



## Caring for the injured: Exploring the immediate and long-term consequences of injury in medieval Cambridge, England

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### ABSTRACT

**Objective:** To combine paleopathological and biomechanical analysis to reconstruct the impact that a severe skeletal injury had on an individual's ability to function and participate in medieval society.

**Materials:** Three medieval individuals from Cambridge, England with ante-mortem fractures to the lower limb were analyzed.

**Methods:** Plain X-rays were used to determine the degree of malunion, rotation and overlap of each fracture. Cortical bone architecture of the injured individuals and 28 uninjured controls were analyzed using micro-computed tomography ( $\mu$ CT). Clinical and functional consequences were examined using the Bioarchaeology of Care framework.

**Results:** The mechanism of injury, the secondary complications, and the extent of the care received was reconstructed for each individual. Bilateral asymmetry in the cortical bone architecture revealed the long-term alterations to each individual's gait.

**Conclusion:** Each of these individuals survived a severe injury resulting in chronic physical impairment, though not all would have been considered 'disabled'.

**Significance:** This research contributes to the discussion about medieval care provision and social constructions of disability by illustrating how an interdisciplinary approach provides insight into the experiences of those with physical impairments. The integration of  $\mu$ CT imaging within the Bioarchaeology of Care model is a novel approach with great potential for application across the field.

**Limitations:** Biomechanical analysis was restricted to cortical geometry.

**Suggestions for future research:** Further study of bilateral asymmetry in trabecular architecture could complement our understanding of altered loading modalities in past societies.

### 1. Introduction

Skeletal injuries and their potential to cause physical impairment were an ever-present risk to people living in the medieval period (see Dittmar et al., 2021a; Grauer and Miller, 2017; Judd and Roberts, 1999). Recent research conducted on the inhabitants of medieval Cambridge shows that 32 % (n = 86/267) of individuals with postcranial elements had one or more fractures (Dittmar et al., 2021a). In most cases, the observed skeletal trauma was consistent with an accidental injury, likely

sustained through occupational or everyday activities. Nearly all of these fractures were well healed, indicating that the vast majority of people survived such accidents. However, given the severity of some of the skeletal trauma observed, it is likely that several individuals may have died if care had not been provided. Even then, many suffered permanent physical impairments that reduced their ability to work and participate within medieval society.

Identifying the provision of care for people with physically impairing conditions in past societies is well documented in the paleopathology

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literature (Tilley and Oxenham, 2011; Málaga and Makowski, 2019; Luna et al., 2008; Trinkaus and Zimmerman, 1982). The recently developed Bioarcheology of Care framework offers a practical framework for exploring the provision of care in both prehistoric and historic contexts (Tilley, 2015; Tilley and Schrenk, 2017). Through the assessment of human skeletal remains, this model enables the identification of individuals who would have likely needed assistance from others in order to survive with chronic illnesses or physical impairments (Tilley, 2015).

The aim of this study is to reconstruct the experience of individuals with visible physical impairments from medieval Cambridge by interpreting macroscopic, radiographic and biomechanical data. By placing fully contextualized data derived from skeletal remains into the Bioarcheology of Care framework, we demonstrate that an interdisciplinary approach can enhance our understanding of how physical impairments were experienced and how medieval communities viewed and treated its less fortunate members.

### 1.1. (Dis)ability in medieval England

Extensive research has been conducted on the ways that ‘disability’ intersects with medieval society and religious practices (Eyler, 2016; Gilchrist, 2012; Metzler, 2006; Turner, 2010; Wheatley, 2010). Within this growing body of literature, much research has focused on how concepts of disability were influenced by Christian beliefs surrounding the afterlife and notions of sin and morality (see Gilchrist, 2012; Metzler, 2006; Wheatley, 2010), with descriptions of physical impairments in the Bible often serving as the foundation. In the Bible, certain physical impairments including ‘lameness’ and ‘blindness’ are presented as divine punishments for misdeeds (see Deuteronomy 28:28; 28:65; John 5:14, *The Holy Bible (King James version), 1611*). The Bible also presents many examples of miracle cures for such ailments as the result of compliance with religious and moral laws, or from some form of religious sacrifice. Such notions were reinforced by the Fourth Lateran Council of 1215, which directly associated bodily ailments to sin, explicitly stating that divine intervention was important in the treatment of such illnesses (see Amundsen, 1992). The propagation of the idea that sin was responsible for physical manifestations enabled the church to maintain control over how disability and the disabled were perceived (see Wheatley, 2010).

Although perceptions of disability as a punishment for one’s sins, or those of one’s parents, certainly existed during the medieval period, this is not representative of all medieval attitudes. In her seminal work, Metzler (2006) concludes that there was no fully delineated concept of disability in the High Middle Ages, so perceptions of impairment, disability, and disease were highly ambiguous (Eyler, 2016; Metzler, 2006). There is mounting evidence that medieval society often focused on how the loss of physical function affected an individual’s ability to participate within society and perform the duties expected of them. As such, the degree to which an individual was capable of making a living and supporting themselves was practically used as an indicator of ‘disability’ (Metzler, 2013). Even those with visible physical or mental impairments may not necessarily have been considered disabled as long as they were able to carry out the task associated with their particular role within society (e.g., work, marry) (Turner, 2010: xiv–xv).

## 2. Materials and methods

### 2.1. Materials

Skeletal remains of three adult individuals from medieval burial grounds in Cambridge, UK were assessed. The individuals were selected because they had at least one ante-mortem fracture to the lower limb that likely impacted function (see Galloway and Wedel, 2014; Sauer, 1998 for criteria). Two of these individuals (PSN 93, PSN 335) were buried in the cemetery of the Hospital of St John the Evangelist; the

other (PSN 723) was buried in the cemetery associated with the rural (areas with a mixture of rural and urban activities) parish of All Saints by the Castle (Fig. 1).

#### 2.1.1. The Hospital of St John the Evangelist

The Hospital of St John the Evangelist existed from c. 1195 until it was dissolved to create St John’s College in 1511 (Cessford, 2015). Textual evidence indicates that the Hospital was an ecclesiastical institution intended to provide pastoral and spiritual care for the poor and infirm (Rubin, 1987). The Hospital’s cemetery was excavated in 2010–2011 by the Cambridge Archeological Unit. During the excavation, approximately 400 complete and partial in situ burials were uncovered (Cessford, 2015). The majority of the individuals buried in the cemetery are believed to have been inmates of the Hospital (Cessford, forthcoming).

#### 2.1.2. All Saints by the Castle

The parish of All Saints by the Castle, located north of the river, was likely founded c. 940–1100. The parish was used until 1365, when it was amalgamated with a neighboring parish following population loss due to the plague. The graveyard was excavated in 1973, with more skeletons uncovered in 1988 and 1994 (Cessford et al., forthcoming). As a parish church, All Saints represents the normal place of burial for most medieval people. This parish was socio-economically mixed but generally rather poorer than those in the town center (Casson et al., 2020: 143–4).

