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Did Early Pleistocene hominins control hammer strike angles when making stone tools?

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ABSTRACT

In the study of Early Pleistocene stone artifacts, researchers have made considerable progress in reconstructing the technical decisions of hominins by examining various aspects of lithic technology, such as reduction sequences, hammer selection, platform preparation, core management, and raw material selection. By comparison, our understanding of the ways in which Early Pleistocene hominins controlled the delivery and application of percussive force during flaking remains limited. In this study, we focus on a key aspect of force delivery in stone knapping, namely the hammerstone striking angle (or the angle of blow), which has been shown to play a significant role in determining the knapping outcome. Using a dataset consists of 12 Early Pleistocene flake assemblages dated from 1.95 Ma to 1.4 Ma, we examined temporal patterns of the hammer striking angle by quantifying the bulb angle, a property of the flake's Hertzian cone that reflects the hammer striking angle used in flake production. We further included a Middle Paleolithic flake assemblage as a point of comparison from a later time period. In the Early Pleistocene dataset, we observed an increased association between the bulb angle and other flake variables related to flake size over time, a pattern similarly found in the Middle Paleolithic assemblage. These findings suggest that, towards the Oldowan–Acheulean transition, hominins began to systematically adjust the hammer striking angle in accordance with platform variables to detach flakes of different sizes more effectively, implying the development of a more comprehensive understanding of the role of the angle of blow in flake formation by ~1.5 Ma.

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1. Introduction

The skills and knowledge that early stone knappers possessed to produce sharp-edged stone flakes is one of the most pressing queries to address for understanding behavioral and cognitive developments in human evolution. At the heart of this is the notion of control—how did early humans control the knapping process to produce the desired outcomes, and how did their knapping capabilities change over the course of human evolution? To answer these questions, researchers have focused on characterizing the technical decisions of past tool production by reconstructing the stone reduction process and sequence that hominins used to produce flakes (Delagnes and Roche, 2005; Braun et al., 2008c). In Early Pleistocene archaeology, the application of this approach, mostly through artifact analysis (e.g., flake scar direction, refitting elements, etc.) and replicative experiments, has yielded substantial insight into various aspects of early hominin technological behavior (Delagnes and Roche, 2005; Harmand, 2007; Braun et al., 2008c; Sharon, 2009; Stout et al., 2009, 2010; Nonaka et al., 2010; Toth and Schick, 2018, 2019), including the identification of reduction trends and technical rules in the production of Oldowan and Acheulean tools (Newcomer, 1971; Toth, 1982, 1985; Bradley and Sampson, 1986; de la Torre, 2004; Delagnes and Roche, 2005; Stout et al.,

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2005, 2009, 2010; Harmand, 2007; Braun et al., 2008a, 2009; Goldman-Neuman and Hovers, 2009; Sharon, 2009; de la Torre et al., 2012; Reti, 2016; Shipton, 2016, 2018; Toth and Schick, 2019).

However, to fully comprehend hominin flaking behavior, it is necessary to also reconstruct the flaking techniques and gestures applied by past toolmakers, including the various ways that force or load were applied for flake production. The importance of percussive force delivery for successful flake removals has been repeatedly demonstrated in modern knapping experiments, where the flaking result is strongly influenced by factors such as the trajectory of the arm swing, the placement and support of the core, and the angle at which the hammer contacts the core (Biryukova et al., 2005; Biryukova and Bril, 2008; Bril et al., 2010; Nonaka et al., 2010; Vernooij et al., 2012; Rein et al., 2013; Cueva-Temprana et al., 2019; Williams-Hatala et al., 2021). These findings also highlight force delivery and associated gestures and manual techniques as important elements in learning stone knapping skills. Moreover, how past hominins applied percussive force would have been constrained biomechanically by the hand and wrist morphology. These are features that may have varied among hominin species over time (Susman, 1998; Biryukova et al., 2000; Tocheri et al., 2005, 2007; Bril et al., 2010; Williams et al., 2010, 2012; Marzke, 2013; Williams-Hatala et al., 2021). As such, identifying force delivery techniques in Early Pleistocene stone tool production is key to understanding not only the level of skill and control that the hominin toolmakers had over the knapping process but also the connection between early stone tool manufacture and hominin biomechanical evolution.

