Secular evolution of femoral morphology from a clinical perspective

Running headline: Secular evolution of femoral morphology

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Introduction

Intramedullary nailing is the surgical method of choice for the treatment of proximal femur or femoral shaft fractures. Implant manufacturers aim to design implants fitting for the broadest possible population segment. As complete morphological data sets of long bones are not widely available, anatomical collections of historical dry bone specimens may represent abundant additional sources of morphological 3D-data for implant design, provided they are consistent with present populations. This study aims to investigate secular trends and age-related changes of femoral morphology of the Caucasian population over the past 800 years.

Materials and Methods

Computer graphical measurements of 3D-datasets of right and left femora derived from CT scans, representative of the present Caucasian population, were compared to computer graphical measurements of 3D-datasets of right and left femora derived from CT scans of specimens from a historical medieval European bone collection.

Results

Clinically relevant parameters of historical medieval European femora were found mostly consistent with correlative data of the present Caucasian population. Additionally, for some of the evaluated parameters, particularly anteversion, morphological differences significantly correlated to individual age and sex could be identified, whereas other parameters such as caput-collum-diaphyseal (CCD) angle or radius of anterior femoral bowing were not correlated to individual age or sex.

Conclusion

The findings suggest that more recent historical specimen collections may be a convenient and easily accessible source of new 3D morphological data, as well as to complement
existing data, to be used by researchers and manufacturers for the development of intramedullary femoral nails.

**Keywords**

3D models, medieval, femur, anatomy, intramedullary nail, Iceman
INTRODUCTION

Locked intramedullary nailing is the surgical method of choice for the treatment of proximal femur or femoral shaft fractures (Court-Brown et al., 2006; Kuntscher, 2014), which represent a common and significant health problem among older people in the modern world (Johnell and Kanis, 2004), with a well-established increased risk of death after hip fracture (Abrahamsen et al., 2009; Berggren et al., 2016; Kannegaard et al., 2010). Low-energy trauma is the predominant mechanism of injury in older population subgroups, while femur fractures in younger individuals are mostly the result of either high-energy traumata or stress fractures (Court-Brown et al., 2006; Weiss et al., 2009).

Implant manufacturers aim to design implants fitting for the broadest possible population segment, generally attempting to fit at least 50% of a target patient population (Schmutz et al., 2010; Schmutz et al., 2008b). As a consequence the design of intramedullary femoral nails has continuously evolved from a straight model at the time of their introduction in 1940 to the nail design with a radius of curvature (ROC) of 1500–2000 mm for most of the commercially available nails today (Kuntscher, 2014).

Previous studies have evaluated femoral morphology across present populations, ethnicities, and age groups with regard to the clinical relevance of encountered variations, related to intramedullary nail fixation of intertrochanteric fractures (Schmutz et al., 2016; Schmutz et al., 2017; Yuan et al., 2017). Clinically relevant differences in femoral geometry have been reported particularly between Asian and Caucasian populations with imperative implications for more population-specific designs of femoral nail implants; these include overall length, amount of anterior bowing, caput-collum-diaphyseal (CCD) angle and overall morphology of the femoral neck (Hwang et al., 2008; Leung et al., 1996; Pu et al., 2009). Also, a mismatch between the medullary canal and currently available femoral nail implants in respect to age-related differences of the anterior curvature of the femur has been discussed (Collinge and Beltran, 2013). Therefore, there is a substantial clinical interest in acquiring consistent and validated morphological 3D data for the design of femoral nail implants.

However, at present morphological data of long bones, especially such representative of the
younger (< 60 years) living population is not widely available. Although in theory, morphological 3D data from the present living population should be available from clinical imaging data (CT and MRI), there are considerable associated limitations. Plain 2D radiographs (AP pelvis and lateral hip) still constitute the standard in diagnostic imaging of suspected adult hip fractures (Sheehan et al., 2015; Ward et al., 2014). If further diagnostic imaging is required, localized MRI (MRI pelvis and affected hip without contrast) or, as second-line modality, CT (CT pelvis and hips without contrast) are performed, which do not cover the entire femur (Ward et al., 2014). Diagnostic scans of the entire femur are primarily used for surgical planning of complex fractures (Sheehan et al., 2015).