## 2.2. Methods

### 2.2.1. Osteological methods

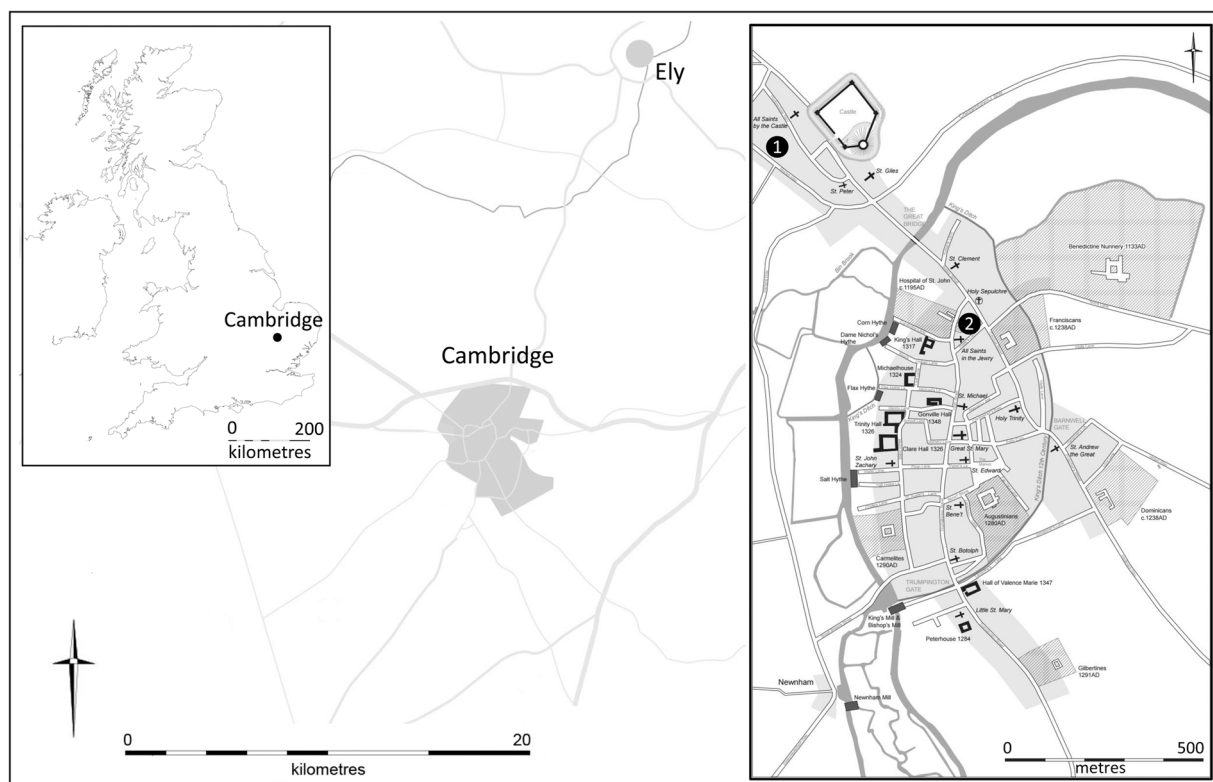
The human skeletal remains were assessed as part of the “After the Plague: Health and History in Medieval Cambridge” project. Each skeleton was assigned a project-specific “personal skeleton number” (PSN) that served as a unique identifier. Age-at-death was estimated by assessing pubic symphyseal morphology (Brooks and Suchey, 1990), auricular surface morphology (Buckberry and Chamberlain, 2002), and the sternal rib ends (İşcan et al., 1984; 1985). Biological sex was estimated by examining the morphological characteristics of the pelvis and skull (Brickley, 2004; Buikstra and Ubelaker, 1994; Phenice, 1969; Schwartz, 2007) and aDNA analysis (Inskip et al., 2019).

Each fracture was macroscopically assessed and described (see Brickley, 2004) and plain X-rays were used to determine the degree of angulation, rotation and amount of overlap. X-rays were taken by Reveal X-ray Imaging Solutions using a portable DR-Go x-ray digital radiography (DR) system. The causative mechanisms and the forces applied to a bone were inferred from the fracture morphology (see Galloway et al., 2014; Redfern and Roberts, 2019). These data were used to reconstruct potential causes of specific injuries and to estimate the physical consequences that followed.

### 2.2.2. Biomechanical methods

Past activity is reflected in bone structure, based on the adaptive capacity of the tissue to mechanical loading. This principle has been employed in the functional interpretation of skeletal morphology; studies have long concentrated upon assessing bone mechanical properties from diaphyseal cross-sections (Shaw and Stock, 2013; Stock and Pfeiffer, 2001; Ruff and Hayes, 1983). This approach has revealed varying levels of bilateral asymmetry throughout history, mostly in the upper limb, related to an uneven loading of the left and right arms (Sládek et al., 2016; Stock et al., 2013; Trinkaus et al., 1994; Shaw, 2011). Comparing right and left side cross-sectional geometry has also been applied to the lower limbs to assess impaired mobility (see Cowgill et al., 2015; Gilmour et al., 2019; Nystrom and Buikstra, 2005; Oxenham et al., 2009).

Using micro-computed tomography ( $\mu$ CT), the cortical bone architecture of the femora and tibiae of the three injured individuals was analyzed and compared to data derived from 28 individuals from the



**Fig. 1.** Top left: Map of the United Kingdom showing the location of Cambridge; Center: map of the area surrounding Cambridge; Right: map of Cambridge c. 1350 showing the location of 1) All Saints by the Castle parish burial ground, 2) the detached burial ground of Hospital of St John the Evangelist (map created by Vicki Herring, modified by Jenna Dittmar).

Hospital without skeletal injuries to the lower limb. All bones were scanned using a Nikon Metrology XT H 225 ST HR scanner housed at the Cambridge Biomechanics Center, in the Department of Zoology at the University of Cambridge. Each bone was placed in an acrylic tube and scanned with energy source settings of 140 kV and 100  $\mu$ A, with an integration time of 708 ms and 720 projections per scan. Bones were reoriented anatomically following Ruff (2002) and exported as a stack of TIFF files. Cortical geometry was analyzed at the midshaft.

Cross-sectional properties were calculated using the BoneJ plugin (1.4.3) for ImageJ (1.52e) (Doubt et al., 2010). The total amount of tissue in the cross-section is the cortical area (CA) and is a measure of tissue quantity and compressive strength. The second moment of area is the bending rigidity along a particular axis, and the sum of minimum and maximum bending rigidity is interpreted as torsional or twice the average bending rigidity of the bone and is commonly used as an indicator of the bone's mechanical competence. Bilateral asymmetry in bone structural properties was calculated as (right-left)/(average of left and right).

### 2.2.3. Bioarchaeology of Care framework

The four-stage Bioarchaeology of Care methodology was used to infer the clinical and functional consequences experienced by each individual and to explore the possible provision of care (see Tilley, 2015; Tilley and Schrenk, 2017). In stage 1, each individual was macroscopically assessed, and the long bones of the lower limbs were micro-CT scanned; pathological lesions were described and a differential diagnosis was conducted. In stage 2, modern clinical sources were consulted to estimate the functional impact of the observed fractures to determine the likelihood that an individual required support or assistance. This study extends upon the previously published method by including an examination of the cortical bone architecture of the femora and tibiae in order to assess the long-term functional consequences of the observed injuries. In stage 3 a 'model of care' was produced. Textual sources and

archeological data were used to refine details about caregiving during the medieval period and about life in the Hospital. The interpretation of the 'model of care' (stage 4) was also contextualized by consulting documentary sources and previous historical research about disability during the medieval period, which enabled the social perceptions of disability to be discussed.

### 2.2.4. Defining 'disability'

There are several definitions of 'impairment' and 'disability', and although often related, these concepts are distinct. The terminology used in this work is drawn from the social model of disability. 'Physical impairment' is the physical condition that causes a loss or deviation of function, while 'disability' is a socially constructed concept that relates to the perception of a somatic condition (Shakespeare, 2013). One criticism of the social model is that it does not consider how factors such as gender or age influence the interpretation of disability. However, this work overcomes this limitation by including a discussion how these factors likely influenced each individuals' experience. Although the distinction of the terms 'impairment' and 'disability' have been considered problematic within disability studies, we argue that differentiating these terms remains appropriate and necessary with regards to the study of human skeletal remains.

### 2.2.5. Dating methods

Each skeleton was dated based on the documented use of the burial grounds and the stratigraphic location within the burial sequences. Stratigraphic sequences were radiocarbon dated and Bayesian modeling was employed to refine the date of death. By incorporating osteological estimates of age-at-death, it was possible to calculate when individuals were probably born (Cessford and Alexander, forthcoming).

### 3. Exploring physical impairment using biomechanical assessment

#### 3.1. PSN 335

The skeletal remains of a mature adult female (PSN 335), aged between 45 and 65 years at the time of her death, were uncovered from the burial ground of the Hospital of St John the Evangelist. She lived in the later 13th century, dying between 1296 and 1323. Several pathological features were observed including:

- a healed intracapsular fracture of the right femoral neck (described in detail below) (Fig. 2).
- multiple well-healed rib fractures, which likely occurred in at least two episodes. Fractures are present on the right 3rd rib, the right 10th/11th rib, and on three adjacent left ribs (6, 7, 8).
- a healed fracture to the right forearm resulting in detachment of the styloid process on the ulna and a shelf-like projection on the distal end of the radius.
- a healed fracture on the inferior aspect of the body of the fourth lumbar vertebrae.
- a healed hairline fracture on the posterior aspect of the right patella.

