Special issue adaptive tools for resilient bones: biostatistical approaches to past physical activity in osteoarchaeology

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SPECIAL ISSUE PAPER

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Abstract

In this introduction to the special issue, *Adaptive Tools for Resilient Bones: Biostatistical Approaches to Past Physical Activity in Osteoarchaeology*, we discuss the outcome of the workshop held in Leiden (the Netherlands; November 18–19, 2021). We review statistical approaches to entheseal changes and present a series of new contributions to this field. These research, commentary, and review articles present different statistical approaches to entheseal changes and reflect the current state of research in the field.

KEYWORDS
activity, entheseal changes, statistics

1 | INTRODUCTION

Investigations into physical activities of past individuals and populations have been an enduring goal of bioarchaeology. Jurmain and colleagues referred to activity reconstruction as the Holy Grail of bioarchaeology, simultaneously highlighting the value and potential impact of such research and, equally, the difficulty of attaining such an ambitious objective (Jurmain et al., 2012). With Angel, Kennedy, Merbs, and Dutour publishing some of the earliest case studies of musculoskeletal modifications to the skeleton, this line of research has been continually studied from an osteoarchaeological perspective for more than five decades (Angel, 1966; Dutour, 1986; Kennedy, 1983; Merbs, 1983).

The *International Journal of Osteoarchaeology* has a long history with activity-related research. In 1998, the journal published a special issue on "Stress Markers," which focused on methodological approaches to quantifying and standardizing skeletal indicators of activity (Peterson & Hawkey, 1998). More than a decade later, the *International Journal of Osteoarchaeology* published another special issue related to activity, which focused on technical and theoretical advances in entheseal changes research (Henderson & Alves Cardoso, 2013). In addition to these transformative special issues, there have also been numerous impactful publications relating to interdisciplinary perspectives, methodological advancements, experimental studies, terminology, questions regarding contributing factors, and critiques (see Acosta et al., 2017; Djukić et al., 2015, 2020; Godde et al., 2018; He & de Almeida Prado, 2021; Henderson et al., 2016; Karakostis et al., 2018; Karakostis, Jeffery, et al., 2019; Karakostis, Wallace, et al., 2019; Karakostis, Haeufle, et al., 2021; Karakostis, Reyes-Centeno, et al., 2021; Michopoulou et al., 2015, 2017; Milella et al., 2015; Niinimäki & Salmi, 2016, 2021; Nikita et al., 2019; Nolte & Wilczak, 2013; Salmi et al., 2020; Villotte & Knüsel, 2013; Villotte et al., 2016; Wallace et al., 2017).

However, one crucial point seemed to be lacking from this list—statistical clarity. Although this topic was discussed in a previous special issue, a lack of statistical transparency persisted (Robb, 1998). For this reason, the authors organized a two-day workshop entitled, *Adaptive Tools for Resilient Bones: Biostatistical Approaches to Past Physical Activity in Osteoarchaeology* held at the University of Leiden, the Netherlands (November 18–19, 2021). The objective of the conference was not to select the single best statistical approach, nor define an all-encompassing set of statistical guidelines. Rather, the goal was to discuss the advantages and disadvantages of various statistical methods currently being applied to entheseal changes and activity-related research more broadly. We consider this workshop to be a success, with more than 300 registered attendees from 44 countries. We present here a brief discussion on the history of statistical approaches to activity related studies in bioarchaeology as well as a series of articles, which illustrate new research and review perspectives, that are a product of the Adaptive Tools for Resilient Bones workshop.

2 | STATISTICAL INQUIRY

As mentioned above, statistical approaches to entheseal changes have been diverse (Table 1). It is important to note that the statistical test of choice is often directly related to the how entheseal changes data has been recorded (e.g., continuous, ordinal, and binary dichotomy). At a most basic level, descriptive statistics are frequently used. This often involves reporting measures of central tendency (e.g., mean) and sometimes includes measures of variability (e.g., standard deviation, variance, minimum and maximum variables, kurtosis, and skewness). While these data are certainly informative, particularly if complete (i.e., measures of variability and measures of variance), many studies have adopted statistical approaches that allow for comparisons (e.g., between populations, time periods, and sexes).

The chi-square test has been used to assess whether two variables are associated. Bivariate correlations have been employed to examine the strength and direction of a linear relationship between two continuous or ordinal variables. This usually involves questions pertaining to the degree to which two variables are related (e.g., entheseal changes and age). Some authors opt for Pearson's correlation coefficient, while others argue that the more conservative nonparametric Spearman's rank correlation coefficient is more appropriate for entheseal data.

