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BRIEF COMMUNICATION

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Sex differences in adult famine mortality in medieval London

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Abstract

Objectives: Recurrent famine events during the medieval period might have contributed to excess mortality during the Black Death in London, England (c. 1349–1350). Previous research using conventional methods of age estimation revealed that adult males experienced lower risks of mortality under "normal" (attritional) but not famine mortality conditions following the Black Death. However, given the biases inherent in conventional age estimation methods, this study reassesses sex differences in risks of medieval adult famine mortality using ages estimated via transition analysis, which avoids some of the limitations of conventional age estimation methods.

Materials and Methods: We apply hazards analysis (the Gompertz model of adult mortality) to ages estimated for human skeletal remains (n = 1245) from London cemeteries dated to the pre-Black Death (*c.* 1000–1250 CE) and post-Black Death (*c.* 1350–1540 CE) periods.

Results: The results reveal no sex differences in risks of mortality before the Black Death but indicate that adult males faced lower risks of mortality after the Black Death during conditions of normal and famine mortality.

Conclusions: These findings largely support those of our previous research, which suggested that selective mortality during the Black Death or sex-biased improvements in standard of living following the epidemic reduced risk of mortality for adult males in the post-Black Death period under normal mortality conditions. However, the use of transition analysis age estimates also revealed a reduced risk of mortality for post-Black Death adult males under famine conditions.

KEYWORDS
bioarchaeology, Black Death, hazards analysis, subsistence crises

1 | INTRODUCTION

Famine, defined as a widespread shortage of (or reduced access to) food, is a complex phenomenon that is variably influenced by factors such as environmental conditions, market forces, and sociopolitical conditions (Ó Gráda, 2007; Sen, 1981). Famine was an important determinant of population dynamics in preindustrial populations in the past, and though it has become less common, globally, since the 19th century (Alfani & Ó Gráda, 2018), it persists as a periodic threat to human health and survival. In addition to the immediate negative effects of famine (i.e., starvation and increased susceptibility to infectious disease), it can also exert intergenerational effects (Heijmans et al., 2008; Tobi et al., 2014). Thus, famine has the potential to powerfully shape human populations dynamics and health over both the short- and long-term. The occurrence of famine and the severity of its effects can reflect the resilience of human systems (see e.g., Itō & Curtis, 2019), and biological and social vulnerabilities at the individual level. With respect to the latter, for example, during famines over the last 250 years, it has often been observed that those at highest risk of death are males, children, and adults over the age of 45, though there is variation in these trends (Ashton, Hill, Piazza, & Zeitz, 1984; Morgan, 2013; Ó Gráda, 2007; Watkins & Menken, 1985; Zarulli et al., 2018).

Bioarchaeological studies of famine have the potential to expand our understanding of temporal and geographic variation in the experiences and outcomes of famine in the past (see e.g., Geber, 2015; Horocholyn & Brickley, 2017). Our own research has focused on medieval England, which experienced numerous severe famines, including the 14th-century Great Famine, which is estimated to have killed 10–15% of the population (Campbell, 2016). It is possible that the cumulative effects of medieval famines contributed, at least in part, to the extraordinarily high mortality levels estimated for England during the Black Death (DeWitte, 2015), demonstrating the immediate and long-term devastating effects that famine can produce.

Previous research on famine mortality patterns in medieval London revealed significant associations between skeletal makers of developmental stress (linear enamel hypoplasia and short achieved adult stature) and burial in famine contexts, suggesting that people who experienced physiological stress early in life were subsequently more likely to die during episodes of medieval famine than would have been true under normal ("attritional") mortality conditions (DeWitte & Yaussy, 2017; Yaussy & DeWitte, 2018; Yaussy, DeWitte, & Redfern, 2016). Further, previous analysis of sex differences in risks of adult mortality under famine and normal mortality conditions (Yaussy et al., 2016) found that prior to the Black Death in London (*c*. 1349–1350), adult males and females experienced similar risks of mortality under both famine and attritional conditions, but that after the epidemic, adult males experienced lower risks of mortality in the context of attritional (but not famine) mortality conditions.

