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Stature and frailty during the Black Death: the effect of stature on risks of epidemic mortality in London, A.D. 1348–1350

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ABSTRACT

Recent research has shown that preexisting health condition affected an individual's risk of dying during the 14th-century Black Death. However, a previous study of the effect of adult stature on risk of mortality during the epidemic failed to find a relationship between the two; this result is perhaps surprising given the well-documented inverse association between stature and mortality in human populations. We suggest that the previous study used an analytical approach that was more complex than was necessary for an assessment of the effect of adult stature on risk of mortality. This study presents a reanalysis of data on adult stature and age-at-death during the Black Death in London, 1348–1350 AD. The results indicate that short stature increased risks of mortality during the medieval epidemic, consistent with previous work that revealed a negative effect of poor health on risk of mortality during the Black Death. However, the results from a normal, non-epidemic mortality comparison sample do not show an association between stature and risks of mortality among adults under conditions of normal mortality. Fisher's exact tests, used to determine whether individuals who were growing during the Great Famine of 1315–1322 were more likely to be of short stature than those who did not endure the famine, revealed no differences between the two groups, suggesting that the famine was not a source of variation in stature among those who died during the Black Death.

1. Introduction

Adult stature reflects, among other things, exposure to chronic stress during development (Haviland, 1967; Powell, 1988; Roberts and Manchester, 2005). According to Steckel (Steckel, 1995: 1903) stature is "a net measure that captures not only the supply of inputs to health but demands on those inputs." Children who are malnourished or fighting infection and disease must expend precious energy resources in basic tissue maintenance and the immune response, diverting energy from growth and development to these most essential metabolic functions. Therefore short adult stature, relative to other individuals within the population, likely indicates poor health and poor nutrition during the developmental years, at least if everyone's genetic composition with respect to stature is similar.

In general, stature is positively correlated with health condition throughout an individual's life (Komlos and Baur, 2003), and inversely associated with risk of mortality (Gage and Zansky, 1995). In contemporary populations, tall people have greater reproductive success (Pawlowski et al., 2000) and survive longer than their short peers (Steckel, 1995; Gage and Zansky, 1995; Waaler, 1984), while short people are more likely to develop chronic diseases later in life, suffer from cardiovascular issues, and die young relative to tall peers (Deaton, 2007; Paajanen et al., 2010).

Bioarchaeological evidence tends to support the assertion that there is an inverse association between stature and mortality (Gunnell et al., 2001; Kemkes-Grottenthaler, 2005; Steckel, 2005; Watts, 2010), though not without exception (Usher, 2000; DeWitte and Wood, 2008). Gunnell et al. (2001) examined the association between stature and mortality in a skeletal sample from northeast England, dating from the 9th through the 19th centuries and found, for both males and females and for all long bones, the odds ratio of death before 30 years of age decreased as long bone length (a proxy for stature) increased. A one standard deviation increase in bone length was associated with a 10–20% decline in the risk of death before age 35, though the pattern was only statistically significant

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for overall bone length index (the mean of the z-scores for all long bones) and humeral length. Likewise, Kemkes-Grottenthaler (2005) found the odds of survival beyond age forty, for both males and females, increased by as much as 15% for each one standard deviation increase in bone length, for all long bones except the radius, in a European skeletal sample dating between 500 and 1900 A.D. Steckel (2005) explored the relationship between stature and mortality in an aggregate sample of skeletal remains from the Western hemisphere, dating between 4500 B.C. and the early 20th century and found that among 15–30 years olds, a five centimeter decrease in femur length was associated with a 4.6 percent decrease in the probability of survival. Recently, in a sample from northern England dating between the 10th and 15th centuries, Watts (2010) found that females who failed to survive beyond 25 years of age were significantly shorter than those who did, though there were no statistically significant results for males. On the other hand, Usher (2000) examined osteological material from a 12th century Danish cemetery from the village of Tirup using a multi-state model of health and mortality, and did not find an effect of femur length on risk of mortality.

