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RESEARCH ARTICLE

# *Allen's fossa*—An attempt to dissolve the confusion of different nonmetric variants on the anterior femoral neck

**Andrea Göhring**

Faculty of Biology, Department of Biology I, Anthropology and Human Genomics, Ludwig Maximilian University of Munich, Planegg, Germany

**Correspondence**
Andrea Göhring, Ludwig Maximilian University Munich, Faculty of Biology, Department of Biology I, Anthropology and Human Genomics, Grosshaderner Str. 2, 82152 Planegg-Martinsried, Germany.
Email: andrea.goehring@lrz.uni-muenchen.de

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## Abstract

A comparison of different studies is only possible if the same guidelines are used. However, due to the rather imprecise description of the different nonmetric traits on the anterior femoral neck (i.e., *Allen's fossa*, *femoral plaque*, *Poirier's facet*), it is impossible to compare the results of different authors. This is especially the case for the variant called *Allen's fossa* or *cervical fossa of Allen*, which has severely been mistaken in a lot of previous studies. As a consequence, a clarified and more detailed definition of this variant is required what enables the comparison of the results of different investigators. This study gives a detailed overview on the variety of different terms, which are often used simultaneously. The aim of the study is to develop a clarified definition of the term *Allen's fossa*, including the description of any sex- or age-related differences, based on morphological examinations of archaeological skeletal remains from Karacamirli (Azerbaijan), Unterigling (Germany), and Ur (Iraq). *Allen's fossa* is shown to be usually bilaterally present in individuals of all age classes, including infants and rather old individuals, without any signs of modifications with increasing age. In addition, the variant is present in both sexes with the same manifestation. These findings are in contrast to other studies, what is very likely the result of previously mistaken variants. The study provides a detailed definition of *Allen's fossa* and a clear distinction from other variants at the femoral neck. The presented guidelines will allow a better comparability between different investigators in further studies. Individual differences, including vascular deficits and pathological conditions, can cause a considerable amount of variations in the manifestation of *Allen's fossa*, which is most likely caused by grinding of the zona orbicularis on the femoral neck.

KEYWORDS

*Bertaux' empreinte, cervical fossa of Allen, cribra femoris, eminentia articularis colli femoris, empreinte iliaque, femoral plaque, Poirier's facet*

# 1 | INTRODUCTION

## 1.1 | The non-metric trait called *Allen's fossa*

The femoral non-metric variant called *Allen's fossa* was first described by Allen (1884) as follows: "The neck is marked in front near the articular surface by a faint depression, which is often cribriform in appearance, and may receive the name of the cervical fossa" (Allen, 1884). Since then, a variety of studies was published, which also tried to give an explanation on the way how this *fossa* develops (e.g., Angel, 1964; Kate, 1963; Meyer, 1924, 1934; Odgers, 1931). However, several different names were used, which are sometimes probably identical to the *fossa* as defined by Allen (1884), while some authors clearly mistake the latter variant for other femoral variants (i.e., *Poirier's facet* and *femoral plaque*) leading to confusion. The goal of this study is to dissolve the confusion about the term *Allen's fossa* and develop a new and more precise definition of *Allen's fossa* in order to obtain a better comparison of morphological results of different studies. The following study focuses only on anterior variants of the femoral neck, while posterior facets, for example, the posterior cervical imprint of Walmsley (1915) (*Walmsley's facet*), are not covered in detail.

## 1.2 | Different terms and their definitions

Finnegan and Faust (1974) differentiated three main variants at the anterior side of the femoral neck, namely, *Allen's fossa*, *Poirier's facet*, and (*femoral*) *plaque*. These three variants are located close to each other; however, they can be differentiated as follows:

A. Position (see Figure 1)

While *Allen's fossa* is located "near the anterior superior margin of the femoral neck close to the border of the head" (Finnegan & Faust, 1974), *Poirier's facet* is located at the "articular surface of the femoral head toward the anterior portion of the femoral neck" (Finnegan & Faust, 1974). *Plaque* is located in the same area as *Poirier's facet* and partly also *Allen's fossa* (Finnegan & Faust, 1974). However, *plaque* can also be distinguished according to its appearance (see B).

B. Appearance

Allen (1884) described the *cervical fossa* as "cribriform in appearance". About 1 $cm^2$ of bone (sometimes even more) is eroded exposing the underlying trabeculae, what is a unique identifier for this variant (Finnegan & Faust, 1974; Mann et al., 2016). *Poirier's facet* is smooth; the respective area is only slightly bulged (Finnegan & Faust, 1974). In contrast, *plaque* has the appearance of a fingerprint with a bony rim. *Allen's fossa* can be distinguished from both *Poirier's facet* and *plaque* because the *fossa* is not bordered by a bony rim and the underlying trabeculae are only visible in *Allen's fossa* (Mann et al., 2016).

