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Original scientific paper

Skeletal Frailty at Kałdus, a Medieval Poland Early Piast Dynasty Cemetery

Alexandra C. Tuggle[1], Kathryn E. Marklein[2,3] and Douglas E. Crews[1,4]

[1]The Ohio State University, Department of Anthropology, Ohio, USA
[2]University of Louisville, Department of Anthropology, Kentucky, USA
[3]University of Louisville, Center for Archaeology and Cultural Heritage, Kentucky, USA
[4]The Ohio State University, College of Public Health, Ohio, USA

ABSTRACT

The objective of this project is to assess skeletal frailty, as estimated using a skeletal frailty index (SFI), at the medieval Polish site of Kałdus to better evaluate the impacts of living and social environments on individuals within this urbanizing population. We assessed biological frailty in adults from the Global History of Health Project database. 11 skeletal and dentoalveolar biomarkers were selected as representative of childhood and adulthood frailty and aggregated into an SFI by summing their occurrence in each individual. Cumulative skeletal frailty scores were tabulated for each individual and could range from 0 (no skeletal markers of stressors present) to 11 (all skeletal markers of stressors present) based on the presence or severity of lifetime stressors that altered their living bones. As many skeletal frailty markers correlate with age, SFIs were compared between individuals within specific age groups: 18–25 (n = 21), 26–35 (n = 31), 36–45 (n = 31), and >45 (n = 25) years. In the overall sample, SFI averaged 4.13 (range 0–9, sd = 1.98). Among males (n = 56), SFI averaged 4.45 (sd = 1.90; range 1–8); among females (n=52), it was 3.79 (sd = 2.03; range 0–9). SFI was lowest in the youngest age group, 2.38 (sd = 1.83; range 0–6) and highest in the oldest, 5.48 (sd = 1.50; range 2–9; $p < 0.001$). In these medieval skeletons, SFI distributions were significantly different between males and females only when accounting for age ($p = 0.044$), with females exhibiting higher mean frailty within each age group. Skeletal frailty, as estimated from biomarkers of skeletal stress, suggests these individuals were exposed to considerable stress throughout their lives. As Poland's written history in the medieval period is sparse, assessing skeletal frailty provides an alternative way to understand the lives and experienced stressors of its inhabitants. Further research connecting skeletal frailty to burial context and isotopic evidence will illuminate connections of SFI with diet, lifestyle, and health in medieval Poland.

Key words: *stress, biomarkers, skeletal frailty index, morbidity-mortality paradox, resilience*

Introduction

Frailty in bioarchaeology

For all species the environment is a significant stressor, and changing environments have an effect on health. As such, all organisms have evolved ways to temporarily halt and delay stressors sufficiently long enough to reproduce[1]. However, over time all species eventually succumb to multiple, energy-demanding and consuming processes, many of which leave traces on skeletons indicating severe trauma, illness, nutritional deprivation, and damage during life. Jointly, these skeletal indicators reflect stressors an individual experienced during their lifetime. In the living, such cumulative, stressor-induced changes contribute to the development of a frail phenotype related to adverse health outcomes[2]. Phenotypically, frailty is not solely due to aging and senescence; rather frailty is a specific phenotype occurring secondary to stressors and morbidity experienced during life[3,4]. In living people, the frail phenotype results from sarcopenia (progressive loss of skeletal muscle mass), which leads to bone loss, neuropathy, and subsequent weakness, exhaustion, reduced walking speed, decreased physical activity, and weight loss[2,5,6].

Such phenotypic outcomes are not directly observable in bioarchaeological samples of skeletal remains[7]. We must rely on known skeletal and dental markers of pathological, degenerative, and chronic conditions in the living to evaluate relationships between stress, health, morbidity, and mortality in the past. Multiple proposed methods have been utilized to understand how these markers relate to the health of the deceased. In 1984, Cohen and Armelagos[8] edited a seminal work, *Paleopathology at the Origins of Agriculture*, exploring the transition to an ag-

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ricultural lifestyle and its effects on population health. Since this publication, measurement and diagnostic standards for skeletal data collection have been established and applied to samples worldwide[9–13]. Despite universally accepted measurement standards, how skeletal data are interpreted in relation to questions of health, frailty, and stress differs among researchers. Many approaches exist for assessing health in the past[14–19].

In 1992, Wood and colleagues[19] raised a debate concerning the paradoxical way health can be interpreted in the bioarchaeological record when it is based on skeletal biomarkers of stress: the osteological paradox. The osteological paradox identifies the conceptual problems inherent to skeletal analyses that potentially confound any interpretation of health, including demographic nonstationarity, selective mortality, and hidden heterogeneity. A common approach to analyzing biomarkers in skeletal samples is comparing gross prevalence counts of specific pathological conditions on skeletons by biological sex and age-at-death. Frailty and health, in general, are affected by many factors, for example genetics, socioeconomic status, nutrition, behaviors, environmental variation, and secular trends. Therefore, the meaning and relevance of aggregate-prevalence values must be interpreted with caution when suggesting possible underlying population variation in susceptibility to disease and death[19]. Furthermore, individuals exhibiting some or even extensive skeletal lesions may have been less frail than others in the same population who died without visible lesions.

Following Wood et al.[19], other methods were proposed to address the paradoxical nature of skeletal markers as indicators of health in the past. Hazard models[17,18,20,21] elucidate individual patterns of health rather than population averages. Hazard models are based on the principle that skeletal samples are comprised of the frailest individuals, with frailty conceptualized as greater mortality risk[17,22]. Statistical methods utilized by hazard models diminish issues of selective mortality and hidden heterogeneity. However, among living humans, frailty is viewed not as a mortality risk, but as a phenotype that develops after time and is highest among long-term survivors[2,5,6].

Recently, Marklein et al.[15,23] reported a skeletal frailty index (SFI) based upon theory, research, and methods for assessing frailty in living samples. Therein, skeletal frailty is conceptualized as a syndrome measuring multiple cumulative responses to stressors, rather than a measure of increased susceptibility to death, and determined on both *individual* and *site* levels. As a result, the SFI differs from the Health Indices calculated through the Global History of Health Project (GHHP), as the Health Index scores reflect the composite "health" of the skeletal sample, whereas the SFI reflects the composite frailty within an individual[24]. While the Health Index is useful for wide-ranging cross-population comparisons, it is inadequate for interpreting human variation and levels of physiological stress in many ways[25]. It cannot reveal individual-level frailty or compare average frailty across groups (e.g., age, sex, location), which is the purpose of this research. Although the analytical approaches differ, the GHHP Health Index is based on similar or identical standards for diagnosing conditions composing the SFI (Supplemental Table). The SFI accounts for accumulated somatic stress as well as resilience to past stressors. Individuals who are more resilient may live longer and survive more stressors throughout their lifetimes, often at the cost of increased frailty and irreparable skeletal damage. The original index included 13 biomarkers indicative of stressors experienced during life. The SFI was applied to archaeological samples from London to address the question of differential frailty between monastic and nonmonastic communities in the medieval town. Later, a more parsimonious 11-biomarker SFI was proposed and shown to exhibit similarly statistically robust and meaningful results[23]. Thus far, the SFI has been applied only to samples from medieval London[15,23]. In this study, an 11-biomarker SFI is applied to a medieval Polish sample (Kałdus) derived from the Global Health History Project database to evaluate patterns of frailty among Kałdus' residents during a period of distinct cultural change.