One of the authors (SND) of this paper assessed the relationship between stature and risk of mortality in a previous study of the mortality patterns of the 14th-century Black Death (DeWitte and Wood, 2008). In that previous study, a variety of skeletal stress markers were examined to determine whether the Black Death was selective with respect to frailty or if preexisting health condition had no discernable effect on risk of death during the epidemic. The results indicated that people with cribra orbitalia, porotic hyperostosis, tibial periostitis, and enamel hypoplasia were more likely to die during the Black Death than their peers without these skeletal pathologies. Thus, it appears that in general, people in poor health before the epidemic were more likely than their healthier peers to die during the Black Death. However, the previous study failed to find an effect of adult femur length (which was used as a proxy for stature) on risk of death during the Black Death.

The previous study used a multi-state hazards model of morbidity and mortality (Usher, 2000) to evaluate the relationship between skeletal pathology and risk of mortality. This model has two living states, and the third state is death, to which everyone eventually transitions. The first living state, State 1, includes people without visible skeletal stress markers, and the other living state, State 2, includes people with stress markers. The transitions between each of the living states and death are determined by age-specific hazard rates. The model allows for the estimation of the differential risk of death associated with having skeletal stress markers, so it is possible to determine for a particular population whether people with stress markers were at higher or lower risks of mortality than their peers without stress markers. The model also includes a transition from State 1 to State 2. This transition, from a condition of not having a particular stress marker to developing the stress marker in response to physiological stress, is appropriate for stress markers such as enamel hypoplasia, porotic hyperostosis, cribra orbitalia, and periostitis, for which the transition from State 1 to State 2 can occur at various childhood or adult ages. However, femur length was assessed only for adults in the previous study – i.e., the analysis of the relationship between stature and mortality was restricted to people who had completed their growth. Because of this, it might not be necessary to include the transition from State 1 (in this case, average or above-average femur length) to State 2 (i.e., short femur) in order to understand how stature might have affected risks of mortality during the Black Death. Though there is certainly variation in achieved adult stature, for individuals who survive to adulthood, there is thereafter no risk (and thus no variation in the risk) of making the transition from State 1 to State 2 (i.e. from average or tall stature to short stature). It is possible that the previous study failed to find a relationship between stature and risk of mortality because it used an analytical approach that was unnecessarily complex for this particular stress marker.

The study presented here is a reanalysis of data on adult long bone length and age-at-death, using a simpler, and thus more appropriate analytical approach than that used in the previous study of the effect of stature on Black Death mortality. The approach used here has the benefit of requiring the estimation of fewer parameters; such a consideration is often important in paleoepidemiology given the relatively small sample sizes typical of bioarchaeological assemblages. The simpler model does suit the goals of this study, so we are therefore not sacrificing insight in favor of simplicity.

To further our understanding of the factors contributing to variation in adult stature and mortality risk within this population, we also examine variation in long bone length within East Smithfield with respect to year of birth to determine whether individuals who were growing (and thus highly vulnerable to malnutrition) during the Great Famine, 1315–1322, were discernibly shorter than others in the sample.

2. Materials and methods

2.1. Skeletal samples

2.1.1. East Smithfield Black Death cemetery

The medieval Black Death skeletal material for this study comes from the East Smithfield cemetery in northeast London, near the Tower of London. The East Smithfield cemetery is one of only a few excavated cemeteries with both documentary and archaeological evidence clearly linking it to the 14th-century Black Death (Grainger et al., 2008).

The Black Death, which arrived in London through the port of Melcombe-Regis, Dorset, in the fall of 1348 (Gottfried, 1983; Horrox, 1994), ravaged the population of London until the spring of 1350, killing an estimated one third to one half (or more) of the city's population in under two years (Sloane, 2011). According to records from the Church of the Holy Trinity, which note the exact location and dimensions of the burial ground, the East Smithfield cemetery was founded in late 1348 in anticipation of the overwhelming mortality associated with the Black Death (Hawkins, 1990). Archaeological excavations, carried out by the Museum of London's Department of Greater London Archaeology in the 1980's, revealed several rows of individual graves, alongside three mass burial trenches. The trenches were two meters wide, 95–125 m (or possibly greater) in length, and filled end to end with carefully arranged skeletons, stacked as many as five deep in places, suggesting the site was used as an emergency burial ground. It is estimated that 2400 individuals were interred in the East Smithfield cemetery, over 600 of whom were disinterred and are in the care of the Museum of London's Centre for Human Bioarchaeology. Stratigraphic evidence indicates the burials were completed in a single phase, and there is no evidence of interments after 1350 (Grainger et al., 2008), so it can be safely assumed that most, if not all, of the individuals interred in East Smithfield cemetery died as the result of the Black Death.