A central aspect of force delivery in flaking is the hammer strike angle, or the angle of blow. Here, the angle of blow refers to the angle between the hammer strike and the perpendicular of the core platform (Fig. 1). Modern knappers generally adjust the angle of blow by tilting the core platform in relation to the direction of their hammer strike (Whittaker, 1994, 95). The control of the angle of blow is often considered implicit knowledge of flaking mechanics that is shared among knappers. Modern knappers have observed that changing the angle of blow can substantially alter the flaking outcome and are known to adjust it to suit different knapping conditions and goals (Crabtree, 1968; 1975; Johnson, 1975; Ranere and Browman, 1978; Callahan, 1985; Sollberger, 1986; Whittaker, 1994; Geribàs et al., 2010). For instance, Boëda (1993) postulated that in classic Levallois flake removal an axis of percussion perpendicular to the striking platform is more desirable as it could potentially guarantee that the flake fracture travels parallel to the plane of intersection between the two hemispheric surfaces of the core. However, striking a hammer perpendicularly straight into the platform carries the risk of crushing the platform or generating step fractures. On the other hand, tilting the core to strike obliquely generates an outward force that could facilitate flake removal and increase the possibility of a feathered termination (Crabtree, 1966; Callahan, 1984; Cotterell and Kamminga, 1987; Whittaker, 1994; Fischer-Cripps, 2007). An acute or oblique angle of blow has been found to be preferred for making Oldowan types such as choppers or chopping tools and for making Acheulean handaxes (Cueva-Temprana et al., 2019). This type of flaking is also associated with blade production technologies and/or soft hammer percussion in the Late Pleistocene (Crabtree, 1972; Newcomer, 1975; Clark, 2012).

Altering the angle of blow has also been shown to produce flakes of different size and shape and can even cause platform lipping by non-conchoidal or bending fracture (Hellweg, 1984; Whittaker, 1994; Soriano et al., 2007; Bataille and Conard, 2018; Schmid et al., 2019, 2021). This observation is confirmed by controlled flaking experiments which showed that, with all else being equal, compared with a more perpendicular strike, an oblique angle of blow relative to the platform produces flakes that are smaller, shorter, and have a less prominent bulb of percussion, hence they are lighter in mass (Fig. 1; Speth, 1975; Dibble and Rezek, 2009; Magnani et al., 2014). Essentially, by adjusting the angle of blow, knappers can not only effectively control the flake initiation and termination phases but also alter flake size. Thus, it makes sense that learning how to modify the angle of blow and apply a suitable percussive blow represent key skill elements that separates novices from expert knappers (Geribàs et al., 2010; Vernooij et al., 2012; Cueva-Temprana et al., 2019).

Given the importance of the angle of blow to knapping, determining when and how hominins controlled this parameter during knapping is critical to understanding the evolution of tool making behavior. However, a limited number of studies have attempted to gauge the angle of blow on flakes based on basic principles of Hertzian fracture in conchoidal flaking (Crabtree, 1972; Dibble and Whittaker, 1981; Whittaker, 1994). Building on previous work, Li et al. (2022) presented a new method to quantify the angle of blow on archaeological flakes based on the principle that, in conchoidal fracture, the direction of the hammer blow can cause the Hertzian cone to tilt in different ways after fracture initiation (Lawn et al., 1984; Chaudhri and Chen, 1989; Chaudhri, 2015). The variation in the tilt of the Hertzian cone can be measured on a feature of the flake's bulb of percussion, termed the 'bulb angle' (Fig. 2; Li et al., 2022). When the angle of blow is closer to 0° (i.e., striking perpendicularly to the platform), the bulb angle on the detached flake would be larger; when the angle of blow increases and becomes more oblique relative to the platform, the resulting bulb angle becomes smaller (Fig. 2). Li et al. (2022) tested the method using several experimental datasets produced under both controlled and flintknapping settings, and demonstrated that the bulb angle can serve as a reliable and direct proxy of the angle of blow during flake production.

