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Cranial vault trauma and selective mortality in medieval to early modern Denmark

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To date, no estimates of the long-term effect of cranial vault fractures on the risk of dying have been generated from historical or prehistoric skeletons. Excess mortality provides a perspective on the efficacy of modern treatment, as well as the human cost of cranial injuries largely related to interpersonal violence in past populations. Three medieval to early modern Danish skeletal samples are used to estimate the effect of selective mortality on males with cranial vault injuries who survived long enough for bones to heal. The risk of dying for these men was 6.2 times higher than it was for their uninjured counterparts, estimated through a simulation study based on skeletal observations. That is about twice the increased risk of dying experienced by modern people with traumatic brain injuries. The mortality data indicate the initial trauma was probably often accompanied by brain injury. Although the latter cannot be directly observed in skeletal remains, it can be inferred through the relative risks of dying. The ability to identify the effects of selective mortality in this skeletal sample indicates it must be taken into account in paleopathological research. The problem is analogous to extrapolating from death register data to modern communities, so epidemiological studies based on mortality data have the same inherent possibility of biases as analyses of ancient skeletons.

selective mortality | cranial trauma survival | violence | premodern Denmark

The aftereffects of head trauma are a major concern in modern medicine (1). However, for historical and prehistoric populations, there are no quantitative assessments of the long-term effects of such injuries, with the risk of dying estimated from skeletal samples being the most obvious way of doing so. Skeletons serve as a measure of the extent to which modern treatment and subsequent care have improved the outlook for survivors of trauma severe enough to fracture the cranial vault. Much of the cranial trauma in the distant past resulted from interpersonal violence, so these fractures provide a unique perspective on the human cost of conflicts that occur within communities up to the outright warfare that takes place between societies (2, 3).

The effect of selective mortality acting on people who experienced differential exposure or susceptibility to life-threatening diseases or trauma was brought to the attention of paleopathologists a quarter century ago (4). Debates continue over whether it is of any real significance when characterizing the health of past populations (5–16), although it has been shown that various conditions had an effect on mortality (17–23). That is largely because what comes to the paleopathologist's attention often indicates survival well beyond the original traumatic or disease episode, including cranial vault trauma with its potentially debilitating neurological consequences (24, 25).

Through a simulation study, healed cranial vault fractures are used to show that selective mortality has a measurable effect in archaeological skeletal samples. The simulation, based on skeletal observations, is a means of estimating the magnitude of the increased (or decreased) risk of dying associated with healed cranial vault trauma, even if only slightly different from what everyone else experienced. Of primary importance are the age distributions of people—in this instance, men—with and without evidence of cranial vault injuries. Although the focus is on past societies, the problem is analogous to extrapolating from death register data to modern communities. Epidemiological studies based on mortality data have the same inherent possibility of biases as analyses of ancient skeletons.

Skeletal Samples

The skeletons came from three medieval to early modern Danish cemeteries dating to the late 12th to early 17th centuries. The graveyards held the remains of the inhabitants of rural and urban communities, so they collectively represent a cross-section of the population at that time. Two sites, Tirup (ca. AD 1150–1350) and St. Mikkel (ca. AD 1100–1529), were located in Jutland, and the third, Sortebrødre (ca. AD 1240–1610), was on the adjacent large island of Fyn. Odense, where the Sortebrødre churchyard was located, was inhabited by several thousand people during the period when most of the burials took place following the 1530s Reformation (26). St. Mikkel was located on the outskirts of a similarly sized town (27). Tirup, a small village, was likely occupied by less than a hundred people, and by the mid-14th century it had disappeared (28).

There were altogether 822 complete or partial skeletons, with Sortebrødre ($n = 451$) contributing the most individuals, followed by Tirup ($n = 217$) and St. Mikkel ($n = 154$). Of these skeletons, 236 adult males (>15 y) had enough of the cranium present in good condition for purposes of analysis (Table S1).

