Common orthopaedic trauma may explain 31,000-year-old remains

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ARISING FROM T. R. Maloney et al. *Nature* https://doi.org/10.1038/s41586-022-05160-8 (2022)

The fascinating discovery of skeletal remains in Borneo of an individual (TB1) with absent left distal tibia, fibula and foot from 31,000 years ago[1] has been proposed as evidence of a contemporaneous sophisticated amputation procedure. Maloney et al.[1] infer from the bony abnormalities that surgical amputation is the only possible explanation and, furthermore, that the limb shows no evidence of infection. We dispute the conclusion that these skeletal remains provide evidence of a transosseous surgical amputation and that the limb shows no signs of infection. We propose that the skeletal findings have more plausible alternative explanations, such as the natural history of an injury pattern commonly encountered in blunt orthopaedic trauma, an open distal tibia/fibula fracture with growth-plate involvement.

From the perspective of orthopaedic trauma surgeons practicing in this field, the exclusion of blunt trauma as a potential mechanism of injury is a rather reductionist approach to a differential diagnostic puzzle with several missing pieces from thousands of years ago. Maloney et al.[1] dismissed blunt trauma with the assertion that it "typically causes comminuted and crushing fractures". To support this statement, they cited an isolated case report of an axis fracture[2] (the second cervical vertebra in the neck). We disagree with the statement and suggest the supporting citation is inadequate. Oblique fracture patterns such as TB1's are frequently observed from blunt trauma in clinical practice[3].

Physeal (growth plate) fractures of the distal tibia and fibula are common injuries in adolescents[4]. The most common subtype[5] involves fracture through the distal tibial physis and into the metaphysis (Salter–Harris type II[6]), and typically occurs concomitantly with a distal fibula fracture[7]. It is not uncommon that the medial apex of the fracture pierces through the skin[8,9], while the foot displaces laterally, as seen in Fig. 1. The mean age of people presenting with this Salter–Harris type II injury to the distal tibia and fibula is 12–13 years[7], which corresponds to the predicted age of injury for the individual of whom the skeletal remains were discovered in Borneo, given he or she is estimated to have died aged 19–20 (a predicted 6–9 years after suffering the injury)[1]. The typical mechanism of these injuries is forced inversion or eversion while the foot is fixed in position on the ground. In Borneo 31,000 years ago, this may have eventuated from any slip or misstep whilst running, or a jump from low height. Today, open ankle fractures are managed with intravenous antibiotics, tetanus prophylaxis and expeditious debridement with open reduction and internal fixation in the operating theatre.

In Borneo 31,000 years ago, the natural history of an open physeal ankle fracture without modern surgical care could quite plausibly have produced the findings encountered in TB1's skeletal remains. In some cases, the inoculation of bacteria into exposed bone could result in acute infection progressing to overwhelming sepsis and death. In other cases, a chronic osteomyelitis can develop, often with the formation of a life-long draining sinus[10]. Survival with chronic osteomyelitis was described on many occasions in the pre-antibiotic era[11]. In the 1830s, Nathan Smith, a professor of surgery at Yale University, suggested that most people with osteomyelitis he observed survived with the condition, writing "a very great majority of patients survive the attack, albeit with long confinement, protracted suffering and great emaciation."[12]. The "long confinement, protracted suffering" was most probably TB1's fate during his young adulthood. It is highly implausible that either surgical amputation or an open fracture, in the absence of antiseptics, anaesthetics or antibiotics, could occur without a subsequent established infection. Furthermore, the bony changes shown in figure 3 of Maloney et al.[1] are typical of chronic osteomyelitis—the cortical thickening of the distal tibia and fibula are consistent with involucrum, and the small bony defect of the distal tibia could represent an area of sequestrum. The evidence of bone lysis and necrosis at the distal tibial and fibula, which Maloney et al.[1] refer to in the caption of figure 3b, could quite plausibly occur secondary to infection[13]. The suggested mechanism explains other characteristics of the skeletal findings—the missing malleolar parts of the distal tibia and fibula are consistent with common adolescent fracture patterns, and the small size of the left tibia and fibula relative to the right is highly suggestive of physeal arrest, which is a common complication of displaced physeal fractures[7,14].