A data source that is gaining popularity, particularly in the field of forensic science, is the growing number of libraries containing post mortem (PM) CT data (Bedford and Oesterhelweg, 2013; Fliss et al., 2019; Okuda et al., 2013; Reynolds et al., 2018). Although the practice of routine forensic PM CT scans is increasing, not all institutions are performing whole-body scans. Some institutions restrict the scan volume to head and/or torso and do not include the extremities, as the latter are not essential for certain PM analyses, and/or in order to reduce scan time, cost and image data size (Grabherr et al., 2017; Juźwik et al., 2019; O'Donnell et al., 2007). Therefore, such data is often not suitable for anatomical studies focusing on intact long bones. In addition, accessing libraries of PM CT data can be restrictive for research projects outside forensic science or not contributing to the coronial process.

For implant design purposes, however, a scan of the entire intact bone is required (Rathnayaka et al., 2012). While MRI has been used as a non-ionizing alternative to CT for this purpose, this approach is severely limited by the high costs and time required for the acquisition and processing of 3D MRI bone data (Rathnayaka et al., 2012; Schmutz et al., 2008a; Van den Broeck et al., 2014). In the past, researchers and manufacturers have, therefore, successfully used bones from various collections of specimens from the 1800s to mid-1900s as an alternative data source for the development of osteosynthesis implants (Goyal et al., 2007; Jantz and Jantz, 1999). Since there are numerous large anatomical
collections of historical and ancient dry bone specimens worldwide (Salceda et al., 2012), such specimen collections may represent a conveniently accessible additional source for morphological 3D-data, provided that the measurements show the necessary consistency with data from the present population. Secular changes, such as the steady increase of average human height throughout the western world since the 19th century (Cole, 2000, 2003; Staub et al., 2016), may, however, have affected relevant morphological aspects of long bones and may, therefore, present a problem in this regard.

This study, referring to one of our earlier publications (Schmutz et al., 2017), aims to investigate secular trends and age-related changes of femoral morphology of the Caucasian population over the past 800 years by comparing computer graphical measurements of available 3D-datasets derived from CT scans representing the present Caucasian population and computer graphical measurements of 3D-datasets derived from CT scans of a historical European medieval bone collection, dated to approximately 1000-1200 AD (Olsen et al., 2016). Additionally, data from a significantly older Caucasian specimen, a natural ice mummy from the Neolithic period, dated to approximately 5250 BP (Bonani et al., 2016), is compared. Should secular changes of femoral morphology over the past 800 years be negligible in respect to the fitting of intramedullary femoral nails, larger and more recent specimen collections (e.g., such as the Hamann-Todd human osteological collection of the Cleveland museum of natural history, dating from 1910-1940 (Mensforth and Latimer, 1989)) may, in fact, be very opportune and conveniently accessible sources for morphological 3D-data, or to complement limited available data, to be used for the future development of orthopedic implants and devices.
MATERIALS AND METHODS

The presented data combines a total of N= 69 measured femora, including a subgroup representative of the present Caucasian population, a subgroup from a historical medieval European bone collection, as well as two additional, significantly older Caucasian specimens and a natural ice mummy from the Neolithic period.

3D Morphologic Bone Data

A total of 47 femora (37 female, 10 male, 29 right, 16 left) were used as a representative sample of the present living Caucasian population of proximal femur or femoral shaft fracture patients (Court-Brown et al., 2006; Kuntscher, 2014). The 3D models reconstructed from postmortem CT data, were available from a previous anatomical study (Schmutz et al., 2017). The CT scans had been obtained from specimens in Switzerland (n = 11) and North America (n = 36). The average age of this cohort was 81 years (± 9 years).

The compared historical medieval specimens are part of a bone collection, excavated from a monasterial cemetery in Dahlheim, Germany. It has been dated to approx. 1000-1200 AD (Olsen et al., 2016). The Dalheim skeletal collection is currently curated at the Institute of Evolutionary Medicine at the University of Zurich, Switzerland. From the collection, a total of 20 entire femora (10 female, 10 male) were suitable for this study. Average estimated age at death of these skeletal remains was 44 years (± 13 years) (Olsen et al., 2016). For further comparison additional measurements of a Neolithic human ice mummy (known as Ötzi or Iceman), dated to 5250 BP from the South Tyrol Museum of Archaeology, Bolzano, Italy, were taken (Bonani et al., 2016; Monge and Ruhli, 2015; Seiler et al., 2013).

