = 30)

	Observer A–Observer B		Observer A1–Observer A2	
	Vertical diameter	Horizontal diameter	Vertical diameter	Horizontal diameter
Mean of each series (mm)	57.5 (A) 57.8 (B)	56.1 (A) 55.0 (B)	57.6 (A1) 57.5 (A2)	56.1 (A1) 56.1 (A2)
Mean difference (mm)	−0.3	1.1	0.2	−0.1
Mean absolute difference (mm)	0.8	1.1	0.5	0.3
Concordance correlation coefficient	0.949	0.911	0.979	0.993

Note. A concordance correlation coefficient close to 1 indicates a strong concordance between two series of values.

3.2 | Asymmetry in each group and differences between groups

The preservation of the coxae was a limiting factor in the Hungarian archaeological groups. The composition of the samples of acetabula for which the index could be calculated is presented in Table 2.

As a first step, we evaluated the bilateral asymmetry of the acetabular shape, excluding the individuals with only one observable acetabulum (Table S1 and Figure 4). In all cases, the acetabula were not circular on average, but they tended to be a bit higher than wide (IOA lightly superior to 1), which corresponds to a normal morphology (Bräuer, 1988). In all groups, we observed a bilateral asymmetry, although it was not significant (Wilcoxon signed-ranks test: RD⊕: $Z = -0.943$, $p = 0.345$; RD⊖: $Z = -1.542$, $p = 0.123$; EXTRA: $Z = -1.451$, $p = 0.147$), but this asymmetry was inverted in the case of the RD⊕ group compared with the RD⊖ and EXTRA groups. Although the median and the variation were greater on the left side concerning the RD⊕ group, the spread of the values appeared to be higher on the right side in the two other groups (median and interquartile range in particular).

TABLE 2 Composition of the samples of observable acetabula in the Hungarian archaeological groups with riding deposit (RD⊕) and without riding deposit (RD⊖), and in the extra-group (EXTRA)

			Observable acetabula			
Sample groups	Adult males	Adult males with at least one observable coxal bone	Left	Right	Total	Pairs of observable acetabula
RD⊕	16	12	8	10	18	6
RD⊖	51	33	26	29	55	22
EXTRA	47	46	43	42	85	39
Total	114	91	77	81	158	67