Historical Context: Medieval Poland

The beginning of Poland's medieval period is associated with the rise and baptism of Piast Duke Mieszko I in AD 966. This resulted in the consolidation of the Polish State and the beginning of Christianization in the area[26]. Prior to this time, Poland was occupied by a diverse tribal, largely pagan population of native Polanes and Slavs who practiced agriculture and animal husbandry[26]. The transition that began with Mieszko I in AD 966 marked the beginning of considerable social, religious, and economic upheaval that affected relations within Poland for centuries[27].

During the second half of the tenth century, many castle-towns arose to meet the needs of an extensive, more organized state. This network of towns served as economic, administrative, judicial, and defensive centers of the new Polish state under the ruling Piast dynasty[26,27]. Christianization was likewise a political tool used to consolidate the diverse ethnic groups and integrate them into the new state organization. However, Christianity was not accepted meekly by all and often had to be imposed with military force. Complete Christianization did not occur until the 12th and 13th centuries with construction of monasteries across Poland. For the period in between, the church was deeply unpopular and seen as a foreign institution forced upon the populace by the ruling class for political gain[28,29].

Although Mieszko I succeeded in uniting the Polish state, the reigns of his successors Mieszko II (1025–34), Bolesław II (1058–81), and Bolesław III (1102–38) were tumultuous, marked by revolt and invasion[29]. The Piast state lacked a clear means of succession, and thus the periods between rulers were times of political strife and upheaval, often leaving Poland with no ruler at all. At the beginning of the 13th century, Poland's political organization began to fracture. A total of five Piast duchies existed in 1202. This number grew to nine by 1250 and seventeen by 1288. As order devolved, it became harder and harder to defend the north-eastern borders against the onslaught of pagan Prussian tribes. In 1227, Conrad I Duke of Maso-

via (1202–1247) positioned the Teutonic Knights, a German Catholic military order, in a defensive position in Chełmno, a city along the east bank of the Vistula River (Lukowski & Zawadzki, 2001). The Teutonic Order became a formidable military force and succeeded in subduing the Prussian tribes over the next 50 years. At home, they imposed German Law or "Ordenstaat" that contributed to the increasingly German character of the area[26].

Although political turmoil was frequent across Poland throughout the 12th and 13th centuries, rural settlements experienced increases in their population growth. This is attributed to improved economic conditions and substantial advances in agricultural technology[26,27]. With corresponding regional economic development, centers of territorial power, or strongholds, developed rapidly throughout the nation. The main strongholds, known as *sedes regni principales,* built sacral structures accompanied by a church administrative system. Such regional centers were surrounded by many ancillary settlements producing goods necessary to sustain the strongholds. Over time, these centers and their associated auxiliary settlements became vibrant hubs for trade, craftsmanship, and urban development[27].

One of these early urban centers was Kałdus, located in modern-day Chełmno, Poland along the banks of the Vistula River (Figure 1) and on the border between former West Prussia and Pomerania, near a large, constructed mound currently called Mount Saint Lawrence, or St. Lawrence's Hill. During the 10th century, this hill was a sacred gathering place for pre-medieval pagan rituals[30,31]. The area around St. Lawrence's Hill was sparsely populated prior to medieval times yet held considerable sacral importance for the local tribal community as evidenced by the presence of a pagan altar with many offerings[31]. After Christianization began in the area around the 11th century, a large basilica was erected atop the altar to offset pagan associations with the area. However, the basilica was never completed and was likely abandoned during a pagan revolt in AD 1030[30,32].

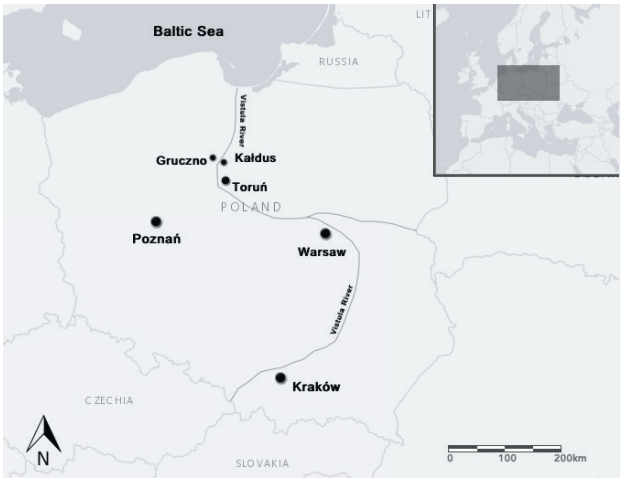

Fig. 1. Map of Poland with location of Kałdus (Created with ArcGIS).

Chudziak[32] postulates that the investment made into the basilica's construction coupled with the large area of the stronghold and surrounding settlements indicates that Kałdus was once one of the *sedes regni principales.* However, despite grandiose plans and powerful religious and military influence, Kałdus never gained the projected status indicated by its regional importance during the early Piast state. Although Kałdus' economic importance gradually declined over the medieval period as nearby settlements such as Torún expanded, it certainly played an important role in the early state system[25]. In addition, Kałdus is home to two of the most notable cemeteries in medieval Poland, including the cemetery examined here (Kałdus site 4). Burials recovered therefrom reveal an exceptional diversity of social and ethnic backgrounds including Christian, pagan, and Scandinavian-style burials, and have been the focus of recent archaeological research[27,28,30–34].

Objectives and hypotheses

The purpose of this research is to assess skeletal frailty during a period of cultural change in urbanizing medieval Poland. Poland's early history is rife with political upheaval, war, social change, migration, religious conflict, subsistence transition, and outside cultural influences[26]. The available skeletal materials provide data to investigate connections between frailty, resilience, and history in medieval Poland.