If researchers want to compare the means of two populations (e.g., population groups and time periods), a *t*-test or nonparametric Mann–Whitney *U* have been used. Multivariate correlations are also applied in scenarios where multiple variables are being compared ANOVA/ANCOVA/Factorial ANOVA, as well as the nonparametric Kruskal–Wallis, have been utilized. The Wilcoxon signed-rank test (nonparametric version of paired *t*-test) has been used, typically to test bilateral asymmetry within individuals.

More recently, various forms of regression have been applied to entheseal changes data. Generalized linear models (GLM) are a type of linear regression that allows for the study of the impact of multiple independent predictor variables and their interactions. Generalized estimating equations (GEE) are similar to GLM but allow for the analysis of longitudinal data. This brief summary is not exhaustive but highlights some of the major trends in statistical approaches in entheseal changes analysis in the past few decades.

3 | A BRIEF OVERVIEW OF PAPERS IN THIS SPECIAL ISSUE

In addition to this introduction, this special issue consists of seven contributions, including research articles, review articles, and short reports. Here, we will briefly highlight these papers and their unique additions to the field.

In a compelling contribution, Villotte and Santos discuss the relationship between age-at-death and entheseal changes and, in doing so, question the "muscle-use" hypothesis that osteoarchaeologists often rely upon in their interpretations. Thirty fibrous and fibrocartilaginous attachment sites were examined in a large sample ($n = 721$), originating from four collections (all European, 18th–20th centuries), where sex and age have been identified. Spearman's rank correlation coefficients and Fisher's exact tests were used to examine the relationship between age-at-death and entheseal changes. Logistic regression and log-linear models were applied to examine the interaction between age, sex, and entheseal severity. Adjusted standardized residuals were then utilized to identify which contributing factors impacted entheseal changes the most. Lastly, generalized odds ratios were employed to assess if the distribution of entheseal changes scores differed across age groups. Villotte and Santos found that the majority of fibrous points of attachment prior to the fourth decade were stage B (slight modifications affecting the margin and/or inner part of the enthesis), with stage C entheseal changes (major modifications affecting the margin and inner part of the enthesis) increasing with age. The authors note that, while these results seem to support the "muscle use" hypothesis, this should be used with caution as more histological and experimental analyses are required. Fibrocartilaginous entheses were found to increase across age classes, with the most major changes occurring in the fifth and sixth decade of life. These findings suggest that entheseal changes in young or middle adult skeletons may actually reflect microtrauma during life; however, this is increasingly unreliable with age.

Cheverko and colleagues present new entheseal data from a context of emergent inequality in the San Pedro de Atacama oases. Through the analysis of four contemporary sites (Middle Period AD 400–1000; $n = 210$) of varying status, the authors examine the intersection of physical activity and increasing social and economic disparity. Thirty-four entheses were examined (17 per side) and data were then combined into joint categories (shoulder, elbow, wrist, hip, knee, ankle). ANCOVA and Factorial ANOVA were used to compare entheseal scores between sites. Both approaches allow for direct comparisons between multiple groups, while controlling for covariates—in this case, the most significant potential covariate was deemed to be age. Factorial ANOVAs were used to test the dependent variable (entheseal changes) against two or more categorical variables (i.e., linear interaction), while ANCOVAs were suited for numeric and ordinal variables as predictors. Cheverko and colleagues found that the elite site of Casa Parroquial had lower entheseal scores in most joints. These data suggest a varied lived experience, manifesting in embodied labour practices, between high-status and low-status groups in San Pedro de Atacama during a period of population expansion, trade network development, and socioeconomic inequality institutionalization.

Nikita and Radini elucidate how labour, activity, and daily life changed from the Anglo-Saxon period (6th–9th centuries CE) to the Medieval period (11th–16th centuries CE), in the East Midlands (England; $n = 151$). This is a critical time period in history, as it marks