The apparent change over time in sex differences in risk of attritional mortality might reflect the effects of selective mortality during the Black Death or of changes in standards of living following the epidemic. We speculated that the disproportionate deaths of frail males during the Black Death relative to females might have produced lower average frailty among males in the aftermath relative to females; alternatively, documented improvements in diet after the Black Death, which possibly contributed to improvements in health in general (DeWitte, 2014, 2018), might have benefitted males more substantially than females, leading to greater gains in average levels of health for males after the epidemic (Yaussy et al., 2016). We further suggested that the lack of a discernible sex difference in mortality risk during post-Black Death famines might reflect inherent female biological advantages (such as the immune-boosting effects of estrogen) that essentially leveled the playing field during times of food scarcity. As is often the case with bioarchaeological studies, these previous findings yielded equally plausible interpretations and have thus stimulated further study using additional evidence.

The previous study of sex differentials in famine vs. attritional mortality (Yaussy et al., 2016) used data on adult age-at-death estimated using conventional methods of age estimation and obtained from the Wellcome Osteological Research Database (WORD) hosted by the Museum of London Centre for Human Bioarchaeology (*n* = 713 attritional burials; *n* = 814 famine burials). Specifically, adults were assigned to one of four age intervals (18–25, 26–35, 36–45, and 46+ years) by Museum of London researchers based on morphological features of the pubic symphysis (Brooks & Suchey, 1990), iliac auricular surface (Lovejoy, Meindl, Pryzbeck, & Mensforth, 1985), and costochondral junction (Işcan, Loth, & Wright, 1984; Işcan, Loth, & Wright, 1985), and dental wear (Brothwell, 1981). The advantage of using the WORD data is the large sample sizes that are available. However, it has been long established that there are limitations to conventional adult age-at-death estimation methods. These limitations include age-mimicry, whereby estimated ages are biased toward the age-distributions of known-age reference samples (Bocquet-Appel & Masset, 1982), and open-ended terminal age categories, which preclude examination of patterns at later adult ages (Milner & Boldsen, 2012; Milner, Wood, & Boldsen, 2019). These limitations raise the question of whether the previous findings with respect to adult risks of mortality might have been affected by age-estimation method. Therefore, this study reassesses sex differentials in adult mortality in London during conditions of famine and attritional mortality using adult ages that we recently estimated via the method of transition analysis (Boldsen, Milner, Konigsberg, & Wood, 2002), which avoids some of the limitations of conventional methods, as detailed below.

2 | MATERIALS AND METHODS

2.1 | Skeletal samples

All samples of adult human skeletal remains (total *n* = 1245; famine *n* = 385; attritional *n* = 860) for this study come from medieval London cemeteries and are curated at the Museum of London Centre for Human Bioarchaeology. The sample sizes from each cemetery and their respective time periods and mortality type (famine or attritional) are shown in Table 1. Our previous study (Yaussy et al., 2016) used samples of human skeletal remains only from the St. Mary Spital cemetery; this study uses famine burials exclusively from St. Mary Spital, but our attritional sample is drawn from several cemeteries in addition to St. Mary Spital.

TABLE 1 Samples sizes from the medieval London cemeteries

		Mortality type sample size	
Site	**Time period**	**Attritional**	**Famine**
Guildhall Yard	Pre-Black Death	31	–
St. Mary Spital (Periods 14/15)	Pre-Black Death	334	305
St. Nicholas Shambles	Pre-Black Death	108	–
St. Mary Graces	Post-Black Death	208	–
St. Mary Spital (Period 17)	Post-Black Death	179	80

2.1.1 | Pre-Black Death sample: St. Mary Spital, Guildhall Yard, and St. Nicholas Shambles