With a distal tibia and fibula fracture already present and necrosis of the bone and surrounding soft tissues occurring due to infection, terminalization of the limb—that is, cutting through the remaining soft tissues—is a more plausible scenario. This is a substantially different proposition from the primary transosseous surgical amputation described in Maloney et al.[1], which states that the bone must have been cut with a sharp instrument. It is impossible to know whether loss of the foot occurred around the time of injury, or weeks to months later. If an arterial injury accompanied the initial bony injury, and the limb suffered distal ischaemia as a result, a dry gangrenous process may even have autoamputated the limb without any assistance.

We cannot exclude the possibility of rarer causes to explain these skeletal remains—for example, congenital transverse deficiency of the lower limb, a rare congenital anomaly that can manifest as a hypoplastic limb with absent foot[15]. If TB1 were born with this condition, weightbearing on the footless lower limb without a durable heel pad could have caused ulceration and the chronic infective changes that we observe in the bony architecture of TB1's distal tibia and fibula.

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Fig. 1 | Plain radiograph of a distal tibia and fibula fracture. A plain radiograph of a distal tibia and fibula fracture involving the physis (growth plate) in a 14-year-old individual.

Overall, we find that the conclusions drawn by Maloney et al.[1] are unconvincing. Performing primary supra-articular transosseous surgical amputation through the thick cortices of the tibia without specialized metallic tools (at least chisel and saw) would be very difficult and is highly improbable. If the people in Borneo were performing lower-limb amputation using 'sharp instruments', it would have been easier to perform transarticular amputation through the soft tissues of the ankle joint, where it is not necessary to transect thick cortical bone. This is not the pattern observed in these skeletal remains.

We suggest that interdisciplinary input from expert orthopaedic trauma surgeons and bone and joint infection experts would be of value in archaeological studies such as this to aid in formulating plausible explanations of injury mechanism and infectious processes, as palaeopathology is unlikely to cover the breadth of specialized understanding required. Unfortunately, our concerns are not limited to the explanation of the missing part of the skeleton. Figure 3a of Maloney et al.[1] contains a photographed reconstruction of TB1's bony anatomy, with the distal portion of the right tibia placed back-to-front such that the medial malleolus is incorrectly articulating with the distal fibula. As an image that is likely to be frequently reproduced, and that has already had considerable media attention, this requires correction. Although we cannot support the conclusions of Maloney et al.[1], we nevertheless consider the findings described to be of great interest. Even if TB1 did not undergo a transosseous surgical amputation, the findings demonstrate evidence of an individual who, 31,000 years ago, must have had enormous kin support to survive for several years after a severe open injury, which of itself seems a notable detail about our ancestors.

Reporting summary

Further information on experimental design is available in the Nature Portfolio Reporting Summary linked to this Article.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-023-05756-8.

Data availability

All relevant data are included in the Article.

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Author contributions Z.J.B. initiated this Comment. N.J.M. prepared the first draft manuscript. All of the authors revised and approved the final manuscript.

Competing interests The authors declare no competing interests.

Additional information

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Specimen provenance	Not applicable. This is a letter to the editor concerning a publication regarding paleopathology. No new data was collected for our letter.
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Matters arising

Reply to: Common orthopaedic trauma may explain 31,000-year-old remains

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REPLY TO Murphy et al. *Nature* https://doi.org/10.1038/s41586-023-05756-8 (2023)

We appreciate the accompanying technical Comment by Murphy et al.[1]—a group of practicing orthopaedic surgeons—on our original paper[2]. However, we strongly disagree with their conclusion that a reductionist approach was taken in the diagnosis of surgical amputation in a 31,000-year-old individual (TB1) from Borneo. We note that a complete systematic differential diagnosis was indeed completed (Extended Data Table 1); this process involved careful consideration of the most common and banal conditions first, such as accidental fracture, before considering the possibility of more rare and unusual circumstances. Through this iterative process, fracture was first eliminated as a possibility, followed by natural causes of amputation.