For this study, a sample of 127 adults (81 males, 46 females) was selected from the East Smithfield cemetery collection and analyzed by the first author (SND) at the Museum of London Centre for Human Bioarchaeology. This sample comprises all of the excavated adults from East Smithfield who were preserved well enough to provide sufficient data on age (using the method described below), sex, and femur and tibia measurements. This study only includes adults because we wanted to examine the relationship between stature and mortality risk among people who had completed growth at the time of their deaths. By excluding sub-adults from this study we avoid a number of potential confounders that would affect an analysis of stature-for-age. Specifically, imprecision in sub-adult age at death estimates may cause children whose ages were underestimated to appear taller for their age than was actually the case, while those for whom age was overestimated might appear short for their age. Further, the timing of skeletal fusion, as well as growth spurts, differs between males and females, so any analysis of stature-for-age would have to be sex specific, a condition which cannot be met given the limitations of present methods for determining sex from sub-adult skeletal remains.

2.1.2. Medieval Danish cemeteries: St. Mikkel and Albani Church

For this study, the results from the East Smithfield cemetery were compared to those from a normal (i.e. non-epidemic) mortality sample from two medieval Danish urban parish cemeteries: St. Albani Church, Odense, and St Mikkel Church, Viborg. These cemeteries, which date to the 1100s- mid 1500s, form part of the current Anthropological Database at Odense University, Denmark (ADBOU) collection. One advantage of using these Danish cemeteries is the ability to select a pre-Black Death sample from them based on the arm positions of the interred individuals. This is important because post-Black Death burials should be avoided given that the epidemic caused dramatic demographic changes throughout Europe (Gottfried, 1983; Bowsky, 1971; Herlihy, 1997; Cohn, 2002; Hatcher, 1977), and according to Paine (2000), episodes of catastrophic mortality can have effects on the demographic profile of a population that are evident for decades. Previous analysis of medieval and post-medieval burials of known date from Denmark revealed a series of changes in the predominant arm position of buried individuals, and arm position during this time period provides dates with narrower margins of error than those produced by radiocarbon dating (Jantzen et al., 1994; Kieffer-Olsen, 1993). The Danish sample used for the current study includes adults interred with arm positions used exclusively or predominantly before the Black Death arrived in Denmark in 1350, and thus it provides a baseline of normal, non-epidemic mortality patterns for comparison with East Smithfield.

There are several other advantages to using the Danish cemeteries in addition to obtaining a pre-Black Death normal mortality sample. The Danish sample is sufficiently large to allow for the estimation of the parameters of the model used in this study, and it is drawn from a population that was similar economically, socially, and demographically to that of southern England up to the time of the Black Death (Poulsen, 1997; Benedictow, 1993; Sawyer and Sawyer, 1993; Roesdahl, 1999; Widgren, 1997). The Danish cemeteries are also from urban areas and were centers for politics, religion, and trade during the Middle Ages, though on a smaller scale than London. Lastly, there were probably genetic similarities between the two populations, which persist today, as a result of the pre-Conquest Norse settlement of England (e.g. Capelli et al., 2003). All of these similarities between the samples mean that observed mortality pattern differences between the East Smithfield and Danish cemeteries can be at least partly attributed to differences between Black Death and normal medieval mortality. However, given that the two samples are not from the same population, if mortality patterns differ between the East Smithfield and Danish cemeteries, potential population differences must also be considered as an explanation.

For this study, a combined sample of 86 individuals (43 males, 43 females) was selected from the St. Mikkel and St. Albani Church cemeteries and analyzed by SND at the University of Southern Denmark (Syddansk Universitet). This sample includes all of the adults from these cemeteries who died before the Black Death and were preserved well enough to yield data on age, sex, and long bone lengths.