The pre-Black Death sample (*c*. 1000–1250 CE, *n* = 778) was drawn from three cemeteries: Guildhall Yard, St. Mary Spital (SRP98), and St. Nicholas Shambles. Guildhall Yard dates to the 11th – early 13th centuries, St. Nicholas Shambles dates to the 11–12th centuries, and St. Mary Spital was in use from 1120 to 1540 (Bowsher, Dyson, Holder, & Howell, 2007; Connell, Gray Jones, Redfern, & Walker, 2012; Schofield, 1997; White, 1988). Burials in St. Mary Spital are assigned, based on radiocarbon dating in conjunction with archaeological context, to one of four periods: Period 14 (c. 1120–1200), Period 15 (c. 1200–1250), Period 16 (c. 1250–1400) and Period 17 (c. 1400–1539) (Sidell, Thomas, & Bayliss, 2007). Our pre-Black Death sample comes from Periods 14 and 15. The Guildhall Yard and St. Nicholas Shambles samples represent attritional mortality, whereas the St. Mary Spital sample includes both attritional burials and mass burials associated with famine mortality (Connell et al., 2012).

2.1.2 | Post-Black Death sample: St. Mary Graces and St. Mary Spital

The post-Black Death sample (*c*. 1350–1539 CE, *n* = 467) comes from St. Mary Spital Period 17 (*c*. 1400–1540) and the cemetery associated with the Cistercian Abbey of St. Mary Graces, which was in use from 1350 to 1538 (Grainger, Hawkins, Cowal, & Mikulski, 2008). The sample from St. Mary Graces represents attritional mortality, and, as noted above, the sample from St. Mary Spital includes both attritional and famine burials.

2.2 | Age estimation

We estimated adult ages using transition analysis (Boldsen et al., 2002), which avoids the limitations associated with conventional methods mentioned above. In transition analysis, data from a known-age reference collection are used to obtain the conditional probability, $Pr(c_j|a)$, that an individual will exhibit a particular age indicator stage or suite of age indicator stages given the individual's known age. Using Bayes' theorem, this probability is combined with a prior distribution of ages at death to estimate the posterior probability that a skeleton (for whom age is being estimated) died at a certain age given that it displays particular age indicator stages. It is in this way, by combining the conditional probability, $Pr(c_j|a)$, from a known-age reference sample with a prior distribution of ages at death, that transition analysis avoids age mimicry (Boldsen et al., 2002). For this study, transition analysis was applied to skeletal age indicators on the pubic symphysis and the iliac auricular surface and to cranial suture closure as described by Boldsen et al. (2002). The Anthropological Database, Odense University (ADBOU) Age Estimation software was used to estimate individual ages-at-death. The ADBOU program uses a conditional probability estimated from the Smithsonian Institution's Terry Collection, and we selected the informative "archaeological" prior distribution of ages at death. Though the archaeological prior represents a generalized preindustrial mortality curve and is thus appropriate for our medieval sample (Bullock, Márquez, Hernández, & Ruíz, 2013), its use poses the risk of underestimating the ages of people 70 years of age and older (the alternatives are a uniform prior that tends to lead to overrepresentation of the oldest ages and a forensic prior that is not appropriate for use for ancient populations) (Milner & Boldsen, 2012). For this study, we are not concerned by the potential underestimation of the oldest ages, as the method was used for all individuals in our samples and our focus is population-wide patterns rather than the numerical values of individual age estimates themselves.

Given the current lack of macroscopic sex estimation methods for non-adults that are comparable in accuracy to methods applied to adult skeletons (described below), we did not estimate sex for individuals below the age of 15. Thus, for all analyses in this study, the minimum age for inclusion in the sample is 15 years. Previous bioarchaeological studies have suggested that non-adults in England were at the greatest risk of death during the medieval period, generally (Lewis, 2016), and during famines, specifically (Yaussy & DeWitte, 2018). Thus, a large and particularly vulnerable portion of the population—non-adult individuals—were excluded from our investigation, and our findings are therefore only informative about sex differentials among adults. Thus, we are not certain whether our findings are generalizable across the medieval lifecourse.

