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A life on horseback? Prevalence and correlation of metric and non-metric traits of the "horse-riding syndrome" in an Avar population (7th-8th century AD) in Eastern Austria

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ABSTRACT: Musculoskeletal stress markers allow the reconstruction of occupational and habitual activity patterns in historical populations. The so-called horse-riding syndrome summarizes several musculoskeletal markers which are commonly interpreted as indicators of habitual horse riding. The individual symptoms of the horse-riding syndrome, however, are still critically discussed. The skeletal remains of mounted warriors are especially suited for the analysis of skeletal markers commonly associated with a life on horseback. According to historical sources, early medieval Avar warriors were highly skilled in mounted archery and other types of mounted combat. An "equestrian lifestyle", with many hours per day spent on horseback, was presumably a precondition for this. Hence, the historical and archaeological context of the human osteological material examined in this study is a particular asset for analyzing the so-called "horse-riding syndrome".

The aim of this study is to contribute to methodological research on the "horse-riding syndrome", by testing possible associations between different characteristics of this syndrome within the adult population of the Avar cemetery Csokorgasse (7th-8th century AD) from Vienna, Eastern Austria. 149 Avar adult individuals (72 females and 77 males) were included in the study. Poirier´s facets, cribiform changes, plaque, as well as five qualitative traits of the *Os coxae* and the lower limb bones, the index of ovalization of the acetabulum (IOA), and the entheses robusticity score (ERS) were determined.

Males and females differed significantly in the prevalence of Poirier´s facets, cribriform changes, and gluteal entheses. Furthermore, males showed significantly higher IOAs and ERS than females. Significantly positive associations between quantitative and qualitative traits of the horse-riding syndrome could be documented. Poirier´s facets, pronounced gluteal entheses, the index of ovalization of the acetabulum (IOA), and the entheses robusticity score were significantly related independent of sex and age. From the results of the present study we can conclude, that the association patterns between three major characteristics of the "horse-riding syndrome", i.e. "Poiriers Facet" on the proximal femur, ovalization (vertical elongation) of the acetabulum, and pronounced entheses on the bony pelvis and the lower limb bones – typical markers of the "horse-riding syndrome" - may indeed be a valid set of traits for detecting habitual horse riders in archaeological contexts.

KEY WORDS: horse-riding syndrome, life on horseback, Avar warriors, Poirier´s facets, entheses robusticity

Original article

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Introduction

During the last decades, interest in the analysis of association patterns between occupational or habitual activity and the occurrence of musculoskeletal stress markers in historical populations has increased steadily (Palfi & Dutour 1996; Pany-Kucera et al. 2008; Villotte et al. 2010; Havelkova et al. 2011), although, from a methodological point of view, the interpretation of such traits is still difficult (Jurmain et al. 2012). A typical activity pattern that might result in manifest skeletal markers is horse-riding because it is an activity for which *Homo sapiens* is not really adapted. Horse riding and spending a lot of time on horseback has a long tradition, especially in Eurasia. The prerequisite for horseback riding, was the domestication of the horse. Archeological evidence associated the earliest horse domestication with the Botai culture of northern Kazakhstan around 3500 BC (Outram et al. 2009). Recent DNA analyses, however, falsified the assumption that this prehistoric breed is the ancestor of all recent horses, and therefore it is still controversially discussed when and wherein Eurasia the earliest horse domestication took place (Li et al. 2020; Taylor, Barron-Ortiz 2021; Librado et al. 2021). Despite these ongoing debates, there is no doubt that the domestication of the horse (*Equus caballus*) had an enormous impact on human cultural evolution, subsistence, economy, mobility warfare, and social organization (Anthony 2007). Horses and first of all horse riding changed the human lifestyle substantially and accelerated human migration and cultural interactions across huge distances. People learned to spend many hours per day on horseback, a behavior that brought many cultural and economic advantages for humans, but also led to painful pathological changes in the musculoskeletal system of horses and riders. Several studies described the pathological manifestations of horse riding on the skeletons of horses (Bulatovic et al. 2014; Pluskowski et al. 2010; Taylor et al. 2015). The impact of life on horseback for humans and the identification of skeletal markers indicating habitual horse riding among humans however are still discussed controversially. Several pathological conditions such as fractures associated with falls from the horse, coxarthrosis, schmorl´s nodes, osteoarthritis of the spine and the upper and lower limb bones, enthesopathy but also non-pathological joint changes, and pronounced muscle marks or entheses have been associated with habitual horse riding (Palfi 1992; Bagagli et al. 2012; Baillif-Ducos et al. 2012; Khudaverdyan et al. 2016; Pany-Kucera, Willtschke-Schrotta 2017; Fornaciari et al. 2014; Anđelinović et al. 2015).