Besides these fractures, PSN 335 also exhibited:

- lamellar bone nodules on the visceral surfaces of multiple ribs, suggesting that she may have experienced a chronic respiratory condition.
- subperiosteal new woven bone formation on the anterior aspect of the sacrum and on the right iliac wing.
- osteoarthritis in her spine, right wrist (probably related to the aforementioned forearm fractures), and in both of the first metatarsophalangeal joints.

#### 3.1.1. PSN 335: Macroscopic and biomechanical assessment of fracture

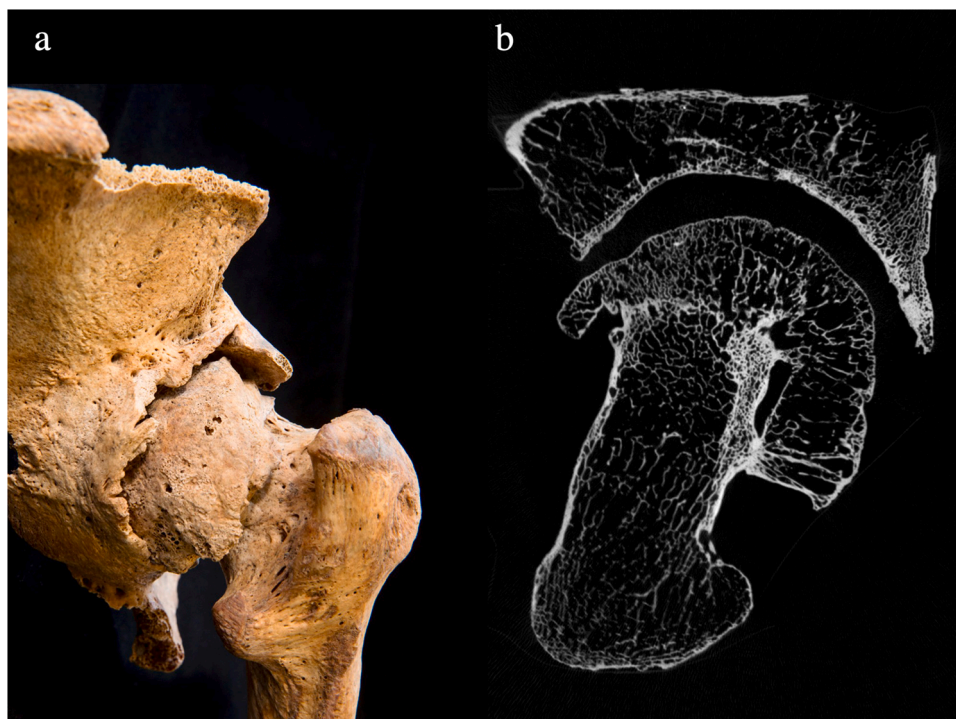
As a result of the impacted intracapsular fracture to the neck of the right femur, the femoral head was displaced posteroinferiorly, resulting in shortening of the femur length by 1.5 cm compared to the left side. Fractures of this type commonly occur secondary to osteoporosis and osteopenia (Pasco et al., 2006). Macroporosity and destruction of the cortical bone on superior aspect of the femoral head suggests that the blood supply was interrupted resulting in avascular necrosis. Substantial degenerative changes on the femoral head and heterotrophic ossification of the acetabular labrum and capsule was observed. A bony ‘bridge’ between the acetabular margin and the anterior aspect of the femoral neck indicates joint ankylosis. The extent of the ossification of the soft tissues surrounding the hip indicates a complete loss of movement in this joint, with the joint held in 45 degrees of flexion.

The cross-sectional geometry of the femora and tibiae revealed a reduction in the amount of cortical tissue (CA) and torsional rigidity (J) on the affected (right) side (Fig. 3, Fig. 4), resulting in substantial left-directional asymmetry. The asymmetry was not nearly as pronounced in the total subperiosteal area, which might indicate that accelerated bone loss on the right side, rather than increased formation on the left, drove this patterning. This potentially occurred as a result of the altered joint loading following the fracture.

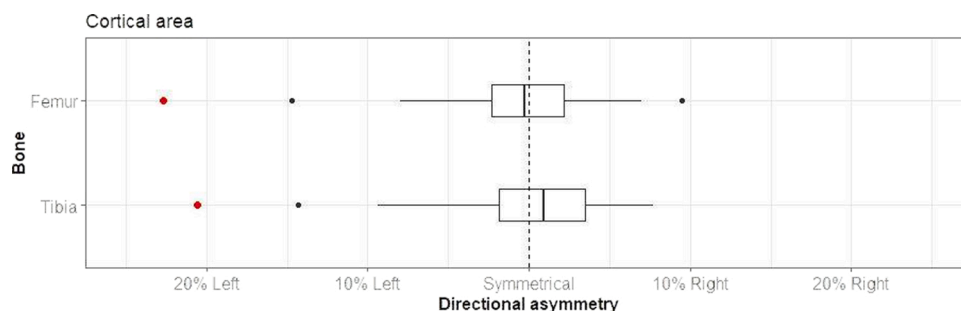
#### 3.1.2. PSN 335: Model of care

In modern clinical contexts, hip fractures have outcomes that range from full recovery to death (Dyer et al., 2016). It has been repeatedly shown that less than half of the individuals who experience a hip fracture return to their pre-fracture level of physical function within twelve months (Magaziner et al., 2003; Osnes et al., 2004). The ability for a patient to regain full physical function depends on multiple factors, including cognitive status, surgical interventions, age, and the presence of other comorbid conditions such as osteoporosis (Cauley, 2013). Social and economic factors including social support and living arrangements also play a role in recovery (Auais et al., 2019).

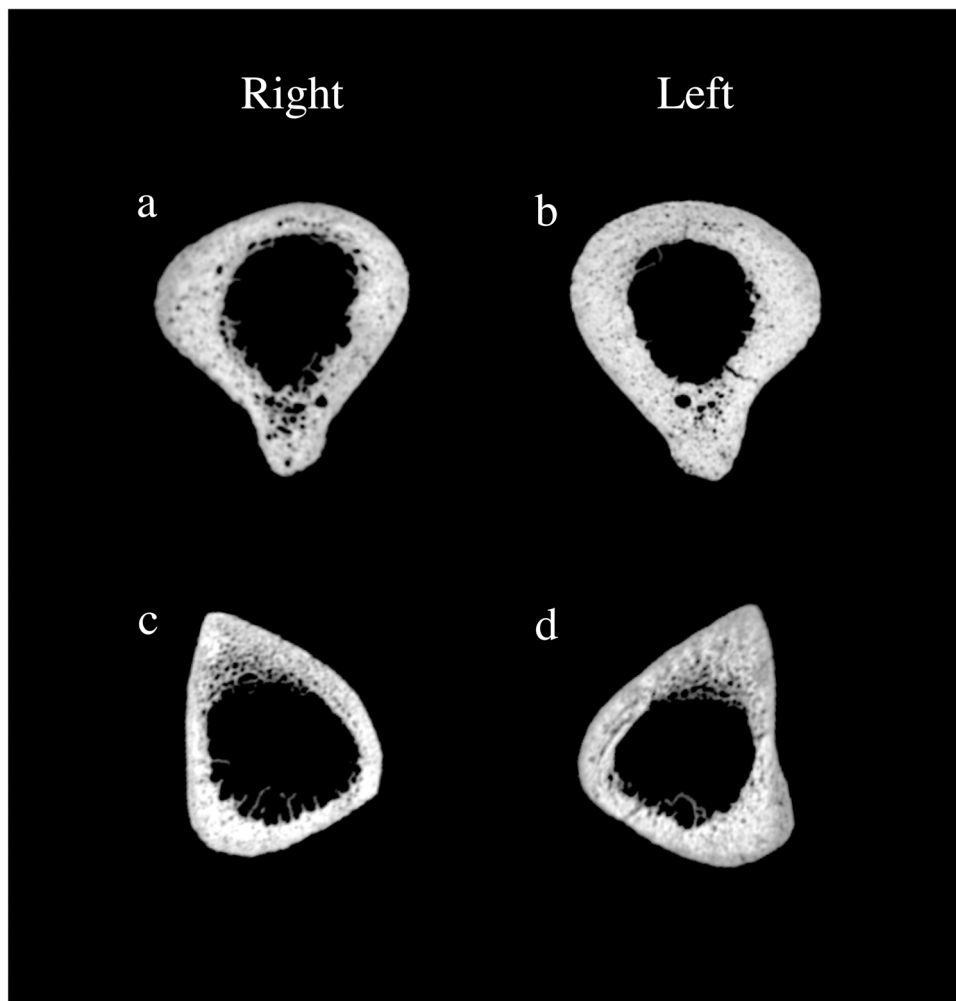
The impact of this injury would have been immediate and long



**Fig. 2.** a) Posterior view of right hip joint of a mature adult female (PSN 335) showing heterotopic ossification and ankylosis secondary to intracapsular fracture b) cross section of  $\mu$ CT showing the displacement of the femoral head secondary to impacted intracapsular fracture. Photograph by Susan Jones,  $\mu$ CT scans by Bram Mulder.