CT scan protocols

The medieval femora were scanned with a standard clinical CT scanner (SOMATOM Definition Flash, Siemens Healthineers, Forchheim, Germany). Image data were acquired using the following protocol settings: helical scan, 120 kVp, 1 mm slice thickness, 0.5 mm slice spacing, pixel size 0.3 x 0.3 mm². The CT data of the Iceman’s femur was made
available from a CT scan (SOMATOM Sensation 16, Siemens) taken in 2005 (Pernter et al., 2007). The images were acquired with the following parameters: 120 kVp, 0.75 mm slice thickness, 0.7 mm slice spacing, pixel size 0.71 x 0.71 mm².

3D Model Generation

For all specimens (modern, historical and prehistoric) 3D models representing the outer and inner cortex surfaces of the femur were generated from CT data using a multi-threshold segmentation (Rathnayaka et al., 2011). After segmentation and 3D reconstruction (Amira 5.4, Visage Imaging, Germany), all models (STL-files) were imported into a dedicated reverse engineering software package to take the anatomical measurements (RapidForm 2006, Inus Technology Inc.; Seoul, Korea). To construct the required reference geometries in RapidForm 2006, processing steps and measurements were executed analogously, as described in detail in one of the author’s previous publications (Schmutz et al., 2017). For the readers benefit, a short description of the measurements is provided below.

Measurements of antecurvature

The radius of the 3D canal antecurvature was determined from a best-fit circle to the center points of 20 axial cross-section curves, equally spaced along the diaphysis of the inner bone cortex model (Fig. 1). To determine how close a circle can approximate the antecurvature, the distances between the best-fit circle and an interpolation curve fitted to the 20 canal centers was measured. The corresponding ROC measurements were also obtained from projections of the 3D canal interpolation curve onto the AP and lateral planes, respectively.

Angulation of antecurvature plane relative to neck axis and lateral plane

During fracture treatment surgery, the proximal bone fragment is stabilized by insertion of a screw/blade through the nail into the femoral neck. Therefore, the axial rotation of the nail’s antecurvature plane relative to the axis of its proximal locking element will affect the
congruency between inserted nail design and patient anatomy. For this reason, the angle (\(\alpha\) in Fig. 1) between antecurvature plane and neck axis was measured. Since the antecurvature is seldom aligned with the lateral plane, the angle (\(\beta\) in Fig. 1) formed by the antecurvature and lateral planes was measured.

**Measurements of proximal femur anatomy**

The proximal measurement plane was created from the tangent (Fig. 2) and the center of the femoral head (Fig. 3). The proximal shaft axis was defined as the line of best fit to the centers of the seven most proximal canal cross-section curves (Fig. 1) and projected onto the measurement plane (Fig. 3). The neck axis was defined as the line from the center of the femoral head through the midpoint of the shortest neck distance (Fig. 3).

Definitions of some reference points:

- Point C is the canal center at the diaphyseal proximal end
- Point C', the projection of point C onto the proximal shaft axis, is the start of the proximal lateral nail bend
- Point B' is the projection of Point B (center of lesser trochanter) onto the proximal shaft axis
- Point E, the nail entry point, is defined as the intersection of the line (5° lateral to the proximal shaft axis) from Point C' with the posterior bone surface
- Point D is the canal center at the diaphyseal distal end

The exact position of the greater trochanter's tip could not be identified with enough certitude on some of the historical and prehistoric specimens, due to minor post-mortem damages. Therefore, to avoid artificial disparities of measurements involving the trochanter's tip, measurements E-T und T-PSA were combined to represent the distance entry point to proximal shaft axis (EPSA). All other reference points could be precisely identified on all specimens.
The following linear distance measurements were obtained: EF, FC', B'C', EPSA, C'D (Fig. 3). Nail length was measured as the distance ED. The CCD angle was measured between the neck and proximal shaft axes.

**Measurements of femoral version**

Version was quantified using three slightly different methods:

1. **Version-3D:** In the 3D space, version was quantified as the angle between the neck axis and the AP plane (Fig. 1).