For more than 20 years the so-called "horse-riding syndrome" which comprises a number of traits on the human skeleton that are discussed as indicators that the individual in question practiced horse riding as a habitual lifetime activity (Anđelinović et al. 2015; Baillif-Ducros, McGlynn 2013; Berthon et al. 2019; Belcastro et al. 2001). The majority of these traits are non-metric, such as the so-called "Poirier's Facet", plaque, cribriform changes of the femoral neck, pronounced entheses of the upper limbs, and the *Os coxae* (Radi et al. 2013; Lawrence et al. 2018), spinal changes, coxarthrosis, but also traumatic lesions and fractures of the limb bones, thorax, shoulder girdle or the skull (Anđelinović et al. 2015; Bagagli et al. 2012; Bailif-Ducros 2012; Baillif-Ducros, McGlynn 2013; Belcastro et al. 2001). Berthon et al. (2019) developed the "Index of Ovalization of Acetabulum (IOA)", a useful tool for quantifying one of the major characteristics of the "horse-riding syndrome": The vertical elongation (i.e. ovalization) of the acetabulum. In addition, Berthon et al. (2019) analyzed and discussed the usefulness of entheseal changes as indicators of horseback riding. However, entheseal changes differ between age groups and the sexes and might be the results of pathologies such as traumata, metabolic diseases, or inflammatory processes (Jurmain et al. 2012) Therefore, the interpretation of entheseal changes as indicators of habitual riding is quite bold.

The identification of valid indicators of habitual horse riding is of great bioarchaeological and historical interest. Hence, we aim to contribute to this ongoing methodological research, by analyzing the association patterns between entheseal changes of the lower limbs and the *Os coxae* in relation to other non-metric and metric traits frequently used as indicators of habitual horse-riding, within the adult population of the early medieval (7th–8th century AD) Avar cemetery Vienna-Csokorgasse from Eastern Austria.

The Avar mounted warriors

The Avars, a nomadic tribal confederation originating in Inner or Central Asia, ruled over the entire Carpathian Basin from the year 568 AD, when their allies, the Lombards, migrated to Italy, to around 800 AD, when Charlemagne's Frankish armies destroyed the Avar Empire (Anke et al. 2008; Daim 2003; Pohl 1988). The majority of the archaeological evidence from the Avar period, including the earliest Avar burials from the end of the 6th or the beginning of the 7th century AD, was found in present-day Hungary. However, Avar burials were also found in present-day Slovakia, Romania, Croatia, Serbia, the Czech Republic and the Eastern part of present-day Austria, where several large Avar burial grounds such as Leobersdorf (Grefen-Peters 1987), Vienna-Csokorgasse (Grossschmidt 1990), Münchendorf (Berner et al. 1992), Zillingtal (Herold 2011), or Vösendorf (Pany-Kucera, Willtschke-Schrotta 2017) have been excavated. In this paper, we focused on the human skeletal remains of the burial ground Vienna-Csokorgasse, which was used during the entire period of Avar settlement in present-day Eastern Austria – from at least the mid-7th century until the end of the 8th century AD.