Surgical amputation was the remaining scenario left that completely described the characteristics that we observed in the bone. As is standard for palaeopathological analysis, a detailed description of the pathology was undertaken, including recording of the location and aspect of affected bone, the type of bone affected, the mechanism of injury, the degree of healing, complications to healing, force and fracture type. This detailed analysis means that certain aspects of trauma were excluded from the differential diagnosis due to the specific location of the injury. It was at this stage that physeal fractures, which Murphy et al.[1] correctly recognize as common fractures in early adolescence, were disregarded from the differential diagnosis as the affected portion of the bone was at the site of the mid to distal lower third diaphysis and not near to the distal metaphyseal region (Fig. 1). We surmise that Murphy et al.[1] may have mistaken the thin cortices of TB1's tibia and fibula for that at the diaphyseal-to-metaphyseal transition in the bone that is naturally thin. However, with TB1, the cortices in these bones (and indeed also the left femur) are thin due to extreme atrophy that probably occurred over a number of years. We acknowledge that two-dimensional photographs and radiographs can misrepresent to readers injuries that, in reality, occur in three dimensions. Thus, we provide publicly available three-dimensional computed tomography files of the amputation.

Moreover, the age of 6 to 9 years after surgery is a minimum age based on the minimal timing required for the completion of bone remodelling in the major long bones and, given the size of the lower limb bones, it is probable that the injury occurred in childhood. As Murphy et al.[1] are aware, physeal stasis can have diverse traumatic origins as well as stasis of longitudinal growth in general[3,4]. Experimental animal studies demonstrate the importance for muscular activity to initiate longitudinal growth of bones through biomechanical strain. Thus, the small size of the left limb bones can be readily attributed to the existing evidence for bone atrophy related to muscle wastage[5].

We are uncertain what Murphy et al.[1] are referring to in their second paragraph when relating the cervical fracture to the force applied to the amputation site. Although it is possible that the cervical vertebral fracture occurred in the same event that led to the need for amputation of the lower limb, the limitations of bone response prevent us from investigating this possibility any further. Owing to the lack of empirical evidence, we refrain from speculating on the motivation or underlying cause that led to the decision to amputate. It is of course possible that the trauma described by Murphy et al.[1] was the ultimate mechanism of injury that led to the child's limb being surgically amputated at the location of the distal diaphysis. We clarify that we are not saying oblique fractures of the long bone shafts do not occur from blunt force trauma but are atypical in cases from an accident (excluding modern situations including transport), particularly one where the fibula and tibia were both fractured.

Murphy et al.[1] point out in detail the requirements for their proposed scenario to have occurred but do not see the improbability of such a condition in the context of the Pleistocene tropics of Borneo. They do suggest soft tissue-only surgery as an alternative that would have involved antisepsis and debridement, which is arguably a far more sophisticated (and therefore less parsimonious) form of care that would have required a complex understanding of the anatomical basis for infection to specifically remove the infected tissue (rather than performing an entire amputation). If the fracture was not reduced through fixation, as is the case in modern Western surgical practices, a dead foot would have probably been an extreme impediment for the rugged mountainous terrain, and far more painful than a stump. Moreover, the fractured foot would have been susceptible to repeated infection as it was carried throughout the environment.

Murphy et al.[1] incorrectly describe the remodelled bone as osteomyelitis. To support their argument, they report an anecdote in a review on the history of osteomyelitis that is from a single memoir of an American surgeon published in 1831, whose patients received