Significance

Neurocranial fractures and their aftermath took a toll on people in premodern societies, much like today. Archaeological information on skeletal trauma, however, typically consists of mere tallies of injuries, much like other disease-related lesions. We quantify the increased risk of dying for men with healed cranial vault fractures, an approach that can be adapted to any pathological condition. In medieval to early modern Denmark, head-injured men experienced a relative risk of dying about double that of modern people, probably in large part because of differences in medical care and social support. This approach provides a means of measuring the extent, hence consequences, of excess injury and disease-related mortality across the full range of human societies extending into the distant past.

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ANTHROPOLOGY

Sex was estimated by G.R.M. for the entire sample. The great majority of the assessments are likely to be accurate because in blind trials in other work he correctly classified 98.5% of 813 modern known-sex skeletons from three continents. Only males were included in this study because females had too few cranial fractures for analytical purposes. Male and female mortality patterns were different, which prevented the sexes being combined.

Ages were estimated by G.R.M. for two samples, Sortebrødre and St. Mikkel; S.W. and J.L.B. estimated those for Tirup. Adult ages separately estimated by members of the research team are similar in examinations of European and American known-age skeletons, and there is a high correlation between estimated and actual ages (29, 30). The men who were not injured ranged in age from 15.5 to 72.5 y, and those with fractures from 17.5 to 65.0 y. The ages are midpoints of age intervals assigned to individual skeletons.

Bone fracture information was mostly collected by G.R.M., assisted at times by the late Ulla Freund under J.L.B.'s direction. Only healed fractures identified through visual examinations of skeletons are included here, although a few perimortem fractures are also present in the collections. In all cases, healed fractures showed considerable evidence of bone remodeling (Figs. 1 and 2). Many were simple depressions in the external table of the cranial vault, although some were indicative of more severe injuries, including deep cuts with heavy sharp-edged weapons such as swords and axes. It is usually impossible to identify what caused specific injuries, but it is likely that much of the trauma was from interpersonal violence. That differentiates historical populations from modern ones where traffic accidents are a common cause of head injuries. In all cases, the people in this analysis lived for a prolonged period following the traumatic incidents, to judge from the appearance of the bones.

As in all archaeological samples, the Danish skeletons were often incomplete. To be included here, the frontal and both parietal bones had to be present. That facilitated the recognition of healed fractures because the three bones had to be intact, hence well preserved. Ten frontal bones had fractures, and the left and right parietals had seven apiece. Only one person had a healed fracture elsewhere on the neurocranium. It was a radiating fracture on an occipital bone that originated in a massive depression fracture on a parietal. This individual, in fact, had two separate injuries, one on each parietal bone. One other individual had been hit twice, once on the frontal bone and again on a parietal. So the frontal and parietal bones serve as a reasonable estimate of the people who suffered severe cranial vault trauma, but afterward survived for a lengthy period.

Fig. 1. A shallow depression fracture is present on the right side of the frontal bone in this Sortebrødre cranium. It is typical of the minor injuries seen on cranial vaults.

Fig. 2. A massive depression fracture can be seen on the left parietal of a Sortebrødre cranium, and a radiating fracture extends to the occipital bone. It is one of the most severe injuries that had healed.

Combining skeletons from separate sites is often necessary to secure large samples for rigorous quantitative analyses. That is true even of conditions, including cranial vault fractures, that occur relatively often in archaeological collections.

Having three sites representing a town, a community immediately outside of a town, and a rural village means that the skeletons provide an overall picture of what Danes of the 12th to early 17th centuries experienced. Major sociopolitical, economic, and demographic changes occurred during this half millennium, but they did not have the same impact in every community and on all segments of society. In the absence of precise temporal controls on individual burials and specific knowledge of local events, it is not possible to tease apart the exact circumstances that impinged on various segments of the three communities. So what these skeletons provide is a general depiction of life during the early part of Denmark's existence as a unified state when it was still a largely agrarian society dominated by small settlements. This period preceded the great growth of cities, commerce, and population associated with industrialization that only began in earnest in the 19th century.

Turning to the skeletons, trauma frequencies in the three samples are not significantly different from one another (χ^2 test, $P > 0.05$). The same is true when cemetery-of-origin and age-at-death are explanatory variables in a logistic regression analysis.