Previous research (Hyland 1994; Bede 2012; Baron 2018; Anke et al. 2008; Daim 2003) has demonstrated that horses were an important aspect of life in the Avar Empire. According to the historical sources (for example the Byzantine military handbook "Strategikon"; see Dennis 1984; Hyland 1994), the Avars, at least in the initial period of their history, were not only equestrian nomads but also accomplished mounted warriors. Avar warriors' outstanding skills in mounted archery, but also in fighting alternately with different weapons from horseback, appear to have been a major cause of their military success, especially when they first arrived in Europe in the late sixth and early seventh century AD. The archaeological evidence (more than 60,000 Avar-period burials from Central and Eastern Europe, but only few excavated settlement sites; Anke et al. 2008) supports this view, although it is clear that the Avar Empire was extremely diverse regarding the cultural and ethnic background, as well as the subsistence strategies and ways of life, of its population. A considerable proportion of men's burials in Avar cemeteries includes weapons (arrowheads, remains of compound bows, lance-heads, sabers, swords, axes) as grave goods. Significantly, the phenomenon of horse-human burials and other rituals involving horses and horse tack as part of the burial custom in the Avar period is diverse, with considerable regional and chronological differences, which appear to reflect a range of cultural traditions (Fedele 2020; Bede 2012; Baron 2018; Anke et al. 2008). Throughout the Avar period, horse-human burials constitute only a small, variable proportion of all Avar period burials (10% on average; see Bede 2012), which could suggest that this burial custom was reserved for high-status individuals. Similarly, the abundance of a wide range of valuable items of personal adornment and grave goods in horse-human burials may indicate that only members of the Avar elite were buried with horses and/ or horse riding equipment (such as the metal components of horse tack). Significantly, stirrups also occur in horse-human burials, from the Early Avar Period (late 6th–early 7th century AD) onwards. Some researchers have suggested that Avar mounted warriors were the first "cavalry" that used stirrups on a regular basis (Anke et al. 2008; Daim 2003) and that the Avars may have played an important role in transmitting this innovation in early medieval Europe (Curta 2008; Csiky 2021). In principle, mounted combat is possible without stirrups or saddle. However, the use of stirrups has several advantages, such as stabilization of the rider when fighting with a lance, or in horseback archery: If the horseback archer stands up in the saddle using the stirrups, this can facilitate fast, precise shooting with a bow and arrow. In this context, it is not surprising that the Avar mounted warriors, with their outstanding skills in mounted archery, appear to have played a major role in the transmission of this equestrian innovation in Eurasia (Curta 2008; Csiky 2021).

The aim of this paper is to contribute to the methodological discussion on the "horse-riding syndrome", by examining whether specific morphological variations of the anterior femoral head-neck junction ("Poirier's Facet", "Plaque" and "Cribra", according to Radi et al. (2013) and the index of ovalization of acetabulum IOA (Berthon et al. 2019) associate with other potential characteristics of the "horse-riding syndrome". Avar populations are ideally suited for methodological research on the skeletal indicators of horse-riding, because, due to the historical context, it is likely that Avar adult populations include a considerable number of individuals who had spent much time on horseback.

The following hypotheses were tested:

1) The index of ovalization of the acetabulum (IOA) is significantly higher for adults with a "Poiriers Facet", plaque, cribriforme changes, pronounced gluteal entheses, a pronounced *Linea aspera* on the *Os femoris,* a curved *Trochanter major,* exostosis ("spicules") in the *Fossa trochanterica*, exostosis ("spicules") in the *Fovea capitis* and osteoarthritis on the upper outline of the patellar surface on the same side.

2) The index of ovalization of the acetabulum (IOA) correlates positively with the entheses robusticity scores of the lower limbs.