Measuring the bulb angle provides an opportunity to examine if and perhaps how Early Pleistocene hominin toolmakers managed the angle of blow during the knapping process and test hypotheses about their knapping techniques. For instance, it is clear that the earliest hominin toolmakers were capable of systematically and effectively producing flakes with sharp edges (Režek et al., 2018; Braun et al., 2019; Reeves et al., 2021). It is possible that these early hominins were already skilled at adjusting the angle of blow to facilitate and control the flaking outcome. If this is the case, we would expect a significant relationship between bulb angle measurements and other flake attributes, such as size, shape, and termination type among Early Pleistocene assemblages. However, because flake size, shape and termination type are also influenced by other knapping factors, some of which may be systematically associated with different angles of blow (e.g., on-edge versus platform strikes; see Magnani et al., 2014), it can be difficult to differentiate the relative effect of the various factors involved in the process.

In this study, we employ a different approach to investigate how Early Pleistocene hominins managed the hammer striking angle in stone flaking. Specifically, we examine whether hominins adjusted the angle of blow alongside other independent knapping parameters in flake production, namely exterior platform angle (EPA) and platform depth (PD). These two variables are independent knapping attributes that have been shown to exert substantial influence on flaking outcome in repeated experiments (Speth, 1972; Dibble and Whittaker, 1981; Dibble and Pelcin, 1995; Dibble and Rezek, 2009; Režek et al., 2011; Magnani et al., 2014; Leader et al., 2017; Dogandžić et al., 2020). Archaeological evidence suggests that hominins as early as 2.58 Ma managed these two platform attributes in flake production (Režek et al., 2018; Braun et al., 2019; Reeves et al., 2021). If Early Pleistocene hominins modified the angle of blow in accordance with EPA and PD, it would indicate that

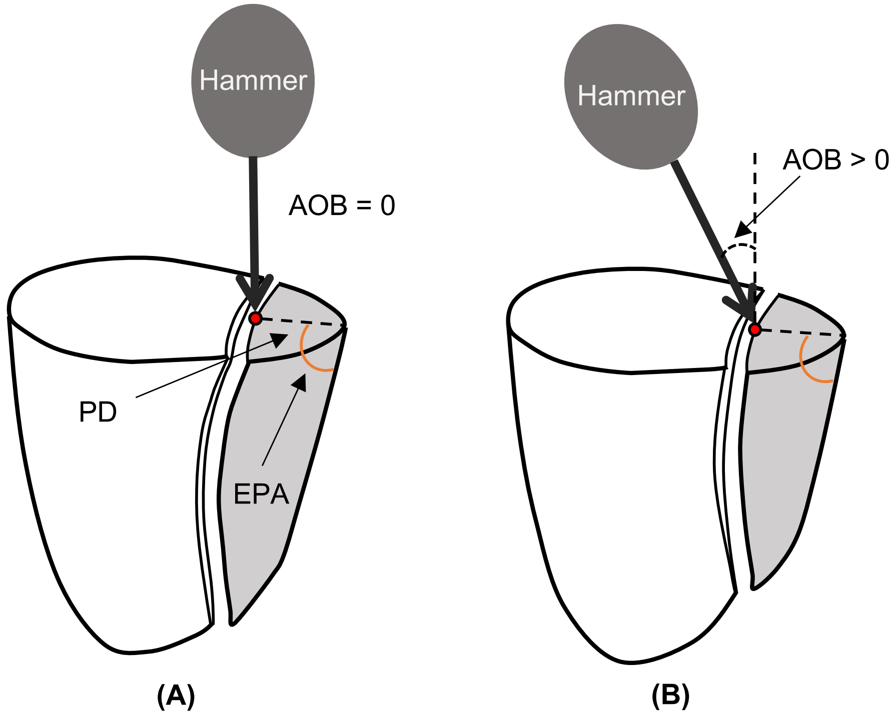

Figure 1. Schematic illustration of the effect of the angle of blow (AOB) on flaking. Angle of blow is measured as the angle between the hammer strike direction and the perpendicular of the platform surface. A) shows the scenario when the AOB is perpendicular to the platform (equal to zero), and B) shows the scenario when the AOB is oblique (or is positive). The red dot refers to the point of percussion. PD = platform depth; EPA = exterior platform angle.