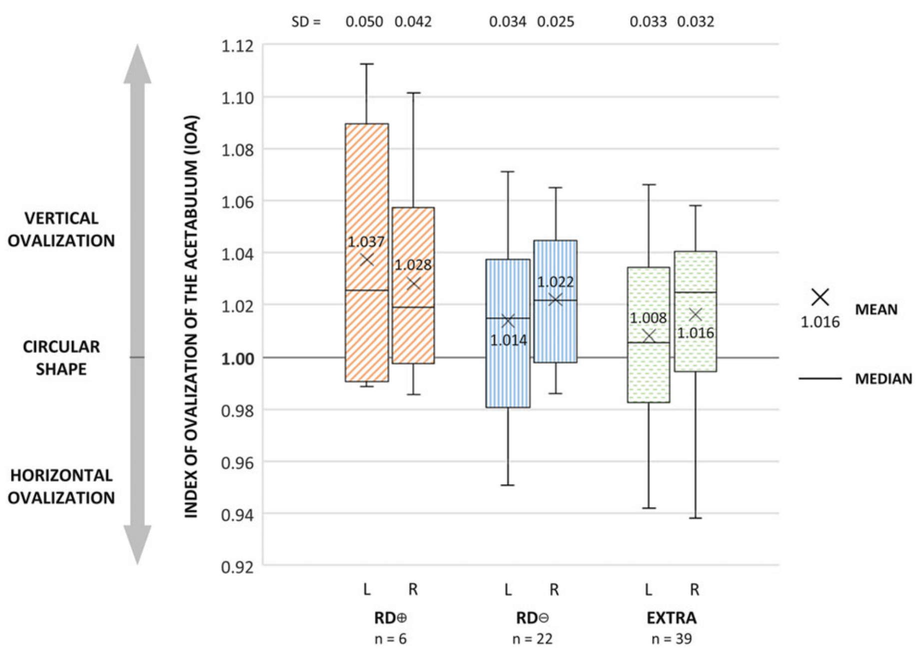

FIGURE 4 Asymmetry of the index of ovalization (vertical/horizontal diameter) of the acetabulum (IOA) on paired coxae of the Hungarians with riding deposit (RD⊕) and without riding deposit (RD⊖), and in the extra-group (EXTRA). *SD* = standard deviation [Colour figure can be viewed at wileyonlinelibrary.com]

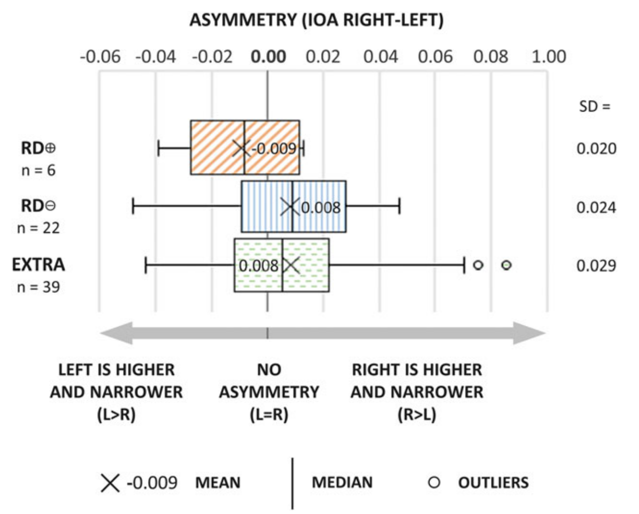

FIGURE 5 Difference between the right and left indices of ovalization of the acetabulum (IOA) in the Hungarians with riding deposit (RD⊕) and without riding deposit (RD⊖), and in the extra-group (EXTRA; a positive result indicates right values superior to the left values, and a negative result indicates the contrary). *SD* = standard deviation [Colour figure can be viewed at wileyonlinelibrary.com]

Thus, the acetabula tended to exhibit a vertical ovalization more important on the left side in the RD⊕ group and on the right side in the RD⊖ and EXTRA groups.

We also calculated the difference between the right and left index values for each pair of acetabula to compare the degree and direction of bilateral asymmetry between the groups (Table S1 and Figure 5). The tendencies concerning the bilateral asymmetry were confirmed, with a negative median in the RD⊕ group and a positive median in the RD⊖ and EXTRA groups, respectively. The left acetabula in the RD⊕ group appeared to be higher and narrower than the right ones, but they tended to be shorter and wider than on the right side in the RD⊖ and EXTRA groups. Although the differences between groups were not significant (Mann–Whitney test: RD⊕/RD⊖: U = 38, p = 0.117; RD⊕/EXTRA: U = 76, p = 0.171; RD⊖/EXTRA: U = 389, p = 0.548, two-tailed), we observed that the direction of the asymmetry differed between the RD⊕ and the other groups.

3.3 | Differences of acetabular shape between groups

The index values were then compared between each group, for the left and right acetabula taken separately and combined, without considering if one or both sides were observable in an individual (Table S1 and Figure 6). The RD⊕ group was characterised by a higher median value and a greater variation (especially interquartile range) compared with the RD⊖ and EXTRA groups, which showed similar distributions. The differences were not statistically significant between the groups for the left side (Mann–Whitney test: RD⊕/RD⊖ L: U = 80, p = 0.330; RD⊕/EXTRA L: U = 125.5, p = 0.228; RD⊖/EXTRA L: U = 520.5, p = 0.634, two-tailed) and for the right side (RD⊕/RD⊖ R: U = 108, p = 0.234; RD⊕/EXTRA R: U = 146.5, p = 0.140; RD⊖/EXTRA R: U = 566.5, p = 0.619, two-tailed). When left and right indices were combined, the differences were not significant between RD⊕ and RD⊖ groups (U = 374.5, p = 0.123) and RD⊖ and EXTRA groups (U = 2158.5, p = 0.445), but the differences observed between RD⊕ and EXTRA groups were statistically significant (U = 538.5, p = 0.049, two-tailed).