**Fig. 3.** Bilateral asymmetry in lower limb cortical area, relative to the variation observed in controls. Values for PSN 335 are positioned on the far left of the figure and highlighted in bold and red.



**Fig. 4.** PSN 335 a) 50% cross section of right femur, b) 50% cross section of left femur, c) 50% cross section of right tibia, d) 50% cross section of left tibia.  $\mu$ CT images by Bram Mulder.

lasting. Although it is not possible to determine her exact age when this fracture occurred, the common association with osteopenia or osteoporosis suggests that she was an older adult at the time of injury. If this was the case, the rate of fracture healing was likely affected. Immediately after the fracture occurred, she likely experienced a substantial amount of pain. In modern clinical contexts, hip fracture patients have reported persistent pain lasting anywhere between three to six months, and greater levels of pain have been associated with higher risks for cardiovascular events, depression, delirium, slower rates of remobilization, and poorer health-related quality of life (Abou-Setta

et al., 2011). A minority of individuals, however, have reported only slight pain associated with hip fractures, with some experiencing no difficulties walking following a fracture (Brunner, et al., 2003). Although it is not possible to know how much pain this individual experienced, the considerable reduction in cortical bone of the right leg indicates that this leg experienced limited loading for a substantial period of time, likely due to pain associated with walking.

During her initial period of immobilization, she would have had great difficulty self-provisioning and attending to self-care. Someone, possibly a family member, would have had to acquire and prepare food

for her but she may have been able to eat and drink without assistance. Although basic manipulation of objects in her immediate environment would probably have been manageable, controlling her body position would have been challenging and likely painful. As such, she would have needed help re-positioning herself in bed, especially if the fractures to her forearm and hip coincided. She would have also been unable to perform self-care tasks including the maintenance of basic personal hygiene (bathing and self-cleaning) and toileting.

Given the severity of the secondary complications (i.e., osteoarthritis, heterotrophic ossification), the effects of this injury clearly persisted until the end of her life. Today, hip fracture patients experience significant medium-to long-term declines in their physical functioning and quality of life following injury (Dyer et al., 2016; Marottoli, et al., 1992; Tosteson et al., 2001). Studies have reported that between 20% and 60 % of patients experienced a deterioration in independence and were reliant on others for performance of domestic activities, including chores and weekly shopping one year after experiencing a hip fracture (Archibald, 2003; Keene et al., 1993; Magaziner et al., 2000). Reduction in the ability to perform self-care (including washing and dressing) following a hip fracture has also been reported (Magaziner et al., 2000; Pitto, 1994). Magaziner et al., (2000) found that 44 % of patients required assistance with washing two years following a hip fracture and 63 % of individuals required assistance getting on and off the toilet.

The long-term ambulatory consequences of this injury can be inferred by the presence of ankylosis of the hip in 45 degrees flexion and the loss of cortical bone in the right femur and tibia. Once the fracture healed, PSN 335 was mobile but placed her weight primarily upon her left leg. The fixed flexion in the hip joint would have led to a functionally short limb, so the foot would not have reached the ground without the individual compensating by tilting her pelvis into extension and plantarflexing her ankle and forefoot. Eburnation on the superior-lateral aspect of the head of the first metatarsal and the proximal articular facet of the first proximal phalanx, as well as the presence of an osteochondral defect, suggests that she placed stress across the joint by walking with the big toe flexed downwards at about 90 degrees, in an awkward, tip-toe position. This would have resulted in an irregular step-hop gait. It is likely that she walked using a prosthetic aid, possibly a walking stick in her right hand or a single crutch held under her right arm, to help her maintain her balance.

Previous research that explored the osseous changes associated with crutch use has suggested that the upper brachial and pectoral skeleton, as well as the bones in the wrist and hands, are the most likely to have observable changes (Knüsel et al., 1992; Knüsel and Göggel, 1993). Unfortunately, in the case of PSN 335, this was unable to be assessed due to a combination of taphonomic damage that prevented accurate measurement from being taken and the ante-mortem fracture to the right ulna and secondary degenerative changes to the distal radius and carpals.

### 3.1.3. Provision of care

During the medieval period, the household was an economic unit where all members worked together to sustain themselves (Howell, 2009). Rigid gender roles existed in the division of labor (Mate, 1999), and women were most likely to be the providers of care within the medieval household. Wives were expected to care for their families and servants, but women also cared for the sick in more formal roles as nurses in hospitals (Ward, 2016). These women would bathe and feed patients, as well as wash linens and clean. The Hospital of St John the Baptist in Oxford had several women servants performing these roles in the 1380s (Ward, 2016). However, there is no textual or archeological evidence to suggest that women held these roles at the Hospital in Cambridge.

There are several plausible scenarios for the context of PSN 335's injury and her relationship to caregivers. This is dependent upon when this injury occurred (before or after she was admitted to the Hospital). It is important to consider that medieval hospitals took many forms and

served many functions (Cullum, 1991). The Hospital in Cambridge primarily provided pastoral care, so it is unlikely that PSN 335 would have entered the Hospital to receive care for her injury. However, if this injury occurred while she was in residence at the Hospital, she would have likely been cared for by staff members. If this injury occurred prior to her admittance in to the Hospital, it is likely that family members or neighbors would have cared for her. Following her recovery, she may have continued to live at home with her family for some time before entering the Hospital. If she outlived them, she may not have been able to support herself, and she could have been admitted into the Hospital as a result. As such, the reason for her entering the Hospital would not have been her medical needs but her inability to support herself.

### 3.2. PSN 93

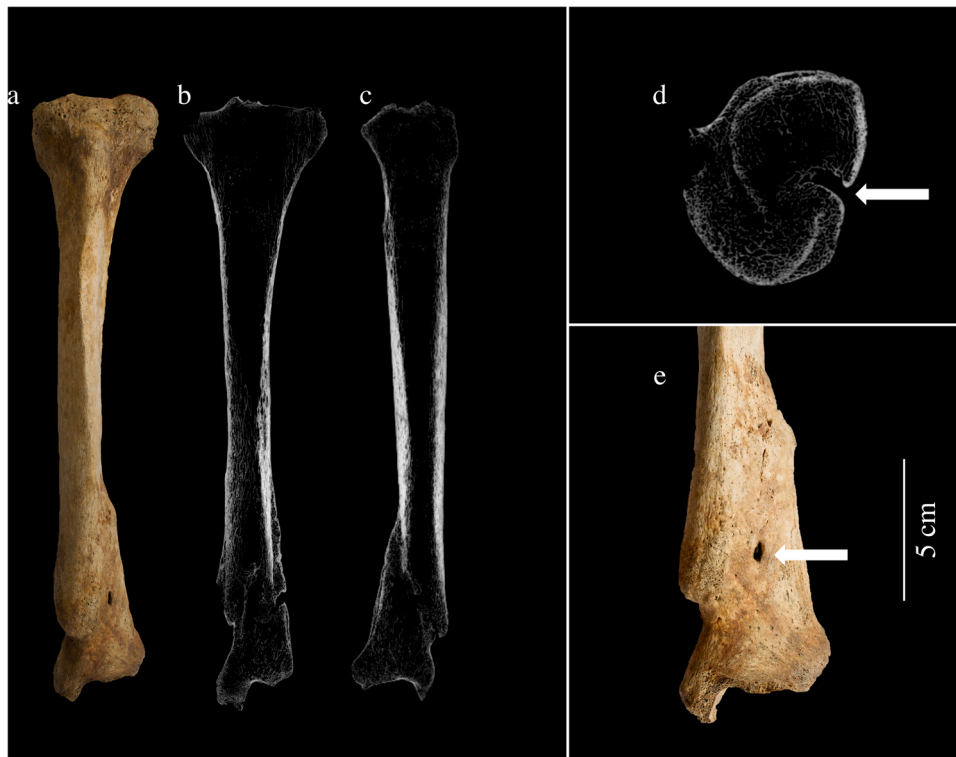
PSN 93 was an older adult male (60 + years old at time of death) buried in the cemetery of the Hospital of St John the Evangelist; he lived in the later 14th – early 15th centuries, dying between 1410 and 1454. Several fractures were observed on his skeleton including an ante-mortem fracture to a rib, and ante-mortem spiral fractures to the left tibia and fibula. Degenerative changes were noted in both of his hip joints. This individual also had scooped-out lytic lesions with overhanging margins on several pedal elements, including on the medial aspect of both heads of the first metatarsals. The observed lesions are consistent with gout (see Dittmar et al., 2021b). Flowing ossifications that have a 'dripping candle wax' appearance were observed on the right-hand side of multiple thoracic vertebral bodies, with T6–9 ankylosed. T10 also displayed bone proliferation on the right aspect of the vertebral body, but was unfused. The vertebral disc spaces were preserved, and the sacroiliac joints were unaffected (see Dittmar et al., 2021b). The observed changes are consistent with a diagnosis of Diffuse Idiopathic Skeletal Hyperostosis (DISH) based on the diagnostic criteria outlined by Rogers and Waldron (2001).