2.3 | Sex estimation

We estimated sex based on the following sexually dimorphic features of the skull and pelvis using the standards described in Buikstra and Ubelaker (1994): glabella/supraorbital ridge, supraorbital margin, mastoid process, external occipital protruberance/nuchal crest, mental eminence, ventral arc of the pubis, subpubic concavity, ischiopubic ramus ridge, and the greater sciatic notch. For individuals for whom the skull and pelvis indicated different sexes, the pelvic scores were subjectively weighted more heavily than were features of the skull, given that estimations of sex based on features of the pelvis alone have been shown to be more accurate than those based on features of the skull alone (Meindl, Lovejoy, Mensforth, & Carlos, 1985; Walrath, Turner, & Bruzek, 2004). That is, in cases in which the skull of an individual was ambiguous with respect to sex, but the pelvis strongly indicated one sex or the other, the individual was assigned the sex indicated by the pelvis. The possible inclusion of individuals misclassified with respect to sex in the samples used for this study would possibly result in underestimates of true differences between the sexes in risks of mortality.

2.4 | Statistical analyses

Following Yaussy et al. (2016), sex differences in adult mortality were assessed using hazards analysis, specifically by estimating the effect of sex (male vs. female) on a baseline (Gompertz) hazard model. The Gompertz model is a biomathematical hazard model of mortality reflecting the physiological processes associated with aging that influence mortality (Gage, 1988, 1989; Wood, Holman, O'Connor, &

TABLE 2 Maximum likelihood estimates of the effect of the sex covariate (with standard errors in parentheses) and likelihood ratio tests (LRT) of H_0: Effect of sex covariate = 0

	Attritional			Famine		
Time period	Sex (*SE*)	LRT	*p*	Sex (*SE*)	LRT	*p*
Pre-Black Death	0.01 (0.09)	0.022	.88	0.01 (0.1)	0.006	.94
Post-Black Death	−0.18 (0.1)	3.35	.067	−0.49 (0.2)	4.3	.038

Ferrell, 2002). Importantly, hazard models that have relatively few parameters, such as the Gompertz model, can be informatively applied to the small skeletal samples sizes that are typical of bioarchaeological studies (Milner et al., 2019), as they accommodate missing data without imposing any particular pattern on the existing data.

The two-parameter Gompertz mortality function is age-dependent and includes two parameters (Gompertz, 1825) that, in combination, describe the relatively low risk of mortality typical of younger adult ages and an increase in the risk of death with senescence (Wood et al., 2002). With sufficiently large sample sizes, a Gompertz-Makeham model can be informatively fit to skeletal data; this model adds a third parameter, Makeham's (1860) age-independent component, to the Gompertz model. However, it is often difficult to estimate the age-independent component with paleodemographic samples (Gage, 1988; Herrmann & Konigsberg, 2002; Nagaoka, Hirata, Yokota, & Matsu'ura, 2006), and indeed, preliminary analyses of the data used for this study indicated that the Makeham parameter did not improve the fit of the model to the data relative to the two-parameter Gompertz model. For this study, sex was modeled as a covariate affecting the Gompertz model using a proportional hazard specification:

$$h_i(t_i|x_i\rho) = h(t_i)e^{(x_i\rho)}$$

where the baseline Gompertz hazard $h(t_i) = \alpha e^{\beta t}$, t_i is the age of the ith skeleton in years, x_i is the sex covariate (females are coded as 0, and males are coded as 1), and ρ is the parameter representing the effect of the covariate on the baseline hazard. A positive estimate for the parameter representing the effect of the sex covariate would suggest that males faced higher risks of death compared to females, while a negative estimate would suggest males experienced lower risks of death. We caution overinterpretation of the numerical estimates of the parameters. We view them as providing general measures of differences (or a lack thereof) in mortality and caution readers against taking the numerical estimates at face value as precise measures of risks of mortality.

Model parameters were estimated separately for the famine and attritional burials using maximum likelihood analysis with the program *mle* (Holman, 2005). A likelihood ratio test (LRT) was used to assess the fit of the full model compared to the baseline model, which does not include sex as a covariate. The LRT tests the null hypothesis that there is no difference in risk of mortality between the sexes (H_0: effect of sex covariate = 0). The LRT was computed as follows: LRT = $-2[\ln(L_{\text{sex}}) - \ln(L_{\text{baseline}})]$, where LRT approximates a χ^2 distribution with df = 1. For all analyses, p-values less than .1 are considered suggestive of a trend worth further consideration.