4 | DISCUSSION

Our results must be regarded in close connection with the archaeological data concerning the Hungarian samples. In a cemetery of a semi-

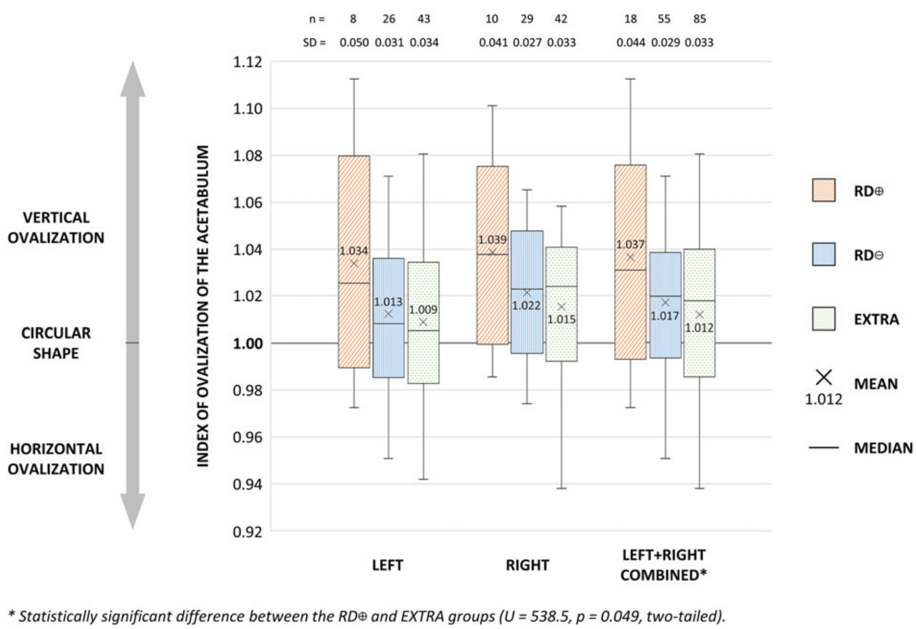

FIGURE 6 Index of ovalization (vertical/horizontal diameter) of the acetabulum (IOA), by side and combined, on unpaired coxae of the Hungarians with riding deposit (RD⊕) and without riding deposit (RD⊖), and in the extra-group (EXTRA). *SD* = standard deviation [Colour figure can be viewed at wileyonlinelibrary.com]

nomadic population, known for using armies of mounted archers, the presence of horse riding equipment or horse bones in the graves of some individuals strongly suggests that they were riders during their life. However, it also raises several hypotheses regarding the funerary practices (Härke, 1997) as the deposits might concern only the riders or a part of them or not be related with riding but with various social or religious aspects instead. The elements originally deposited in the graves might also not have been preserved (e.g., taphonomic processes, disappearance of organic materials, and lootings). Thus, it must be acknowledged that some individuals who initially had a deposit in their grave may have been finally included in the RD⊖ group, contributing to mitigate significant differences between both Hungarian groups.

Our study revealed that the subjects from burials with archaeological items related with horse riding showed an increased overall acetabular vertical ovalisation compared with the ones from the graves with no funeral goods of this type. The IOA values of individuals of this last group are similar to the ones of the extra-group subjects, which almost certainly did not practise horse riding, intensively or regularly.

Although we should not exclude the possibility that this skeletal modification could also result from other postures, it is clearly compatible with horse riding: The vertical ovalisation of the acetabulum results from the pressure applied by the femoral heads on the acetabula when the hip is placed in the rider position (Auvinet, 1999; Baillif-Ducros et al., 2012; Humbert, 2000).