2. **Version-2D:** To obtain version measurements corresponding to those from axial CT data (Koerner et al., 2013) or axial radiographic projections (Reikeras et al., 1982), we measured the angle formed by the neck axis projected onto the axial plane, and the AP plane (Fig. 1).

3. **Version-Physical:** To correspond with measurements taken on physical specimens, or oblique-view photographs of cadaver bones, we measured the angle between the neck axis and a plane fitted to the most posterior aspects of the femur (Hoaglund and Low, 1980; Toogood et al., 2009; Zuber et al., 1988).

Anteversion was recorded as positive values and retroversion as negative values.

**Measurements of femoral length**

Instead of subject height as in our previous study (Schmutz et al., 2017), we have used bone length in our study, since the former was not available for the medieval specimens. The maximal femoral length was measured as the distance from the most distal point on the medial condyle to the most proximal point on the femoral head (measurement technique after Martin) (Martin and Saller, 1957). The physical medieval specimens were measured with an osteometric board. On the 3D models, the measurements were obtained by finding the
distance between two planes orthogonal to the shaft axis vector, with one being fitted to the most distal and the other to the most proximal point on the model.

**Statistical analysis**

The level of statistical significance was set to \( p < 0.05 \) for all tests, which were conducted with standard statistical software (IBM SPSS Statistics 24.0; Chicago, IL, USA). In a first step, descriptive statistics for continuous and categorized data were produced. Due to the limited sample size and debatable normal distribution, conditions for a t-test between modern and medieval datasets were not met. Therefore, the Mann-Whitney U test for independent samples was used to test for significant differences between modern and medieval samples. As we have conducted multiple tests, a Benjamini Hochberg (BH) correction of the obtained p-values was performed in order to control for false positive discoveries (Type 1 errors). A false discovery rate (FDR) of 10% was considered acceptable for our study. The BH method was chosen over a Bonferroni correction, as the latter is known to be highly conservative and increase the probability of producing false negatives (Type 2 errors). In a second step, associations between max bone length, age, sex, body side and all assessed femoral measurements were explored using non-parametric correlation analyses after Spearman (due to a limited sample size and a debatable normal distribution, the conditions for Pearson’s correlation coefficient were not met).
RESULTS

Assessed measurements and parameters of the subgroup representative of the present living Caucasian population were found to be mostly consistent with those of the medieval European subgroup (Table 1). While mean femoral length was nearly identical, modern female (439 ± 23.1 mm) and male (478 ± 17.1 mm) femora were slightly longer compared to medieval (female: 432 ± 24.8 mm, male: 466 ± 32.8 mm). Statistically significant differences between the modern and the medieval subgroup were found for anteversion (two measurement methods), mean distance of shaft curve to fitted circle (on AP plane), max distance of shaft curve to fitted circle (on AP plane) as well as for individual age and sex. Statistically significant differences between the two subgroups could neither be found for any other of the assessed femoral measurements or femoral length or body-side.

Results are presented in Table 2.

Subsequent bivariate (Spearman) correlation analyses showed statistically significant correlation of each of the aforementioned differing parameters anteversion (all three measurement methods), mean distance of shaft curve to fitted circle (on AP plane), maximum distance of shaft curve to fitted circle (on AP plane) as well as for individual age and sex. Due to the significant differences in the medieval and modern subgroups’ individual age and sex, the correlations of age and sex with femoral length were also analyzed, which showed a significant correlation only with sex. Anteversion (all three measurement methods), and mean distance of shaft curve to fitted circle (on AP plane) significantly correlated with individual age. Two anteversion measurements (Angle neck axis and AP plane, angle neck axis projected onto axial plane and AP plane), and 12 distance measurements (distances of shaft curve to fitted circle as well as to circle on lateral plane; distances: EF, FC’, B’C’, C’D, ED, EPSA) showed statistically significant correlation with sex. In addition to the same 12 distance measurements that correlated with sex, maximal femur length also significantly correlated with both the radius of circle fitted to shaft curve in 3D and projected onto the lateral plane, and mean distance of shaft curve to fitted circle (on AP plane). Body-side significantly correlated only with the radius of circle fitted to shaft curve on lateral plane, and
with distance EF. All other measurements did not show any statistically significant correlation with individual femur length, body-side, sex, or age.