Material & Methods

Sample

The sample for this study was taken from the adult population of the Avar cemetery of Vienna-Csokorgasse (Großschmidt 1990): The early medieval burial ground Csokorgasse in Vienna is one of the largest cemeteries of the Avar period in present-day Austria, consisting of 755 burials within 705 graves (Streinz 1977; Streinz & Daim 2018). According to archeological and zooarcheological data, this Avar cemetery was in use from the second quarter of the 7th century AD (Early Avar Period 2) to the final Third of the 8th century (Late Avar Period 3). The latest phase of the cemetery includes four "equestrian burials" (Streinz 1977; Baron 2018), where the deceased was buried with a horse (including equipment for riding), and rich grave goods, including weapons (bow and arrow, sword, saber).

In the present sample, all individuals of the age groups adult and older, with at least one proximal femur and one *Os coxae* (sufficiently well-preserved for scoring non-metric and metric traits), were included. The reason for focusing exclusively on the age groups "adult and above" was the consideration that non-metric traits of the proximal femur, in particular, "Poirier's Facet" could be observed best only if the epiphysis of the femoral head is already closed.

The total sample consists of 149 individuals – 60 individuals with both proximal femora well-preserved and 89 with either the left or the right proximal femur sufficiently well-preserved to record the traits in question. Approximately half of the 149 individuals in our sample were identified as female (n=72), the other as male (n=77).

Sex and age determination

Sex and age at death of the individuals were estimated by a combination of various standard techniques (Phenice 1969; Meindl, Lovejoy 1985; Lovejoy 1985; Lovejoy et al. 1985; Brooks, Suchey 1990; Buikstra, Ubelaker 1994; White, Folkens 2005). For details regarding methods applied to sex and age determination see Bühler and Kirchengast (2022a). In terms of chronology, the sample is evenly distributed, one third belongs to the early (625 to 675 AD), middle (675 to 735 AD), and late phases (735 to 800AD) of the cemetery, respectively. For a detailed description see Bühler and Kirchengast (2022a).

Qualitative (non-metric) traits

As classical components of the horse-riding syndrome, „Poirier's facets" (Anđelinović et al. 2015), as well as associated traits, such as Allen's fossa/ cribriform changes, and plaque (Lawrence 2018; Radi 2013), were examined. For definitions and scoring, we used the methods described by Radi et al. (2013).

The following qualitative traits were scored as present or absent, according to the method described by Anđelinović et al. (2015): On *Os femoris* a pronounced *Linea aspera*, a curved, pronounced *Trochanter major*, exostosis in *Fossa trochanterica*, exostosis in *Fovea capitis*, and pronounced entheses (of gluteal muscles) on *Os coxae.* According to Bailiff-Ducros and McGlynn (2013), we scored the presence of osteoarthritis on the upper outline of the patellar surface on *Os femoris*, as an indication of possible stirrup use.

Quantitative (metric) traits

To calculate the index of ovalization of acetabulum (IOA); according to Berthon et al. (2018), the maximum vertical diameter of acetabulum (VEAC) and the maximum horizontal diameter of acetabulum (HOAC) were measured twice by one investigator (B.Bühler) in mm, to 1 decimal using a digital caliper. The IOA is defined as VEAC/ HOAC and facilitates the detection of the "vertical elongation of the acetabulum" ("Ovalization") in quantitative terms. For a detailed description of reliability control, see Bühler and Kirchengast (2022a).

In addition, the entheses robusticity score was determined. Entheses robusticity was scored according to Mariotti et al. (2007) for the 7 entheses of the lower limb on a scale of 0 (absence), 1 (weak), 2 (moderate) to 3 (very pronounced): For each individual, the average entheses robusticity score was calculated from 7 entheses, separately for the left and right side. These 7 entheses are 3 entheses per side on the femur (*M. gluteus maximus, M. vastus medialis, M. iliopsoas)*, 2 entheses per side on the tibia (Quadriceps tendon; *M. soleus*), 1 enthesis per side on the patella (Quadriceps tendon) and 1 enthesis per side on the calcaneus (Achilles tendon).