TABLE 1 Examples of statistical approaches applied to entheseal changes research

Associations	Chi-square	Alves Cardoso & Henderson, 2013
		Bakirci et al., 2020
		Campanacho & Santos, 2013
		Godde & Taylor, 2013
		Listi, 2016
		Milella et al., 2012
	Pearson's	Nolte & Wilczak, 2013
	Spearman's	Bakirci et al., 2020
		Lieverse et al., 2013
		Milella et al., 2012; Milella, 2014
		Niinimäki, 2012
		Nikita et al., 2019
		Palmer et al., 2016, 2019
		Schrader, 2012, 2015
	Odds ratio	Acosta et al., 2017
		Laffranchi et al., 2020
Differences between groups	*t*-test	Karakostis, Jeffery, & Harvati, 2019
		Nolte & Wilczak, 2013
	Mann–Whitney *U*	Alves Cardoso & Henderson, 2013
		Bakirci et al., 2020
		Carballo-Pérez et al., 2021
		He & de Almeida Prado, 2021
		Laffranchi et al., 2020
		Niinimäki & Baiges Sotos, 2013
		Palmer et al., 2016, 2019
		Refai, 2019
		Santana-Cabrera et al., 2015
		Schrader, 2012, 2015
		Yonemoto, 2016
	ANOVA/ANCOVA	Godde et al., 2018; Godde & Taylor, 2013
		Niinimäki, 2012; Niinimäki & Salmi, 2021
		Schrader & Buzon, 2017
	MANOVA	Bousquié et al., 2022
		Milella et al., 2015
		Thomas, 2014
	Kruskal–Wallis	Alves Cardoso & Henderson, 2013
		Lieverse et al., 2013
		Schrader, 2012
		Yonemoto, 2016
Differences within group	Wilcoxon	Listi, 2016
		Milella, 2014; Milella et al., 2012
		Niinimäki, 2012
		Refai, 2019
		Santana-Cabrera et al., 2015
Regression	Logistic	Alves Cardoso & Henderson, 2013
		Campanacho & Santos, 2013
		Godde & Taylor, 2013

(Continues)

TABLE 1 (Continued)

		Myszka et al., 2020
		Salega & Grosskopf, 2022
	Linear	Bakirci et al., 2020
		Listi, 2016
	Least squares	Niinimäki, 2011
	Ordinal	Henderson et al., 2013, 2017
	GLM/GEE	Alonso-Llamazares et al., 2022
		Becker, 2019
		Castro et al., 2022
		Henderson & Nikita, 2016
		Kubicka & Myszka, 2020
		Laffranchi et al., 2020
		Mazza, 2019
		Michopoulou et al., 2015, 2017
		Nikita, 2014
		Villotte et al., 2010
Other	Principal components analysis (PCA)	Karakostis et al., 2017
		Kubicka & Myszka, 2020
		Santana-Cabrera et al., 2015
		Yonemoto, 2016
	Nonlinear PCA	Milella et al., 2015
	Bayesian	Alonso-Llamazares et al., 2022
	3D landmark-based geometric morphometrics	Casado et al., 2019; Karakostis et al., 2018; Karakostis, Haeufle, et al., 2021; Karakostis, Reyes-Centeno, et al., 2021

the foundations of urbanization, increasing population size, and socioeconomic stratification. The authors examined seven fibrocartilaginous entheses and cross-sectional geometric properties of the upper limb long bones. They innovatively used the Mean Measure of Divergence (for binary data, i.e., entheseal changes) and Mahalanobis distances (for continuous data, i.e., cross-sectional geometry) to examine and visualize similarities in activity patterns within and between assemblages. Additionally, the authors utilized the Shapiro–Wilk test to assess normality; ANOVA for inter-assemblage comparisons; Kruskal–Wallis, followed by pairwise Mann–Whitney tests, for those datasets lacking normal distribution; independent *t*-tests and Mann–Whitney tests for sexual dimorphism assessment, as well as GLM for exploring the effect the assemblage, sex, age, and body size on EC expression. Nikita and Radini found a general lack of sexual dimorphism, with the exception of cross sectional geometry for the medieval St. Peter's collection. For most assemblages, this suggests no pronounced gender-based division of labour was in place during either the Anglo-Saxon or medieval period. One other assemblage stood out in terms of entheseal changes; individuals at Austin Friars, a medieval monastery, had markedly gracile entheseal changes, which aligns well with the theorized limited physical activities they would have been engaged in. In conclusion, Nikita and Radini suggest activity during the Anglo-Saxon period may have been less complex and less diversified than the later Medieval period; however, there were notable similarities between the assemblages of these periods.