Results are presented in **Table 3**.

The femur of the Iceman also lies within the range of the modern and historical subgroups, but in some cases differs by more than one standard deviation from the mean (Table 1).
DISCUSSION

In this study, for the first time, historical and prehistoric specimens were compared with modern bones with regard to the particular requirements for intramedullary nail development. To the best of our knowledge, this is the most comprehensive study of 3D anatomical measurements comparing medieval and modern populations. Intramedullary nails have been used since the 1940s to treat femoral fractures. (Martins et al.) Since then, the nail design has been continuously improved, from the first cephalomedullary nail in 1967 and the first gamma nailing device in 1993, whereby the radius of curvature (ROC) of intramedullary nails has been reduced from an initial 4000 mm to 1500-2000 mm for most commercially available nails today (Wolinsky et al., 2002). Measurements show that a circular arc of constant radius in a single plane can approximate the curvature of the medullary canal since the natural 3D shaft curvature of the medullary canal on average deviates less than 0.5 mm (maximum around 3 mm) (Schmutz et al., 2017). Single bow nails are consequently featured in most of the currently popular implants.

Clinical, computer graphical, and biomechanical studies have shown that the similarity between nail and bone ROC is one of the key factors affecting the anatomical fitting of the implanted nail (Bazylewicz et al., 2013; Collinge and Beltran, 2013; Park et al., 2016; Schmutz et al., 2016; Yuan et al., 2017). A Scottish study (Bruns et al., 2002) reported that femora have become increasingly longer and straighter over the last 600 years (medieval: max length = 43.5 cm, ROC = 119 cm vs modern: max length = 44.8 cm, ROC = 158 cm). In contrast, our findings show close to equal mean values for medieval (max length = 44.9 cm, ROC = 96 cm) and modern (max length = 44.8 cm, ROC = 97 cm) measurements. This might be explained by the significant difference in sex distributions, with significantly more females (n = 37) than males (n = 10) in our modern subgroup. Since females have shorter femora than males on average, and ROC positively correlates with femoral length (Maratt et al., 2014), it is likely that the higher number of females lowered the mean femoral length, and
consequently also the mean ROC of our modern subgroup. The fact that the modern mean femur length of our sample is identical to the modern Scottish study suggests that, due to the positive correlation ($r_s = 0.55, p < 0.001$) of femur length with sex and the unequal ($p = 0.020$) sex distribution, our modern bones were longer on average. Further, our medieval femora were also longer (1.4 cm) on average since their mean length equals that of the modern Scottish study. The Scottish study reported a significantly larger ROC for the modern femora even though their length was not significantly longer than the medieval. Since all their samples originated from the same northeastern Scottish population, the authors of that study concluded that the differences between periods are most likely due to different nutritional or functional demands. In both studies, ROC was determined from an equal number of points ($n = 20$) along the shaft. However, in the Scottish study, the measurements were taken on the exterior anterior bone surface, whereas in our study in the center of the medullary canal, respectively. A study by one of the authors shows that there are significant differences between the canal center and anterior external radii of the shaft, with the external ROC being significantly ($p < 0.0001$) larger (Schmutz and Phan, 2017). This would explain the smaller mean ROC values obtained in our study. While some studies reported increased shaft bowing with age (Karakaş and Harma, 2008; Onoue et al., 1979), our data showed no correlation between age and ROC, or a difference in mean ROC despite the significant age difference between our historical and modern subgroups.