Our main hypothesis posits that SFI at medieval Kałdus (site 4) will differ by age, consistently increasing with age, but not by sex, as previous research (isotopic analysis) has shown no significant dietary differences between males and females at Kałdus[34]. In other medieval European settings, skeletal frailty, assessed by osteological marker (e.g., linear enamel hypoplasia, porotic hyperostosis, cribra orbitalia, and tibial periosteal reaction) counts, differed significantly between males and females[15,20,35], so it is possible this trend may be observed on the continent. Given age and frailty are associated significantly across skeletal and living samples, we also hypothesize the SFI would increase with age. Identifying variations in skeletal frailty by age and sex provides new information for interpreting lives of medieval Kałdus' residents. Archaeology and history present a record of growth at Kałdus as a regional settlement, perhaps as one of the *sedes regni principales,* and aspects of their diet[27,32–34,36], but this is not a complete picture of the medieval Kałdus experience. Here we examine their physical responses to life's stressors by assessing their skeletal pathological lesions and frailty, complementing previous historical analysis.

Materials and methods

Materials

Medieval Polish skeletons from Kałdus site 4 interred between AD 900 and 1200 were excavated by Wojciech Chudziak from 1996–2006 (n=601). Data are currently

curated as part of the Global History of Health Project (GHHP) and are used here with permission from Professors Richard Steckel and Tomasz Kozłowski. All determinations of pathological lesions and skeletal measurements were completed by Tomasz Kozłowski from the Nicolaus Copernicus University in Torún, Poland. This research utilized assembled data from the GHHP database: the authors neither diagnosed nor recorded pathological lesions on skeletons. Pathological conditions were recorded according to standards outlined in the GHHP Data Collection Codebook[24]. Although the original SFI was scored and tabulated according to standards outlined in the Museum of London's Osteology Method Statement[37], the GHHP skeletal metrics and codes were directly translatable to "high" and "low" frailty assessments for individual biomarkers (Supplemental Table). Only adult individuals were included in this analysis. Sex estimation was based on sexually dimorphic features of the pelvis and/or cranium[11]. Age estimation used macroscopic degenerative changes in the pubic symphysis[38]. Both methods are outlined in the GHHP Data Collection Codebook[24]. Individuals who could not be definitively classified as biological female or male were excluded from this analysis.

Here, we examine skeletons from one of two fully excavated cemeteries at Kałdus, site 4, dating broadly to the mid-10th century to the early-13th century CE[31]. Those reported here date mainly to the period of Christianization and state-formation in Poland, the 10th and 11th centuries[26,27]. Site 4 includes a heterogeneous assortment of burial styles: pagan, Christian, and Scandinavian; some with, others without grave goods (e.g., knives, flint, jewelry, buckets, and bowls); some supine, others in flexed positions, and laid along both North-South and East-West axes[32]. Such variability in mortuary practices reflect historical cultural and religious transitions at medieval Kałdus[32,34,39–40].

Within the GHHP database, Kałdus site 4 is represented by 601 individuals. Of these, 108 (18%) met preservation criteria needed to estimate a 11-biomarker SFI. This sample included all adults with sufficient remains to assess all 11 metric and nonmetric biomarkers, with definitive determinations of sex and age classifications (Figure 2). Each of these 108 individuals was assigned to one of four age classes (18–25, 26–35, 36–45, and >45 years) according to Museum of London criteria[15]. Thereby, this sample presents a sequence from young to older adults. This sample displays one notable disparity, disproportionately more interments were of females in the early age classes and more males in the later (Figure 2).

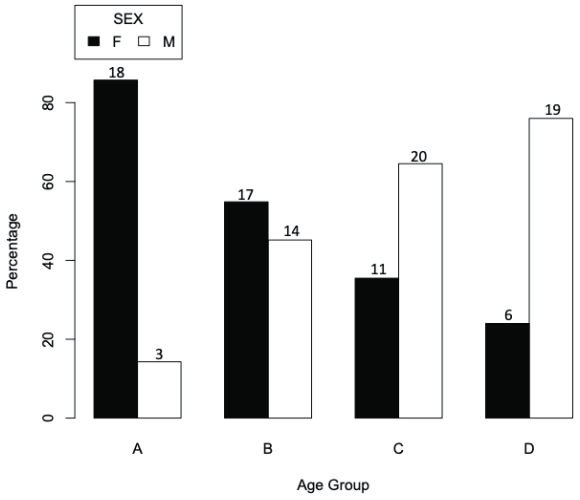

Fig. 2. Distribution of sex in each age group (A=18-25, B=26-35, C=36-45, D=>45 years) in the Kałdus site 4 sample (n=108).

Methods

Following criteria outlined by Marklein et al.[15,23], a modification of the 13-biomarker SFI is utilized. For every individual, 11 rather than 13 frailty biomarkers, including both skeletal and dentoalveolar, were included in the dataset; diagnostic criteria were based on the GHHP Data Collection Codebook[24] (Table 1). Biomarkers used here capture four major categories of lifetime stressors: growth, nutritional deficiency and infection, activity, and trauma. An individual's SFI is determined by assessing each available biomarker as either indicating greater frailty during life or not and incorporating them into a single frailty construct. For example, for nonmetric biomarkers (e.g., linear enamel hypoplasia, cribra orbitalia, osteoarthritis), presence indicates greater frailty and is scored "1", whereas absence is scored "0". For metric variables (e.g., femoral length and head diameter), the lowest quartile, including shortest lengths and smallest diameters, is scored 1, while other quartiles are scored 0. Once scored, biomarker values are summed for each individual as an estimate of their SFI.

Calculated thus, the SFI quantifies individual skeletal frailty as a single value, possibly ranging from 0–11. This is different from comparing population and subsample frequencies for individual biomarkers. As a composite, SFI includes multiple indicators of lifetime stressors that penetrated to the skeleton during life into a single index. Thus, the SFI provides an individual gestalt of skeletal growth, damages, loses, and disease responses, a gestalt that may be compared between and among skeletal individuals, and across skeletal samples for sex, age, occupation, burial location, time period, and other independent variables. As described by Marklein and colleagues[15,23], SFIs utilize skeletal indicators of stressful conditions occurring during life that the individual survived to determine their accumulated frailty at their life's end.