2.2. Age estimation

Ages were estimated using the method of transition analysis described by Boldsen et al. (2002). Transition analysis avoids the biases associated with traditional methods of age estimation and provides point estimates of age and individual standard errors for those point estimates, even for older adults (i.e. rather than a broad terminal adult age category). In transition analysis, data from a known-age reference collection are used to obtain the conditional probability, $Pr(c_j|a)$, that a skeleton will exhibit a particular age indicator stage or suite of age indicator stages given the individual's known age. This conditional probability is combined, using Bayes' theorem, with a prior distribution of ages at death to determine the posterior probability that a skeleton in the cemetery sample died at a certain age given that it displays particular age indicator stages. In transition analysis, the prior distribution of ages at death can either be an informative prior based on documentary data or a uniform prior. By combining the conditional probability, $Pr(c_j|a)$, from a known-age reference sample, with a uniform or informed prior distribution of ages at death, transition analysis avoids imposing the age distribution of the reference sample on the target sample, and is thus preferable to traditional methods of age estimation (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), and the ADBOU (Anthropological Database, Odense University) Age Estimation software was used to determine individual ages-at-death and the standard errors associated with those point estimates. The ADBOU program uses a conditional probability estimated from the Smithsonian Institution's Terry Collection that an individual at a given age will be in the observed age indicator states. The program also uses an informative prior distribution of ages at death based on data from 17th-century Danish rural parish records (the Gompertz-Makeham parameter estimates for this prior are: $\alpha_1 = 0.01273$, $\alpha_2 = 0.00002478$, and $\beta = 0.01618$).

Age-at-death data (including standard errors as described below) from East Smithfield were used to determine each individual's year of birth to identify those people whose growth and development might have been adversely affected by the Great Famine, 1315–1322. For these analyses, we examined the effects of famine on growth from conception to age 20 and its effects on prenatal/early postnatal growth, separately. We assessed growth from conception to age 20 to capture as much of the effects of famine on growth as possible. However, we are also interested in the possible effects of malnutrition on immune function and not just its possible negative effects on adult stature. It is possible that malnutrition has the most deleterious effects on long-term immune function when it occurs during prenatal and early postnatal growth – i.e. when many components of the immune system experience their primary growth and development (Moore et al., 1999). Given this possibility, we also restricted analyses to individuals who were *in utero* or neonates during the Great Famine.

For the first analysis, where we assessed the effects of famine on growth from conception to age 20, we included individuals born between 1296 and 1323 in the "famine growth group"; we included individuals born in 1323 in this group because their growth *in utero* might have been adversely affected during the Great Famine. For this analysis, individuals born before 1296 (and who were thus 20 years old or older during the Great Famine) and those born after 1323 were considered as a single "non-famine growth" group for analysis. For the second analysis, where we focused on the effects on prenatal and early postnatal growth, only individuals who were born between 1314 and 1323 were included in the "famine growth" group, and individuals born before 1314 and those born after 1323 were placed in the "non-famine growth" group. Given that the standard errors associated with point estimates of age were large for some individuals, to more accurately compare the "famine" versus "non-famine" groups rather than using just the point estimates of age, we assigned people to these groups using the interval defined by the point estimate of age plus and minus one standard error (using each individual's estimated standard error).

2.3. Stature

This study uses measurements of the femur and tibia as proxies for adult stature. When using stature as a measure of frailty in paleodemographic investigations, researchers often estimate overall stature for each individual from long bones using a regression function derived from known-stature reference samples. For example, the stature-estimation formulae produced by Trotter and Gleser (1952, 1958) have been used frequently by paleodemographers, archaeologists, and forensic anthropologists over the past several decades (e.g., Hershkovitz, et al., 1993; Reale et al., 1998; Robb et al., 2001; Papathanasiou, 2005). However, stature estimation is complicated by between-population differences in stature. Because of this, the ideal reference sample would be one that was very similar to the cemetery sample in terms of genetic composition, diet, and exposure to other factors that affect adult height; unfortunately, such reference samples are rarely available for bioarchaeological studies. Because we are not interested in adult stature *per se*, but rather are using it as a measure of health or physiological stress, we avoid the potential problems associated with estimating stature by directly comparing long bone lengths within each cemetery sample.