Two of the three mean anteversion measurements of our modern subgroup were significantly smaller than for the medieval subgroup, which is in agreement with published findings (Version-physical: 9.7° for Hammann-Todd Collection, dated early 20th century; 18.3° for Libben Collection, dated ca. 13000 AD) (Moats et al., 2015) attributed the greater anteversion in the Libben population to habitually squatting while at rest. As our medieval femora stem from a monasterial cemetery, a higher than average proportion of individuals likely performed genuflection during their prayer sessions (Müller et al., 2013). Compared with squat, kneeling postures (near full on the left knee, near 90° on the right knee) showed
significantly higher internal rotation of the tibia, with opposite results found for the knee (Pollard et al., 2011). Therefore, it is conceivable that internal rotational forces in the knee and tibia, during extended periods of kneeling, could have contributed to the larger anteversion found in the medieval specimens. The anteversion measurements of our modern femora are in close agreement with published values of Caucasians. Our mean anteversion of 14.5° (Version-2D) closely matches the 14.7° of a comparable CT scan measurement on 508 (mean age 65 years, 240 males) left femora (Dong et al., 2014), while Atkinson (Atkinson et al., 2010) reported lower (males 8°, females 9°) values for the same comparable CT scan measurements on 100 femora (mean age 53 years, 61 males). As age (3 measurements) and sex (2 measurements) significantly correlate with anteversion, the significant differences in their distribution within our two subgroups indicate that they could be confounding factors. While some studies reported no significant age and sex differences in femoral version (Atkinson et al., 2010; Maruyama et al., 2001), a more recent study found significantly larger anteversion in females and a significant decrease with age (Hartel et al., 2016). Therefore, it is uncertain whether secular changes caused a decrease in femoral version over the last 800 years, or whether differences in age and sex distributions also contributed to our findings.

While Moats (2015) reported significantly larger CCD angles for the modern (129.2°) compared to their medieval (122.0°) samples, the angles of our modern (126.0°) femora were considerably lower, but the medieval (123.4°) were similar. Compared to other CCD angles of modern Caucasian, our value is slightly below the 127.7° reported by Dong (2014) but considerably larger than the 121.9° reported by Hartel (Hartel et al., 2016). The finding that the angles in our modern femora were only slightly but non-significantly larger than the medieval, is possibly influenced by the significantly higher age and number of females in our modern sample since the CCD angle decreases with age and is smaller in females compared to males (Hartel et al., 2016). However, sex and age did not correlate with the CCD angle for our data.
The only other significant differences between medieval and modern femora were the mean and maximum distance of the shaft curve to the fitted circle on the AP plane. However, clinically and regarding implant design, the minimal differences (0.1 mm, 0.3 mm) between the mean distances are insignificant.

In our study, we obtained all measurements from the Iceman’s left femur, as the right contained three cylindrical holes midshaft from bone samples taken previously. The maximum length of the Iceman’s left femur (420 mm), measured on the 3D model, was slightly longer than the reported measurement of the right (411 mm) based on CT slices (Ruff et al., 2006). This small difference is likely the result of bilateral asymmetry, which was higher in medieval and pre-industrial populations (Auerbach and Ruff, 2006; Kujanová et al., 2008). The Iceman’s femur is shorter than the mean of our medieval and modern samples, but still within 1 SD of the respective means. He is considered small, even in comparison to European male samples from the Upper Paleolithic period through to the Bronze Age (Ruff et al., 2006). However, his femur shows considerably less bowing (ROC = 1251 mm) than would be expected based on his bone length and stature. This also seems to contradict the observed decrease in anterior femoral bowing from Neanderthals, Upper Paleolithic to archeological, and recent human populations (De Groote, 2011). His femur is also shorter than all our medieval femora with a ROC > 1000 mm. His active lifestyle throughout his life and over rough terrain would be expected to increase AP bending of the lower limb, particularly in the region around the knee (Ruff, 1987). However, Ruff’s (Ruff et al., 2006) finding that this appears to be more expressed in the Iceman’s tibia due to the overriding effect of body shape more proximally might explain his relatively straight femur.

The Iceman’s anteversion (all three measurements) is close to the mean values of our medieval sample but considerably higher than our modern mean. This does not follow the trend of the reported increasing anteversion from Neanderthals to recent populations (De
Groote, 2011). The Iceman’s relatively wide femoral shaft shows evidence of adaptation to relatively high loads in the mediolateral direction and has been attributed to his relatively wide body frame (Ruff et al., 2006). As the Iceman’s body was discovered in the Tyrolean Alps, at an altitude of about 3200 m (Seidler et al., 1992), together with his movements prior to his death (Müller et al., 2013) along with his involvement in transhumance between low and high altitudes (Müller et al., 2003; Oeggl et al., 2007) suggests that he was accustomed to traveling long distances over rough terrain. Walking and stair climbing has shown to create internal rotation moments of the proximal femur shaft of 1.8% and 2.3% BW (Bergmann et al., 2001). Internal moment forces over extended periods might explain his larger anteversion compared to modern femora. They might also have contributed to the Iceman’s strong medial inclination of his femoral antecurvature plane, which is just within the range of our medieval samples, but well outside the range of our modern femora. In contrast, on average, the antecurvature plane inclined laterally in our medieval and modern samples.