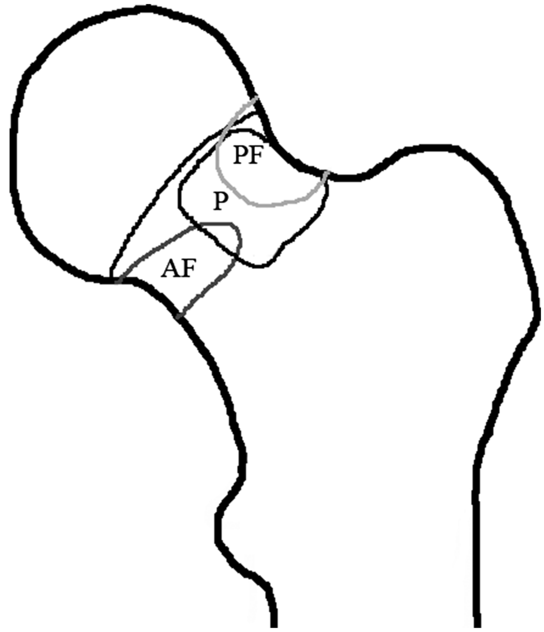


**FIGURE 1** Schematic figure illustrating the approximate position of *Allen's fossa* (AF; dark gray), *Poirier's facet* (PF; light gray), and *femoral plaque* (P; black) on the anterior side of the femoral neck. Note the relative position of the nonmetric variants to the epiphyseal line of the femoral head

C. Expansion (see Figure 1)

*Poirier's facet* and *plaque* can be distinguished from each other with respect to their location. *Poirier's facet* extends the articular surface of the femoral head to a certain degree at the anterior-lateral side (Odgers, 1931; Prescher, 2018). While *Poirier's facet* is a distinct facet next to the femoral head, *plaque* extends from the area of *Poirier's facet* toward the area of *Allen's fossa* on the femoral neck (Finnegan & Faust, 1974).

# 2 | MATERIAL AND METHODS

The morphological results of the examination of archaeological human remain from different localities (Karacamirli [Azerbaijan; Late Bronze Age/Early Iron Age to Middle Ages], Unterigling [Germany; Middle Ages], Ur (Iraq; Ur III to Neo-Babylonian period]) are used to illustrate *Allen's fossa* and distinguish this non-metric variant from, for example, *Poirier's facet* and *plaque*. Because distinct photographs of *Allen's fossa* are rare or other variants are erroneously named *Allen's fossa* (see Section 3.1), different cases of *Allen's fossa* are illustrated indicating the variety of this variant.

The individuals' sex was determined based on multiple criteria of pelvis, skull, and femoral head (see, e.g., Cunningham et al., 2016; Grupe et al., 2015; Herrmann et al., 1990; Schaefer et al., 2009; White & Folkens, 2005). Criteria of the pelvic bones (e.g., arc composé, subpubic concavity, and sulcus praeauricularis) are more meaningful than criteria of both the skull (e.g., *glabella*, *margo* *supraorbitalis*, and *gonion angle*) and the femur (diameter of the caput femoris) due to the functional difference in the pelvis of males and females. Where only skull and/or femur could be determined, individuals were determined as "probably male" and "probably female," respectively. If the number of determinable features was too low or if no feature could be determined, the sex of the respective individual remained undetermined ("nd").

In the case of at least adult individuals, the age at death was determined using the closure of epiphyses and apophyses (Schaefer et al., 2009) and the closure of cranial sutures (Herrmann et al., 1990), the state of the facies symphysialis (Acsádi & Nemeskéri, 1970) and facies auricularis (Buckberry & Chamberlain, 2002), and the dental chart (e.g., intravital tooth loss and abrasion). For non-adult individuals, the age determination was based on epiphyseal and apophyseal closure (Schaefer et al., 2009), the fusion of parts of the skull (e.g., fontanel and mandible), vertebrae, and the pelvis (Herrmann et al., 1990; Schaefer et al., 2009), the tooth development (AlQahtani et al., 2010), and long bone measures (Stloukal & Hanakova, 1978). Six different age classes can be distinguished: Infans I (0–6 years), Infans II (7–12 years), Juvenis (13–19 years), Adultas (20–39 years), Maturitas (40–59 years), and Senilis (60 to *x* years) (see Herrmann et al., 1990).

In the case of Ur (Iraq) and Karacamirli (Azerbaijan), the photographs shown within this study were taken during the field seasons in 2017 (Ur, Karacamirli) and 2019 (Ur). Photographs of the specimens from Unterigling (Germany) were taken at the Biocenter of the Ludwig Maximilian University, Munich (Germany) in 2012. In total 146, 38, and 40 individuals from Ur, Karacamirli, and Unterigling, respectively, were anthropologically investigated of which 37.7% (21 adults and 34 children), 26.3% (7 adults and 3 children), and 97.5% (30 adults and 9 children) allowed the examination of at least one femur.