Statistical Analysis

Statistical analyses were performed using the SPSS program version 25.0. Although a normal distribution can be assumed for some metric parameters according to the results of the Kolmogorov-Smirnov test, mainly nonparametric tests were applied due to the small sample size. Group differences were tested for statistical significance using Mann-Whitney U-tests and Kruskal-Wallis-tests. In addition, Spearman correlations, crosstabs, and multiple regression analyses were computed. Results were considered significant when p = 0.05 and highly significant when p = 0.001.

Results

Prevalence of non-metric traits

Table 1 demonstrates the prevalence of qualitative traits according to sex for the left and the right side separately. Significant sex differences could be proved for Poirier´s facets, cribriform changes, gluteal entheses, and osteoarthritis at the patella for both sides. With the exception of the curved Trochanter major, males showed always a higher prevalence of the qualitative traits. The two quantitative traits, IOA and Entheses robusticity score differed significantly, between the sexes, males showed a significantly higher IOA and significantly higher Entheses robusticity scores than females.

Table 1. Prevalence of traits associated with horse-riding according to sex (chi-squares, Mann-Whitney U-tests)

	right side							left side						
	total		males		females			total		males		females		
Qualitative traits	n	%	n	%	n	%	Sig.	n	%	n	%	n	%	sig
Poirier‘s Facet	26	27.9	16	34.8	10	21.3	**0.011**	29	24.8	20	35.1	9	15	**0.046**
Plaque proximal femur	42	45.2	23	50.0	19	40.4	0.512	57	48.7	29	50.9	28	46.7	0.883
Cribriform changes proximal femur	125	83.9	59	76.6	63	87.5	**0.014**	123	82.6	62	80.5	64	88.9	**0.002**
gluteal enthuses	98	76.0	63	96.9	35	54.7	**0.001**	98	76.0	63	95.5	35	55.6	**0.001**
pronounced *Linea aspera*	90	88.2	45	90.0	45	86.5	0.817	104	83.2	56	88.9	48	77.4	0.220
curved *Trochanter major*	31	50.0	12	37.5	19	63.3	**0.040**	60	61.9	26	56.5	34	66.7	0.154

	right side							left side						
	total		males		females			total		males		females		
Qualitative traits	n	%	n	%	n	%	Sig.	n	%	n	%	n	%	sig
exostosis in the *Fossa trochanterica*	39	58.2	25	73.5	14	42.4	**0.010**	68	66.7	36	73.5	32	60.4	0.161
exostosis in the *Fovea capitis*	42	48.8	26	63.4	16	35.6	**0.010**	50	44.2	29	51.8	21	36.8	0.267
osteoarthritis on the upper outline of the patellar surface	43	62.3	27	81.8	16	44.4	**0.005**	60	67.4	39	83.0	21	50.0	**0.004**
Quantitative traits	x	sd	x	sd	x	sd		x	sd	x	sd	x	sd	
Index of ovalization (IOA)	1.04	0.02	1.05	0.02	1.04	0.02	**0.020**	1.04	0.02	1.05	0.02	1.04	0.02	**0.037**
Entheses robusticity score	1.99	0.41	2.12	0.38	1.85	0.40	**0.001**	1.92	0.38	2.14	0.36	1.87	0.45	**0.001**

Associations between quantitative (metric) and qualitative (non-metric) traits associated with the "Horse Riding Syndrome"

As demonstrated in table 2, the IOA was higher among Avars with a Poirier's Facet than among those without a Poirier's Facet. On the left side, this difference was statistically significant. A significantly higher IOA was found among adults with pronounced gluteal entheses on the *Os coxae*. This was true of the right as well as on the left side. No significant group differences in the IOA of the right as well as left acetabulum were found between Avar individuals showing a pronounced *Linea Aspera*, a curved *Trochanter major*, an exostosis in the *Fossa trochanterica*, exostosis of the *Fovea capitis,* and those Avar adults who did not show these traits. In contrast, the average IOA of the left proximal femur was significantly higher among Avar individuals showing signs of osteoarthritis along the upper edge of the patellar surface.

