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Knock-Knees: Identifying genu valgum and understanding its relationship to vitamin D deficiency in 18th-19th century northern England

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Running Head:
Knock-Knees: Identifying genu valgum

Abstract:
Genu valgum is a condition in which a person's knees angle inwards and touch one another creating a 'knock-kneed' appearance during life and potentially causing pain and walking difficulties. The most common cause of genu valgum is medial torsion of the proximal tibia, such that the lateral side becomes more weight bearing. It is considered a feature of vitamin D deficiency and many other pathological conditions. Currently, bioarchaeologists lack clear diagnostic criteria to identify genu valgum in skeletal remains and it is therefore likely to be under-reported. The aim of this study was to develop a method for diagnosing genu valgum and apply it to the analysis of adult skeletons from two 18th-19th century skeletal collections from the North of England. Six individuals from Coach Lane and three from Fewston showed evidence of genu valgum. All of these individuals had other skeletal indicators of vitamin D deficiency. We discuss the relationship between vitamin D deficiency and genu valgum alongside other possible etiologies identified in the clinical literature. The individuals who presented with vitamin D deficiency related genu valgum in this study were diagnosed with adolescent rickets. Individuals who were vitamin D deficient in early childhood were more likely to be vitamin D deficient later in life and exhibit more advanced genu valgum. Genu valgum is often overlooked in the paleopathological literature but its presence may be an important indicator of broader health problems.

Key Words:
Residual rickets
Post medieval
Tibial torsion

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1.0 INTRODUCTION:

The diagnostic criteria for identifying vitamin D deficiency in skeletal remains have developed substantially over the last few decades (Brickley et al., 2018; 2010, 2007; 2005; Brickley and Ives, 2008; Mays et al., 2009. Much of this diagnostic work has been conducted on human remains dating from the 18th to 19th centuries in northern Europe, when rickets and osteomalacia were endemic. This research focuses on genu valgum, more frequently referred to as 'knock-knees', which has been associated with vitamin D deficiency during adolescence (Mallet et al. 2004). In the clinical literature genu valgum refers to internal proximal tibial torsion: an inward twisting of the tibia, which leads to in-toeing of the foot (Sass and Hassan, 2003; Staheli, 1994). Genu valgum can also be caused by metatarsus varus (a foot deformity) and increased femoral anteversion (an inward twisting of the femur) (Graham, 2007). The latter form is less common, and this study therefore focuses on proximal tibial torsion only.

There are multiple ways to assess genu valgum within a clinical context, but there is no current method for identifying or measuring genu valgum systematically from the skeleton. The lack of clear guidelines for its diagnosis in dry bone has led to its under-representation within the paleopathological literature. The aim of this study was to establish a method for measuring tibial torsion in skeletal remains. This method was then applied to adult individuals with skeletal indicators of vitamin D deficiency during childhood from two post-medieval skeletal samples from the North of England (Fewston, North Yorkshire and Coach Lane, North Shields).

2.0 BACKGROUND:

2.1 The Tibia:

The knee (patellofemoral) joint is one of the most heavily loaded in the human frame (Reilly and Martens, 1972). In about 95% of adults, the tibia is anatomically naturally twisted; the distal end is laterally rotated with respect to the proximal end (Hutter and Scott, 1949). The normal adult lower leg can exhibit up to 20° of external torsion to allow the feet to lie parallel or turn slightly outwards (Scheuer and Black, 2000). This non-pathological lateral twist is necessary to prevent a pigeon-toed gait (Aiello and Dean, 1990). True pathological torsion is a twisting about the axis of an individual bone (not the entire leg) and should be distinguished from normal twisting (Scheuer and Black, 2000).

2.2 Malalignment of the Knee:

Malalignment of the lower extremity overloads one compartment at the expense of another (D'Lima et al., 2012). Multiple factors such as genetics, age, trauma, obesity, arthritis, and vitamin D deficiency can play a role in knee malalignment (D'Lima et al., 2012; Espandar et al., 2010; Pearce and Cheetham, 2010). There are two main type of malalignment in the lower extremity; the first is genu varum, or 'bow legged' and the second is genu valgum or 'knock-knees' (Figure 1). The knees of a person with genu valgum may still touch while the feet remain apart in a wide-based stance. Genu valgum can be caused by physiological factors, congenital conditions, trauma, joint disease, metabolic and endocrine disorders, infections, and neoplastic disease (Engel and Staheli, 1974; Espandar et al., 2010; Flynn et al., 2015; Fraser et al., 1995; Gettys et al., 2011; Mycoskie, 1981). However, here we focus specifically on its presence in individuals that show other skeletal indicators of vitamin D deficiency during childhood.

In a knee with malalignment, the load-bearing axis line passes lateral or medial to the knee instead of through the midline, resulting in increased forces across the lateral or medial tibiofemoral compartment instead of equal force across both compartments (Sharma, 2007). Genu valgum places abnormal stress on the knee, hip, and ankle, increasing the load (and pressure) of the lateral compartment (Hartigan et al., 2011). As little as 3° to 5° of increased tibial malalignment can induce a 50% increase in transmitted force in the lateral compartment (D'Lima et al., 2012).With an internal knock-knee deformity of about 10°, the force on the lateral side of the joint increases from 400 newtons to about 1200 newtons (Reisse et al., 2015). There is also joint space narrowing between the lateral femoral and tibial condyles. If the condition persists, the individual will have difficulty performing the thrust motion and circumduction necessary to walk correctly as it creates a more medial thrust movement and a gait with shortened steps (Hensinger, 1989).