#### 3.2.1. PSN 93: Macroscopic and biomechanical assessment

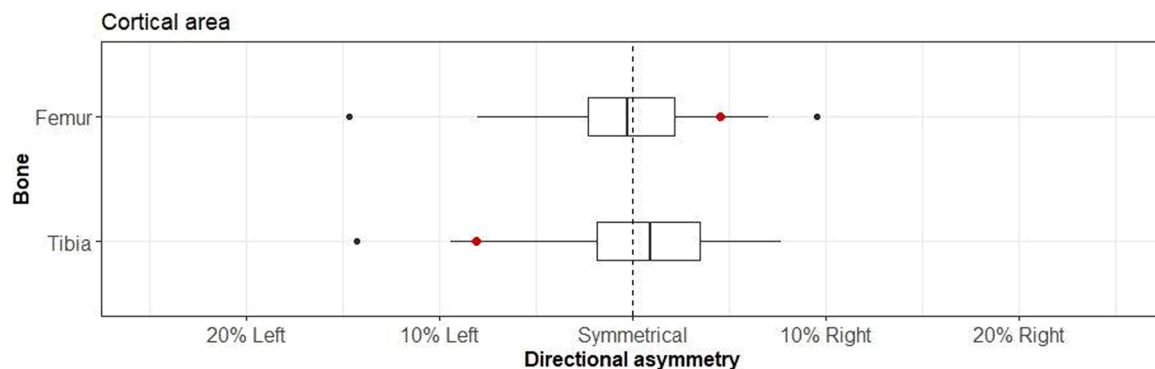
Well-healed spiral fractures were present on the distal third of the left tibia diaphysis and the middle third of the left fibula diaphysis (Fig. 5). The fracture to the tibia is malaligned; the distal fragment is in 20 degrees of valgus tilt and 45 degrees of external rotation. The fracture site shortening, coupled with the valgus angulation, led to an overall shortening of the tibia by 30 mm compared to the right side. The malalignment of the fracture resulted in the anterior displacement and medial rotation of the talocrural (ankle) joint, which likely would have caused an altered gait pattern; his foot would have pointed outwards and the knee pointed forwards. Though it is possible that he may have been able to compensate by internally rotating the leg at the hip.

Spiral fractures occur as the result of rotating force applied along the axis of a bone, for instance when the body is in motion while one foot is planted in place. The presence of a cloaca on the antero-inferior aspect of the fracture indicates osteomyelitis was a complicating factor of this injury. Osteomyelitis is an inflammatory bone disease that affects the medullary cavity that can lead to progressive bone destruction. In this case, the micro-organisms are likely to have entered the body through the fracture site via an overlying wound to the skin. Pathognomonic features of chronic osteomyelitis include the presence of necrotic bone (sequestrum), the formation of new bone (involucrum), and the exudation of pus, typically through a cloaca (Fig. 5).

With clear macroscopic evidence of malunion, it was predicted that evidence of greater loading on the right side would be evident in the  $\mu$ CT scans. However, the results do not clearly indicate this. Although the right femur was found to have greater CA and J than the left, the reverse was found for the tibia (Figs. 6, 7). This could be related to the relative shortening of the left tibia, which would make the left and right midshaft not entirely homologous. Moreover, neither the tibial nor femoral asymmetry was beyond the normal variation observed in the control sample, with bilateral differences in both elements below 10 %. The



**Fig. 5.** (a) Photograph and  $\mu$ CT cross sections of the left tibia (PSN 93) in the (b) A-P plane, (c) M-L plane and (d) axial plane showing a well-healed spiral fracture to the distal tibia complicated by (e) secondary osteomyelitis (cloaca indicated with arrow). Photographs by Jenna Dittmar,  $\mu$ CT images by Bram Mulder.



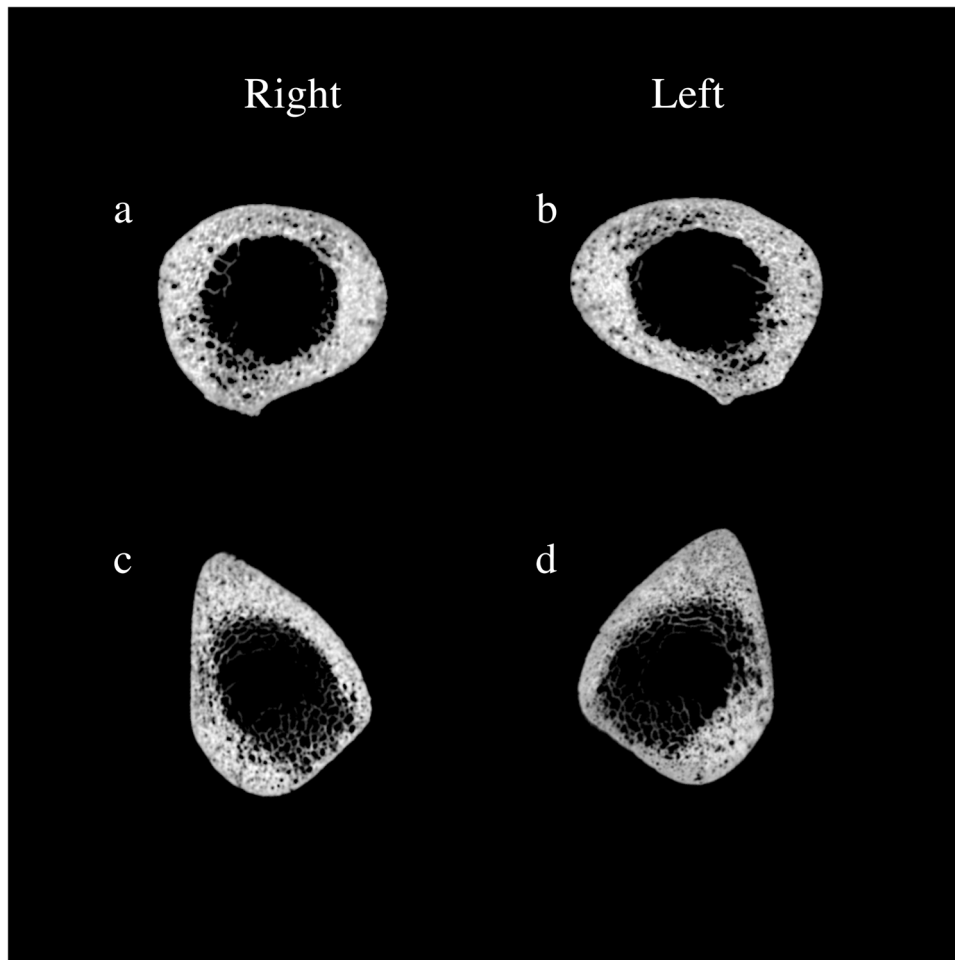
**Fig. 6.** Bilateral asymmetry in lower limb cortical area, relative to the variation observed in controls. Values for PSN 93 are bold and highlighted in red.

biomechanical evidence, therefore, suggests that the bone healed adequately to allow the patient to walk, although with a slightly modified gait. The lack of a consistent directional preference in asymmetry could be from relatively symmetrical loading once the fracture had united.