The entheses robusticity scores of the left and right side were always higher among Avar adults showing the quantitative traits mentioned above. Significant group differences were found for Poirier´s facet, gluteal entheses, pronounced *Linea aspera*, exostosis in the *Fossa trochanterica*, exostosis in the *Fovea capitis,* and osteoarthritis on the patellar surface.

The IOA of the left acetabulum correlated significantly positively with the entheses robusticity score for the left (rho=0.243; p=0.033) as well as the entheses robusticity score of the right lower limb (rho=0.326; p=0,005). No significant associations between the IOA of the right acetabulum and the entheses robusticity scores for the left and the right lower limb could be observed.

In the last step, the association patterns between the entheses robusticity scores and Poirier´s facets and IOA corrected for sex, age group, and chronological phase, were tested using multiple regression analyses. The entheses robusticity score of the left side was independently significantly associated with the occurrence of Poirier´s facet, the IOA, and the age group. The entheses robusticity score of the right lower limb was independently significantly associated with sex, the age group, and the Poirier´s facet as well as the IOA (table 3).

Table 2. IOA and Entheses score according to the prevalence of qualitative traits (Mann-Whitney U-tests)

	Index of Ovalization right (IOA)							Index of Ovalization left (IOA)						
Trait	trait present			trait absent				trait present			trait absent			
	n	x	sd	n	x	sd	sig	n	x	sd	n	x	sd	sig
Poirier's Facet	10	1.053	0.018	29	1.042	0.020	0.112	14	1.061	0.015	47	1.037	0.017	**<0.001**
Plaque proximal femur	22	1.043	0.019	18	1.042	0.021	0.479	32	1.038	0.018	34	1.046	0.018	0.087
Cribriform changes	56	1.041	0.018	12	1.049	0.027	0.207	55	1.041	0.019	13	1.042	0.024	**0**.342
gluteal enthuses	57	1.046	0.021	16	1.031	0.016	**0.011**	54	1.045	0.020	17	1.033	00.02	**0.030**
pronounced *Linea aspera*	40	1.048	0.021	3	1.033	0.006	0.169	57	1.044	0.020	6	1.042	0.018	0.741
curved *Trochanter major*	16	1.045	0.018	17	1.045	0.017	0.790	42	1.049	0.020	14	1.040	0.021	0.508
exostosis in the *Fossa trochanterica*	22	1.046	0.019	17	1.039	0.016	0.136	46	1.041	0.019	21	1.041	0.017	0.871
exostosis in the *Fovea capitis*	20	1.042	0.023	24	1.044	0.019	0.774	26	1.045	0.021	37	1.043	0.018	0.613
osteoarthritis on the upper outline of the patellar surface	20	1.050	0.019	14	1.039	0.018	0.115	38	1.044	0.017	17	1.037	0.020	0.062
	Entheses score lower limbs right							**Entheses score lower limbs left**						
Trait	trait present			trait absent				trait present			trait absent			
	n	x	sd	n	x	sd	sig	n	x	sd	n	x	sd	sig
Poirier's Facet	19	2.23	0.28	60	1.92	0.42	**0.004**	18	2.22	0.44	78	1.94	0.36	**0.005**
Plaque proximal femur	41	2.07	0.33	41	1.91	0.47	0.110	56	2.04	0.31	51	1.95	0.45	0.103
Cribriform changes proximal femur	116	1.98	0.41	22	2.06	0.43	0.217	119	2.02	0.43	25	1.98	0.34	0.303
gluteal enthuses	91	2.09	0.36	20	1.64	0.38	**0.001**	96	2.10	0.35	21	1.62	0.39	**0.001**
pronounced *Linea aspera*	86	2.00	0.39	3	1.50	0.44	**0.015**	103	2.06	0.39	8	1.59	0.43	**0.001**
curved *Trochanter major*	31	1.98	0.37	27	1.87	0.43	0.167	60	2.01	0.45	28	1.89	0.43	0.127
exostosis in the *Fossa trochanterica*	39	2.11	0.34	27	1.67	0.35	**0.001**	67	2.09	0.43	33	1.79	0.39	**0.001**
exostosis in the *Fovea capitis*	40	2.13	0.38	43	1.81	0.38	**0.001**	49	2.16	0.35	58	1.89	0.41	**0.001**
osteoarthritis on the upper outline of the patellar surface	43	2.04	0.39	25	1.73	0.39	**0.001**	60	2.12	0.39	25	1.76	0.35	**0.001**