2.3 Measuring Genu Valgum in Living Populations:

To measure knee angle in living people a vertical axis is used as a reference line from which the anatomical and mechanical axes are determined (Cherian et al., 2014). The mechanical axis is always a straight line which passes through joint centers, connecting the proximal and distal joints; representing the weight bearing line (Hartigan et al., 2011). The anatomical axis is the line that follows the curvature of a bone and passes through the center of the diaphysis from the proximal to the distal end, also known as the mid-diaphyseal line, bisecting the bone (Cherian et al., 2014) (Figure 2).

For the lower extremities the vertical axis extends from the center of the pubic symphysis inferiorly to the floor. The normal mechanical axis of the leg is determined by drawing a line from the center of the femoral head through the medial spine of the tibia, to the center of the talus (Figure 2) (Cherian et al., 2014). The mechanical axis represents the way force is transmitted from the ground and proximally through the knee; running approximately at a 3° slope compared to the vertical axis (Hartigan et al., 2011). Within a clinical setting, the knee angle is measured using these axes (Figure 2).

To measure the tibiofemoral angle, the angle between the anatomical axis of the femur and the anatomical axis of the tibia is measured first, followed by the angle of deviation between the mechanical axis and the anatomical axis (Cherian et al., 2014; Hartigan et al., 2011; Heath and Staheli, 1993). The tibiofemoral angle can be expressed indirectly by measuring the intermalleolar distance first, defined as the distance between the medial malleoli of the distal tibiae while the patient touches their medial femoral condyles together (Baruah et al., 2017). Intercondylar distance is a measurement used to indicate the degree of genu varum; defined as the distance between the medial femoral condyles when medial tibial malleoli are touching (Ganavi, 2016). Measuring techniques include photographic, clinical measurements, radiographic, and CT scanning (Ganavi, 2016). Regardless of the measurement or technique used, knee angles are generally measurable with a precision of only 1° (Oginni et al., 2004). While these measurements can produce an accurate diagnosis of knee malalignment in living people, they cannot be applied to skeletal remains. Here will we explore how such a diagnosis might best be achieved.

2.4 Types of Genu Valgum:

There are two types of genu valgum, physiological and pathological. As a result of normal intra uterine positioning, infants are born with genu varum; this varus neutralizes at 1.5-2 years (Baruah et al., 2017). As this natural physiological change occurs, the knee will undergo a transition from varus to valgus, progressing to knock-knees from 2 years onwards (Baruah et al., 2017; Bohm, 1993). The vast majority of genu valgum cases are physiologic, affecting males and females equally, and tend to resolve spontaneously (Sass and Hassan, 2003) with individuals reaching an adult tibiofemoral angle of 5-7° by the age of 7-8 years (Heath and Staheli, 1993; Salenius and Vankka, 1975; Sass and Hassan, 2003).

Females show a slightly greater degree of valgus by 1°, possibly related to their wider pelvic morphology (Espandar et al., 2010; Oginni et al., 2004). One study found a statistically significant difference in tibiofemoral angles between sexes particularly in adolescent years (at ages 13, 14 and 16 years) (Arazi et al., 2001). Ancestry is also significant in terms of the range of normal variation of the tibiofemoral angle. In a population of modern Nigerian adolescents, normal valgus variations averaged 11.06°-11.20° for males and 11.62°-11.79° for females; females had significantly higher valgus angles than males ($p<.05$) (Tella et al., 2010). In European children this was found to be much lower, at 4.4° for males and 5.5° for females, and similarly in Turkish adolescents, 6.6° for males and 7.5° for females (Arazi et al., 2001; Cahuzac et al., 1995) (see supplementary materials for more information).

2.5 Pathological Genu Valgum:

Individuals with pathological genu valgum have tibiofemoral angles that are outside two standard deviations of the mean (Engel and Staheli, 1974; Heath and Staheli, 1993; Salenius and Vankka, 1975). Pathological genu valgum results from disruptions of the normal metabolic process of bone remodeling, which can result from a number of underlying causes (Table 1). For osteoid to properly mineralize an adequate supply of minerals, normal circulating concentrations of the vitamin D metabolites, and optimal osteoblast function are required (Francis and Selby, 1997). Without these components, instead of a tightly ordered columnar (vertical) arrangement, the cartilage cells become disorganized and horizontally splayed (Brickley and Ives, 2008, p. 90). In this weakened state, bones are increasingly susceptible to mechanical forces, one of the outcomes being pathological genu valgum.

Without medical intervention, the pathological genu varum and valgus deformities acquired in adolescence (13-17 years) do not correct because the tibiofemoral epiphyses have already begun or have finished fusing (Scheuer and Black, 2000). The overall rate of correction for pathological genu valgum even with surgical correction, decreases significantly as children get older, specifically at the age of puberty. Ballal et al. (2010) showed that children under the age of 10 years had a correction rate of 1.4° per month, compared with 0.6° per month for older children ($p = 0.05$).

Previous studies on living populations, using various methods (including CT scanning) have reported pathological tibial torsion between 20° and 40° (Eckhoff et al., 1994; Hutter and Scott, 1949; Jakob et al., 1980). Pathological genu valgum often results in knee pain, osteoarthritis in the lateral compartment, gait problems, and difficulty or inability to straighten the leg (Espandar et al., 2010; Hensinger, 1989; Pearce and Cheetham, 2010). In Karachalios et al. (1994), lateral dislocation or subluxation of the patella was reported in knees with a valgus deformity of 30° or more.