### 3.2.2. PSN 93: Model of care

Immediately following injury, he would not have been able to bear weight on his left leg. As a result of his decreased mobility, he likely experienced difficulty self-provisioning, but as his upper limbs were unaffected, he would have been able to eat and drink without assistance. The performance of self-care tasks may have been restricted initially, and he likely would have needed help with toileting. Provision of care would likely have been necessary for a few months as fractures to the distal third of the tibial shaft are classically slow to unite and even slower when infection is present. This is due to the interruption of blood supply to the bone marrow (endosteal blood supply) and the relatively poor vascularization of soft tissues surrounding the bone.

The presence of osteomyelitis suggests that PSN 93 may have experienced an open fracture (i.e. the bone penetrated through the skin), which allowed micro-organisms to enter the body through the fracture site. The tibia is the most common site of open fractures, as the subcutaneous location of the tibia makes it vulnerable to direct injury and extensive soft tissue damage (Emami et al., 1996; Zinberg, 1989). Some clinical reports state that 60–70% of open fractures are contaminated with bacteria (Tsukayama and Gustilo, 1990). Today, the most common causative species are the usually commensal staphylococci, with *Staphylococcus aureus* and *Staphylococcus epidermidis* responsible for the majority of cases (Kavanagh et al., 2018). In modern times, osteomyelitis is difficult to treat and can be associated with a high morbidity and possible mortality (Parsons and Strauss, 2004). In this case,  $\mu$ CT scans indicate that bony union was successful, and that mobility was (largely) regained after the fracture occurred. However, the infection of the medullary cavity, which remained active until the time of death, would have continued to cause symptoms throughout the individual’s life. Patients with chronic osteomyelitis can present a variety of symptoms,



**Fig. 7.** PSN 93 (a) 50% cross section of right femur, (b) 50 % cross section of left femur, (c) 50 % cross section of right tibia, (d) 50 % cross section of left tibia.  $\mu$ CT scans by Bram Mulder.

including localized bone and joint pain, erythema, swelling, fevers, night sweats, and a draining sinus (Parsons and Strauss, 2004). Individuals with chronic osteomyelitis often have periods of quiescence followed by flare-ups that can continue throughout life (Tsukayama, 1999).

### 3.2.3. Provision of care

Due to the extensive amount of healing, it is likely that PSN 93 was injured a considerable time before his death. Initially, while he was unable to bear weight on his leg, assistance with feeding, toileting and cleaning would have been necessary. This was likely provided by members of his family or the members of a group that he belonged to such as a scholarly or religious community. After regaining mobility he presumably would have been able to function in society but would have been chronically troubled by periodic flare-ups of active infection. With age, this injury, as well as the other conditions and ailments that this individual experienced, likely affected this individuals' well-being and abledness. As DISH is a progressive condition, it is possible that he experienced spinal stiffness, loss of range of motion, pain and radiculopathy (Vaishya et al., 2017). However, this is difficult to infer, as DISH is sometimes asymptomatic. It is possible that the combination of these conditions could have been a factor in his being admitted to the Hospital. However, given that his injury would not have prevented his ability to function in society, and that the Hospital would not have provided unique therapy, it is possible that he was admitted to the Hospital for some other reason (e.g., if he were an aged, poor scholar).

### 3.3. PSN 723

PSN 723 was an older male (60 + years of age at time of death) buried at the parish cemetery of All Saints by the Castle, who lived between the 10th and 12th centuries, and was buried between 940 and 1150. A number of pathological lesions were present, including multiple carious lesions and several abscesses, one of which perforated the right maxillary sinus. Several joints had evidence of degenerative change including the hips, and osteoarthritis was present in the left knee, on the head of the right first metatarsal, and in the cervical spine. Two cervical vertebrae (C3–4) were ankylosed, and osteophytes were present on the bodies of the lumbar vertebrae. An osteochondral defect was observed on the right patellae, along with enthesophytes on the antero-superior margin. The most notable pathological feature on this skeleton is a length discrepancy between the tibiae and fibulae.

#### 3.3.1. PSN 723: Macroscopic and biomechanical assessment

There are several possible causes for the observed length discrepancy between the lower limbs. The differential diagnosis includes congenital shortening of the tibia and fibula, neuromuscular disorders causing paralysis, tumors, osteomyelitis during childhood that damaged the proximal tibial growth plate, and a tibial plateau fracture with growth plate interruption (Moseley, 2006). Congenital disorders that lead to shortening of the entire limb, such as hemiatrophy, will not apply to this case as the femora are of equal length. Tibial deficiency, a rare condition that can lead to a short tibia and normal femur, can present in severity ranging from a short bone of normal appearance, to a bone that is



deficient at one end, or completely absent (Morrissy et al., 2006, 1345). However, congenital shortening, such as tibial deficiency, is an unlikely diagnosis here due to the appearance of the proximal tibial metaphysis and epiphysis, where the tibial plateau is displaced posteriorly relative to the metaphysis. Neuromuscular conditions causing paralysis, such as poliomyelitis, was also considered, as it can lead to a short tibia and fibula (Moseley, 2006). However, this seems unlikely, as the femur and foot appear normal, which would not be the case for a neuromuscular disease affecting this limb. There is no evidence for a tumor, so this option was also excluded. Osteomyelitis occurring in childhood (likely caused by the hematogenous spread of bacteria from elsewhere in the body) was also considered, as bacteria in the blood stream can settle in the metaphysis of long bones and destroy the adjacent bone. If located close to a growth plate, bacteria could destroy the growth plate and cause reduced growth in the bone (Harik and Smeltzer, 2010). However, this scenario is also unlikely, as the lateral radiograph of this tibia shows that the articular surface of the tibial plateau is displaced posteriorly relative to the tibia shaft (Fig. 8). The appearance of the tibia is consistent with a displaced fracture through the proximal tibial growth plate during childhood, with resulting damage to the growth plate and growth arrest.

The consequence of the fracture was the shortening of the lower limb, with the left tibia measuring 66 mm shorter than the right (R: 392 mm, L: 326 mm). The approximate age that growth terminated in the left tibia was estimated using standardized growth curves. Over the age of five, the proximal tibial growth plate grows at about 9 mm per year (Dimeglio, 2006: 58). Conservative estimates for a 66 mm discrepancy suggest that the injury took place at least 6–7 years prior to the cessation of growth in the tibia, which occurs around the age of 15–16 in boys. Therefore, this injury likely occurred when he was around 8–9 years old.

There are several possible ways that this individual may have compensated for the asymmetry between the length of his legs. Common compensatory mechanisms for those with structural limb length inequalities include calcaneal eversion, knee extension, toe walking, circumduction, and hip or knee flexion (steppage gait) (Khamis and Carmeli, 2017). These compensatory mechanisms can amplify forces across a smaller joint contact area, which can lead to an increased risk of developing osteoarthritis (Golightly et al., 2007), as is observed in this

individual. The presence of osteoarthritis in the right hip, in the left knee and on the head of first metatarsal are suggestive of abnormal mechanical joint loading.

The presence of osteoarthritis in the right hip aligns with clinical studies that report that osteoarthritis in the hip is more common in the longer limb than the shorter limb (Friberg, 1982; Tallroth et al., 2005), as the longer limb is bearing increased loads for longer durations (Bhave et al., 1999). The osteoarthritic changes in the left knee and on the head of the first metatarsal are more difficult to explain given the complex nature of compensatory ambulatory mechanisms. Compensatory mechanisms can occur simultaneously in both the longer and shorter lower limb and can change over time (Khamis and Carmeli, 2017). The relationship between osteoarthritis and limb length inequality remains under investigation and future research is necessary to understand incidence, progression, and symptom severity (see Golightly et al., 2007).