During growth and development, severe stressors may alter or disrupt skeletal and dental growth, permanently imprinting on the skeleton. During critical growth periods, stressor exposures may lead to shorter stature, decreased skeletal robusticity, and linear enamel hypoplasias (LEH), all still observable at later ages and after death[41–43]. Such biomarkers index early stressors and relate to mortality risks across modern settings[44,45]. Stature is an acknowledged general indicator of health in adult-

TABLE 1

SKELETAL BIOMARKERS OF FRAILTY INCORPORATED INTO THE INDEX WITH DESIGNATED SCORES AND MEASUREMENTS FOR FRAILTY AND FRAILTY CUT-POINTS

Stress category	Frailty Measure	Scores and measurements	Frailty score "1"
Growth	Femoral length	Length	Lowest quartile*
	Femoral head diameter	Diameter	Lowest quartile**
	Linear enamel hypoplasia	Present/absent	Present
Nutrition and infection	Cribra orbitalia	Present/absent	Present
	Porotic hyperostosis	Present/absent	Present
	Dental pathology	Present/absent	Present
	Periosteal reaction	Active/healing/absent	Active
Activity	Osteoarthritis	Present/absent	Present
	Degenerative joint disease (limbs)	Present/absent	Present
	Degenerative joint disease (vertebrae)	Present/absent	Present
Trauma	Fracture	Present/absent	Present

Table adapted from Marklein et al.[15]

*Male femoral length quartiles: $x \leq 434$ mm, 434 mm $\leq x <$ 456 mm, 456 mm $\leq x <$ 478 mm, $x \geq 478$ mm; female femoral length quartiles: $x \leq$ 394.75 mm, 394.75 mm $\leq x <$ 426.5 mm, 426.5 mm $\leq x <$ 458.25 mm, $x \geq$ 458.25 mm.

**Male femoral head diameter quartiles: $x \leq 45$ mm, 45 mm $\leq x <$ 48 mm, 48 mm $\leq x <$ 51 mm, $x \geq 51$ mm; female femoral head diameter quartiles: $x \leq 40.5$ mm, 40.5 mm $\leq x <$ 44 mm, 44 mm $\leq x <$ 47.5 mm, $x \geq 47.5$ mm.

hood in both living and bioarchaeological samples; thus, femoral length provides a proxy for adult stature[16,44,46–49]. Stature varies significantly between males and females across populations; thus, quartiles for scoring femoral length are sex specific.

Femoral head diameter assesses bone robusticity in the skeleton[43]. In the living, relatively low bone robusticity contributes to frailty. This may be associated with poor walking performance, low physical activity, and slow walking speed, increasing risks for poor health outcomes[2] and falling[50]. Individuals with femoral length and femoral head diameter in the lowest quartile for their population's sex-specific distributions were scored "1", all others "0". These individuals may have suffered greater undernourishment during childhood or other stressors resulting in their short stature and low bone robusticity. Research among modern populations shows short-statured individuals, relative to others in their population, suffer poorer health outcomes and increased morbidity later in life[45,51]. Variable genotypes also impact stature and may have influenced achieved heights[52], particularly in urbanizing, economic, and genetically-diverse settings, such as Kałdus in the 10th – 11th centuries.

Linear enamel hypoplasias (LEH) are visible grooves on teeth corresponding to disrupted then recovered enamel formation following both mild and severe stressors experienced during tooth development[42,53–56]. Rarely are LEH attributed directly to genetic factors[57], but occur as responses to social and metabolic stress, infection, neonatal disruptions, malnutrition, and systemic poor health occurring early in life[53,58]. Bilateral LEH is a strong signal for systemic childhood stress. However, sample preservation at Kałdus site 4 favored use of a less conservative assessment. Here we identify any LEH (or multiple LEH) as a stressor response, scored as "1", while absence was scored "0".

Both poor nutrition and infections may compromise immune function, preventing the system from effectively warding off disease, fighting infection, and retaining normal function. Thus, poor nutrition is an indicator of the frailty phenotype[42,59]. Here, evidence of nutritional and infectious stress is recorded as the presence of cribra orbitalia, porotic hyperostosis, dental pathology (indicated by abscesses and antemortem tooth loss), and periosteal reaction. Cribra orbitalia and porotic hyperostosis are areas of macroscopic pitting on the orbital roofs and external cranial vault, respectively[42]. Previously viewed as evidence of iron-deficiency anemia, recent research suggests these conditions more likely reflect changes in marrow production caused by hemolytic and megaloblastic anemias or blood loss[60]. Though cribra orbitalia and porotic hyperostosis are not caused exclusively by iron-specific deficiencies, they result from considerable nutritional stress during growth and development, poor sanitation, and infectious disease burden. Specifically, cribra orbitalia is associated with severe vitamin C deficiency and porotic hyperostosis is associated with severe vitamin B12 deficiency[60]. These deficiencies can be associated with nutritionally deficient plant-based diets (and thus nutrient-deficient milk and weaning foods), childhood diarrheal diseases, and intestinal parasites. Here, presence of cribra orbitalia and porotic hyperostosis were scored "1" for present and "0" for absent.

In the SFI methodology originally proposed by Marklein et al.[15], periodontal disease was suggested as a measure of oral health and an indicator of systemic health associated with a chronically compromised immune system[56,61]. In the Global Health History Project database oral health is as-

sessed through abscesses and antemortem tooth loss which are analyzed here. Antemortem tooth loss results from distinct etiological pathways including severe periodontal disease resulting in alveolar recession, severe caries, dental attrition resulting in exposed pulp cavity, abscessing, and trauma[62]. Abscesses are bony lesions at the apex of dental roots typified by pus accumulation from bacterial infection. They may result from caries or rapid tooth wear exposing the dentin and may eventually cause antemortem tooth loss[63]. Abscesses severely affect dietary intake and disease resistance and can be life threatening. Here, dental pathology is scored "1" when either abscess or antemortem tooth loss is present, "0" when both are absent.

Periosteal reactions, non-specific skeletal lesions wherein membranes surrounding the bone (periosteum) become inflamed, cause macroscopic changes to bone surfaces[12,42,64,65]. An active periosteal reaction is indicative of frailty and associates with higher mortality risk, whereas healing lesions likely represent healthier or less frail phenotypes[66]. Therefore, periosteal reaction was scored "1" for active but not healing lesions. Healing lesions and those with no sign of periosteal reaction were scored "0". The tibia is one of the bones most commonly affected by periosteal reaction, possibly due to lack of soft tissue covering the bone leaving it less buffered from the environment[42]. Additionally, the tibia is not as vascularized as are other bones. Consequently, immune responses tend to manifest slowly making it a better area to view chronic rather than acute infection[67]. For this reason, periosteal reaction was only scored "1" if present on the tibia and active.

Repetitive motion stresses joints and leads to painful, sometimes immobilizing conditions. Activity biomarkers are included in this SFI because of the immobilizing and painful nature of osteoarthritis, degenerative joint disease, and intervertebral disc disease[68]. These conditions inhibit the completion of daily tasks and quality of life[2,69–70]. The GHHP database does not include intervertebral disc disease. Thus, degenerative joint disease of the vertebrae was available and included as a biomarker. Because severity of these three conditions is difficult to assess from skeletal remains, the presence of a condition across any joint scored "1", absence "0".