2.6 Vitamin D Deficiency:

Rickets is the chronic deficiency of vitamin D during growth; characterized by an accumulation of unmineralized osteoid and poorly formed bone, resulting in weakening. As a consequence, weight-bearing bones bow anterior- posteriorly or medio-laterally (Brickley and Ives, 2008, p. 92; Pitt, 1995). Like other metabolic conditions, skeletal changes related to childhood vitamin D deficiency manifest in the areas where bone growth is most rapid (Brickley and Ives, 2008, pp. 22–23). The upper limbs are most often subjected to biomechanical stress during the crawling stage of childhood. After the child begins walking the lower limbs are subjected to continuous biomechanical stresses. The knee, as a load bearing joint, can be susceptible to biomechanical damage and any resulting malalignment (Stevens and Viđarsdóttir, 2008).

In rickets, other bones can also deform under the influence of muscular contraction (Mays et al., 2006). The metaphyses of the growing long bones expand and resemble the widened end of a trumpet; this reflects excessive unmineralized cartilage causing an increase in length and width in the growing plates of the bones (Brickley et al., 2005; Mays et al., 2009). In addition to changes in the long bones, there may be nodular prominences in the costochondral areas of the ribs, alterations in pelvic and dental development, and thinning of the cranium (D'Ortenzio et al. 2016; Steinbock, 1976, p. 266). The features of rickets carried into adulthood depend on various factors: survival of the child into adulthood, age at development, healing/remodeling rates, and access to sunlight and proper nutrition during maturation.

2.7 Genu Valgum and Rickets:

Genu valgum can occur in children with rickets as young as 3 or 4 years of age but is most frequently associated with vitamin D deficiency in adolescence (Dick, 1922, pp. 150–152; Mallet et al., 2004). When genu valgum is observed in adults, it is usually an outcome of changes during adolescence (Moncrieff et al., 1973). For the proximal epiphysis of the tibia, fusion is generally completed at 13-17 years in females and 15.5-19.5 years in males (Scheuer and Black, 2000). The distal epiphysis of the tibia fuses later in life, 14.5 years in females and 16.5 years in males, with 100% fusion by 20 years (Scheuer and Black, 2000). Age of fusion might 'capture' defects that occur in adolescent rickets because once the tibia is fully formed, there is no longer the possibility of spontaneous correction or healing.

It has been hypothesized that a high amount of stress or strain on bones already weakened through vitamin D deficiency will further contribute to genu valgum (Chantraine, 1985; Witvrouw et al., 2009). The onset of knock-knees during adolescence was often observed by 19th and early 20th century physicians and was occasionally associated with the occupational demands of factory work (Dick, 1922). More recent studies have found cases of genu valgum amongst adolescents of ethnic minorities with darker skin tones residing in Northern European countries and hence susceptible to vitamin D deficiency (Gettys et al., 2011; Mallet et al., 2004).

Clinically, genu valgum has been noted as an occasional feature of vitamin D deficiency (Holick, 2006; Pearce and Cheetham, 2010). In the paleopathological literature genu valgum has been associated with Vitamin D deficiency, but there has been a lac of clear diagnostic guidelines (including degrees of angulation) for the condition in skeletal remains (Brickley and Ives, 2008, p. 146; Lewis, 2007, p. 142; Ortner, 2003, p. 490; Unnanutana et al., 2011), which likely contributes to its under-recording.

3.0 SKELETAL MATERIAL:

The Coach Lane and Fewston skeletal samples were chosen for an assessment of genu valgum because evidence of vitamin D deficiency had previously been identified and recorded (Gowland et al. 2018, Newman and Gowland 2019). Coach Lane is an 18th-19th century cemetery located in North Shields, Tyne and Wear. A total of 236 individuals were excavated, of which 147 were assessed to be adults (Langthorne, 2012). A previous study found that 44% of the non-adult skeletons (< 20 years) from Coach Lane had some evidence of rickets (Gowland et al., 2018) and this study found 18% (26/143) of adults were recorded with at least one unusually bowed or curved upper or lower long bone. Four adult individuals were not included in the sample for analysis because of poor preservation. Adults from Coach Lane with macroscopic features such as residual bending in the long bones, alteration in the rib angle, lateral straightening of the ribs, kyphosis, and scoliosis, as well as features visible radiograph such as thickening and buttressing of the cortical bone and Harris lines were determined to have residual rickets by the authors. The age and sex of the Coach Lane adults had previously been recorded by the second author following standard criteria (Brooks and Suchey, 1990; Buikstra and Ubelaker, 1994; Lovejoy et al., 1985).

The Fewston site represents the partially excavated churchyard of St. Michael and St. Lawrence, North Yorkshire and yielded 151 individuals. The prevalence of rickets in the non-adults in this sample was similar to Coach Lane (45%). Preservation of the skeletons was mixed, and only 44 of the 97 recovered adults had suitably preserved skeletal elements for inclusion in this study. Caffell and Holst (2010) estimated the age and sex of the Fewston skeletons following the criteria outlined above and of these 6/44 adults had skeletal indicators of residual rickets.

4.0 A NEW METHOD FOR ANALYZING GENU VALGUM:

4.1 Measuring Genu Valgum in Skeletal Remains:

As with living populations, there are multiple ways to assess genu valgum in dry bone. The method described here was developed to assess tibial torsion/genu valgum once the proximal tibia has completed fusion. Since we cannot measure the tibiofemoral angle in dry bone, the angle of torsion of the proximal tibia will establish the degree of genu valgum, similar to the measurement of intermalleolar distance in clinical contexts.