Skeletons from the three cemeteries, therefore, could be combined to increase the overall sample size. It is also possible to use the combined site mortality profile in a simulation designed to estimate the increased risk of dying for survivors of cranial vault trauma.

For estimating years at risk, only skeletons over the age of 15 y were included. Some individuals perhaps suffered trauma earlier in life. Nevertheless, 15 y is a satisfactory approximation for modeling purposes because the chance that childhood fractures were retained in recognizable form in adult skeletons is rather low considering the bone growth that occurs before maturity. Shallow depressions of the outer table, healed examples of which are regularly seen in adult Danish skeletons, would be difficult to detect if the child had lived until adulthood, although more severe early injuries, including major radiating and comminuted fractures, might well be recognized in adults. It is possible that a small fraction of minor injuries, those where only the vault's outer table was depressed, would not be visible in the oldest skeletons because of a lifetime of bone remodeling. That is unlikely, however, to pose a major problem because even shallow depressions are readily visible on the normally smooth surfaces of the well-preserved, intact bones chosen for study.

Analytical Procedures

The skeletons are obviously a mortality sample, which creates difficulties when translating observations, in this instance bone fractures, into epidemiological statistics characterizing once-living populations (4, 13, 15, 23). Here, that is done through simulated ages at death, generated from parameters derived from skeletal observations, for men with and without healed cranial vault fractures.

The mean rate of fracture accumulation (R) was estimated by taking into account the number of men, their mean age, the crania observed, and those with fractures (Eq. **1**):

$$R = 1 - \left(1 - \frac{number\ of\ crania\ with\ fractures}{number\ of\ crania}\right)^{\left(\frac{1}{mean\ age - 15}\right)}. \qquad [1]$$

For the simulation study, the two parameters of the best-fitting Gompertz survival function were estimated from a Kaplan–Meier survival curve using age interval midpoints for 236 males with frontal and parietal bones (Eq. **2**):

$$S(age) = e^{-\int_{15}^{age} \alpha \cdot e^{\beta \cdot (z-15)} dz}, \qquad [2]$$

$$\alpha = 0.0096,$$

$$\beta = 0.06.$$

What is modeled is long-term survival with a cranial injury relative to life expectancy without such trauma; that is, it is an estimate of the acquired risk that affects a survivor for the remainder of his life. The age when an individual experienced his trauma (*LesionAge*) is simulated in Eq. **3**, where R is the rate of acquiring a cranial fracture (Eq. **1**), and x is a random number following a uniform distribution from 0 to 1 ($x \sim U[0,1]$):

$$LesionAge = \frac{\ln(x)}{\ln(1-R)} + 15. \qquad [3]$$

Eq. **4**, derived from Eq. **2**, uses the previously estimated values for α and β to simulate ages of death for 100,000 men in accord with the Gompertz survival function. Once again, x is a random number from a $U[0,1]$ distribution, generated independently from the x values in Eq. **3**:

$$Age = \frac{\ln\left(1 - \frac{\beta}{\alpha} \cdot \ln(x)\right)}{\beta} + 15 = \frac{\ln\left(1 - \frac{0.06}{0.0096} \cdot \ln(x)\right)}{0.06} + 15. \qquad [4]$$

Our immediate concern is with simulated individuals whose *Age* from Eq. **4** is larger than *LesionAge* from Eq. **3**; they are people who survived a cranial vault injury. For these individuals, a new age-at-death is simulated as a function of the relative risk of dying (*RR*) associated with having a healed fracture of the frontal or parietal bones. Their life expectancy from the injury onward, therefore, is different from that of males who never experienced such fractures.