Evidence of skeletal trauma suggests interpersonal conflict or traumatic accidents during life, possibly disrupting normal functioning and daily lives[71]. Due possibly to increasing social stress in medieval Poland, trauma is particularly prevalent in these skeletons. Based on the type of injury, trauma reflects stressful accidents or interpersonal violence; both suggest stressful conditions may have existed[71]. We scored any sign of antemortem or perimortem trauma "1" and absence "0", assuming, regardless of location, any such injury affecting the skeleton during life likely would impair physical activity.

Statistical analyses

Individual SFIs were calculated for the entire sample (n=108). Then means, standard deviations, and observed ranges by sex and age category were determined. Welch's two sample t-tests were used to determine the significance of differences in SFIs by sex and by-sex-within-age category for the full sample and within each age group. We applied ANOVA to test the significance of differences by age group and applied ANCOVA to test for significant influences of sex on the SFI while controlling for age. We report all p-values and suggest statistical significance at $p \leq 0.05$ and a possible trend when $0.05 < p \leq 0.10$. In addition, we report overall prevalence for all biomarkers and use Student's t-tests for metric biomarkers and Pearson's Chi-square tests for non-metric biomarkers to determine differences between males and females for each. All statistical analyses were performed using R version 3.6.1[72].

Results

Gross prevalence

While gross prevalence does not describe individual frailty, it does provide an overview of stress-related conditions within a sample and identifies conditions contributing most to skeletal frailty. Here, the most prevalent conditions are dental lesions, periosteal reaction, osteoarthritis, and degenerative joint disease of both the limbs and vertebrae (Table 2). Femoral length and femoral head diameter are significantly smaller in females (both $p < 0.001$), while porotic hyperostosis ($p = 0.035$) and degenerative joint disease of the vertebrae (IVD) ($p = 0.007$) occur more frequently in males, among whom they also increase with age. Fractures ($p = 0.065$) also occur more frequently in males, although not significantly so. Males exhibited significantly more fractures to their long bones than females ($p = 0.002$), although no other significant fracture patterns emerged.

It is useful to compare gross prevalence data to skeletal frailty indices here to determine which conditions are contributing most to skeletal frailty. The most prevalent conditions in this sample commonly are associated with chronic lifetime nutritional and activity-related stressors in the living[42,60,66,68–69].

11-biomarker SFI

In the 108 skeletons analyzed from Kałdus site 4, skeletal frailty averaged 4.13 (sd = 1.98; range = 0–9) (Table 3). Skeletal frailty averaged 4.45 (sd = 1.90; range 1–8) among males, higher than among females, who averaged 3.79 (sd = 2.03; range 0–9), but not quite significantly so ($p = 0.086$). Skeletal frailty generally is highest among older groups, being lowest at ages 18–25, the youngest age group, 2.43 (sd = 1.91; range 0–6), and highest among the oldest, 5.28 (sd = 1.43; range 2–9, $p < 0.001$), ages 45+ years, as expected. Skeletal frailty did not differ significantly by sex in the initial analysis without including age as a covariate ($p = 0.086$) (Table 3). However, this sample exhibits considerably higher proportions of males interred at older ages and females at younger ages. Thus, to control for age-related variation

TABLE 2

AVERAGE FEMORAL LENGTHS (MM), FEMORAL HEAD DIAMETERS (MM), AND GROSS PREVALENCE VALUES OF SKELETAL AND DENTAL LESIONS AMONG MALES AND FEMALES

	Male (N=56)	Female (N=52)	p-value
Femoral length (mm)	453	418	<0.001*
Femoral head diameter (mm)	48.5	42.5	<0.001*
Linear enamel hypoplasia	0.34	0.37	0.777
Cribra orbitalia	0.04	0.06	0.587
Porotic hyperostosis	0.30	0.13	0.035*
Dental pathology	0.50	0.60	0.316
Periosteal reaction	0.57	0.44	0.180
Osteoarthritis	0.70	0.60	0.196
Degenerative joint disease (limbs)	0.70	0.62	0.276
Degenerative joint disease (vertebrae)	0.64	0.38	0.007*
Fracture	0.30	0.15	0.065

* Results significant at the 0.05 level 11-biomarker SFI

in frailty, we applied ANCOVA including age as a covariate. In this analysis, skeletal frailty did vary significantly by sex when accounting for age ($p = 0.044$) (Table 4). Furthermore, although males had a higher average SFI when the total sample was examined (Table 3), within each individual age group females had higher average SFI (Figure 3, Table 4). Further dissection of this sex differential within age categories revealed that frailty differed significantly by sex exclusively in the 26–35-year age group ($p = 0.032$) with females higher (Table 4). This age group is the only one with a similar number of males and females (14 and 17, respectively). Frailty did not differ significantly by sex in the 18–25, 36–45, and >45-year age groups ($p = 0.186$, $p = 0.156$, and $p = 0.747$, respectively) (Table 4). Comparing all age groups, the youngest age group (18–25 years) showed significantly lower SFI than all other groups (Table 5a). Additionally, the 25–36-year age group differed significantly from the two older groups, but the 36–45 year did not differ from the >45-year group. Within males, the youngest age group differed significantly from the 36–45 year and >45-year groups, but not the 26–35-year group. While the 26–35-year group differed significantly from the 36–45 and >45-year groups. Within females, only the youngest age group differed significantly from all others (Table 5b).

TABLE 3

RESULTS FOR SKELETAL FRAILTY BY SEX (WELCH TWO SAMPLE T-TEST)

	N	Mean SFI	Standard deviation	Range	p-value
Male	56	4.45	1.90	1–8	0.086
Female	52	3.79	2.03	0–9	
Total	108	4.13	1.98	0–9	

TABLE 4

RESULTS FOR SKELETAL FRAILTY BY SEX WITHIN EACH AGE GROUP (WELCH TWO SAMPLE T-TEST) AND BY SEX WITH AGE AS A COVARIATE (ANCOVA)

Age group	Male			Female			Total				p-value
	N	Mean SFI	SD	N	Mean SFI	SD	N	Mean SFI	SD	Range	
18–25	3	1.33	1.15	18	2.61	1.97	21	2.38	1.83	0–6	0.186
26–35	14	2.86	1.83	17	4.35	1.84	31	3.61	1.71	1–7	0.032*
36–45	20	4.30	1.78	11	5.09	1.22	31	4.74	1.65	1–8	0.156
>45	19	5.21	1.27	6	5.50	1.97	25	5.48	1.50	2–9	0.747
Total											0.044 *

* Results significant at the 0.05 level

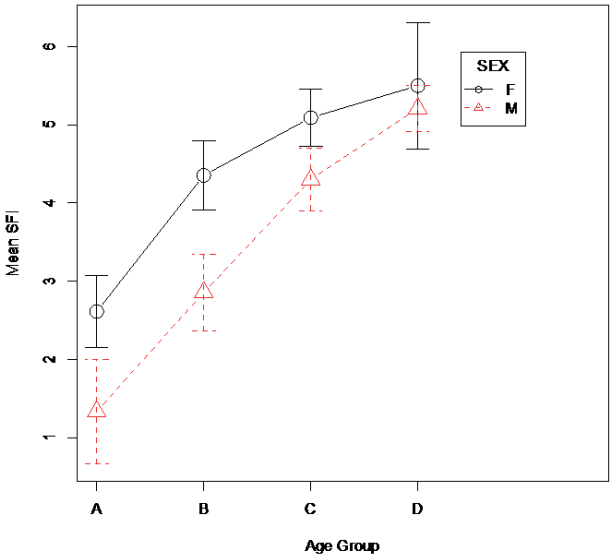

Fig. 3. Results for mean skeletal frailty by sex within age groups (A=18–25, B=26–35, C=36–45, D=>45 years).