An anterior-posterior view of the proximal end is recommended for evaluating the mechanical axis and angular deformities. This method works best if the talus is present. One must distinguish normal vs pathological torsion using the rotational angle between two units, which is the turning of one bone (the tibia) in relation to another at a joint, like the talus (Scheuer and Black, 2000). In this study, the tibia was placed on its posterior aspect on a flat surface. The distal end was rotated to place it in anatomical position, as it would be when articulated with the talus. This allows any medial rotation of the proximal end to be easily identified. If tibial torsion is present, the lateral epicondyle will be lifted from the flat surface. It is key not to over rotate the distal tibia thus artificially increasing the angle of torsion: correct anatomical position is crucial for this method. If the medial malleolus of the tibia is directly touching the surface it is laying on, then the tibia has been over rotated.

The angle of torsion is best measured using a protractor placed on the table adjacent to the proximal surface of the tibia. The angulation is defined as the distance between the flat surface where the proximal end of the tibia touches the surface most laterally and the most superior projecting edge of the medial articular condyle. When assessing angulation, tibiae without genu valgum may range from 0-11° to allow individual variation. Slight, moderate, and severe genu valgum can be around 12°-20°, 21°-30°, and 31°+ respectively (Figure 3).

Insert Figure 3.

The graded system used here is based on the tibiofemoral angle measurements from populations of European descent (Cahuzac et al., 1995; Heath and Staheli, 1993; Salenius and Vankka, 1975). In the reported studies, individuals over the age of 15 years had a tibiofemoral range of two standard deviations from 0-11°, with 11° being the highest recorded. Thus, 0-11° of tibial torsion was regarded as being within the normal range of variation for Coach Lane and Fewston, while greater than 11° was considered pathological genu valgum. This graded system can be adapted for the particular skeletal sample being analyzed; the definitions of slight, moderate, and severe refer to the Coach Lane and Fewston individuals and provide an example of how the severity of genu valgum might be assessed. To consider what is within the normal range of variation and what should be considered slight, moderate, or severe genu valgum for a population, see the attached supplementary materials for information on ancestry and sex for the population under study.

4.2 Description:

In an individual with genu valgum, the medial articular condyle of the tibia sits more posteriorly, and the lateral condyle sits antero-medially. The weight bearing force is applied to the lateral side; therefore, the knee bends medially, thus changing the position of the medial and lateral condyles. The femoral neck can show signs of torsion as well (Wagner and Barcak, 2012).

The torsion can shift the proximal articular facets and change the positioning of the femoral condyles (Figure 4). The articular surface of the lateral condyle can sit more anteriorly and medially than is usual, crossing into the medial condyle's normal position. Both articulation sites can intersect the intercondylar tubercles, rendering a section of the lateral condyle largely unused. The following section provides the results of the application of this method to assess genu valgum in individuals from both sites with evidence of residual rickets.

5.0 RESULTS:

5.1 Coach Lane:

Of the 26/143 (18.18%) adult individuals in Coach Lane with skeletal signs of vitamin D deficiency, four presented with residual bowing in the upper long bones and 22 presented with residual bowing in the lower long bones. Six of these 26 individuals presented with genu valgum (23.1%) (see Table 2), the other 20 individuals presented with either normal or bowed tibiae (20/26 - 76.9%). All six individuals with genu valgum were estimated to be male or male query. Age ranges included three young middle adults (26-35), one old middle adult (36-45), one mature adult (45+), and one adult (18+). One of the six presented with femoral neck torsion, while the remaining five individuals presented with normal femora. SK78 was the only individual to display residual bending in the upper arms bones as well as lower long bone deformities.

5.2 Fewston:

From the 6/44 (13.6%) individuals in Fewston affected with residual rickets, three presented with genu valgum (see Table 3). SK80 and SK177 showed signs of residual bending in the upper and lower long bones.

5.3 Summary:

Of the nine adults identified with genu valgum from the two sites, four individuals exhibited a slight angulation, two had moderate angulation, and three had severe angulation. Three individuals with residual bending deformities in the upper long bones all showed moderate or severe genu valgum of 30° or more (Coach Lane SK78, 30°; Fewston SK80, 33° and SK177, 43°). This implies that those who suffered from vitamin D deficiency during early childhood (crawling age) were more likely to be vitamin D deficient in late childhood/adolescence and show more advanced skeletal changes later in life. Lastly, the genu valgum measurements at

Fewston (31-43°, n=3) were all in the severe category and higher, compared to the slight and moderate degree of tibial torsion seen at Coach Lane (12-30°, n=6).

6.0 DISCUSSION:

The method presented above provides for the first time a clear technique for identifying and measuring the severity of genu valgum in skeletal remains. This was necessary because existing techniques described in the clinical literature are simply not applicable to the skeleton. The method was applied to two skeletal collections dating from the 18th-19th centuries from the North of England that have previously been identified as having high prevalence rates of Vitamin D deficiency (Gowland et al. 2018; Newman et al. 2019). The prevalence of Vitamin D deficiency in industrialized post-medieval cities from the UK, such as Coach Land and Fewston, is generally high compared with preceding and later periods(Roberts and Cox 2003; Mays et al. 2006).

Potentially, the gait disturbances associated with genu valgum and changes in force distribution between compartments (such as difficulty performing thrust motion and circumduction, medial thrust, shortened steps, and difficulty or inability to straighten the leg) altered the way in which the individuals in both Coach Lane and Fewston were able to perform daily and occupational activities.