Concerning the difference of direction of the bilateral asymmetry in the case of the RD⊕ group, Molleson (2007) discussed, for instance, that the occurrence of degenerative joint changes on the medial condyle of the left knee in individuals from Spitalfields, London, might be explained by riders mounting a horse from the left side. In addition, experienced riders can develop a pelvic asymmetry in response to back pain (Hobbs et al., 2014). In the context of the Hungarian Conquest period, we might wonder if an asymmetry could result from the movements involved in mounted archery in particular.

Despite strict sampling criteria and bone preservation limitations, this group of 32 ancient Hungarian individuals including at least 16 adult males represents, to the best of our knowledge, the largest homogeneous anthropological sample investigated for horse riding with direct archaeological evidence for each individual. Our promising results support the hypothesis that the vertical ovalisation of the acetabulum may represent a potential indicator for the practice of horse riding, among a set of other skeletal changes that will be tested. The question of the riding style will be another point of interest as we ignore so far if the steppe nomad style of the early Hungarians (Uray-Kőhalmi, 1972) and other riding styles may result in different bone modifications. A future comparative analysis should allow us to identify the possible existence of specific or common features according to the riding style.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

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REFERENCES

Alves Cardoso, F., & Henderson, C. (2013). The categorisation of occupation in identified skeletal collections: A source of bias? *International Journal of Osteoarchaeology*, *23*, 186–196. https://doi.org/10.1002/oa.2285

Anđelinović, Š., Anterić, I., Škorić, E., & Bašić, Ž. (2015). Skeleton changes induced by horse riding on medieval skeletal remains from Croatia. *The International Journal of the History of Sport*, *32*, 708–721. https://doi.org/10.1080/09523367.2015.1038251

Anthony, D. W. (2007). *The horse, the wheel, and language: How Bronze-Age riders from the Eurasian steppes shaped the modern world*. Princeton, NJ: Princeton University Press.

Auvinet, B. (1999). Lombalgies et équitation. *Synoviale*, *83*, 25–31.

Baillif-Ducros C., McGlynn G. 2013. Stirrups and archaeological populations: Bio-anthropological considerations for determining their use based on the skeletons of two Steppe riders. Poster presented at the Schweizerischen Gesellschaft für Anthropologie annual meeting, Neuchâtel, 16 November 2013.

Baillif-Ducros, C., Truc, M. C., Paresys, C., & Villotte, S. (2012). Approche méthodologique pour distinguer un ensemble lésionnel fiable de la pratique cavalière. Exemple du squelette de la tombe 11 du site de « La Tuilerie » à Saint-Dizier (Haute-Marne), VIe siècle. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, *24*, 25–36. https://doi.org/10.1007/s13219-011-0049-8

Belcastro, G., Rastelli, E., Mariotti, V., Consiglio, C., Facchini, F., & Bonfiglioli, B. (2007). Continuity or discontinuity of the life-style in central Italy during the Roman imperial age-early middle ages transition: Diet, health, and behavior. *American Journal of Physical Anthropology*, *132*, 381–394. https://doi.org/10.1002/ajpa.20530

Belcastro, M. G., & Facchini, F. (2001). Anthropological and cultural features of a skeletal sample of horsemen from the medieval necropolis of Vicenne-Campochiaro (Molise, Italy). *Collegium Antropologicum*, *25*, 387–401.

Belcastro, M. G., Facchini, F., Neri, R., & Mariotti, V. (2001). Skeletal markers of activity in the Early Middle Ages necropolis of Vicenne-Campochiaro (Molise, Italy). *Journal of Paleopathology*, *13*, 9–20.

Berthon W., Tihanyi B., Révész L., Coqueugniot H., Pálfi G., Dutour O. 2016. A contribution to the definition of “horse riding syndrome”: The mounted archers from the Hungarian Conquest (Xth century

AD). Poster presented at the 21st European Meeting of the Paleopathology Association, Moscow, 15–19 August 2016.