The maximum lengths of the femur and tibia were measured using an osteometric board (Buikstra and Ubelaker, 1994). Only complete femora and tibiae were measured. Analyses were done using the sum of each individual's femur and tibia lengths. For model estimation, individuals were assigned a score of 1 ("short stature") if their femur + tibia measurements were more than one standard deviation below the mean for their sex; individuals whose measurements were less than one standard deviation below the mean or were higher than the mean for their sex were assigned a score of 0 ("average or tall stature").

2.4. Sex determination

Sex was determined by scoring features of the skull and pelvis using the standards described in Buikstra and Ubelaker (1994). The following dimorphic features of the skull and pelvis were scored: 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. The accuracy of these individual skeletal features, or various combinations thereof, for the purposes of sex determination has been shown to range from 68 to over 96 percent (Ubelaker and Volk, 2002; Phenice, 1969; Rogers, 2005; Williams and Rogers, 2006; Walker, 2005; Sutherland and Suchey, 1991; Graw et al., 1999). Multiple skeletal indicators of sex were used for this study given that including more than one indicator improves the accuracy of sex determination (Rogers, 2005; Williams and Rogers, 2006; Meindl et al., 1985; Walker, 2008). Because other researchers have demonstrated that sex determinations based on the pelvis are more accurate than those based on features of the skull (Meindl et al., 1985, Walrath et al., 2004), in the event that the skull and pelvis indicated different sexes for an individual, we subjectively weighted the pelvic features more heavily than features of the skull for that individual.

2.5. Gompertz model

To assess the relationship between stature and risk of death during the Black Death and conditions of normal medieval mortality, stature was modeled as a covariate affecting the Gompertz model of adult mortality within the East Smithfield and Danish cemeteries:

$$h(a) = \alpha e^{\beta a}$$

where a is age, α is the risk of death associated with senescence at the moment of birth and β is the rate at which this risk increases with age (Gage, 1988). Because the Gompertz model requires the estimation of just two parameters, it makes efficient use of the available skeletal data. The model can be applied to relatively small samples, as it smoothes random variation in mortality data without imposing any particular age pattern on the data (Gage, 1988).

The East Smithfield cemetery is clearly a catastrophic cemetery, created for and used for a relatively brief period of time during a devastating epidemic, rather than an attritional cemetery, which is characterized by the gradual accumulation, over relatively long periods, of people who died primarily from normal, non-catastrophic causes. This does not necessarily mean that mortality was independent of age in the East Smithfield cemetery, as there is evidence that the risk of death did, in fact, vary with age (i.e. was not age-independent) during the Black Death. The first author previously found that the risk of mortality during the Black Death increased with adult age (i.e. older adults were at higher risks than younger adults), similar to patterns observed in the normal, non-epidemic Danish sample (DeWitte, 2010). Given evidence that Black Death mortality was selective with respect to age, as are many normal causes of death, and the age-at-death distribution in the East Smithfield cemetery thus reflects such selectivity, it is as appropriate to apply the Gompertz model to East Smithfield as to the normal mortality sample.

We have used the Gompertz model in this study rather than the Gompertz-Makeham model (which includes an age-independent component in addition to the Gompertz senescent hazard) for two reasons. First, the age-independent (i.e. residual) component of the Gompertz-Makeham model is not likely necessary for East Smithfield given the catastrophic nature of the cemetery. Inclusion of the senescent component for the East Smithfield sample is valid given that there are factors associated with aging that could have increased risks of dying during the Black Death, e.g. accumulated DNA damage or general declines in physiological functioning that could have negatively affected immune competence (Gage, 1989). However, although there might have been people in the East Smithfield cemetery who died from causes other than the Black Death, and those other causes might have been age-independent causes (e.g. accidental deaths), such people are likely to be a tiny minority of those buried in the cemetery. Therefore, modeling the age-independent component of the Gompertz-Makeham model is not strictly necessary for East Smithfield. For consistency and comparability, we also exclude the age-independent component in our analysis of the normal mortality comparison sample. Secondly, estimating the age-independent component is often difficult to do using paleodemographic data (Herrmann and Konigsberg, 2002; Nagaoka et al., 2006). In a previous analysis of mortality patterns in the East Smithfield and Danish samples, estimates of the parameter representing the age-independent component of mortality did not differ significantly from zero (DeWitte, 2010).