In comparison to contemporary sites, such as St. Martin’s in Birmingham (5.11%), Coach Lane’s crude prevalence for vitamin D deficiency is significantly higher (18.18%) (Brickley et al. 2001, 132-133). The latitude of Coach Lane is higher, and the North East was recorded in the 19th century as being a focal point for vitamin D deficiency (Gowland et al. 2018). North Shields was also associated with the coal-mining industry, an occupation that deprived workers of access to the small amounts of sun available. Coal mining during this time was a predominately male job, conceivably a factor in the presence of genu valgum in only males at Coach Lane. Perhaps, the early age at which boys started working in coal mines (and factories) was also a factor. The added stress and strain of working a laborious job likely exacerbated the development of genu valgum during the adolescent growing period and the continued lack of vitamin D prevented adequate remodeling or healing.

At Fewston, both females (2/3) and males (1/3) showed signs of genu valgum. The limited number of individuals with genu valgum at Fewston prevents any further discussion on meaningful differences relating to sex. Interestingly, however, it is hypothesized that some of these individuals may have been factory workers and this is an occupation that has been linked in the historical literature with genu valgum (Gowland et al. 2018).

Following the clinical literature, it seems likely that the individuals with genu valgum in the Coach Lane and Fewston individuals represented those suffering from vitamin D deficiency during adolescence and the pubertal growth spurt. In some, this was a continuation of vitamin D deficiency in earlier childhood. It is evident that many more individuals in our skeletal samples were vitamin D deficient at some stage in their lives and it is important to note that slight pathological genu valgum in childhood can heal prior to epiphyseal fusion should the deficiency abate. Only the severe skeletal features resulting from vitamin D deficiency in childhood will persist into adulthood, specifically residual bending and increased cortical thickness and buttressing (Brickley et al., 2010). By understanding the age at which different skeletal changes indicative of vitamin D deficiency manifest we can glean more information regarding the stage of the life course that this deficiency occurred and its duration. For example, residual bending deformities in the upper long bones suggests early childhood rickets, while genu valgum indicates adolescent vitamin D deficiency. This information may allow interpretations relating to infant and early childhood care, but also later childhood nutrition and activities such as working practices.

7.0 CONCLUSION:

This study focuses on the skeletal trait most commonly associated with genu valgum, proximal tibial torsion. The criteria outlined above for identifying proximal tibial torsion in dry bone is intended to improve the diagnosis of genu valgum in bioarchaeology. The method described here aligns with the clinical literature, which emphasizes the medial torsion of the proximal end of the tibia due to weight bearing forces and insufficient mineralization of osteoid. Any condition which results in weakened bone during the growing years, can result in tibial torsion, thus genu valgum. The most common etiologies are trauma, vitamin D deficiency, and obesity. For this study, the focus was specifically on recording genu valgum in skeletons with evidence of vitamin D deficiency. Given that genu valgum is strongly associated with vitamin D deficiency in adolesences, this information provides additional useful information regarding the age at which a child suffered that may have a bearing on social factors (e.g. in these contexts probable child labor). As with all bioarchaeological analyses, contextual information such as time period, cultural practices, socio-economic factors, and environmental conditions are crucial for supporting etiological interpretations. With more attention given to genu valgum in the future, the prevalence of this condition can be more readily assessed, along with associated disturbances to gait and pathological conditions. Analysis of genu valgum can contribute to our understanding of a myriad of underreported or difficult to identify pathological conditions, increasingly our breath of knowledge of disease in the archaeological record.

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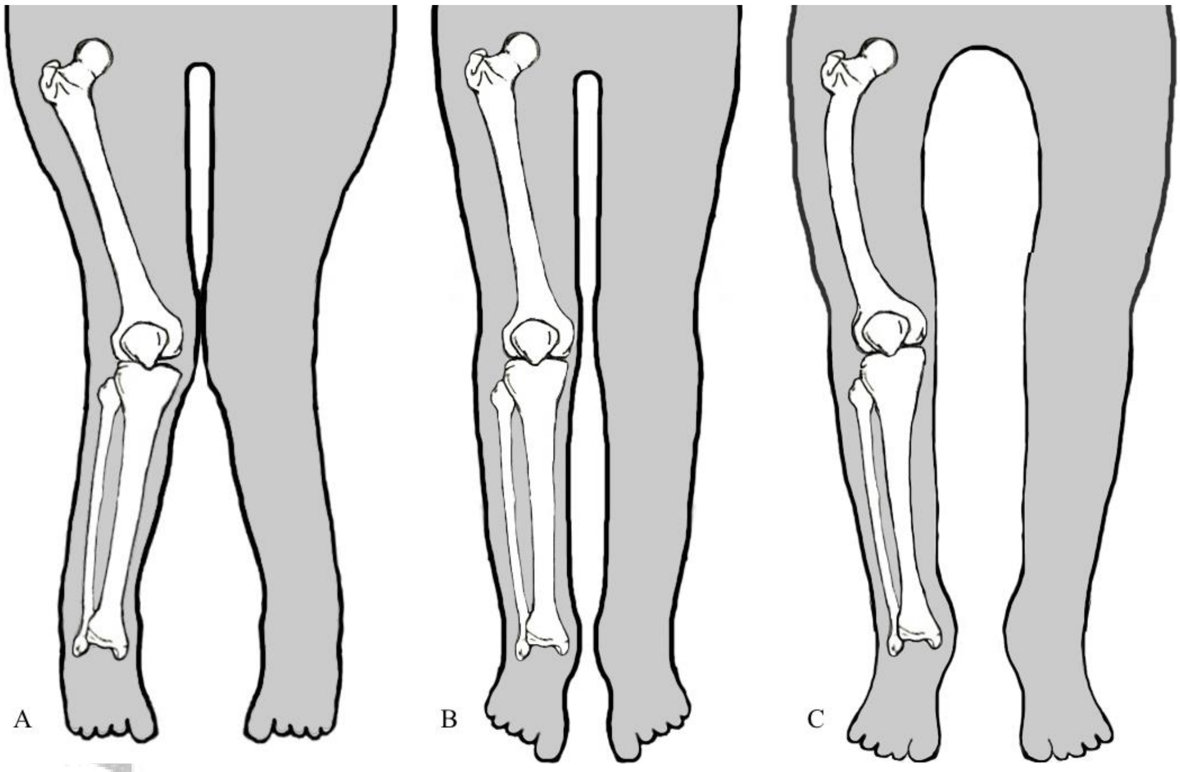