In order to clarify the misunderstanding of the term of "*Allen's fossa*" an extensive literature review was performed. The published cases of *Allen's fossa* are validated according to both the description of the non-metric variant within the text and the illustrated photographs or sketches. This will help to get an understanding from where the confusion around the variant might have originated.

## 3 | RESULTS

### 3.1 | *Allen's fossa* in contrast to *cribra femoris/femoralis*, *eminentia*, *empreinte/imprint*, *Porier's facet*, and *plaque*—A clarified definition

A detailed literature review on terms used for different variants on the femoral neck is given in Supporting Information S1.

Based on the terminology, at least four different types of non-metric traits have to be distinguished on the anterior aspect of the femoral neck (also see Section 3.1): *Bertaux' empreinte/plaque/Krause's eminentia/Sauser's eminentia*, *fossa*, *Poirier's empreinte/Poirier's facet/Dihlmann's and Frik's eminentia*, and *Odgers's eminentia/Schofield's eminentia*.

It seems logical that an *empreinte* or *imprint* is depressed and thus has to be different from a raised structure called *eminentia* (lat. eminentia = ridge, eminence). The admixture of *empreinte* (or *imprint*) and *eminentia* probably has its roots in the publication by Fick (1904) who explained that Poirier's *empreinte iliaque* (iliac imprint) should be rather named *eminentia articularis colli femoris* (swivel head of the femoral neck) because of the prejudicing assertion of Poirier's terminology (Fick, 1904). However, as mentioned in Supporting Information S1, Fick (1904) described a posterior variant and should not be included here. The *eminentia articularis colli femoris* according to Odgers (1931) and Schofield (1959) is identical to a bony ridge. In contrast, the definition of the *eminentia* after Krause (1909) and the anterior *eminentia* after Sauser (1935) is identical to a *plaque*. Accordingly, although *empreinte/imprint* and *eminentia* actually describe different features, they are used simultaneously when describing a non-metric variant on the femoral neck.

Maybe one of the first authors who described *Poirier's facet* was Henke (1863) who explained that the cartilage of the femoral head often proceeds on the neck leading to a more concave appearance. However, Henke (1863) did not name this variation, which has to be *Poirier's facet*. Actually, it was not Poirier (1896) but Bertaux (1891) who mentioned that the articular cartilage of the femur could proceed and act as osseous reinforcement. Although not definitively described by Bertaux (1891) this is most likely what today is known as *Poirier's facet* (whereby it should have actually named *Bertaux' facet*). As mentioned in Supporting Information S1, Poirier (1896) illustrated a sketch, which could indicate *Poirier's facet*, while he described the *empreinte iliaque* as a rough imprint (*empreinte ruguese*), which does not fit to the smooth appearance of *Poirier's facet*. This is further complicated by Regnault (1898) who distinguished *empreinte iliaque*, the smoothly elongated articular surface, from a roughened surface, which he named *empreinte ruguese* (rough imprint). Although the latter describes a plaque, Regnault's *empreinte iliaque* is different from the *empreinte iliaque* of Bertaux (1891), Poirier (1896), or Mafart (1984), who used this term for a *femoral plaque*. It is obvious that Regnault (1898, 1901) used this term for *Poirier's facet*. Evangli-Tramond (1894) used the term *empreinte iliaque* for both *femoral plaque* and *Poirier's facet*. He described a more or less distinct depression accompanied by a bony ridge, while he also mentioned that the cartilage layer on both the femoral head and neck cannot be distinguished. The first description fits to a *plaque*, while the second description fits to *Poirier's facet*.

In contrast to both *empreinte/imprint* and *eminentia*, a *fossa* is more like a pit, which must, however, not be confused with the so-called *herniation pit* of Pitt et al. (1982) (see Supporting Information S1).

*Cribra femoris* (or *cribra femoralis*) has to be distinguished from *Allen's fossa* as well. According to the definition of Rijpma and Maat (2005), compared to *Allen's fossa*, *cribra femoris* is found in a more caudal position on the femoral neck. However, this is hard to define. It is important to emphasize that *cribra femoris* is not a non-metric trait but a pathological condition. The appearance of *cribra femoris* is similar to *cribra orbitalia* with multiple (very) small porosities (see Figure 2). While *cribra femoris* is found at the same location as *Allen's fossa*, these two features can be distinguished from each other as follows: In the case of *cribra femoris*, the area on the femoral neck is convex without any cortical bone margins visible (Figure 2). This appearance is produced by trabecular bone proliferation. On the other hand, *Allen's fossa* (see, e.g., Figure 3) is present as a concave region with distinct cortical bone margins as a consequence of the friction of the zona orbicularis (J. Austen, personal communication, November 18th, 2019; see also Austen & Lewis, 2018, Austen et al., 2019).

It is necessary to clarify the definitions on three non-metric femoral variants located on the anterior side of the femoral neck, namely *Allen's fossa*, *Poirier's facet*, and *femoral plaque*.