TABLE 5

T-TEST RESULTS (P-VALUES) COMPARING (a) ALL AGE GROUPS AND (b) AGE GROUPS BY SEX (MALES IN LOWER LEFT TRIANGLE AND FEMALES IN UPPER RIGHT TRIANGLE)

(a)

Years of age	18–25	26–35	36–45	>45
18–25		0.03*	0.0001*	<0.0001*
26–35			0.05*	0.0008*
36–45				0.09
>45				

(b)

Years of age	18–25	26–35	36–45	>45	
18–25		0.01*	0.0003*	0.01*	Female
26–35	0.13		0.21	0.25	
36–45	0.02*	0.03*		0.66	
>45	0.01*	0.0004*	0.07		
	Male				

* Results significant at the 0.05 level

Discussion

Gross prevalence

Although gross prevalence counts provide a population overview of frailty, they do not estimate individual frailty. The most prevalent conditions observed are indicative of nutritional stressors, systemic infection, and damage from physical activity. Drawing on isotopic evidence[34] as well as historical records[73], the diet at Kałdus largely consisted of rye, millet, or similar cereal grains, fish, and terrestrial animal meat. Many medieval Polish cooking methods destroyed much of the nutritional value of the food being consumed and relied on the heavy addition of spices to cover up poor quality. Fruits were rare and likely available only to the elite. Additionally, the lower classes would have often consumed poorer quality and fatty cuts of meat[73]. Nutritional deficiencies from this diet could be severe as it lacks diversity and breadth and is low in iron, sugar, and vitamins A, B12, C, E, and K. Furthermore, local reliance on trade routes to acquire resources would have made the residents of Kałdus vulnerable to the ebb and flow of goods and shortages in other regions.

Additionally, the high prevalence of activity-related skeletal conditions suggests a lifestyle with high daily workloads. Although Kałdus was not primarily an agricultural site, historical records report life for its residents was far from leisurely[26,27]. Kałdus was an early urban center and economic hub well connected to other regions through trade. While urban areas of medieval Poland likely relied partially on agriculture, animal husbandry, and fishing, occupations in Kałdus were primarily related to trade and specialized industries of the emerging urban markets such as blacksmiths, butchers, builders, and ceramicists[26]. Craft specialization would have involved considerable repetitive movement associated with the trade, leading to degenerative changes in the joints involved. Gendered division of labor is unclear in the historical record, yet there is at least evidence the backbreaking task of laundry was carried out primarily by women of the household. Records also provided accounts of lucrative opportunities for women employed as professional laundresses throughout the medieval period in Poland[74]. It is doubtful the significantly higher prevalence of vertebral degenerative joint disease in males is meaningful in terms of its representativeness of a higher workload in males. Rather, this discrepancy may be a result of the age distribution of the sample (Figure 2), wherein males are more represented at older ages and females at younger ages. In fact, in the oldest age group males and females did not vary significantly in degenerative joint disease of the limbs ($p = 0.33$), degenerative joint disease of the vertebrae ($p = 0.83$), or osteoarthritis ($p = 0.33$).

Gross prevalence results from Poznań, a larger medieval Polish urbanizing center, provide an interesting comparison to Kałdus (Table 6). Betsinger[75] (see also Betsinger and DeWitte[76]) analyzed skeletal indicators of health in three cemeteries dating from AD 950–1250 corresponding to a time of increasing urbanization in Poznań. In this sample, like the Kałdus sample, there is evidence of significant differences between males and females only for porotic hyperostosis ($p = 0.007$) and degenerative joint disease ($p = 0.041$). The prevalence of cribra orbitalia in the Poznań sample males (5%) hardly varies from that at Kałdus (4%). Conversely, females at Poznan show a threefold higher incidence (19%) than observed in our sample (6%), albeit this sample does not represent all females interred at the site. Interestingly, the rates of LEH at

Poznań (62% for males and 50% for females) also are approximately doubled from the Kałdus sample (34% for males and 37% for females). However, traumatic injury at Kałdus (30% in males and 15% in females) is twice as common among males and five times greater among females than at Poznań (15% in males and 3% in females). Additionally, prevalence of porotic hyperostosis at Poznań is 40% for adult males and 9% for adult females, similar to prevalence at Kałdus (30% for adult males and 13% for adult females). Lastly, rates of periosteal reaction at both sites are similarly high, appearing in 30% of males and 44% of females in the Poznań sample, and 57% of males and 44% of females in the Kałdus sample; although males show twice the frequency at Kałdus compared to Poznan, while females are identical.

Betsinger[71] attributes the high prevalence of periosteal reaction in Poznań to poor sanitary conditions, pollution of the water supply, and cramped living conditions that often result from urbanization. This suggests the same might be true for Kałdus, although it had a smaller population. While most biomarkers have similar prevalence at both sites, the prevalence of LEH at Poznań is far higher than at Kałdus. This suggests malnutrition or disease may have been more common during growth and development at Poznań, or that children, who suffered from severe malnutrition and disease at Kałdus, were less likely to survive the acute stressor and died before LEH could develop. The higher rate of traumatic injury at Kałdus is also noteworthy and suggests hard lives for Kałdus' residents relative to Poznań's residents.

TABLE 6

COMPARISON OF GROSS PREVALENCE VALUES OF SKELETAL AND DENTAL LESIONS BETWEEN KAŁDUS SITE 4 AND POZNAŃ

Lesion	Kałdus		Poznań	
	Male	Female	Male	Female
Porotic hyperostosis	0.30	0.13	0.40	0.09
Cribra orbitalia	0.04	0.06	0.05	0.19
Linear enamel hypoplasia	0.34	0.37	0.62	0.50
Periosteal reaction	0.57	0.44	0.30	0.44
Trauma	0.30	0.15	0.15	0.03

Sex

Although not significant, comparisons of the SFI at Kałdus suggested some sex difference in individual frailty ($p = 0.09$), with males above females. Interestingly, once confounding effects of age were controlled, the SFI was significantly different by sex ($p = 0.044$), with females above males. Although males showed higher mean SFI than did females overall, females exhibited higher frailty within every age group examined (Figure 3, Table 4). Evidence suggests that after accounting for the uneven age distribution, a significant disparity in frailty existed between males and females at medieval Kałdus.