New ages-at-death, *AnalysisAge*, are generated from the combination of men who are injured and those who are not. For men without healed cranial vault injuries, *AnalysisAge* corresponds to the original simulated ages (*Age* from Eq. **4**). When $AnalysisAge = Age$, there is no selective mortality and $RR = 1$. If $RR = \infty$, then $AnalysisAge = LesionAge$ for individuals where $LesionAge < Age$ because these individuals immediately died from their injuries; from an osteological perspective, death occurred before signs of healing appeared. Because only visibly healed injuries are of concern in this study, $RR = \infty$ is impossible. For the remainder where $LesionAge < Age$—that is, signs of healing occur at the sites of injury—ages-at-death are simulated using Eqs. **5** and **6**. Survival to *LesionAge* (*SLesionAge*) in Eq. **5** is the probability that an individual survived to age *LesionAge* (Eq. **3**), given a survival function with a mortality rate inflated by *RR*:

$$SLesionAge = e^{-\int_{15}^{LesionAge} \alpha \cdot RR \cdot e^{\beta \cdot (z-15)} dz}. \qquad [5]$$

The ages-at-death of the injured men, in contrast to the uninjured men (*Age*), are simulated as *AnalysisAge* in Eq. **6**. This equation resembles Eq. **4**, with two important modifications. First, x in Eq. **4** is replaced by Lx, a random number uniformly distributed on the interval $[0;SLesionAge]$, meaning $Lx \sim U[0,SLesionAge]$. Replacing x by Lx corresponds to conditioning survival probability on the individual having already survived to *LesionAge*. Second, α is replaced by $\alpha \bullet RR$, which means the age specific risk of dying is inflated by *RR*:

$$AnalysisAge = \frac{\ln\left(1 - \frac{\beta}{\alpha \cdot RR} \cdot \ln(Lx)\right)}{\beta} + 15. \qquad [6]$$

In short, the mortality cost of having survived a healed cranial vault injury is estimated as follows. The fracture accumulation rate is calculated from the frequency of crania with observable fractures and the mean age at death of everyone in the sample (Eq. **1**). The distribution of ages at death for the simulation is described by a Gompertz survival function (Eq. **2**) based on ages of death in the skeletal sample. The age at which an individual receives a fracture that subsequently heals is then simulated (Eq. **3**), taking into account the fracture accumulation rate (Eq. **1**). The age of death for each individual is simulated using Eq. **4**. When the simulated age at death (Eq. **4**) is less than the simulated age of getting a fracture (Eq. **3**), the individual died without a cranial injury. *SLesionAge* in Eq. **5** describes the probability of an individual surviving to *LesionAge* if the individual had received his fracture at age 15. For injured people ($LesionAge < Age$), the simulated age at death (Eq. **6**) is obtained by the Eq. **5** survival function conditioned on the individual's surviving to *LesionAge*.

To characterize the effect of selective mortality on the age structure of people with and without cranial vault fractures, the ratio between the frequencies of people with fractures in the >15- to ≤35-y age group and those in the >35 group was calculated for both the simulated and observed individuals. That is, the frequency of young men with fractures (young men with fractures/all young men) was divided by the corresponding figures for old individuals. Ages were collapsed into two intervals, up to 35 y and above 35, because of the initial sample size. The number of skeletons was large by archaeological standards, but small for quantitative purposes. The age structures of the observed and expected categories were similar because the latter were modeled using parameter estimates derived from the former (Eqs. **2** and **4**).

Results

The 236 males with complete frontal and parietal bones, 21 of which survived fractures, lived a total of 10,033 y. The mean age at death was 42.5 y. Injured men had a mean age of death of 41.0 y, whereas the corresponding figure for those who were not injured was 42.7 (Table S2).

In Table 1, the frequency of cranial vault injuries in the >35-y age group was lower than it was in younger men, consistent with healed fractures being associated with an increased risk of dying. That difference, however, is not significantly different (χ^2 test, $P > 0.05$), nor was it expected to have been significant because the increased risk of dying experienced by trauma survivors was presumed at the outset to have been too low to be detectable in a small sample using conventional statistical tests based on data aggregated into "young" versus "old." The simulation provides a means of quantifying the *RR* implied in the Table 1 observed percentages and ratio, the latter the frequency of young men with healed cranial fractures relative to older men.