Given the disparity between the lengths of the tibiae, it was expected that the biomechanical assessment would reveal uneven loading, caused by relative disuse of the left side. The lower limb cross-sections of the femur and tibia on the right side both had greater cortical area compared with the left (Figs. 9, 10). This supports an interpretation of relative unloading of the left limb. Indeed, visual inspection of the cross-sectional images does suggest increased intracortical porosity in both limb elements on the left side, which may indicate reduced mechanical loading. However, the bending properties were less affected, with the pronounced right-directional bias only visible in the tibia. This might be related to the distinct differences in diaphyseal shape (see Figs. 10c, 10d), most notably in the femur. This suggests that the left and right sides did not differ in loading magnitude, but rather in loading modality, with a more pronounced medio-lateral bending of the left femur. This could have resulted from a modified gait pattern, relying primarily on the function of the right limb. Where a relatively balanced mechanical environment was created for the femur, with little asymmetry, the tibia displayed a strong right-side bias. A strong right-directional asymmetry can indicate uneven loading mechanism of the lower limbs.

### 3.3.2. PSN 723: Model of care

Fractures of the tibia that occur in children between 8 and 10 years old generally take about 1–2 months to unite and become pain free. Immediately following injury, this individual would not have been able to bear weight on the left leg, and this restriction in mobility would have affected his ability to care for himself. He likely experienced some difficulty with self-provisioning and self-care, given that it would have been painful to walk even short distances. Since there is no skeletal evidence that the upper limbs were affected, he would have been able to eat and drink without assistance.

The  $\mu$ CT scans indicate that the union of the fracture was successful and that he was able to regain mobility even though this fracture was complicated by reduced growth of the left tibia. Despite the asymmetry in the lower limb lengths, there is no evidence to suggest chronic disuse. The long-term functional outcome of this injury was uneven mechanical loading that resulted in a permanent altered gait, which led to the development of osteoarthritis in his left knee and both hips. Although it is difficult to determine, it is possible that this individual experienced an increased level of impairment with age that coincided with the development of these secondary complications. As far as we can tell, he remained an active member of society, but one who walked with a limp.

### 3.3.3. Provision of care

In order to understand the immediate and long-term implications of this injury and reconstruct his lived experience, it is important to consider the social age at which this individual was injured. During the high and late medieval periods in England, historical research suggests that childhood lasted until the age of seven (Lewis, 2016). Following this age, many historians recognize a transitional phase between childhood and the independence and autonomy that characterized adulthood.

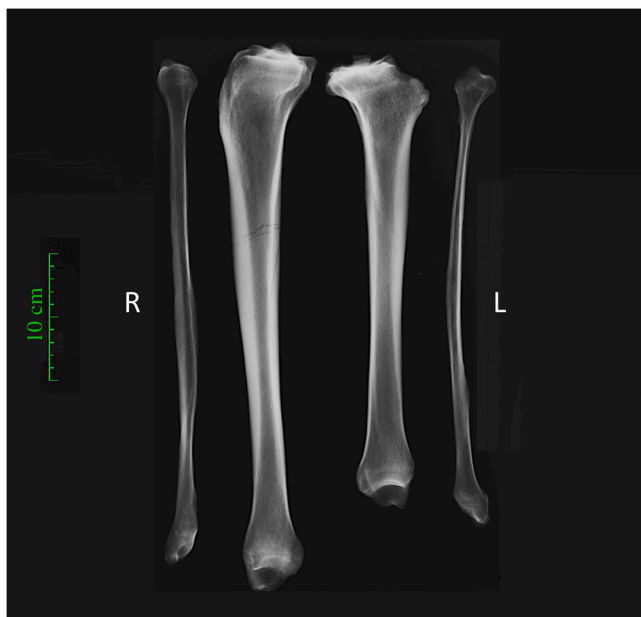
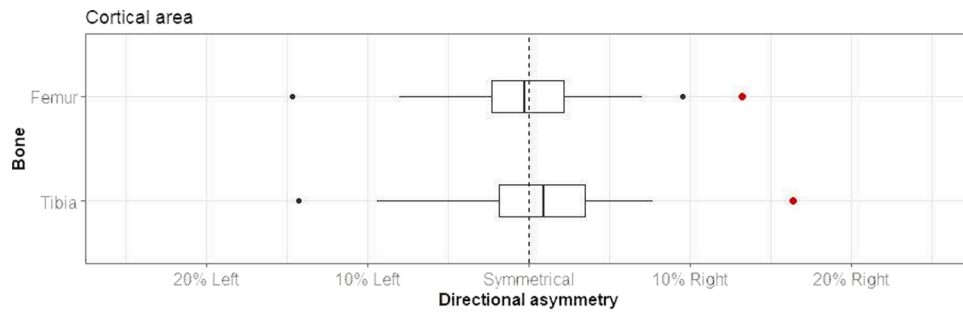
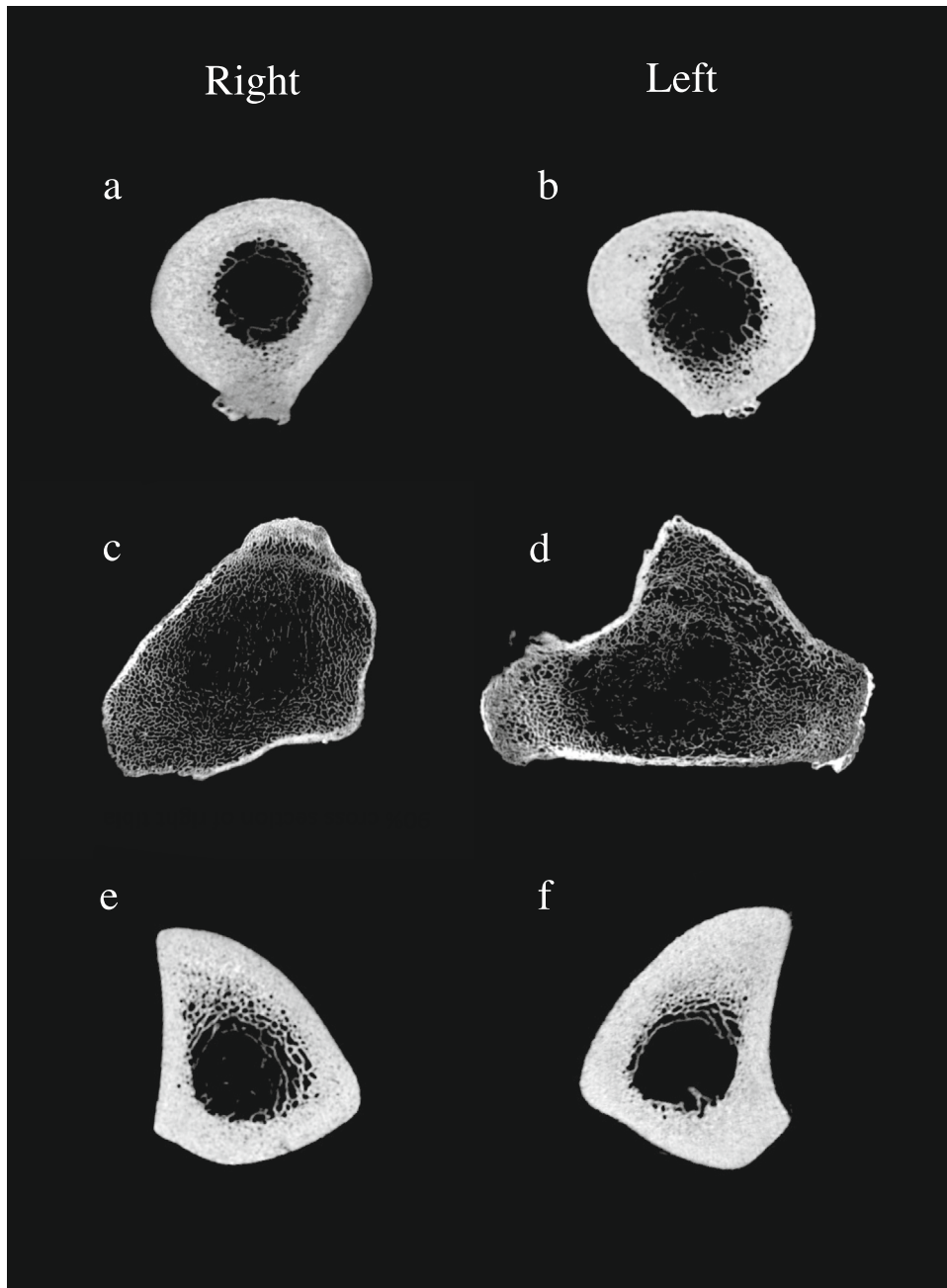


Fig. 8. Lateral view X-ray of tibiae and fibulae of PSN 723, showing the length discrepancy between the right and left elements and the posteriorly displaced tibial plateau relative to the left proximal tibial metaphysis.