*Allen's fossa* (Figure 3) is documented as present if the underlying trabeculae are visible on the anterior inferior aspect of the femoral neck (see also Figure 1). The area of *Allen's fossa* is mainly almost circular in appearance. In contrast to *Poirier's facet*, *Allen's fossa* is not directly adjacent to the articular surface. Furthermore, it is important to mention that *Allen's fossa* does not show a bony ridge or rim (as in the definition after Mann et al., 2016). This is in contrast to *plaque*. Furthermore, *Allen's fossa* is located inferiorly, while both *Poirier's facet* and *plaque* are (usually) positioned on a more superior aspect of the anterior femoral neck (see Figure 1). In fresh bones, no cartilaginous layer is present in the area of *Allen's fossa*. The variability in the manifestation of *Allen's fossa* is visible in the supporting information figures (Supporting Information S2) and in the literature (see, e.g., Mann & Hunt, 2012; Mann et al., 2016; Pearson & Bell, 1919 [type $\beta_r$]; Sheridan, 2020).

*Poirier's facet* is scored as present if there is a direct contact to the femoral head and if the articular surface of the femoral head is elongated onto the neck in anterior-lateral direction, toward the trochanter major (see Figure 4). In addition, *Poirier's facet* is smooth in appearance (see Figure 4) and always covered by articular cartilage in fresh bones (see images in, e.g., Pearson & Bell, 1919 [type $\alpha$]; Radi et al., 2013; Sheridan, 2020, for variability of this trait). On the other hand, *plaque* is scored as present if a rough region on the femoral neck, in the same area as *Poirier's facet*, partly also in the area of *Allen's fossa*, can be found, which shows a quite elevated bony border and is similar to a fingerprint (see Figure 5; see images in, e.g., Pearson & Bell, 1919 [type $\beta/\gamma$]; Radi et al., 2013; Sheridan, 2020, for variability of this trait). In contrast to *Poirier's facet*, *plaque* is usually covered by parts of the retinacula of the hip joint capsule, while fibrocartilage is rare (Angel, 1964).

A typical case of *Allen's fossa* is illustrated in Figure 6. Cancellous bone is visible in a rather circular area. There might be even other cases where *Allen's fossa* does not show such a clear border (see also Mann et al., 2016). Figure 7 shows a modified *Allen's fossa*; however, this is accompanied with a trauma of the left ligamentum collaterale

**FIGURE 2** *Cribra femoris* on the right femur of a child (modified figure from Lewis, 2018; Copyright Elsevier 2018) [Colour figure can be viewed at wileyonlinelibrary.com]


**FIGURE 3** *Allen's fossa* (see arrows) on the right femur of a probably female individual (≥ adult) from Ur (Iraq). The *fossa* is present at an almost circular area. Note the underlying cancellous bone on the inferior aspect of the femoral neck [Colour figure can be viewed at wileyonlinelibrary.com]


**FIGURE 4** *Poirier's facet* (see arrows) on the right femur of a male individual (≥ adult) from Unterigling (Germany). Note the smooth extension of the articular surface of the femoral head toward the superior aspect of the femoral neck [Colour figure can be viewed at wileyonlinelibrary.com]

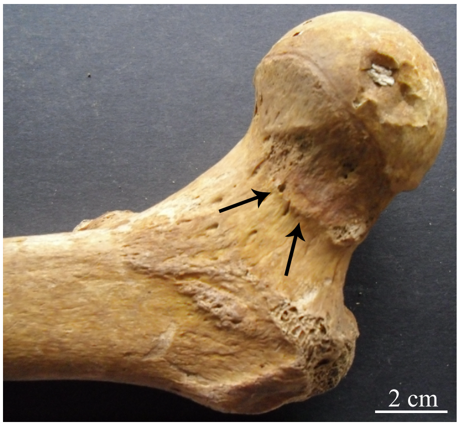


**FIGURE 5** *Plaque* (see arrows) on the left femur of a male individual (30–39 years) from Unterigling (Germany). Note the fingerprint-like imprint on the femoral neck [Colour figure can be viewed at wileyonlinelibrary.com]


**FIGURE 6** *Allen's fossa* (see black arrows) on the left femur of a female individual (23–30 years) from Unterigling (Germany). In this case the *fossa* is present at a broader area compared to the case illustrated by Figure 3 but still does not reach the epiphyseal line (see white arrows) of the femoral head [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 7** Variant of *Allen's fossa* (see arrows) on the left femur of a male individual (50–60 years) from Karacamirli (Azerbaijan) caused by a nonphysiological distress of the leg (Göhring, 2020) [Colour figure can be viewed at wileyonlinelibrary.com]

tibiae and a consequent nonphysiological locomotion (Göhring, 2020). The smoothened and lobulated area is atypical for *Allen's fossa*. In this case, the primary trabecular structure was secondarily grinded due to a nonphysiological posture and motion of the respective individual due to the trauma. Nevertheless, the trabeculae are still partly visible; thus, it can be characterized as a physiologically modified *Allen's fossa*.