The Expected (Exp) column under $RR = 1$ in Table 1 shows the number of fractures for the young and old age groups when there is no selectivity. The best-fitting relative risk conforming to the observed fractures in the skeletal sample is $RR = 6.2$ (Fig. 3). The significance of the difference between the observed and expected fractures is characterized by the χ^2 values for df = 1 of 15.76 for $RR = 1$, and 0.00 for $RR = 6.2$.

In Fig. 3, the expected young to old fracture frequency ratio, generated from the simulation, is plotted relative to the observed fracture ratio. The x axis is the relative risk of dying on a log scale, with $RR = 1$ indicating that injured people experienced no increased risk. The curve depicting the ratio between young and old fracture frequencies is not perfectly smooth because it shows simulation results. The intersection at $RR = 6.2$ of the expected line with the observed values is the increase in the risk of dying for men with healed frontal or parietal bone fractures.

There remains the issue of estimating a confidence interval for the relative risk of dying associated with having a healed cranial vault fracture. The upper limit approaches infinity where the

Table 1. Adult males (*N*), observed healed cranial fractures (Frac), and the percentage (%) injured in each age group

	Observed			*RR* = 1		*RR* = 6.2	
Age interval	*N*	Frac	%	Exp	%	Exp	%
>15 to ≤35	75	9	12.0	2.8	3.7	9.1	12.1
>35	161	12	7.5	18.8	11.7	11.9	7.4
Ratio			1.61		0.32		1.64

Expected (Exp) fractures for males are given for relative risks (*RR*) 1 and 6.2 times higher for men who survived the initial injuries, along with percentages (%). See Fig. 3 for the intersection of observed and expected at 6.2. Ratio is the frequency in the young group divided by the frequency in the old group.

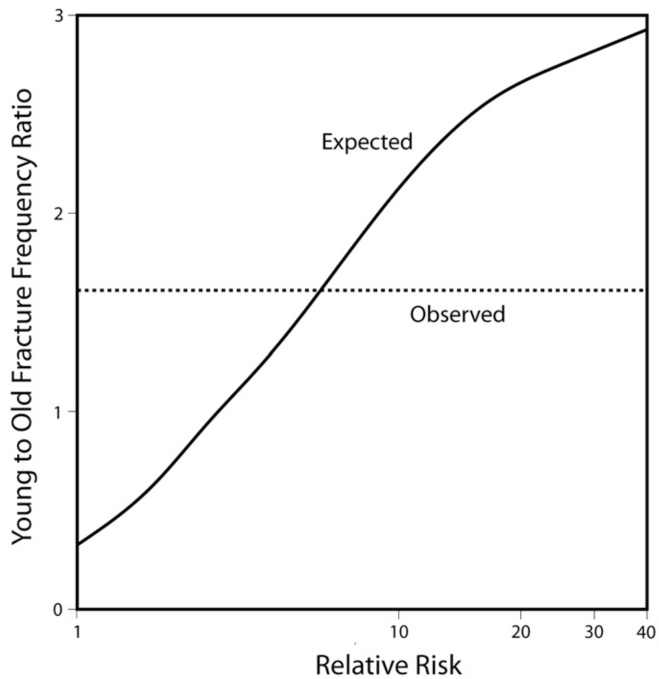

Fig. 3. The ratio of fracture frequencies among young (>15 to ≤35 y) relative to old (>35 y) men for different values of relative risk (*RR*) (solid curve) is compared with the observed value (*RR* = 6.2) (dashed line). Relative risk refers to the number of times greater the risk of dying was for men with healed skull fractures than it was for men who lacked those injuries.

expected age pattern does not differ significantly from the observed age pattern. As explained above, the two age distributions would be identical if everyone died without bone fractures showing signs of healing. Although that cannot be excluded on statistical grounds, the skeletons clearly indicate that many men survived cranial vault fractures. The lower limit is the *RR* value corresponding to the χ^2 value 3.84, indicating $P = 0.05$; in this instance, $RR = 2.3$.