Table 3. Association patterns between the main characteristics of the horse-riding syndrome corrected for sex, age, and chronological period. Multiple regression analyses

	R^2	B	Sig	95% CI	R^2	B	Sig	95% CI
dependent parameter	Entheses robusticity score right				Entheses robusticity score left			
Sex	0.716	-0.23	**0.046**	-0.45 - -0.01	0.704	-0.22	0.059	-0.45 – 0.01
Age group		0.39	**0.001**	0.22 – 0.57		0.37	**0.001**	0.20 – 0.55
Chronological phase		0.02	0.856	-0.16 – 0.19		-0.01	0.954	-0.18 – 0.17
Poirier facet		0.22	**0.011**	0.06 - 0.39		0.24	**0.008**	0.07 – 0.41
Gluteal entheses		0.08	0.285	-0.08 – 0.40		0.09	0.271	-0.08 – 0.26
IOA		13.23	**0.011**	3.35 – 23.11		13.93	**0.009**	3.90 – 23.95

Discussion

Horses played a significant role in cultural evolution and had a lasting influence on human lifestyle: A good example is the historical importance of mounted warriors of equestrian nomadic societies (such as the Huns, Avars, Hungarians, and Mongols) in late antique and medieval Eurasia. The horse-riding techniques of all these equestrian nomadic societies must have focused on controlling the horse effectively without reins, using only the rider's seat and legs, because this is crucial for horseback archery and other types of mounted combat, as well as for daily life activities such as herding and hunting from horseback. As documented, for example, by a Byzantine military handbook compiled around 600 AD (Dennis 1984; Hyland 1994), the Avars, at least in the initial period of their European history, were not only equestrian nomads, but also outstanding mounted warriors. In particular, horseback archery and other types of mounted combat require many hours of training from an early age, in order to master these skills at the level of proficiency required for successful participation in battle and attested by the historical sources. As outlined above, the prevalence of horse-human burials and other burial rituals involving horses and horse tack, frequently together with the weapon types mentioned by the historical sources, indicates the importance of horses for Avar populations, in particular in a military context.

In the present study, the associations between typical, quantitative, and qualitative characteristics of the so-called "horse-riding syndrome", were analyzed using an early medieval, Avar-period (7th–8th century AD) sample from Austria. From a methodological point of view, the historical and archaeological context (Daim 2003; Baron 2018; Fedele 2020; Bede 2012) of the human osteological material examined in this study is a particular asset for analyzing the so-called "horse-riding syndrome": For example, Berthon et al. (2019) have stressed the relevance of the archaeological context for research on the "horse-riding syndrome". Due to the historical and archaeological context summarized above, variations in habitual activity patterns detected within the adult Avar population of the Csokorgasse burial ground may be the result of social, chronological, and sex differences regarding the habitual horse-riding activity. In previous studies, we could show, for example, that habitual horse riding was more common among men than among women (Bühler, Kirchengast 2022a) and also more common among men of higher socioeconomic status than among lower-status men (Bühler, Kirchengast 2022b).