For this study, stature was modeled as a covariate acting upon the parameters of the Gompertz model using a proportional hazard specification:

$$h(a|x_i\rho) = h(a)e^{x\rho}$$

where the baseline hazard $h(a)$ is the Gompertz hazard, x_i is the stature covariate (0 = average or above-average stature, 1 = short stature), and ρ is the parameter representing the effect of the covariate on the baseline hazard. Parameters were estimated using maximum likelihood analysis with the program *mle* (Holman, 2005). A positive or negative estimate for the parameter representing the effect of the covariate on the hazard would suggest people of relatively short stature were at an increased or decreased risk of death, respectively, compared to their taller peers.

A likelihood ratio test (LRT) was used to assess the fit of the full model compared to a reduced model in which the value of the parameter representing the stature covariate was set equal to 0 (H_0: effect of stature = 0). The LRT therefore tests the null hypothesis that short stature was not associated with elevated nor decreased risks of death (i.e. stature had no effect on risk of mortality). The LRT was computed as follows: LRT $= -2[\ln(L_{reduced}) - \ln(L_{full})]$, where LRT approximates a χ^2 distribution with $df = 1$. Though we are wary of reporting statistical significance, given recommendations by major epidemiological and medical journals to avoid doing so (Rothman, 1998; Lang et al., 1998; Cohen, 2011; Goodman, 1999), we consider p-values less than 0.10 to be suggestive of a real effect.

2.6. Fisher's exact test

We used Fisher's exact tests to examine whether growth during the Great Famine affected adult stature by comparing the frequencies of "short" and "average/tall" stature between the "famine growth" and "non-famine" growth groups. The Fisher's exact test was performed using SPSS version 19.

3. Results

Table 1 shows the means and standard deviations for femur + tibia measurement, by sex, within the East Smithfield and Danish samples. Table 2 shows the estimated value of the parameter representing the effect of the stature covariate on the adult risk of mortality and the associated likelihood ratio tests. The positive value of the parameter for the East Smithfield sample indicates that during the Black Death, people who were relatively short were more likely than their taller peers to die during the epidemic. The result of the likelihood ratio test further suggests that adult stature affected risk of death during the epidemic, as it indicates that including the stature covariate improved the fit of the model. The p-value of the likelihood ratio test is 0.07, which though it falls short of the level of significance conventionally selected by researchers, is within the broader definition of statistical significance advocated recently by epidemiologists and medical researchers, who suggest p-values close to or less than 0.10 should be considered suggestive of a real effect (Cohen, 2011; Harvey and Lang, 2010; Mitchell et al., 2010). Similarly, the estimated value parameter representing the effect of the stature covariate is positive in the Danish sample. However, the associated standard error is quite large, and the results of the likelihood ratio test do not indicate an improvement in model fit by including the stature covariate; thus the results should be considered inconclusive for the normal mortality sample.

Table 3 shows the results of the Fisher's exact tests of the association between growth during the Great Famine and adult long bone length in East Smithfield. The results suggest that there is no difference in long bone length between victims of the Black Death who underwent growth during the Great Famine and those who did not.

Table 1
Means and standard deviations for femur + tibia measurements (in mm) by sex in East Smithfield and Danish cemeteries. % "short" = the percent of the sample, by sex, that is more than one standard deviation below the mean.

	East Smithfield			Denmark		
	Mean	Std. Dev.	% "short"	Mean	Std. Dev.	% "short"
Female	752	31	17.4	774	33	18.6
Male	811	41	13.6	853	53	11.6

Table 2
Maximum likelihood estimates (with standard error) of the effect of the stature covariate on adult mortality and results of the likelihood ratio tests.