Becker et al. problematize current approaches to entheseal changes research and provide an innovative alternative to how these data can be interpreted going forward. Oftentimes, entheseal changes research is conducted at the population level, involving numerous entheses, which can result in overwhelming and unclear findings. The authors propose an individual-level approach to entheseal analysis using a large collection of skeletal data ($n = 1203$) from the Tiwanaku culture (500–1100 CE; Bolivia). A total of 37 entheses are examined and grouped into use areas (upper arm, forearm, mid-body, lower body, foot). By applying GEE, Becker and colleagues are able to examine a dependent variable's relationship to both within-subject and between-subject variables (e.g., location, time period, sex, and age). The authors also discuss database design and advocate for the use of one burial or specimen number per individual, for which all associated data can be "anchored," thus facilitating queries, exploratory analysis, as well as, but not limited to, multiresearch use. Using these tools, Becker and colleagues found significant differences between the Tiwanaku core and colony communities, with modelled frequencies often higher in the core than the colony. Females in the Tiwanaku core also had higher entheseal scores than in the colony (upper arm and lower body). Similarly, core males had higher entheseal scores than colony males (upper arm, forearm, mid-body, lower body). Additionally, differences between colonial neighbourhoods were identified, suggesting there may have been specific community function and specialization.

Carballo Pérez and Schrader examine entheseal changes in the Nile Valley during the state formation process (ca. 4800–1750 BCE). This period was a critical phase as agricultural practices were dramatically intensified, more and more people settled into permanent communities, and socioeconomic status became increasingly divided. Multiple skeletal collections from predynastic and early-dynastic Egypt and Nubia ($n = 259$) were examined. Nonparametric tests, namely, Spearman's correlation coefficient, Mann–Whitney *U*, and Kruskal–Wallis, are applied to compare entheseal changes between sexes, sites, time periods, and left and right sides. Results indicate a decrease in entheseal changes early in the predynastic period, which the authors argue may be linked to increasing specialization and sedentism. This is followed by an increase in entheseal changes, which aligns well with the archaeological data that suggests an institutionalization of inequalities around this same time. There is a great deal of variability in entheseal changes between sites, with high-status sites exhibiting lower entheseal changes scores. Lastly, there also appear to be differences in entheseal changes between sexes, potentially indicating gendered labour activities. Women have higher levels of forearm supination and rotation and could have been in repetitive and strenuous activities involving handcrafting, pottery production, as well as planting, collecting, and processing agricultural resources.

In a review article, Karakostis provides a current summary of entheseal research using the Validated Entheses-based Reconstruction of Activity (VERA) method. Several authors have argued that visual assessment of entheseal severity is unreliable, with high inter- and intraobserver error. Karakostis has provided evidence that the VERA method, employing three-dimensional bone models, more accurately defines and quantifies points of muscle and ligament attachment. Additionally, the validity of the VERA approach has been confirmed using experimental studies (Bousquié et al., 2022; Castro et al., 2022; Karakostis et al., 2017; Karakostis, Jeffery, et al., 2019; Karakostis, Wallace, et al., 2019). Karakostis applies size adjustment and multivariate statistical analyses to identify habitual and coordinated muscle groups. Here, Karakostis provides the first step-by-step protocol for univariate and multivariate analysis of VERA quantified data and presents a novel plotting technique, the Group Entheseal Patterning Index. Additionally, techniques for size adjustment, analysis of single entheses, multivariate statistics, biomechanical efficiency, as well as limitations and future objectives, are also discussed in this highly informative and thorough contribution.

The Van der Pas and Schrader contribution reflects a collaboration between a statistician and an osteoarchaeologist. In this commentary, the authors argue that standardizing statistical methods for entheseal changes is not realistic or even desired. Data structure and research questions differ greatly and, therefore, there cannot be a single recommendation for a statistical application. Additionally, examples are provided for how standardization of statistical testing can actually block innovation rather than foster reliability. However, what can be standardized is how statistical analysis with entheseal data are reported within osteoarchaeological studies. The authors use STROBE (STrengthening the Reporting of OBservational studies in Epidemiology) as an example of how guidelines can be put in place to structure data reporting and statistical transparency. While such a STROBE list has not yet been developed for entheseal changes, a list of considerations is provided to help guide authors in their statistical analysis reporting.

4 | CONCLUSIONS

We are very pleased with the outcome of Adaptive Tools for Bones and view this special issue as a step forward in statistical communication within biological anthropology. The contributions in this volume highlight the variety of statistical tests that can and have been used when examining entheseal changes. We suggest that the type of statistical test employed is highly dependent upon the data and research question(s). We hope that this series of publications provide examples and directions for those interested in entheseal changes and activity-related osteological research. Each contribution has aimed to discuss the advantages, limitations, and assumptions of their statistical method of choice. We argue that the first and next step to entheseal changes data handling should be clarity of statistical approach, including how missing data were handled, how statistical assumptions were met (or not), and a complete statistical output, moving beyond just reporting a *p* value (Smith, 2020; Valeggia & Fernández-Duque, 2022).

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CONFLICT OF INTEREST

Authors of this article have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

No data were used in this article.

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