Discussion

The mere number of cranial fractures underscores the fact that interpersonal violence was an ever-present aspect of life for men in medieval to early modern Denmark. Of all males, 8.9% had healed fractures of the cranial vault. Age-corrected, that figure corresponds to around three times the fracture rate in contemporary Denmark [based on *R* (Eq. **1**) and modern Danish fracture data provided by the Accident Prevention Group at Odense University Hospital, as described in ref. 31.] Although in most instances it is not possible to identify the origin of the trauma, the fact that it is heavily weighted toward men—males in the skeletal sample were about four times more likely to have cranial injuries than females—suggests that many cranial fractures resulted from interpersonal violence. That is consistent with the argument, based on written sources, that there was generally more violence in societies hundreds of years ago than there is today (32). Accidents, often occupation related, were also common because there was little to protect people from the hazards of physically demanding work (33).

Fracture frequencies, of course, depend on the rate of fracture acquisition and the period of exposure. If rates of acquisition and years of exposure were the only two processes of importance, then one would expect increasing fracture frequencies with advancing age in archaeological (mortality) samples. Quite the opposite seems to have occurred, as shown in the observed columns in Table 1 where men with healed fractures dropped from 12.0% to 7.5% in the young and old groups, respectively. A decline in frequencies could only come about through a process where the cemetery sample at each age is enriched by people who sustained, but survived, cranial vault fractures. Although these men lived long enough for fractures to heal, they were more likely to enter the mortality sample than men without fractures. Archaeological samples, however, are rarely large enough for simple counts of pathological specimens to be useful when assessing subtle differences in relative risk, such as what might be expected if healed bone fractures were associated with higher mortality.

Through simulating the expected life spans of individuals with and without healed cranial vault trauma, it appears that men with injuries sufficient to produce an indelible mark on the frontal or parietal bones experienced a risk of dying six times that of their contemporaries who avoided such fractures. That is much like today where people who suffer head trauma leading to brain injuries also have a higher risk of dying (34–45). Modern figures vary according to injury severity; where and when the data were collected; sample composition, especially the patient age distribution and inclusion criteria; and posttrauma study duration. Nevertheless, today people with traumatic brain injuries experience roughly two to four times the risk of dying than uninjured people (37, 38, 40–45).

The two sets of figures—cranial vault fractures and traumatic brain injuries—are not directly comparable because one can occur in the absence of the other. Nevertheless, it is reasonable to suppose that brain injuries often accompanied trauma sufficient to fracture the frontal and parietal bones. The cranial vault fractures in the Danish sample, therefore, serve as a crude proxy for traumatic brain injuries with lingering consequences. Although modern relative risks can be within the lower confidence limit of the archaeological sample, it is unlikely the two are indeed the same. Relative to today, effective care was lacking in medieval to early modern Denmark. Injured people now benefit from sophisticated medical procedures plus long-term support and rehabilitation that collectively prolong life. It is not surprising that today's medical and rehabilitative treatments and social services reduce considerably the risk of dying from what it was many centuries ago. Estimating the extent of that improvement is another matter altogether. Although skeletons provide only a rough approximation of relative risk and the modern and archaeological data are not strictly comparable, the Danish data suggest the risk of dying experienced by survivors of cranial vault injuries has been about halved in modern times.

Relative risk is a standard measure of the increased risk of dying within a study population. It can be misleading, however, when used in comparisons of samples with widely different baseline mortality rates. In the medieval and early modern Danish sample, the risk of dying around age 35 was over 40 times what Danes experience today (3.63% versus 0.08%). Therefore, a half-millennium ago the increased risk of dying faced by cranial-fracture survivors of any particular age was many times greater than it might appear from the relative risk values alone.

In modern populations, the relative risk of dying for trauma survivors declines noticeably with advancing age (36, 42, 44). That is a result of an age-increasing background mortality and the fact that the healthiest trauma survivors reach high ages. The latter is an example of selective mortality in a group that was disadvantaged at the outset by their injuries.

Mortality immediately following head injuries must have been high a half-millennium ago in Denmark, much like it is today. There were, in fact, several skeletons in the three-site sample with obvious perimortem cranial trauma, including massive fractures and deep cuts from sharp-edged weapons (swords or axes). Survivors, in contrast, typically displayed trauma that was not as severe, although two men survived grievous injuries from sharp-edged weapons. Unfortunately, the difficulty in consistently identifying examples of perimortem fractures in archaeological bones prohibits unbiased estimates of more or less immediate fatalities from cranial injuries.