Figure 1. Differences in knee alignment, showing the differences between A) genu valgum (knock-knees), B) normal alignment, and C) genu varum (bow legged, bending deformities) respectively (authors own).

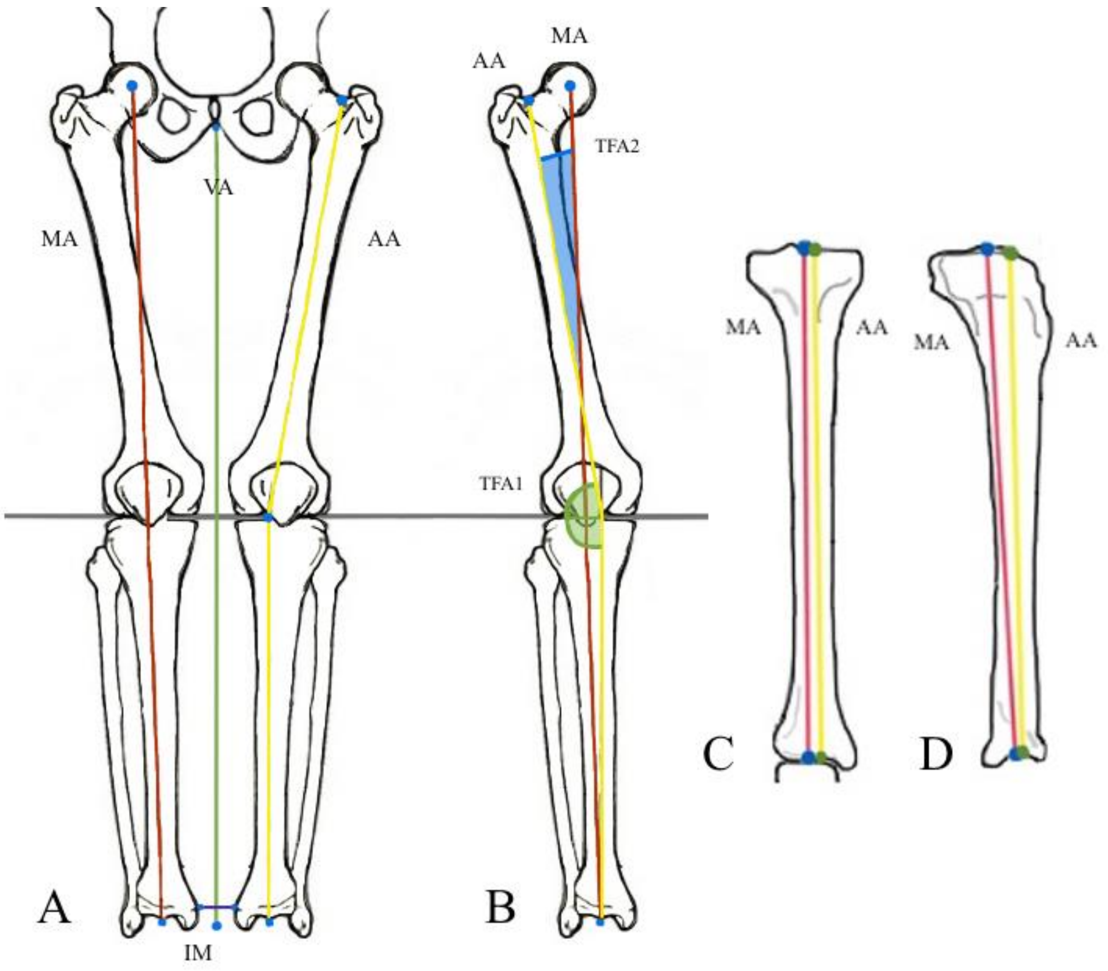


Figure 2.