3 | RESULTS

The estimated values of the parameter representing the effect of sex on adult mortality and the corresponding standard errors and results of the likelihood ratio tests for the pre- and post-Black Death attritional and famine samples are shown in Table 2. Consistent with our previous findings using samples from just the St. Mary Spital cemetery and conventional age estimates (Yaussy et al., 2016), the results of these analyses reveal no differences between adult males and females in risks of mortality before the Black Death during conditions of both normal and famine mortality. This study also finds that the estimated effect of the sex covariate for both the post-Black Death attritional sample and famine samples is negative, and the results of the likelihood ratio tests indicate that inclusion of the sex covariate improves the fit of the model in both cases. The findings of this study with respect to post-Black Death attritional mortality are consistent with those of Yaussy et al. (2016); however, we find evidence of a sex effect on mortality for the post-Black Death famine burials that was not detected in the earlier study.

4 | DISCUSSION

In general, the results of this study, when contrasted with those of our earlier study, suggest that transition analysis age estimates might reveal mortality patterns different from those obtained using conventional age estimates. More specifically, the findings of this study suggest that adult males experienced lower risks of mortality compared to adult females in both the context of normal mortality conditions and during famines in medieval London, at least during the 14th–16th centuries. As mentioned in the Methods section above, our sex estimation methods might result in the inclusion of some people who are misclassified with respect to sex in our sample; that is, an unknown number of individuals we included in the male subsample might actually have been female, and vice versa. This possibility means that the true differences between the sexes in risk of mortality under famine or attritional conditions might be underestimated. Given that our results do suggest differences in risks of mortality between the sexes under both mortality conditions, this possibility does not alter our interpretation of the findings, but does underscore the need to view the numerical results as general indicators of risks of mortality rather than take them at face value.

These findings suggest that the female survival advantage that has been observed in more recent famines (e.g., Dyson, 1991; Zarulli et al., 2018) might not have existed in medieval England (we note that both of these previous studies, though they included individuals of all ages, describe this sex difference specifically among adults, and thus are comparable to our study). Female survival advantages during famines have been attributed to the effects of hormones and body composition. Estrogens generally enhance immune defenses, whereas testosterone tends to reduce immunocompetence (Bouman, Heineman, & Faas, 2005; Fish, 2008; Klein, 2000); given that the majority of deaths during famines are attributed to infectious diseases (Mokyr & Ó Gráda, 2002), these differential effects of hormones can strongly determine disease outcomes and thus mortality in the context of famine. Another inherent buffer for females during famines is their typically higher proportions of body fat and lower muscle mass; the former provides energy stores whereas the latter is more metabolically expensive tissue (Ó Gráda, 2007). We do not suggest that such inherent female biological advantages did not exist in post-Black Death London, but it is possible that these inherent traits were not sufficient to overcome the disadvantages that females might have faced in medieval London. For example, Lewis (2016) found in a study of skeletons from numerous medieval English cemeteries that females (ages 6.6–25 years) suffered more from infection and respiratory disease than their male peers did, which suggests that female children and adolescents were the most vulnerable group at this time. These and other disadvantages might have resulted in the lower estimated risk of mortality for males during times of both normal and famine mortality in medieval London.

The consistent finding, between this study and our previous study, that a discernible sex difference in risk of mortality favoring males emerged in London following the Black Death suggests, as detailed above, that there was a differential effect of the Black Death on patterns of frailty in males vs. females or that males benefitted more substantially from improved standards of living, at least temporarily, after the Black Death than was true for females. The current study does not resolve the question of what mechanism(s) might have produced a male advantage during both normal and crisis mortality conditions in 14th–16th century London. Further study using additional lines of evidence is still needed to determine why health appears to have improved after the Black Death and why it might have done so to differing degrees between the sexes.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

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