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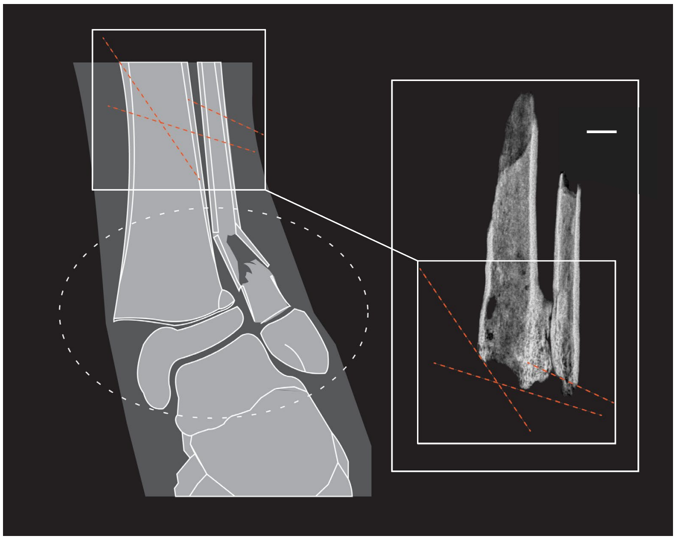

Fig. 1 | A Salter–Harris type II fracture of left tibia and fibula similar to the one presented by Murphy et al. compared with TB1's amputation. The amputation site is more proximal (white box) to the region of Salter–Harris physeal fractures (white dashed oval). At minimum, three different angles of force are present in TB1's amputation (red dashed lines) as opposed to one angle of force in Salter–Harris type II. Medial physis fracture of the tibia is absent in TB1 as is necessary for Salter–Harris type II classification with fibular involvement (see figure 1 of Murphy et al.[1]). Scale bar, 10.0 mm.

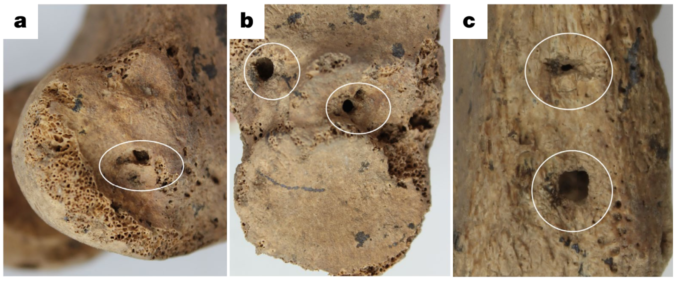

Fig. 2 | Cloacae of the right femur and tibia compared to carnivore puncture holes of the left tibia. a–c, Comparison of cloacae of the right femur (**a**) and tibia (**b**) with the carnivore puncture holes of the left tibia (**c**). The left tibia holes are clearly caused by punctures in dry bone resulting in square jagged margins to the cavities. By contrast, the margins of the holes in the right tibia and femur are rounded due to the constant remodelling process in the development of the cloacae. The femoral cloaca (**a**) also presents with a clear lytic channel consistent with infection.

treatment in hospital[6]. Osteomyelitis in the tropics is more aggressive owing to the greater diversity of the pathogens that cause osteomyelitis, the suitability of *Staphylococcus aureus*—the most common cause of osteomyelitis—to the humidity in the tropical belt and, potentially, the reduced amount of clothes worn in tropical environments increasing the infection risk of exposed wounds[7,8]. Although the mortality rate of untreated sepsis is not documented in the tropics, antibiotic-era in-hospital mortality rates in post-amputation contexts are reported to be as high as 10% and, in the Vietnam War, sepsis was attributed to 12% of deaths in surgical patients, the third leading cause of mortality in that conflict[9–11]. Osteomyelitis, both pyogenic and non-pyogenic, is readily observed in archaeological bone. In pyogenic forms, death of bone leading to sequestrum is readily observable surrounded by a shell of bone known as involucrum. Cloacae—pus draining holes—form to drain the pus from the medullary canal. Although there are circular holes in the bone, these are clearly a result of carnivore puncture and beetle scavenging marks, which are very common causes of post-mortem skeletal damage observed in Southeast Asian archaeological human skeletons (Fig. 2).