	Effect of stature covariate (s.e.)	−2LLR
East Smithfield	0.48 (0.25)	3.16 ($p = 0.07$)
Denmark	0.18 (0.30)	0.32 ($p = 0.57$)

4. Discussion

The results of this study suggest that adult stature had an effect on an individual's risk of mortality during the Black Death such that shorter-than-average individuals were at an elevated risk of dying during the epidemic compared to people of average or above-average height. These results are consistent with those from a previous study that showed that various other skeletal indicators of physiological stress were associated with elevated risks of mortality during the epidemic (DeWitte and Wood, 2008). The results from the normal mortality sample from Denmark at face value also suggest that short stature was associated with elevated risks of mortality, though the standard error associated with the estimate and the results of the likelihood ratio test preclude making definitive conclusions about normal mortality patterns.

These results raise the question: why might shorter people have been at higher risk of death during the 14th-century epidemic? Perhaps relatively short adults were short because of genetically determined, innately compromised immune function relative to others in the population. Having relatively poor immune function would have made these people more highly susceptible to infectious disease during growth and development. During periods of active infection, the energy resources of such individuals would have been shifted away from growth and toward basic body maintenance and immune function. So individuals with compromised immune systems who suffered through episodes of infection during childhood and adolescence might have consequently been relatively short adults. As adults, the poor immune competence of such individuals would have also made them more susceptible to infection or placed them at higher risks of mortality during the Black Death. Previous work has shown that the Black Death was selective with respect to frailty (DeWitte and Wood, 2008), as individuals with skeletal signs of poor health (as described above) were at higher risks of dying during the epidemic than their

Table 3
Results of Fisher's exact test of the relationship between famine growth and adult stature.

Growth period		Short	Average/Tall	Fisher's exact test
Conception − 20 years	Famine	5	29	$p = 1.00$
	Non-famine	3	20	
Conception − 1 year	Famine	2	4	$p = 0.576$
	Non-famine	3	20	

healthier peers. The skeletal lesions used in that previous study might, at least in some cases, indicate individuals with innately compromised immune systems. Similarly, short adult stature and increased risks of mortality during the Black Death might both reflect an underlying lifelong condition of impaired immune competence.

Rather than indicating innately compromised immune systems, short adult stature in our sample might have been the result of malnutrition during development. As described above, in children who are malnourished, basic tissue maintenance and immune response will be prioritized over growth and development, so short adult stature can reflect a history of malnutrition. In addition to affecting stature, nutritional status can strongly influence immune competence (Scrimshaw, 2003; Jones et al., 2010; Hughes and Kelly, 2006; Wolowczuk et al., 2008; Fernandes, 2008; Calder et al., 2006; Floud et al., 1990), with malnutrition *in utero* and during early childhood having long-term or permanent negative effects on immune function and increasing risks of mortality from infectious disease in adulthood (Moore et al., 1999, Sullivan et al., 1993). Relatively short individuals in our sample might have been so because they experienced malnutrition during periods of growth, and therefore suffered lasting immune consequences (regardless of nutritional status at the time of the Black Death), or these people might have experienced malnutrition both during growth and at the time of the epidemic (i.e. the effects of malnutrition on immune competence were immediate during the Black Death).

Differences both in adult stature and in risk of mortality during the Black Death might have been the result of variation in the ages at which people experienced famines (and thus variation in nutritional status during growth and development) before the epidemic. Given that all individuals buried in the East Smithfield cemetery died in 1348–50, it is possible using estimated ages-at-death to determine whether people in our sample underwent growth during periods of famine before the epidemic. We can thereby examine the effects of recorded famine during childhood and adolescence on adult stature in East Smithfield.

In particular, some adults in East Smithfield might have experienced severe malnutrition during the Great Famine, 1315–1322. At the start of the 14th century, with a population of several million, England's agricultural demand had begun to outstrip its land's capacity. Exhausted farmlands, combined with several seasons of unfavorable weather conditions, and devastating livestock epidemics, led to severe food shortages and soaring prices. The famine, coupled with an enteric epidemic that tore through the population in 1316 (Kershaw, 1973), might have negatively affected growth (and thus adult stature), and later, immune response during the Black Death.