**Fig. 9.** Bilateral asymmetry in lower limb cortical area, relative to the variation observed in controls. Values for PSN 723 are bold and highlighted in red, positioned on the far right of the figure.



**Fig. 10.** PSN 723 (a) 50 % cross section of right femur, (b) 50 % cross section of left femur, (c) 90 % cross section of right tibia, (d) 90 % cross section of left tibia, (e) 50 % cross section of right tibia, (f) 50 % cross section of left tibia.  $\mu$ CT scans by Bram Mulder.

Although there remains much debate about when an individual enters and exits this phase of life (Hanawalt, 1992; Weinstein and Bell, 2010), it is likely that PSN 723 was within this ‘adolescent’ phase when he was injured.

There were at least three options for this individual’s life path, and hence the consequences of this injury. First, he may have spent his life working in the fields immediately outside Cambridge. Later in life, he may have inherited his family’s tenement or taken up a vacant holding. Secondly, he may have worked as a generalized laborer in the town of Cambridge. In both cases, following this injury, it is likely that he was cared for by family members such as his mother and/or sister(s). The third option is that he may have been a specialized worker such as a craftsman. This career trajectory often involved leaving home during adolescence to serve as an apprentice. Apprenticeships were essential for inter-generational transmission of skills (Harding, 2009), but they could be costly and were not without risk. It has been estimated that up to 10 % of apprentices died during their indenture (Ben-Amos, 1991; Wrigley, 1969) and many more were seriously injured. An injury, such as the one sustained by PSN 723, would have prevented him from working for at least 6 weeks. If he was serving as an apprentice when injured, it is likely that care was provided by the family members of his master, or possibly by his peers. As adolescent males from poor, laboring or agricultural backgrounds were less often able to afford the steep cost associated with apprenticeships (Lewis, 2016), it is likely that this individual remained an agricultural worker or laborer within his local community.

## 4. Discussion

### 4.1. Charitable care and concepts of (dis)ability

Reconstructing perceptions of disability based on observable physical impairments from archeological human skeletal remains is fraught with challenges and limitations. As previously mentioned, medieval concepts of disability varied, but perceptions of physical ability were often based on how an individual functioned in society. By this, we mean their ability to perform the duties that they were expected to be able to undertake according to their specific social position and their ability to work and support themselves. Those without support networks were forced to beg or to rely on charitable handouts, which often resulted in a shift in their social status (Metzler, 2013).

The context within which these individuals were buried can provide some insight into their social status and their role within the community. Each of the individuals presented here was part of the laboring class who survived their injuries, indicating that care was likely provided during the period immediately following their injuries, and in some cases, in the long-term (as dictated by physical consequences of the injury). In most cases, the primary caregivers were members of one’s family; though care could also have been provided by a member of an individual’s wider support network. Although ‘formal’ medical advice for treating fractures in the form of written ‘surgeries’ was available in Cambridge during the 14th and 15th centuries (Clarke, 2002; Voigts, 1995), including *Chirurgia magna* by Lanfranco of Milan and *Rosa Anglica* by John Gaddesden, there is no archeological evidence to confirm that medical care was provided to any of the individuals in this study.

Within medieval communities, those that were able-bodied had a social obligation to work and to aid those who were unable to do so, assuming the individual was deemed to be ‘deserving’ (see Metzler, 2013). The criteria used to determine who was ‘deserving’ appears predicated on a combination of an individual’s ability to support themselves and moral criteria. In Cambridge, and in many other medieval towns, hospitals for the poor and ‘infirm’ offered support for members of the community. As a small charitable institution, the Hospital in Cambridge primarily provided pastoral care, rather than what we would today consider to be medical treatment. However, medieval concepts of ‘treatment’ and what it meant to be ‘cured’ must be contextualized considering the importance placed upon religious beliefs.

As stated by Horden (1988), if ‘the remission of illness could originate only in the remission of sins’ then such treatments had just as much perceived therapeutic value as did the presence of a physician.

The admission requirements for the Hospital were restricted to prevent the admittance of those with ‘grievous injuries’ and those that were classified as ‘crippled’ (*contracti*) but also admitted people deemed ‘infirm and debilitated’ (*infirmi et debiles admittantur*) (Rubin, 1987: 110, 157–9, 300–01). Exactly what types of conditions fell into these categories remains unknown, but recent research on skeletal injuries in Cambridge found no evidence of peri-mortem fractures in the Hospital cemetery (Dittmar et al., 2021a). This suggests that the admission criteria of those with ‘grievous injuries’ was adhered to. However, the severity of the injuries and secondary complications observed on individuals buried at the Hospital suggests that individuals with long-standing physical impairments were admitted.

The inability to support oneself, perhaps from some combination of medical afflictions, poverty, and lack of family support, was probably the main criterion for receiving the Hospital’s charity. PSN 335 was likely an inmate of the Hospital, as this was the primary reason why women were buried in this location (i.e., she was not allowed to be a scholar or a cleric) (Cessford, forthcoming; Robb, forthcoming). As an inmate, she must have been deemed to be ‘deserving’ of charity’. This shift in her social status was likely accompanied by being viewed as ‘disabled’ within the community. However, it cannot automatically be assumed that every individual buried within a hospital burial ground was a recipient of charity or considered to be ‘disabled’. In the case of PSN 93, an adult male, it is possible that he was a poor scholar or a corrodian who paid to spend the rest of his life in the Hospital, rather than being an inmate. The chronic nature of his condition does support the idea that he may have had difficulty working. If this was the case, it is possible that he was also an inmate and thus would have also been considered ‘disabled’ as he could no longer provide for himself, though there is no way to know for certain.

As has been shown by many researchers over the years, the identification of skeletal trauma is insufficient evidence to presume that an individual would have been ‘othered’ or would have been perceived to be different or ‘disabled’ (Kasnitz and Shuttleworth, 2001). PSN 723, for example, had a chronic and visible impairment, but was likely not considered to be ‘disabled’. Although he would have walked with a limp, his ability to work and provide for himself was not substantially reduced as a long-term result of this injury. Although even if he would have been in a position where he required pastoral care in a charitable institution, the Hospital was not founded until after his death. This limitation complicates our ability to assess how he would have been perceived within medieval society.

## 5. Conclusion

Each of the individuals presented here was a member of the laboring class in a medieval market town who experienced a severe traumatic injury at some point in their lives. They all survived, indicating that care was likely provided through the various stages of recovery. The long-term consequences of the injuries and the degree of chronic physical impairment was identified by contrasting the bilateral asymmetry from multiple skeletal elements. This enabled the extent and the severity of altered loading conditions to be identified. Based on this assessment, it appears that PSN 335 and PSN 93 suffered long-lasting complications from their injuries that likely contributed to their entry into the Hospital. PSN 723 was injured at a young age, and though he lived with a substantially altered gait, the impairment did not appear to impact his ability to provide for himself until his death. This reiterates that the presence of skeletal trauma is insufficient evidence to presume an individual would have been considered ‘disabled’. The ways in which society classified individuals (for instance, as appropriate recipients of charity) was complex and not based upon solely on an individual’s physical condition. Rather, determinations of able-bodiedness and

‘disability’ was determined based on a multitude of factors, including the ability to support oneself and perceived moral behavior.

The findings of this research show that the integration of multiple types of evidence, including macroscopic, radiographic and biomechanical data, offers a more sensitive tool for the analysis of skeletal injuries and associated secondary complications. When historically contextualized and interpreted through the lenses of the Bioarchaeology of Care framework, this interdisciplinary approach enables the lived experiences of impaired individuals to be reconstructed and better understood.

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