Even the variant of *Allen's fossa* illustrated in Figure S1 (Supporting Information S2) is probably caused by a false posture due to an injury of the corresponding (right) tibia. *Allen's fossa* shows a worn appearance, although the trabecular structure is visible (Figure S1; Supporting Information S2). The distal end of the right tibia of this individual (♂, 30–39 years) showed a healed fracture. There might be an interrelationship between the variant of *Allen's fossa* and this injury.

Another variant of *Allen's fossa* is shown in Figure S2 (Supporting Information S2). Even in the case of this femur, the area seems to be grinded. The individual did not show any abnormalities in the hip or leg joints. The variant was rather caused by a ligament defect than by a nonphysiological posture. Another individual also showed a modified *Allen's fossa* in both the right and the left femur. This individual (♂, 20–25 years) suffered from a damage at the lower thoracic and the upper lumbar vertebrae due to physiological distress. This might be in relation to the variant of *Allen's fossa* (Figures S3 and S4; Supporting Information S2).

The mentioned cases illustrate the variability of *Allen's fossa*. In the following, these modified cases of *Allen's fossa* are counted separately ("V").

## 3.2 | *Allen's fossa* with respect to age and sex

*Allen's fossa* is present in infants and elderly individuals (see Table 1). The age at death of the youngest individual of the

**TABLE 1** Overview of the presence of *Allen's fossa* in individuals from Karacamirli (Azerbaijan), Unterigling (Germany), and Ur (Iraq) with respect to both age and sex

| Age class | ♂ | probably ♂ | ♀ | probably ♀ | nd |
|---|---|---|---|---|---|
| Infans I | 2 | 2 | 0 | 0 | 1 |
| Infans I to Infans II | 0 | 0 | 2 | 1 | 1 |
| Infans II | 1 | 2 | 0 | 0 | 1 |
| Infans II to Juvenis | 0 | 0 | 0 | 0 | 1 |
| Juvenis | 0 | 0 | 0 | 1 | 0 |
| Juvenis to Adultas | 0 | 0 | 1 | 0 | 0 |
| Adultas | 2 + V | 0 | 4 | 2 | 0 |
| Maturitas | V | 0 | 1 | 0 | 0 |
| Senilis | V | 0 | 0 | 0 | 0 |
| ≥ Adultas | 0 | 1 | V | 1 | 0 |
| ≥ Maturitas | 1 | 0 | 0 | 0 | 0 |

*Note*: "V" indicates a variant of *Allen's fossa* (see text).
Abbreviation: nd = not determinable.

examined sample exhibiting an *Allen's fossa* was determined as 10 to 12 months (Figure S5; Supporting Information S2). The oldest individual died at an age between 50 and 59 years (Figure S10; Supporting Information S2). There is no overall tendency of increase or decrease in size with increasing age (see Figures 6 and S5–S11; Supporting Information S2). There is quite some variability in size visible. A mature male individual from Ur (Figure S11; Supporting Information S2) and an at least mature male individual from Ur (Figure S11; Supporting Information S2) show a quite small *Allen's fossa*, while it is rather large in a juvenile female from Ur (Figure S7; Supporting Information S2) compared to individuals of similar age (see Figures S8 and S10; Supporting Information S2). Individual differences are probably responsible for this result. Accordingly, an age-related impact on the manifestation of *Allen's fossa* cannot be confirmed.

In addition, *Allen's fossa* is present in both male (e.g., Figures S10 and S11; Supporting Information S2) and female individuals (e.g., Figures 3 and 6 and Table 1). This is also the case for non-adult individuals as shown in Figures S6 and S12 (Supporting Information S2). Thus, the manifestation of *Allen's fossa* does not differ between sexes.

### 3.3 | *Allen's fossa* with respect to siding

Table 2 gives an overview on the bilateral and unilateral presence of *Allen's fossa*. Two individuals under study showed a unilaterally present *Allen's fossa*, which was only found on the left femur, while the right femur did not show any sign of the non-metric trait. This, however, also included a modified *Allen's fossa* (see Figure 7). In some cases, only the right ($n = 10$) or the left ($n = 3$) femur could be examined (Table 2). In the remaining cases of *Allen's fossa*, the variant was present on both femurs ($n = 18$). The unilaterally present variant of *Allen's fossa* in the case of an individual from Karacamirli is most likely caused by a trauma of the left tibiae and consequent unusual locomotion as described above (Section 3.2; see also Göhring, 2020). However, the unilateral variant in a child from Ur (Figure S12; Supporting Information S2) did not have any obvious pathological cause. Accordingly, *Allen's fossa* is usually bilaterally present. However, in some cases (maybe in combination with a pathology and/or a false posture), it might occur only unilaterally. If present on both sides, the size of *Allen's fossa* is comparable on both bones.