Blondiaux, J. (1994). À propos de la dame d'Hochfelden et de la pratique cavalière: discussion autour des sites fonctionnels fémoraux. In L. Buchet (Ed.), *Actes des 6e Journées Anthropologiques (Valbonne, 9–11 juin 1992). Dossier de Documentation Archéologique n° 17*. (pp. 97–109). Paris: CNRS Éditions.

Bräuer, G. (1988). Osteometrie. In R. Knussman (Ed.), *Anthropologie, Handbuch der vergleichenden Biologie des Menschen. Zugleich 4. Auflage des Lehrbuchs der Anthropologie begründet von R. Martin. Band I/1. Wesen und Methoden der Anthropologie* (pp. 160–232). Stuttgart: Gustav Fisher Verlag.

Bruzek, J. (2002). A method for visual determination of sex, using the human hip bone. *American Journal of Physical Anthropology*, *117*, 157–169. https://doi.org/10.1002/ajpa.10012

Bruzek, J., Santos, F., Dutailly, B., Murail, P., & Cunha, E. (2017). Validation and reliability of the sex estimation of the human os coxae using freely available DSP2 software for bioarchaeology and forensic anthropology. *American Journal of Physical Anthropology*, *164*, 440–449. https://doi.org/10.1002/ajpa.23282

Bruzek, J., Schmitt, A., & Murail, P. (2005). Identification biologique individuelle en paléoanthropologie. Détermination du sexe et estimation de l'âge au décès à partir du squelette. In O. Dutour, J.-J. Hublin, & B. Vandermeersch (Eds.), *Objets et méthodes en paléoanthropologie* (pp. 217–246). Paris: Comité des Travaux Historiques et Scientifiques.

Bulatović, J., Bulatović, A., & Marković, N. (2014). Paleopathological changes in an early iron age horse skeleton from the Central Balkans (Serbia). *International Journal of Paleopathology*, *7*, 76–82. https://doi.org/10.1016/J.IJPP.2014.07.001

Capasso, L., Kennedy, K. A. R., & Wilczak, C. A. (1999). *Atlas of occupational markers on human remains*. Teramo: Edigrafital.

Cardoso, H. F. V. (2006). Brief communication: The collection of identified human skeletons housed at the Bocage Museum (National Museum of Natural History), Lisbon, Portugal. *American Journal of Physical Anthropology*, *129*, 173–176. https://doi.org/10.1002/ajpa.20228

Courtaud, P., & Rajev, D. (1998). Osteomorphological features of nomadic riders: Some examples from Iron Age populations located in southwestern Siberia. In M. Pearce, & M. Tosi (Eds.), *Papers from the EAA Third Annual Meeting at Ravenna, 1997. BAR International Series 717, Vol. 1, Pre- and protohistory*. (pp. 110–113). Oxford: Archaeopress.

Djukic, K., Miladinovic-Radmilovic, N., Draskovic, M., & Djuric, M. (2018). Morphological appearance of muscle attachment sites on lower limbs: Horse riders versus agricultural population. *International Journal of Osteoarchaeology*. Advance online publication. DOI: https://doi.org/10.1002/oa.2680

Dutour, O. (1986). Enthesopathies (lesions of muscular insertions) as indicators of the activities of Neolithic Saharan populations. *American Journal of Physical Anthropology*, *71*, 221–224. https://doi.org/10.1002/ajpa.1330710209

Dutour, O. (1992). Activités physiques et squelette humain: le difficile passage de l'actuel au fossile. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, *4*, 233–241. https://doi.org/10.3406/bmsap.1992.2319

Dutour, O., & Buzhilova, A. (2014). Palaeopathological study of Napoleonic mass graves discovered in Russia. In C. J. Knüsel, & M. Smith (Eds.), *The Routledge handbook of the bioarchaeology of human conflict* (pp. 511–524). London: Routledge.

Eng J.T., Baker A., Tang P., Thompson S., Gomez J.M. 2012. Morphometric analysis of acetabular rim shape among ancient Mongolian pastoralists. Poster presented at the 19th Annual Meeting of the Midwest Bioarchaeology and Forensic Anthropology Association, Carbondale, IL, October 2012.