Results of our Fisher's exact test suggest that there is no difference in stature, among victims of the Black Death, between those whose growth (either from conception to age 20 or fetal/neonatal growth) could have been negatively affected during the Great Famine and those who were either done growing before the Great Famine or were born after it ended. These results may indicate that the effects of famine did not strongly affect growth, and by extension, immune function during the Black Death. However, given what we know about stature, health, and mortality in living populations, it is more likely that the pattern of stature variation among Black Death victims is the result of selective mortality during the Great Famine. Mortality during the Great Famine might have targeted the frailest individuals in this population at the time. If those frail individuals were shorter, on average, than survivors of the famine, the result could have been reduced variation in stature (between those who experienced growth during famine and those who did not) among people who ultimately died during the Black Death. Mortality during the Great Famine might have weeded out the shortest, most frail individuals, and those who survived the famine were thus of average or above-average stature. In other words, mortality during the Great Famine may have targeted individuals of short stature, and presumably lowered immune function, just as the Black Death did years later. We should emphasize that we do not argue that the Great Famine had no affect on stature or on heterogeneity in frailty. Rather, our particular approach failed to find an observable difference in stature among adults who died during the Black Death that can be attributed to the effects of the Great Famine.

It is possible that the observed variation in adult stature in East Smithfield reflects variation in nutritional status during development because of social-status mediated differences in access to resources. Unfortunately, the effect of social status on adult stature cannot be evaluated using our sample given the lack of reliable information on individual social status within the East Smithfield cemetery (Grainger et al., 2008).

The lack of an association between stature and mortality in the normal mortality sample from Denmark might indicate that short stature was not associated with increased risks of mortality under conditions of normal, non-epidemic medieval mortality. If so, this analysis has revealed the first example of a skeletal stress marker associated with stronger selective mortality during the Black Death compared to normal, non-epidemic conditions. This runs counter to the first author's previous findings that suggested that though the Black Death disproportionately killed frail people, the epidemic was less strongly selective than were normal causes of medieval mortality (DeWitte and Wood, 2008). These results might indicate that there was variation within and between these populations in the ways in which physiological stressors affected risks of death. Perhaps in the Danish sample the physiological stressors that caused short adult stature affected risks of mortality less strongly than did stressors that resulted in other skeletal markers (i.e. periostitis, porotic hyperostosis, and cribra orbitalia), whereas in London, at least during the Black Death, such a distinction among physiological stressors did not exist.

Alternatively, perhaps childhood mortality was more strongly selective in the Danish population than in the pre-Black Death population of London (i.e. fewer relatively frail individuals survived to adulthood in Denmark than in London). Stronger selective mortality during childhood in Denmark would have resulted in surviving adult cohorts with less heterogeneity in frailty (as measured by stature) than existed in London at the time of the Black Death. Strong selective mortality at earlier ages would reduce or eliminate differences in risks of mortality at older ages in the Danish population. Again, this is inconsistent with the first author's previous finding based on a variety of skeletal stress markers of stronger selective mortality in pre-Black Death Denmark than during the Black Death in London (DeWitte and Wood, 2008). However, the difference between the current study and previous results might reflect differences in the composition of samples used in each set of analyses, i.e. DeWitte and Wood's previous study (2008) used a sample that included people of all ages, whereas the current analysis was restricted to adults. One other possible reason for the observed lack of association between short stature and mortality in the Danish sample is that the sample size was insufficiently small to discern the true pattern.

5. Conclusion

The results of this study provide further evidence of a relationship between stature and risks of mortality, and specifically that short stature was associated with increased risks of mortality during the Black Death. This is consistent with previous research that has found short stature to be associated with increased risks of mortality in both living and past populations (e.g. Steckel, 1995; Gage and Zansky, 1995; Paajanen et al., 2010; Kemkes-Grottenthaler, 2005), and adds to existing evidence that the Black Death did not kill indiscriminately (DeWitte and Wood, 2008; DeWitte, 2010). If we are to fully understand how mortality operated during the Black Death, we need to view the population at risk as having been composed of various sub-populations with varying risks of morbidity and mortality affected by such factors as genetic composition and health and life histories. It is clear that the Black Death was not an indiscriminate killer, but it is also clear that determining who was at elevated risk of death requires approaches that can uncover hidden heterogeneity within the affected population. The results from the Great Famine cohort are tantalizing, highlighting the importance of considering the social and economic context of the individuals that make up the sample, and suggesting further investigation into the effects of the Great Famine on mortality risks during the Black Death is warranted.

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