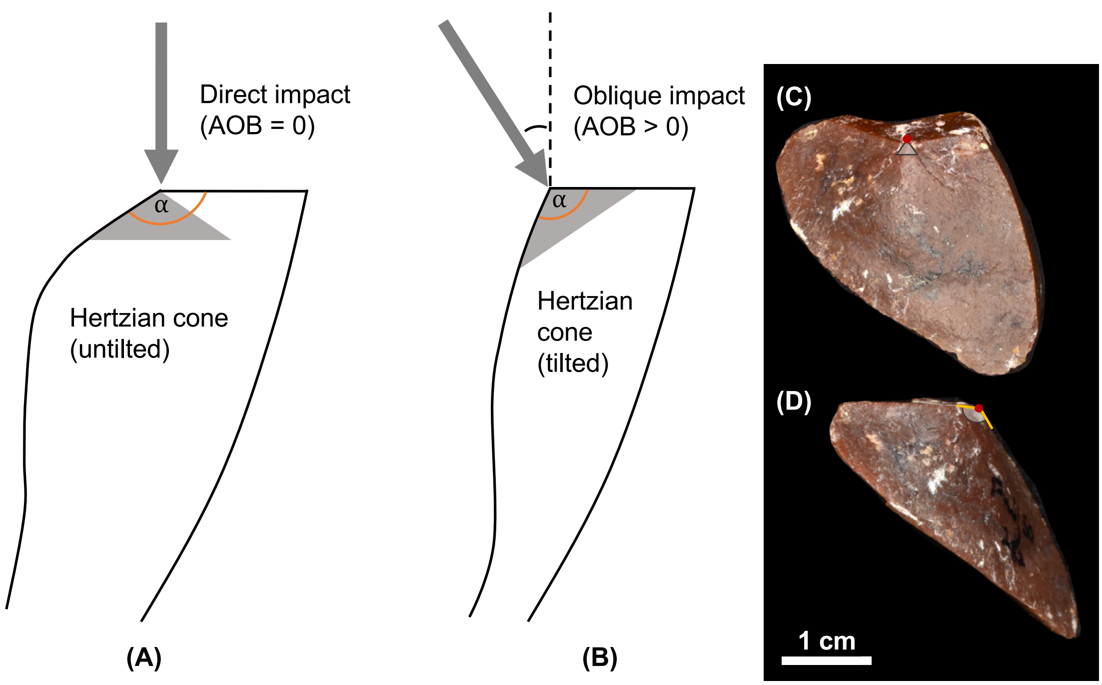

Figure 2. A) Schematic illustration showing the bulb angle on a flake in profile view, depicting the orientation of the Hertzian cone (untilted) when the angle of blow (AOB) is zero. The theoretical bulb angle is calculated as $90^\circ + 0.5\alpha$. B) Schematic illustration depicting the case when the Hertzian cone (tilted) is completely pushed onto the platform by an oblique (positive) AOB, resulting in a theoretical bulb angle equal to α. C) The relative size of the Hertzian cone on a flake from the view of its interior surface. The Hertzian cone is marked by the light grey triangle. D) The relative size of the bulb angle on a flake in profile view. The point of percussion is marked by a red dot; the bulb angle is marked by the yellow lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

these toolmakers systematically adjusted the angle of blow depending on flaking conditions. Adjustments of the angle of blow may be done to facilitate fracture propagation, such as preventing platform crushing and hinged or step flake terminations (especially when EPA are high), and/or as a direct means to control the size and shape of the flaking outcome. Regardless of the actual intention behind the practice, systematic associations between the angle of blow and the two platform variables implies an awareness among hominin toolmakers of the cause-and-effect relationships between various knapping factors.