## 4 | DISCUSSION

### 4.1 | Distinction of *Allen's fossa* from other variants and pathologies

*Allen's fossa* has to be clearly distinguished from a variety of other variants and also pathologies. *Plaque*, also termed *Bertaux' empreinte iliaque*, *Odgers's/Schofield's eminentia* (*articularis colli femoris*), or *iliac imprint*, can be described as a thumbprint on the femoral neck, usually associated with a bony ridge around this area. *Poirier's facet* is the extension of the articular surface of the femoral head toward the neck. This might be similar (but not identical) to a so-called Cam-type deformity where the femoral head loses its sphericity (see, e.g., Zurmühle et al., 2017). Both *herniation pit* and *cribra femoris*/*femoralis* are pathologic conditions. *Herniation pits* are (subcortical) fibrocystic lesions (Kim et al., 2011; Kusma et al., 2009; Pitt et al., 1982; Zurmühle et al., 2017). They are only visible through X-ray analysis. *Cribra femoris*, on the other hand, looks similar to *Allen's fossa*; however, it is convex while *Allen's fossa* is concave (J. Austen, personal communication).

The described differences between *Allen's fossa* and all other variants/pathologies (see Section 3.1 and Supporting Information S1) confirm that *Allen's fossa* should not be admixed with these other terms. Although all these features are located in a similar area (Angel's reactive area), they clearly differ from each other.

Accordingly, three variants (*Allen's fossa*, *plaque*, and *Poirier's facet*) and two pathologies (*cribra femoris* and *herniation pit*) on the femoral neck have to be distinguished.

It has to be kept in mind that the manifestation of *Allen's fossa* (as well as e.g., *Poirier's facet* or *plaque*) can be quite variable (see, e.g., images in Supporting Information S2). Thus, the appearance of *Allen's fossa* in different individuals can be quite divers. However, in all cases, the underlying trabeculae are visible on the anterior inferior aspect of the femoral neck.

Due to the admixture of the different features (see Section 3.1 and Supporting Information S1), the description of the prevalence, side differences, and sex or age distribution of *Allen's fossa* as described in several publications cannot be used as a reference in the present study.

### 4.2 | *Allen's fossa* with respect to age and sex

Several publications mention both age- and sex-specific manifestations of *Allen's fossa*. According to Meyer (1924), the *fossa* is not

**TABLE 2** Overview of unilaterally or bilaterally present *Allen's fossa* in individuals from Karacamirli (Azerbaijan), Unterigling (Germany), and Ur (Iraq)

| | | Unilateral | | ? | |
|---|---|---|---|---|---|
| Site | Bilateral | Right | Left | Right (left nd) | Left (right nd) |
| Karacamirli (Azerbaijan) | 0 | 0 | V | 0 | 0 |
| Unterigling (Germany) | 11 + V | 0 | 0 | V + V | 0 |
| Ur (Iraq) | 6 | 0 | 1 | 8 | 3 |

*Note*: "V" indicates a variant of *Allen's fossa* (see text).
Abbreviation: nd = not determinable.

present in individuals younger than about 30 years. Odgers (1931) noticed an age-related trend with a deeper *fossa* in older individuals. This is also in agreement to the findings of Kostick (1963), who realized the *teenage imprint* (type B) only in young individuals (14–22 years), and the findings of Mann et al. (2016), who mentioned that cribriform defects are more often found in subadult individuals. According to Anderson (1964), all young femora show an uncovered trabecular bone. With age, the area becomes ulcer like, while some adults still show *Allen's fossa*. Angel (1959) also described the variant in children. About 50% of the children in his study were affected (Angel, 1959). Finnegan (1978) found a correlation with age when investigating different age groups (20–29 years vs. 60–69 years) for some, but not all, of the analyzed populations. Saunders (1978) and Verna et al. (2014) detected a (significant) decrease in the frequency of *Allen's fossa* with increasing age, while the variant was frequently present in young children and adolescent individuals.

In this study *Allen's fossa* is present in individuals of all different age classes (see Section 3.2). Consequently, an age-related aspect of *Allen's fossa* cannot be seen. Even young children can show a marked *Allen's fossa* (see, e.g., Figure S6; Supporting Information S2). On the other hand, older individuals do not necessarily exhibit a more pronounced *fossa* (see, e.g., Figure S11; Supporting Information S2). This result is in contrast to the majority of publications, which, however, not all described *Allen's fossa* correctly (Anderson, 1964, Kostick, 1963, Meyer, 1924, 1934, Odgers, 1931, Verna et al., 2014; see Supporting Information S1). The age differences found by Finnegan (1978) and Saunders (1978) could be the result of population-specific trends (see, i.e., Finnegan, 1978). The way of development might play a role here (see Section 4.4) and population-specific activity trends could lead to such differences across populations.