The Iceman’s CCD angle (116.8°) is comparable to Neanderthal (118.7°) (De Groote, 2011), but substantially below the mean of our medieval (123.4°) and modern (126.0°) samples, while still within their range. This is in line with the trend of increasing CCD angles since the Neanderthal (De Groote, 2011).

The distance measurements (EF, FC’, B’C’, EPSA) of the Iceman’s proximal femur are slightly lower than the corresponding means but within the range of our medieval and modern sample, respectively.

To the best of our knowledge, we are the first to report measurements of the Iceman’s ROC, inclination of antecurvature plane, anteversion, CCD angle, and proximal femur dimensions related to intramedullary nail design.
Due to the positive secular trend in average human height, we expected to find more significant differences from such an analysis. Considering, that medieval European male height (ca. 169 cm (Rühli et al., 2010)) was close to 10 cm shorter compared to present average male height (Austrian: 179 cm, Swiss: 177 cm (Bundesamt, 2014; OECD, 2009)). Surprisingly, all measurements of the Iceman’s femur were within the range of our modern sample, despite the difference in his level of activity and diet compared to the present population. Taken together, this may imply that even smaller anatomical differences can be expected between late 1800 to early 1900 or present populations.

However, despite being a comprehensive anatomical 3D measurement protocol of the femur utilizing 3D computer graphical methods, our study may have been limited by a small specimen sample size, particularly for the medieval cohort. Also, due to statistically significantly different distributions between our subgroups, age and sex may have contributed to some of our findings as possible confounding factors. Due to the 10% FDR for our BH correction, we are accepting that 0.6 of our six discoveries are false. Further limitations, which cannot be entirely excluded, are taphonomic alterations or deformations of bone morphology.

CONCLUSION

Clinically relevant parameters of historical medieval European femora were found mostly consistent with correlative data of the present Caucasian population. Additionally, for some of the evaluated parameters, particularly anteversion, morphological differences significantly correlated to individual age and sex could be identified, whereas other parameters such as CCD angle or radius of anterior femoral bowing were not correlated to individual age or sex. Measurements assessed in this study do show the necessary consistency with data from the present population. Historical specimen collections may therefore be an opportune and conveniently accessible source for morphological 3D-data, or to complement limited
available data, to be used by researchers and manufacturers for the development of intramedullary nails. Further studies are required to confirm whether this applies to the development of orthopedic implants and devices in general. To further confirm our findings, similar studies ought to be conducted comparing late 1800 to early 1900 and present populations, not only for Caucasians but other ethnicities as well. The comparison of modern human femoral samples with historical and prehistoric samples (medieval to Neolithic) also indicate that trends in the morphological evolution of the medullary cavity - relevant to the design of femoral nails - are less pronounced than expected.

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Figure 1. Left: Model of inner femoral cortex surface with torus ($\varnothing = 10$ mm) generated from best-fit circle to the 20 cross section curve centers. The torus helps illustrating the rotation of the antecurvature plane relative to the femoral anatomy. Right: Angle $\alpha$ is measured between the antecurvature plane and neck axis. Angle $\beta$ measures the tilt of the antecurvature plane relative to the lateral plane (modified after Schmutz et al. 2017).
Figure 2. Definition of the lateral view nail entry point (E) on the surface of the external bone cortex model. The tangent was created from the entry point to the circle of the anterior bow (modified after Schmutz et al. 2017).
Figure 3. Anatomical points and axes on the proximal measurement plane (modified after Schmutz et al. 2017).

Point B' is the projection of Point B (center of lesser trochanter) onto the proximal shaft axis. Point C', the projection of point C onto the proximal shaft axis, is the start of the proximal lateral nail bend.

Point E, the nail entry point, is defined as the intersection of the line (5° lateral to the proximal shaft axis) from Point C' with the posterior bone surface.

Point F is the intersection of the neck axis with the 5° lateral nail barrel axis.

Point H: center of femoral head.

CCD angle, is measured between neck axis (FH) and proximal shaft axis.