Based on mortality risk, DeWitte[20] observed that females in a medieval London cemetery also were less frail (lower risk of mortality) than their male counterparts. Marklein and colleagues[15] also reported males exhibiting higher SFI in a medieval London sample of monastic and nonmonastic individuals. They posited that sociocultural settings buffering males from early life stressors allowed them to survive more stressors contributing to higher skeletal frailty later in life. Using the 11-biomarker index, we observed a significant sex difference in frailty at Kałdus site 4 when controlling for age. A greater proportion of all interred females examined were aged 18–35 years (67%) than older ages; among males, the majority were 36-plus years (70%; see Figure 2). Likely reflecting selective mortality, but perhaps interment patterns at this site, the majority of females at Kałdus site 4 died in their prime reproductive years, a pattern also observed among urban females in medieval London[77]. Early mortality likely limited their lifetime exposures to stressors and degenerative conditions sufficient to imprint their skeletons. Conversely, higher estimated ages among males suggest conditions favoring survival during earlier life allowed more to experience longer lifespans than females. Those who survived longer then experienced sufficiently more stressors severe enough to affect their skeletons, contributing to higher average skeletal frailty among males and at older ages for both sexes. Supporting this suggestion, the age distribution in our sub-sample resembles closely that reported for of all remains excavated from Kałdus site 4, where, Chudziak[32] reported, 46% of females died between ages 20–29 years, but only 14% of males did. Conversely, 33% of males died between ages 40–49, while only 13% of females did. We suggest, during the early Piast dynasty period at Kałdus, females were less resilient to stressors imposed upon them during their prime reproductive years, ages 18–35 years. Based on lack of sex differences from isotopic evidence, these stressors were not the result of dietary/nutritional differences[34]. At the same time, males apparently experienced fewer stressful conditions and events during these early ages than did females, surviving sufficiently long to express higher overall frailty at older ages. This suggests that while males exhibited greater average frailty, many females may have experienced more stressors sufficient to end their lives at earlier ages.

Age

ANOVA and ANCOVA support the hypothesis that frailty is related significantly to age at Kałdus site 4. Due to the degenerative nature of most conditions associated with the frailty phenotype (e.g., osteoarthritis, degenerative joint disease), frailty and age often correlate significantly in both living and skeletal samples[2,15]. However, frailty also reflects childhood stressors, for example LEH[56]. Thus, frailty not only increases with age but also depends on early life conditions. In a sample from medieval London using the same age categories as here, Marklein et al.[15] reported the youngest age group to have a

consistently higher SFI than the next oldest age group, with frailty increasing incrementally thereafter. Here, frailty is lowest in both males and females at the youngest ages and increases monotonically thereafter (Table 4).

Although we describe our assessment as a "skeletal frailty index," this measure may be more accurately described as indexing an intricate, life-long, three-way interaction among frailty, health, and resilience. Individuals surviving to the oldest ages, although attaining a high SFI score, likely represent the most resilient (e.g., lowest risk of mortality) of their populations[19]. They accumulate multiple skeletal indicators of stress because they survive more of life's stressors over time. Consequently, a high SFI at late age signifies resilience relative to non-survivors who failed to survive sufficiently long to develop skeletal signatures of frailty. At Kałdus site 4, older individuals exhibiting high skeletal frailty likely were the most resilient during life, not those most susceptible to illness, disease, malnutrition, and stressors of pregnancy. They were the survivors to post-reproductive adulthood during a period marked by social change.

Limitations

As is the nature of human remains, preservation is an issue in this sample. The final sample (n=108) examined, though relatively large among bioarchaeological samples, includes only 18% of those interred at Kałdus site 4 (n=601) due to poor preservation. Including only individuals with all 11 SFI biomarkers greatly reduced the available sample. Inherently, skeletal variation among those individuals not included is unknown, as they are not available for analysis. Accordingly, small sample sizes within age categories for each sex prevent broad generalization about this population in many cases.

Another limitation reflects the nature of the SFI methodology itself. Equal weighting of each biomarker and our inability to differentiate levels of severity even within each biomarker is inherently problematic; however, as yet no meaningful weighted scales exist for most biomarkers, we have elected conservatively to give them equal weight. With this methodology, there is no way to distinguish a mild periosteal reaction from violent trauma, or cribra orbitalia from severe chronic intervertebral disc disease causing a significant challenge to mobility and decrease in well-being. Additionally, one cannot discriminate between mild and severe, crippling forms of a condition such as osteoarthritis as both are equally weighted. With fractures in this index, the cause of the trauma is not discriminated between accidental injuries and those inflicted by interpersonal violence, which would indicate a more chronic social stressor in a region rife with political, religious, and cultural tension. However, recent research continues to expand our ability to categorize skeletal indicators as evidence of frailty or resilience. For example, McFadden and Oxenham[78] recently demonstrated how differential categorization of cribra orbitalia may represent either high or low frailty. This may depend on age of occurrence and its association with lower or higher age at survival based on clinical and epidemiological literature. Thus, with closer analysis of the sample and more detailed differentiation in skeletal indicators of stress, a weighted index may be possible in the future.

Conclusions

Utilizing a methodology recently proposed by Marklein and colleagues[15] frailty was examined in a medieval Polish skeletal sample from Kałdus using skeletal biomarkers. Using an 11-biomarker SFI, skeletal frailty was found to be significantly different between males and females, and was higher at older ages. Gross prevalence of frailty in the full Kałdus sample, when compared to another urban medieval Polish sample from Poznań[75,76], suggests these two populations experienced comparable levels of stress and compromised health associated with life in an urbanizing setting, including poor nutrition, systemic infection, and high physical activity.

An important next step in this research is to connect frailty to specific burial context and isotopic evidence in order to elucidate connections between diet, lifestyle, and health. These associations may better illustrate life in medieval Kałdus and the health and lifetime stressors of its inhabitants. Connecting frailty analyses to burial context would also allow us to observe any relationships between religious influences and stress, and complex interactions that might have resulted from this unstable time of political and social change in Poland's history. Connecting frailty to isotopic evidence would further illuminate relationships between local dietary trends and differential access to resources at Kałdus.