The radiographs of TB1's amputated limb (Fig. 1) show a lack of bone radiolucency associated with the development of sequestra, and the localization of radiodense bone only intermediate to the tibia and fibula is consistent with myositis ossification, and not with osteomyelitis, which will result in subperiosteal inflammation and subsequent new bone development on a more diffuse scale around the infected site. The complete lack of subperiosteal change to the tibia and fibula away from the ossified region, as well as the initiation of the subperiosteal new bone, from both the tibia and the fibula, to meet intermediately, is consequently not consistent with osteomyelitis. Moreover, chronic osteomyelitis is expected to be associated with some level of continued subperiosteal activity observed as woven bone and, in this case, the bone is entirely lamellar. Evidence of osteomyelitis in the right limb is available for comparison as well as dry bone examples from prehistoric Southeast Asia associated with and without fracture[12,13].

We do concede the error that the medial malleolus of the right tibia is not placed in anatomical position in figure 3a of our original paper[2]. However, the aim of this figure is to represent the general completeness of the skeleton, and the relationship of the size of the left and right limbs, which we believe the figure succeeds in presenting. Given the medial malleolus is barely discernible, we believe the matter of anatomical correctness to be negligible.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-023-05757-7.

Reporting summary

Further information on experimental design is available in the Nature Portfolio Reporting Summary linked to this Article.

Data availability

CT data are available at Figshare (https://figshare.com/projects/CT_Data_Tebo_TB1_Borneo_Kalimantan/150765).

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Competing interests The authors declare no competing interests.

Additional information
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Correspondence and requests for materials should be addressed to Melandri Vlok or Tim Maloney.
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Extended Data Table 1 | Differential Diagnosis of Tebo 1

Diagnosis	Description of pathology	Relative expected frequency	Reasons for exclusion	Probability	Ref.
Fracture with non-union and/or traumatic amputation at distal diaphysis	External forces causing trauma to the left tibia and fibula.	Frequent	Fractures at the location of both distal tibia and fibula are associated with comminution or crushing fractures from: - Animal attack - Rock fall - Fall from height Multiple sites of force; however, the directions of force are not consistent with a comminution or crushing fracture (i.e., margin is clean). Traumatic amputations very rarely lead to fibular amputation except where a metal blade has been involved or in a high impact accident such as in a motor vehicle collision. Pattern of remodeled bone is not consistent with any evidence for osteomyelitis (e.g., lack of clear development of involucrum, cloacae or sequestrum). Such a fracture and removal of limb would likely be associated with a length of time where pathogens could enter the bloodstream. The probability of survival is minimal.	Implausible	14-18
Amputation- Post traumatic pseudoarthrosis or gangrene	Ischemia or gangrene leads to the loss of the foot and distal leg.	Rare	The lack of evidence for infection or severe ischemia rules out gangrene, a common condition in traditional bone setting contexts in the tropics. There are reports of up to 10% mortality when surgical and medical intervention (in hospital mortality) occurs in tropical environments. Examples of gangrenous lower legs in tropic contexts in diabetics indicate a mortality rate of more than 50%. Bone pattern not consistent with atrophic (tapered), hypertrophic (splayed) forms.	Ruled out	9-11,19,20
Amputation- congenital pseudoarthrosis	Congenitally impaired local vascularization	Rare	Congenital pseudoarthrosis of both tibia and fibula is exceedingly rare, and in most cases does not involve a true non-union of the bone; instead, is associated with bowing not observed in TB1. Requires operative treatment.	Ruled out	19,21
Abnormal Congenital limb development	Portion of the distal limb fails to develop embryonically	Rare	Extremely rare. Occurs spontaneously as well as in several genetic conditions. Bone end develops as a closed limb. No evidence for inclining margins as observed in TB1.	Ruled out	22
Amputation- in utero (amniotic band syndrome)	Tissue originating from the fetal membrane ties, constricts and eventually removes the distal limb.	Rare	Results in very clean margins with a single constrictive force on bones rather than multiple directions of force as observed in TB1. Commonly associated with other malformations such as syndactyly, club foot, cleft lip and palate, and anencephaly. Can result in both open and closed soft tissue around the amputation. Usually multiple amputations.	Ruled out	23-25
Amputation- surgical	Surgical removal of the lower limb	Unknown	See original paper[2].	Plausible	26,27

Refs. [14–27]

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