A. Anterior/posterior. The green line represents the vertical axis (VA). The red line shows the mechanical axis (MA) and the yellow line shows the anatomical axis (AA) (same for B, C, and D). The purple line represents the intermalleolar distance (IM).
B. Anterior/posterior. The green angle represents the tibiofemoral angle as the angle between the anatomical axis of the femur and the anatomical axis of the tibia (TFA1). The blue angle represents the tibiofemoral angle as the deviation of the mechanical axis from the anatomical axis (TFA2).
C. Anterior/posterior view of the R tibia.
D. Medio/lateral view of the R tibia.
(authors own)

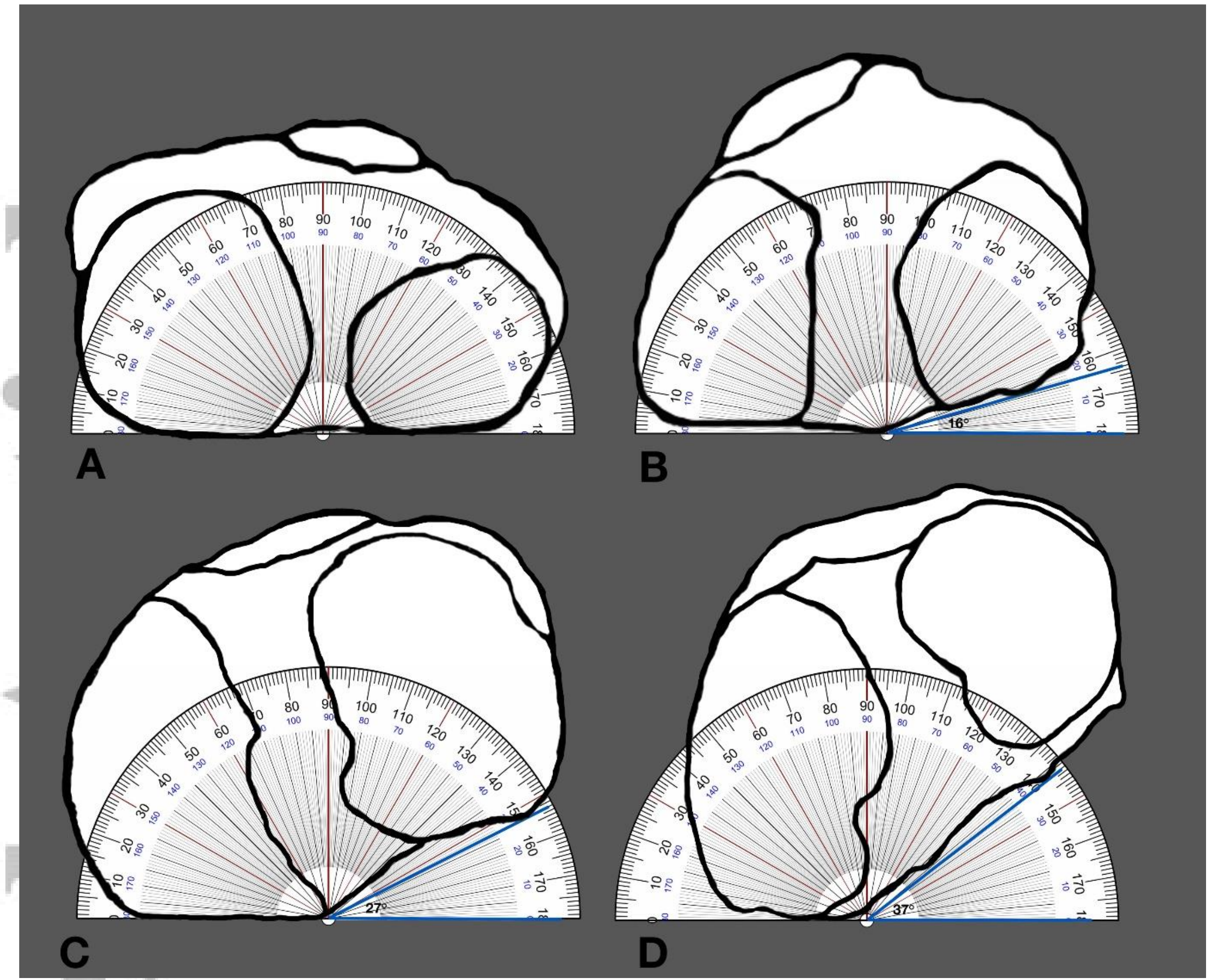


Figure 3. Each of these is a drawing of a right tibia from the Coach Lane or Fewston populations. Image A is of a normal right tibia, there is no angulation of the lateral side. Image B is a case of slight genu valgum, C is moderate and D is severe (authors own).