With respect to sex, *Allen's fossa* is thought to be more often found in males than in females (Odgers, 1931; Saunders, 1978). In contrast, a sex-related occurrence of the variant was not observed by Angel (1959) and Finnegan (1978). The latter is in agreement with the present results. According to the results of this study, *Allen's fossa* is present in both sexes in a similar frequency with 10 (plus three variants) male or probably male cases and 13 (plus one variant) female or probably female cases (see Table 1). This is, however, only based on a quite small sample size and can only be understood as a tendency. Moreover, in the present study, *Allen's fossa* is not more pronounced in males compared to females. Actually, one of the most prominent cases of *Allen's fossa* is observed in a female (see Figure 6). Besides the fact that Odgers (1931) did not describe *Allen's fossa* (see Section 3.1 and Supporting Information S1), population-specific trends are conceivable here.

## 4.3 | *Allen's fossa* with respect to siding

If *Allen's fossa* is present, this is usually the case for both femora. This is also in agreement with the results of Finnegan (1978), Saunders (1978), Goldstein et al. (1980), and Sheridan (2020). According to Schofield (1959) and Kate (1963), who, however, did not define *Allen's fossa* correctly, the variant was more frequent on the left side. In this study, only two individuals form an exception with the unilateral presence of *Allen's fossa*. In one case, the respective individual showed a trauma of the left ligamentum collaterale tibiae, leading to an unusual locomotion (see Section 3.3). In the other case, no pathological cause was obvious on the skeleton of the affected child (see Section 3.3). As a consequence, *Allen's fossa* can be understood as a bilateral variant in the majority of cases, while it might be unilaterally present as an exception. Nevertheless, it is important to mention that several cases of *Allen's fossa* were determined on one femur only, while the associated other femur was missing or could not be determined (see Table 2). Hence, the unilateral presence of the variant might have been more frequent than observed. More case reports are needed in order to investigate this in more details.

## 4.4 | Possible ways of development of *Allen's fossa*

Allen (1884) did not give any potential explanation for the way of development of the *fossa* he described. A variety of different explanatory approaches for the development of *Allen's fossa* has been presented by several authors, who, however, actually did not describe *Allen's fossa* but something different (i.e., *Poirier's facet* and *plaque*). Thus, the explanations given by Meyer (1924, 1934) (development during sleep in lateral position with bent extremities), Pearson and Bell (1919) (development during sleep in lateral position with stretched extremities), Odgers (1931) (development due to medial rotation with extreme bending, contact with the margin of the acetabulum), Kate (1963) (caused by ligament of rectus femoris in upright position), Kostick (1963) (development by stretching [walking and standing] and bending [squatting] of the hip joint), Poirier (1896) (development by frequent sitting or squatting), Djuric et al. (2008) and Smith-Guzmán (2015) (development of cortical defects due to hematopoietic processes related to anemia), and Villotte and Knüsel (2009) (occupational stress marker related to subcortical herniation pit) cannot be seen as valid causes for the development of *Allen's fossa* but describe potential ways how *cribra femoris*, *Poirier's facet*, or *plaque* develop. As the present study focuses on *Allen's fossa*, the above mentioned explanations are not discussed in more detail here.

According to Angel (1964), the only direct causative agent for the development of *Allen's fossa* is the hip joint capsule. The anterior capsule of the hip consists of strong and dense fibers connecting the margins of the acetabulum with the proximal femur (Wagner et al., 2012). The longitudinal fibers of the capsule are relaxed during flexion of the hip, however twisted and lax during full stretching. This leads to a restricted movement within the acetabulum (Harty, 1984). The tissue is anteriorly reinforced by the iliofemoral and the pubofemoral ligament and posteriorly by the ischiofemoral ligament (Burkhart et al., 2020; Harty, 1984; Wagner et al., 2012). While the iliofemoral ligament reinforces the external rotation, the ischiofemoral ligament reinforces internal rotation. The pubofemoral ligament reinforces internal rotation, abduction, and flexion (see, e.g., Wagner et al., 2012). In addition, the circular zona orbicularis (annular ligament) serves as a biomechanical locking ring around the femoral neck responsible for the stability of the hip (Ito et al., 2009; Prescher, 2018; Wagner et al., 2012). Accordingly, under normal physiological conditions, the femoral neck is covered by several layers of ligaments and muscle fibers. No direct contact between the femoral neck and the acetabulum is possible in any posture of the hip joint. Thus, *Allen's fossa* has to be caused by reactions between the femoral neck and a ligament.

A "reactive area" is found directly below a concentration of fibers of the zona orbicularis. In this area, the zona orbicularis crosses the iliofemoral ligament (Angel, 1964). Mann et al. (2016) mentioned biomechanical stress and activity as potential causes of *Allen's fossa*. A vascular deficit (Mann et al., 2016) could then lead to *Allen's fossa* in a certain proportion of individuals.