Higher mortality for survivors of cranial vault trauma could have come about in two ways. Some men might have had greater exposure to violent encounters or hazardous occupations than others, so the cranial injuries are an archaeologically visible marker of ways of life that likely shortened some people's life spans relative to their peers. Alternatively, disabilities acquired from severe blows that resulted in underlying soft tissue damage increased the survivors' risks of dying from the time of their injuries onward. That might include a loss of function or changed behavior, much like the motor, cognitive, and psychological impairment that can follow traumatic brain injuries today. Because only the outcome is observable in archaeological remains—a greater relative risk of dying—it is not possible to discriminate between the two alternatives, both of which probably contributed to our results.

As for the lingering consequences of severe injuries, anything that led to difficulties adjusting to life must have been a major problem in relatively small and largely self-sufficient communities where everyone was expected to contribute substantively to his or her own livelihood. Anything short of full and productive integration into household and community life must have posed a mortality risk, at the very least during periods when food was short. When times were hard, the poor and otherwise disadvantaged members of medieval communities elsewhere in Europe appear to have been more likely to succumb to death than their neighbors (46). Skeletal and documentary sources indicate that people with physical or mental impairments were on occasion the recipients of institutionalized care (33, 47, 48). However, relative to today, the survivors of debilitating trauma enjoyed few formally organized services that acted as safety nets to keep them healthy, hence alive, and instead they had to rely heavily on the generosity of family and community members, or resort to begging and thievery (33, 46). In mid-16th century Denmark, an effort to create new hospitals proved to be unsuccessful, and soon thereafter market towns were again permitted to maintain their own institutions as they saw fit (49). It took until the early 18th century before national legislation was passed to cover care for the poor, although there were earlier local efforts to regulate begging (50). Estimating the excess mortality associated with having previously suffered trauma moves us closer to an understanding of the efficacy of institutional and improvised care in past societies.

By looking at pathological skeletal features in conjunction with age distributions, it is possible to quantify the disadvantage experienced by individuals who survived earlier illnesses and injuries, or who suffered from chronic conditions. The overall objective is to move components of the heterogeneity in the risk of dying from being essentially hidden, or unknown, to measurable, or known.

Of immediate archaeological significance is the potential for healed skeletal trauma to be used as a marker to subdivide populations according to life experiences, analogous to an epidemiological risk factor. Although what precipitated the death of any single individual can only be established on exceedingly rare occasions, it is possible to identify cranial vault fractures (and other pathological conditions) and to measure the increase in mortality associated with them on a population basis. The intent of this work is to identify recognizable skeletal features associated with a greater risk of dying and to assess their effect on populations in terms of lost years of life. It is not to establish what caused the premature death of particular individuals or the mechanisms behind sickness and death.

Such analyses, however, require many skeletons, and that will often require combining samples. In this instance, doing so provides an overall picture of excess mortality associated with healed cranial vault fractures for a temporally long and socially diverse sample. Hundreds of additional skeletons from medieval to early modern Denmark must be examined to extend this proof of concept to finer time intervals and particular segments of society, such as those distinguished by social position, occupation, disease experience, and diet.

Conclusion

We will never know what happened to specific individuals who experienced cranial vault trauma. In general, however, the survivors of these injuries lived shorter lives than they would have otherwise. From the perspective of characterizing life in the past, knowing that a healed cranial vault fracture was associated with an increased risk of dying is important. It is likely that many of these men suffered the lingering effects of traumatic brain injury. They did not die because of what can be observed, the healed bone fracture, but perhaps from circumstances related to what cannot be directly seen, the long-term health consequences of the initial injury. The fact that the effects of selective mortality can be teased out of skeletal samples for healed cranial fractures indicates that it must be taken into consideration in archaeological analyses and, more generally, epidemiological studies based on death data.

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