The results of our present study suggest a significant association between four traits interpreted commonly as indicators of habitual horseback-riding: Poirier´s facets, gluteal entheses at the *Os coxae*, the IOA (= quantifying the vertical elongation of the acetabulum), and pronounced robusticity of the entheses of the lower limbs. These particular traits have already been described as potential indicators of habitual horse riding in previous bioarchaeological research on other populations of habitual horse riders (Anđelinović et al. 2015; Bagagli et al. 2012; Bailif-Ducros 2012; Baillif-Ducros, McGlynn 2013; Berthon et al. 2019; Belcastro et al. 2001). This result is in accordance with the biomechanics of horse riding: The pelvis and legs of the rider play a central role in the communication between rider and horse (Pugh, Bolin 2004), even more so when riding without reins, for example during horseback archery. Hence, it is not surprising that osteological traits detected on the bony pelvis, hip joint, and proximal femur are major characteristics of the "horse-riding syndrome". Even the prevalence of Poirier´s facet within the Avar population from the Csokorgasse burial ground (15–20%) resembles those in the adult population from the nearby Avar cemetery of Vösendorf, where the prevalence of "Poirier's Facet" averaged at 16.3% for adult individuals of both sexes (Pany, Wiltschke-Schrotta 2017).

No significant associations with the IOA or the Entheses robusticity score were found for other non-metric variations of the femoral head-neck junction such as different types of plaque and cribriform variations, which have also been associated with the horse-riding syndrome. Although the different types of plaque may be caused by mechanical stress, at present, they can only be interpreted as unspecific "markers of physical activity" (Lawrence et al. 2018; Radi et al. 2013), because their etiology is still unclear (Radi et al. 2013; Mellado et al. 2014). The interpretation of cribriform changes of the proximal femur is, at present, even more problematic: It is, as yet, not possible to ascertain whether they should be interpreted as general stress markers, caused by malaria or anemia (Pany et al. 2006) or as unspecific markers of physical activity (Radi et al. 2013). Therefore, it may be important to discriminate between pathophysiological cribriform changes occurring by themselves and other types of cribriform lesions, which form on the plaque as herniation pits. The latter may be indeed a result of activity, as suggested by clinical research (Mellado et al. 2014).

Furthermore, for the five other, non-metric traits of the "horse-riding syndrome" which were taken into consideration in this study, the differences regarding IOA between adults with the presence/ absence of the trait in question were relatively small and statistically insignificant. Therefore, in this study the five traits (pronounced *Linea aspera*, curved *Trochanter major*, exostosis at the *Fovea trochanterica*, exostosis in the *Fovea capitis*, and osteoarthritis at the upper outline of the patellar surface maybe not regarded as specific characteristics of habitual horse riding activity, but as indicators of general mobility.

Hence, we could verify our first hypothesis partly. This is also true of the second hypothesis because significant correlations between the left IOA and the entheses robusticity scores were found.

Limitations

Due to the poor preservation of the leg bones and bony pelvis, the actual sample sizes were considerably smaller than the total sample size (n = 149). Another limitation of the research carried out here was the lack of an "outgroup", such as a population of non-horse-riders from a modern reference collection.

Conclusions

The association between several major characteristics of the "horse-riding syndrome" – i.e. "Poirier´s Facet" on the proximal femur, ovalization (vertical elongation) of the acetabulum, and pronounced entheses on the bony pelvis and the lower limb bones, detected within the adult population from the Avar cemetery Csokorgasse – suggests that the "horse-riding syndrome" may indeed be a valid set of traits for detecting habitual horse riders in archaeological contexts.

Authors' contribution

Birgit Bühler designed the study and collected the data. Sylvia Kirchengast formulated the hypotheses. Sylvia Kirchengast did the analysis. Both authors formulated the hypotheses and wrote the text.

Conflict of interest

The authors declare that they have no competing interests concerning this study.

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