For future research, additional samples from settlements surrounding Kałdus, such as Gruczno and Rogowo, should be analyzed. These data will allow us to determine a more complete picture of biological health and stress in this region of Poland during the medieval period. Results from the comparative analyses of settlements with different economies also will illuminate possible relationships between lifestyle and frailty. Addition of contextual information and isotope values to skeletal frailty estimates in the Kałdus sample will help complete this picture of lifestyles and health in medieval times. The skeletal frailty index presented here provides a path forward in exploring the multidimensional, biocultural impacts of urbanization on medieval populaces. Results using the SFI close some of the gaps in the historical record by elucidating individual human variation and life experiences in the past.

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SUPPLEMENTAL TABLE

COMPARING DIAGNOSTIC CRITERIA OF PATHOLOGICAL CONDITIONS USED IN THE SKELETAL FRAILTY INDEX FROM GLOBAL HISTORY OF HEALTH CODEBOOK AND MUSEUM OF LONDON OSTEOLOGICAL METHOD STATEMENT TO DEMONSTRATE THE APPLICABILITY AND USE OF GHHP DATA FOR SFI STUDY.

Frailty Measure	GHHP Codebook*	Osteology Method Statement*
Linear enamel hypoplasia	"only linear grooves clearly seen with the naked eye. A common test for presence of hypoplasias is whether the indentation can be felt with your fingernail" (p. 406)	"Clear groove on the tooth surface" and "clearly felt with the fingernail" (p. 24)
Cribra orbitalia	"A cluster of mostly fine foramina covering a small area" to "Substantial area covered by small and/or larger foramina with a tendency to cluster together" (p. 403)	"pitting of the compact bone varying in size from capillary like impressions to coalescing outgrowths" (p. 53)
Porotic hyperostosis	"Presence of slight pitting or severe parietal porosity" to "Gross parietal lesion with excessive enlargement of bone" (p. 404)	"pitting of the compact bone varying in size from capillary like impressions to coalescing outgrowths" (p. 53)
Dental pathology		
Abscesses	"recognized by a clear drainage passage in the alveolar bone leading from the tooth roots to the external surface of either maxilla or mandible" (p. 406)	Presence of sinus drainage in maxillae or mandible to external or internal surface with note of etiology from dental caries or advanced wear (p. 24)
Antemortem tooth loss		"the full or partial healing of the empty [tooth] socket" (p. 11)
Periosteal reaction	"accentuated longitudinal striations"; "slight, discrete patches of reactive bone"; "moderate involvement of periosteum"; "extensive periosteal reaction… with cortical expansion" (p. 418)	"Bony proliferation…healed or active at the time of death (woven, lamellar or mixed)"; "bony changes overlie the original surface of the bone cortex…in later stages… generalized expansion of the shaft" (p. 38)
Osteoarthritis	"articular surface can be pitted and/or polished (eburnation)" (p. 419)	"Degenerative joint changes"; "defined by the presence of eburnation" (p. 47)
Degenerative joint disease (limbs)	"slight to severe marginal lipping and generative changes"; "complete or near complete destruction of articular surface" (p. 420–21)	"Degenerative joint changes" (p. 47)
Degenerative joint disease (vertebrae)	"Osteophyte formation on at least one vertebral body"; "Extensive osteophyte formation on at least one vertebral body" (p. 421)	Intervertebral disc disease "pitting on and around the centrum" (p. 47)
Fracture (Antemortem and Perimortem)	"Antemortem trauma features bone remodeling in the area of the injury and a well-defined callus formation"; "Perimortem skeletal injuries…lack evidence of healing, typically propagate at an oblique angle…and have a color similar to the undamaged bone surface" (p. 416)	"Note the state of healing (healed, healing, unhealed), the size and type of bone forming the callus (woven, lamellar or mixed). Where the broken ends have not unified, whether the fracture was in the process of unification (healing) or had permanently failed to unite (healed) is noted" (p. 44)

*Diagnostic criteria, which were used to assign high frailty (frailty score "1") from nonmetric frailty measures, are directly quoted from GHHP Codebook[24] and Osteology Method Statement[37].

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A.C. Tuggle

The Ohio State University, Department of Anthropology, 4034 Smith Laboratory, 174 W 18th Avenue, Columbus, OH, 43210, United States

e-mail: tuggle.26@osu.edu

SKELETNA OŠTEĆENJA NA KAŁDUSU, POLJSKOM SREDNJOVJEKOVNOM GROBLJU RANE DINASTIJE PIAST

S A Ž E T A K

Cilj ovog projekta je odrediti skeletnu oštećenost pomoću indeksa skeletnog deficita (SFI) na srednjovjekovnom poljskom nalazištu Kałdus kako bi se bolje procijenili utjecaji životnog i socijalnog okruženja na pojedince unutar ove urbanizirajuće populacije. Kao uzorak koristili smo odrasle osobe iz baze podataka *Global History of Health Project*, a 11 skeletnih i dentoalveolarnih biomarkera odabrano je za procjenu skeletnog stanja u djetinjstvu i odrasloj dobi i njihove individulane vrijednosti zbrojene su u indeks SFI. Kumulativni rezultati sistematizirani su za svakog pojedinca i kreću se od 0 (nema skeletnih biljega stresora) do 11 (svi koštani biljezi stresora su prisutni) na temelju prisutnosti ili težine životnih stresora koji su za života utjecali na koštane promjene. Kako mnogi biljezi na kostima koreliraju s godinama, indeksi SFI su uspoređivani između pojedinaca unutar određenih dobnih skupina: 18–25 (n = 21), 26–35 (n = 31), 36–45 (n = 31), i > 45 (n = 25) godina. U ukupnom uzorku, SFI je u prosjeku iznosio 4,13 (raspon 0–9, sd = 1,98). U muškaraca (n = 56), SFI je u prosjeku iznosio 4,45 (sd = 1,90; raspon 1–8); u žena (n = 52) bio je 3,79 (sd = 2,03; raspon 0–9). SFI je bio najniži u najmlađoj dobnoj skupini, 2,38 (sd = 1,83; raspon 0–6), a najviši u najstarijoj, 5,48 (sd = 1,50; raspon 2–9; p <0,001). U ovim srednjovjekovnim kosturima, raspodjela SFI značajno se razlikovala između muškaraca i žena samo uz kontrolu za dob (p = 0,044), s tim da su žene imale veću srednju vrijednost unutar svake dobne skupine. Utvrđena skeletna oštećenja ukazuju na to da su te osobe bile izložene znatnom stresu tijekom svog života. Kako je poljska pisana povijest u srednjovjekovnom razdoblju oskudna, procjena skeletne oštećenosti pruža alternativni način za razumijevanje života i izloženosti stresu. Daljnja istraživanja koja će povezati oštećenost kostiju s kontekstom pokopa i izotopskim dokazima rasvjetlit će povezanost indeksa SFI s prehranom, načinom života i zdravljem u srednjovjekovnoj Poljskoj.