During vigorous walking, the hip joint is fully stretched—up to 10–15° above the position while standing upright. When walking or running down a hill, the hip joint is strongly extended with slight abduction. In this position, the zona orbicularis is tightly wound around the femoral neck and tightly adjacent to the two parts of the ligamentum iliofemorale (Angel, 1964). In theory, musculus iliopsoas, musculus gluteus maximus, and other flexors of the hip joint should contract in order to stop the movement before the point of maximum flexion of the hip is attained. However, individual variation occurs in the reciprocal innervations mechanism and the control by basal ganglia and cerebellum. Lacking muscle strength could also be a factor here. The zona orbicularis is wound around the femoral neck at the crossover point of the upper branch of the ligamentum iliofemorale. The zona splits into two branches. One branch is wound around the neck of the femur. However, the other branch follows the lower branch of the ligament and reaches the distal part of the femur. If the hip joint is fully stretched, the distal branch of the zona orbicularis is wound around the femoral neck and prevents the extension of the femur (together with the ligamentum iliofemorale). The intersection of zona and ligament is in the area of the femoral neck. Here, the highest pressure is expected. Accordingly, *Allen's fossa* develops in this area. However, the intersection is variable to some extent because the zona can dissociate from the ligament, can run below the ligament, or twine with the latter. This causes *fossae* of variable size. During growth, the zona may improperly cross the iliofemoral ligament, what can be the primary cause of a beginning localized atrophy in the reactive area. With increasing age, this can develop to a *plaque*. If the iliopsoas muscle causes a pressure to the border of the pelvis and the femoral in order to stop the stretching, this can result in a *Poirier's facet* (Angel, 1964).

According to Meyer (1934), the zona orbicularis would not be able to cause such an abrasion. The zona would rip rather than having an effect on the bone (Meyer, 1934). It is conceivable that the zona rips if a bony ridge was additionally present on the neck where the zona would have to slide. However, no ridge was detected on the examined bones. Moreover, from an evolutionary point of view, the construction of a tendon or a muscle strand which rips during grinding movements would be unreasonable. In addition, affected individuals also most likely have a vascular deficit (Mann et al., 2016), what could promote the development of *Allen's fossa*.

Accordingly, the bony reaction leading to, for example, *Allen's fossa* is the result of dynamic factors such as the interaction between zona orbicularis and muscles of the hip (Angel, 1964), for example, the psoas muscle (Mann & Hunt, 2012). This dynamic way of development can also explain the modified cases of *Allen's fossa* as described before (Section 3.1). The smoothened and lobulated appearance as illustrated by, for example, Figure 7 is indicative of grinding of a certain anatomical structure on the femoral neck. This is most likely the zona orbicularis. Individual responses on the same grinding strength of the zona orbicularis are certainly possible and may result in *Allen's fossa* in one individual, while no *fossa* results in another individual. Moreover, different pathological conditions will result in varying modifications of an already present *Allen's fossa* and the development of a huge variability of manifestations of this non-metric trait. A vascular deficit (Mann et al., 2016) can cause a prevalence in some individuals, a pathological condition (e.g., trauma and false posture) can cause a modified form of *Allen's fossa*.

## 5 | CONCLUSION

A variety of terms (*Bertaux' empreinte iliaque*, *cribra femoris/femoralis*, *eminentia articularis colli femoris*, *Poirier's empreinte iliaque*, and *iliac imprint*) are used simultaneously by some authors and however clearly describe other variants (see Section 3.1 and Supporting Information S1). This has to be kept in mind when investigating the results of previous studies.

However, it is important to additionally emphasize that the terms *cribra femoris* (*femoral cribra*, *cribra femoralis*) and *Allen's fossa*, which are synonymously used by several authors, do not describe the same feature. While the presence of *cribra femoris* is a pathological condition probably related to anemia (e.g., Djuric et al., 2008; Lewis, 2018; Smith-Guzmán, 2015) or—even partly connected to that—related to diseases such as tuberculosis (e.g., Blondiaux et al., 2015) or malaria (e.g., Djuric et al., 2008), *Allen's fossa* is a non-metric trait and thus per definition not a pathological condition.

The clarified definition of *Allen's fossa* given in the present study allows a more consistent morphological investigation of variants at the (anterior) femoral neck. In addition, the results of this study demonstrate that *Allen's fossa* is neither age nor sex related, what is in contrast to the results of other authors who have, however, partly mistaken the non-metric trait by mixing it up with other femoral variants (i.e., *Poirier's facet* and *plaque*). Furthermore, *Allen's fossa* is bilaterally present in the majority of cases, while unilateral presence is only exceptional.

Finally, *Allen's fossa* is most likely caused by biomechanical stress and activity, by grinding of the zona orbicularis, and the hip muscles, that is, the psoas muscles (Angel, 1964; Mann et al., 2016; Mann & Hunt, 2012).

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## CONFLICTS OF INTEREST

None.

## ORCID

*Andrea Göhring* https://orcid.org/0000-0002-5117-1948

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## SUPPORTING INFORMATION

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