Engel, P. (2001). *The realm of St Stephen. A history of medieval Hungary, 895–1526*. London: I.B. Tauris Publishers.

Erickson, J. D., Lee, D. V., & Bertram, J. E. A. (2000). Fourier analysis of acetabular shape in Native American Arikara populations before and after acquisition of horses. *American Journal of Physical Anthropology*, *113*, 473–480. https://doi.org/10.1002/1096-8644(200012)113:4<473::AID-AJPA3>3.0.CO;2-5

Fornaciari, G., Bartolozzi, P., Bartolozzi, C., Rossi, B., Menchi, I., & Piccioli, A. (2014). A great enigma of the Italian Renaissance: Paleopathological study on the death of Giovanni dalle Bande Nere (1498–1526) and historical relevance of a leg amputation. *BMC Musculoskeletal Disorders*, *15*, 301. https://doi.org/10.1186/1471-2474-15-301

Härke, H. (1997). The nature of burial data. In C. K. Jensen, & K. H. Nielsen (Eds.), *Burial and society: The chronological and social analysis of archaeological burial data* (pp. 19–27). Aarhus – Oakville, Conn: Aarhus University Press.

Hawkey, D. E., & Merbs, C. F. (1995). Activity-induced musculoskeletal stress markers (MSM) and subsistence strategy changes among ancient Hudson Bay Eskimos. *International Journal of Osteoarchaeology*, *5*, 324–338. https://doi.org/10.1002/oa.1390050403

Henderson, C., & Alves Cardoso, F. (2013). Special issue "Entheseal changes and occupation": Technical and theoretical advances and their applications. *International Journal of Osteoarchaeology*, *23*, 127–134. https://doi.org/10.1002/oa.2298

Hobbs, S. J., Baxter, J., Broom, L., Rossell, L. A., Sinclair, J., & Clayton, H. M. (2014). Posture, flexibility and grip strength in horse riders. *Journal of Human Kinetics*, *42*, 113–125. https://doi.org/10.2478/hukin-2014-0066

Humbert C. 2000. L'équitation et ses conséquences sur le rachis lombaire du cavalier: à propos de 123 observations (MD thesis). Université Henri Poincaré Nancy I: Nancy.

Józsa, L., Pap, I., & Fóthi, E. (1991). Enthesopathies (insertion tendopathies) as indicators of overuse of tendons and muscles in ancient Hungarian populations. *Annales Historico-Naturales Musei Nationalis Hungarici*, *83*, 269–276.

Jurmain, R. (1999). *Stories from the skeleton. Behavioral reconstruction in human osteology*. Gordon and Breach: Amsterdam.

Jurmain, R., Alves Cardoso, F., Henderson, C. Y., & Villotte, S. (2012). Bioarchaeology's Holy Grail: The reconstruction of activity. In A. L. Grauer (Ed.), *A companion to paleopathology* (pp. 531–552). Chichester, UK: Wiley-Blackwell. https://doi.org/10.1002/9781444345940.ch29

Karstens S., Littleton J., Frohlich B., Amgaluntugs T., Pearlstein K. 2017. Palaeopathological indicators of mounted pastoralism during the Mongolian Bronze Age. Poster presented at the 86th Annual Meeting of the American Association of Physical Anthropologists, New Orleans, LA, 19-22 April 2017.

Kennedy, K. A. R. (1989). Skeletal markers of occupational stress. In M. Y. İşcan, & K. A. R. Kennedy (Eds.), *Reconstruction of life from the skeleton* (pp. 129–160). New York: Alan R. Liss, Inc.

Khudaverdyan, A., Khachatryan, H., & Eganyan, L. (2016). Multiple trauma in a horse rider from the Late Iron Age cemetery at Shirakavan, Armenia. *Bioarchaeology of the Near East*, *10*, 47–68.