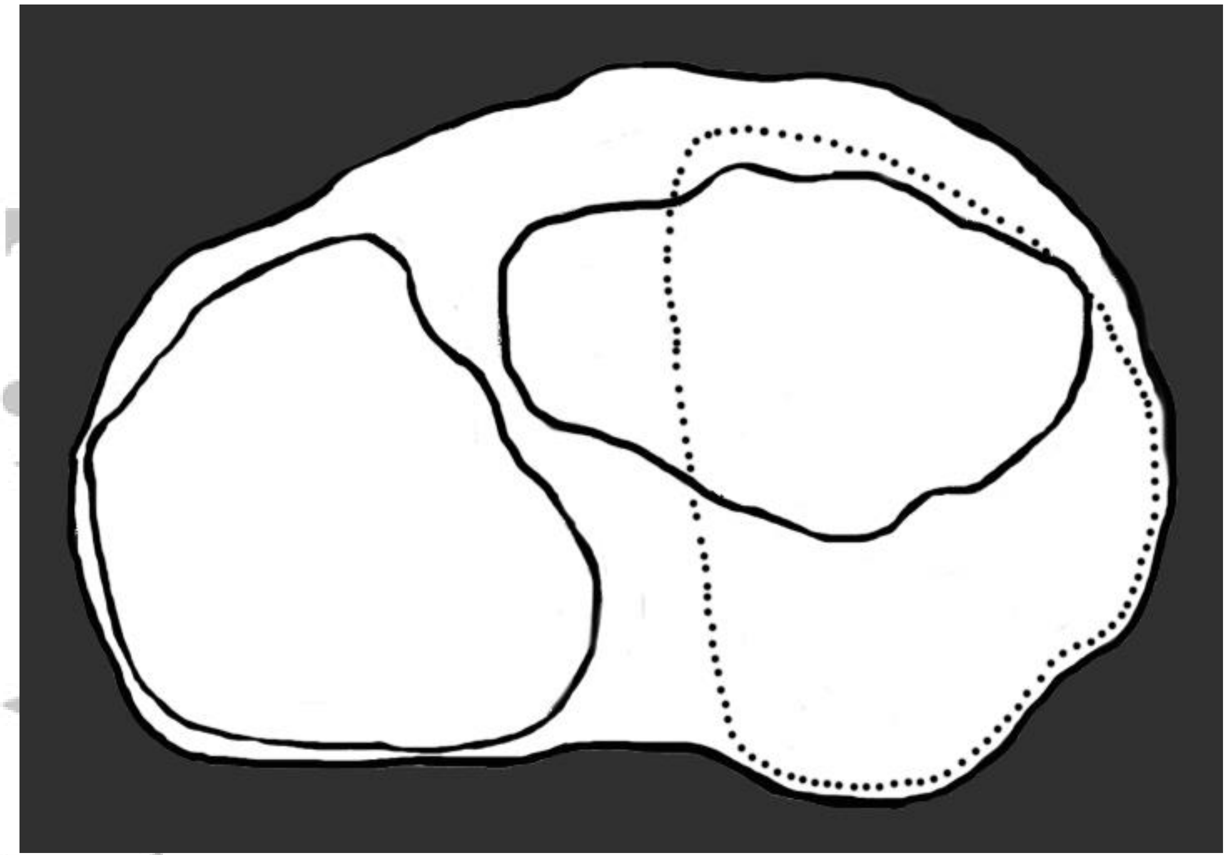
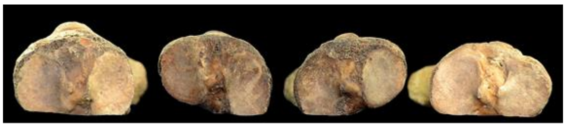


Figure 4. A drawing of the proximal end of a right tibia with a new articular facet on the lateral condyle marked by a solid line. The dotted line is the original lateral articular facet (authors own).

Table 1. Etiologies of Genu Valgum

Causes of genu valgum		Associated Conditions	Source
Bilateral	Physiologic	--	(Engel and Staheli, 1974; Espandar et al., 2010; Heath and Staheli, 1993; Sass and Hassan, 2003).
	Obesity	--	(Arazi et al., 2001; Cahuzac et al., 1995)
	Congenital conditions and skeletal dysplasia	• Chondroectodermal dysplasia • Spondyloepiphyseal dysplasia • Morquio's syndrome • Blount's Disease	(Langenskiöld, 1981; Nunn et al., 2011)
	Metabolic and endocrine disorders	• Juvenile primary hyperparathyroidism • Thalassemia • Homocystinuria- a group of disorders	(Brenton, 1977; Fraser et al., 1995; Galanello and Origa, 2010)
	Infections	• Poliomyelitis	(Joseph and Watts, 2015)
	Juvenile arthritis	--	(Al-Khateeb et al., 2007)
	Other	• Coxa vara • Fluorosis	(Arvind et al., 2012; Ecklund and Jaramillo, 2001)
Unilateral	Trauma	• Physeal injury/fracture • Post-traumatic valgus	(Flynn et al., 2015)
	Benign tumors	• Fibrous dysplasia and osteochondromas	(Peterson, 1989; Zhang et al., 2015)

Table 2. Genu Valgum Coach Lane:

Individual	**Sex**	**Age**	**Genu Valgum** **Slight**	**Moderate**	**Severe**	**Femoral neck torsion present?**	**Residual bending in the long bones present?**
SK145	M?	YMA	12°  NL PL PR NR	-	-	N	Legs: Y Arms: N
SK43	M?	A	16°  PR NR (Left proximal tibia lost PM)	-	-	N	Legs: Y Arms: N
SK115	M?	YMA	17°  NL PL PR NR	-	-	N	Legs: Y Arms: N
SK120	M	MA	17°  NL PL PR NR	-	-	N	Legs: Y Arms: N
SK15	M	YMA	-  NL PL PR NR  NL PL PR NR	27°	-	Y	Legs: Y Arms: N

SK78	M	OMA	- 30° -  NL PL PR NR	N	Legs: Y Arms: Y
Total			6/26 – (23.1%)	1/6	Legs: 6/6 Arms: 1/6

*NL- normal left, PL- pathological left, PR- pathological right, NR- normal right

Table 3. Genu Valgum Fewston:

Individual	**Sex**	**Age**	**Genu Valgum** **Slight** **Moderate** **Severe**	**Femoral neck torsion present?**	**Residual bending in the long bones present?**
SK360	M	MA	- - 31°  PR NR (Left proximal tibia lost PM)	N	Legs: Y Arms: N
SK80	F	OMA	- - 33°  NL PL (Right proximal tibia lost PM)	N	Legs: Y Arms: Y
SK177	F	YMA	- - 43°  NL PL PR NR	N	Legs: Y Arms: Y
Total			3/6 – (50%)	0/3	Legs: 3/3 Arms: 2/3

*NL- normal left, PL- pathological left, PR- pathological right, NR- normal right