Ki, H. C., Shin, E. K., Woo, E. J., Lee, E., Hong, J. H., & Shin, D. H. (2018). Horse-riding accidents and injuries in historical records of Joseon Dynasty, Korea. *International Journal of Paleopathology*, *20*, 20–25. https://doi.org/10.1016/j.ijpp.2017.12.001

Knüsel, C. (2000). Bone adaptation and its relationship to physical activity in the past. In M. Cox, & S. Mays (Eds.), *Human osteology in archaeology and forensic science* (pp. 381–402). London: Greenwich Medical Media Ltd.

Larentis, O. (2017). San Martino di Lundo (Trento) Grave 1. Case study of an individual introducing possibilities markers of horse riding. *Medicina Historica*, *1*, 103–110.

Lin, L. I. K. (1989). A concordance correlation coefficient to evaluate reproducibility. *Biometrics*, *45*, 255–268. https://doi.org/10.2307/2532051

Mariotti, V., Facchini, F., & Belcastro, M. G. (2004). Enthesopathies—Proposal of a standardized scoring method and applications. *Collegium Antropologicum*, *28*, 145–159.

McGrath M.S. 2015. A review of the archaeological and sports medicine literature to determine the biomechanical markers of equestrian activity. University of New Brunswick, Academia.edu. Retrieved from http://www.academia.edu/12094909

Milella, M., Alves Cardoso, F., Assis, S., Perréard Lopreno, G., & Speith, N. (2015). Exploring the relationship between entheseal changes and physical activity: A multivariate study. *American Journal of Physical Anthropology*, *156*, 215–223. https://doi.org/10.1002/ajpa.22640

Miller E. 1992. The effect of horseback riding on the human skeleton. Paper presented at the 1992 Paleopathology Association Meeting, Las Vegas, NV.

Miller E., Reinhard K.J. 1991. The effect of horseback riding on the Omaha and Ponca: Paleopathological indications of European contact. Paper presented at the Plains Anthropology Conference, Lawrence, KS, 13–16 November 1991.

Molleson, T. (2007). A method for the study of activity related skeletal morphologies. *Bioarchaeology of the Near East*, *1*, 5–33.

Molleson, T., & Blondiaux, J. (1994). Riders' bones from Kish, Iraq. *Cambridge Archaeological Journal*, *4*, 312–316. https://doi.org/10.1017/S095977430000113X

Murail, P., Bruzek, J., Houët, F., & Cunha, E. (2005). DSP: A tool for probabilistic sex diagnosis using worldwide variability in hip-bone measurements. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, *17*, 167–176. DOI:10670/1.3p2nbs

Nepper I.M. 2002. Hajdú-Bihar megye 10–11. *századi sírleletei I-II. (Magyarország honfoglalás és kora Árpád-kori sírleletei 3)*: Budapest – Debrecen.

Niinimäki, S. (2012). The relationship between musculoskeletal stress markers and biomechanical properties of the humeral diaphysis. *American Journal of Physical Anthropology*, *147*, 618–628. https://doi.org/10.1002/ajpa.22023

Nikita, E. (2017). *Osteoarchaeology. A guide to the macroscopic study of human skeletal remains*. London, UK: Academic Press.

Oláh S. 1990. *Sárrétudvari-Hízóföld honfoglalás kori temetőjének történeti embertani értékelése* (Doctoral dissertation). József Attila Tudományegyetem: Szeged.

Outram, A. K., Stear, N. A., Bendrey, R., Olsen, S., Kasparov, A., Zaibert, V., … Evershed, R. P. (2009). The earliest horse harnessing and milking. *Science*, *323*, 1332–1335. https://doi.org/10.1126/science.1168594

Pálfi, G. (1992). Traces des activités sur les squelettes des anciens Hongrois. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, *4*, 209–231. https://doi.org/10.3406/bmsap.1992.2318

Pálfi, G. (1997). Maladies dans l'Antiquité et au Moyen-Âge. Paléopathologie comparée des anciens Gallo-Romains et Hongrois. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, *9*, 1–205. https://doi.org/10.3406/bmsap.1997.2472

Pálfi, G., & Dutour, O. (1996). Activity-induced skeletal markers in historical anthropological material. *International Journal of Anthropology*, *11*, 41–55. https://doi.org/10.1007/BF02442202

Pap, I. (1985). A Dabas (Gyón)-paphegyi XI. századi embertani széria (The anthropological series of Dabas (Gyón)-paphegy from the 11th century). In N. Ikvai (Ed.), *Régészeti tanulmányok Pest megyéből. Studia Comitatensia 17* (pp. 387–407). Szentendre: Museums of Pest County.

Perréard Lopreno G. 2007. *Adaptation structurelle des os du membre supérieur et de la clavicule à l'activité: Analyse de l'asymétrie des propriétés géométriques de sections transverses et de mesures linéaires dans une population identifiée (collection SIMON)* (Doctoral dissertation). Université de Genève: Genève.

Pluskowski, A., Seetah, K., & Maltby, M. (2010). Potential osteoarchaeological evidence for riding and the military use of horses at Malbork Castle, Poland. *International Journal of Osteoarchaeology*, *20*, 335–343. https://doi.org/10.1002/oa.1048

Reinhard, K. J., Tiezen, L., Sandness, K. L., Beiningen, L. M., & Miller, E. (1994). Trade, contact, and female health in Northeast Nebraska. In C. S. Larsen, & G. R. Milner (Eds.), *In the wake of contact: Biological responses to conquest* (pp. 63–74). New York: Wiley-Liss.

Révész, L. (2003). The cemeteries of the Conquest period. In Z. Visy (Ed.), *Hungarian archaeology at the turn of the millennium* (pp. 338–343). Budapest: Ministry of National Cultural Heritage, Teleki László Foundation.

Sarry, F., Courtaud, P., & Cabezuelo, U. (2016). La sépulture multiple laténienne du site de Gondole (Le Cendre, Puy-de-Dôme). *BMSAP*, *28*, 72–83. https://doi.org/10.1007/s13219-016-0151-z

Scheuer, L., & Black, S. (2004). *The juvenile skeleton*. London: Elsevier Academic Press.

Taylor, W. T. T., Bayarsaikhan, J., & Tuvshinjargal, T. (2015). Equine cranial morphology and the identification of riding and chariotry in late Bronze Age Mongolia. *Antiquity*, *89*, 854–871. https://doi.org/10.15184/aqy.2015.76

Thomas, A. (2014). Bioarchaeology of the middle Neolithic: Evidence for archery among early European farmers. *American Journal of Physical Anthropology*, *154*, 279–290. https://doi.org/10.1002/ajpa.22504

Tichnell T.A. 2012. *Invisible horsewomen: Horse riding and social dynamics on the Steppe* (Doctoral dissertation). Michigan State University: East Lansing, MI.

Tihanyi, B., Bereczki, Z., Molnár, E., Berthon, W., Révész, L., Dutour, O., & Pálfi, G. (2015). Investigation of Hungarian Conquest period (10th c. AD) archery on the basis of activity-induced stress markers on the skeleton — Preliminary results. *Acta Biologica Szegediensis*, *59*, 65–77.

Uray-Kőhalmi, K. (1972). *A steppék nomádja lóháton, fegyverben*. Budapest: Akadémiai.

Üstündağ, H., & Deveci, A. (2011). A possible case of Scheuermann's disease from Akarçay Höyük, Birecik (Şanlıurfa, Turkey). *International Journal of Osteoarchaeology*, *21*, 187–196. https://doi.org/10.1002/oa.1120

Villotte, S., Castex, D., Couallier, V., Dutour, O., Knüsel, C. J., & Henry-Gambier, D. (2010). Enthesopathies as occupational stress markers: Evidence from the upper limb. *American Journal of Physical Anthropology*, *142*, 224–234. https://doi.org/10.1002/ajpa.21217

Wentz, R. K., & de Grummond, N. T. (2009). Life on horseback: Palaeopathology of two Scythian skeletons from Alexandropol, Ukraine. *International Journal of Osteoarchaeology*, *19*, 107–115. https://doi.org/10.1002/oa.964

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