To test the association between the angle of blow, EPA and PD, we examine the bulb angle (Li et al., 2022) as a measurable proxy for the angle of blow among a number of Paleolithic assemblages. Importantly, the bulb angle is a function of the Hertzian cone and thus not affected by changes in EPA or PD. We examine temporal patterns in the association of the bulb angle, EPA and PD among a number of Early Pleistocene flake assemblages from East Turkana, Kenya, spanning ~2 to 1.5 Ma. We hypothesize that the more recent Early Pleistocene hominin toolmakers had a more developed control over the hammer striking angle during flake production. If this was the case, we anticipate the bulb angle to vary in several ways. First, there should be an association between lower bulb angles and higher EPA, which would reflect the application of oblique hammer strikes to detach flakes from steep (greater than 80°) core edges. This would likely be an attempt to prevent platform crushing and/or facilitate fracture propagation and feather terminations. We also expect to find lower bulb angle values associated with larger PD and flake mass, reflecting a preference for oblique angles of blow in the detachment of larger flakes. Oblique hammer strikes reduce the size and length of the detached flake (Speth, 1975; Dibble and Rezek, 2009; Magnani et al., 2014). Given that knapping force has been shown to be a function of flake mass (Dibble and Rezek, 2009), a reduction in flake size through more oblique hammer strikes would reduce the force required for flake detachment, making it easier for knappers to remove flakes with feather terminations.

2. Materials and methods

2.1. An overview of the study sites

We studied complete flakes from 12 Early Pleistocene assemblages from the Koobi Fora Formation, Marsabit County, Kenya (Table 1). In addition, we studied flake samples from the Middle Paleolithic site of Roc de Marsal, France. We included a Middle Paleolithic sample here because this study is the first application of the bulb angle method to the archaeological record. As a result, we currently lack established models or expectations of archaeological bulb angle variation. The incorporation of Middle Paleolithic data here thus serves as a point of comparison. We assume that the Neanderthals who produced the Roc de Marsal assemblage were competent knappers. This allows us to better interpret any patterns we may observe in the Early Pleistocene record.

Middle Paleolithic assemblage Roc de Marsal is a small south-facing cave site located in a tributary valley of the Vézère River, southwest of Les Eyzies, France (Fig. 3). The lower layers (Layer 9–5) at Roc de Marsal, dated to Marine Isotope Stage 4 (Guérin et al., 2012, 2017), are characterized by Levallois blank production (Sandgathe et al., 2011; Lin et al., 2015). The majority of the artifacts were made from local flint. In this study, we analyzed unretouched Levallois flakes from Layers 9 through 7 (Debénath and Dibble, 1994; Sandgathe et al., 2011; Lin et al., 2015). The assemblage is currently curated at the archaeological center of the Institut national de recherches archéologiques préventives in Campagne, France. We limited our analysis of this assemblage to only flint flakes to avoid raw material variation in the bulb angle (Li et al., 2022). To ensure the reliability of the bulb angle measurements, we randomly sampled the artifact collection to obtain at least 50 complete flakes per layer that have an unlipped platform and a clear bulb of percussion. The overall flake sample was further reduced where the PD ($n = 100$) and the EPA ($n = 23$) can be unambiguously measured.

Table 1
Summary of flakes with bulb angle measured from the 13 archaeological localities in chronological order from youngest to oldest.

Geological member/time period	Locality (site) name	*n*
Middle Paleolithic	RDM (Layers 9–7)	148
Upper Okote and Chari (1.48–1.38 Ma)	FxJj 37	58
	FxJj 63	47
	FxJj 65	33
Lower Okote (1.56–1.48 Ma)	FxJj 16	25
	FxJj 18 IHS	46
	FxJj 20 E	85
	FxJj 50	21
KBS (1.87–1.56 Ma)	FxJj 1	24
	FxJj 3	5
	FxJj 10	39
	FxJj 82	25
Upper Burgi (1.98–1.87 Ma)	FwJj 20	78

RDM = Roc de Marsal, France.

Early Pleistocene assemblages The Koobi Fora Formation is an ideal location to investigate technological decision making in the Early Stone Age as it possesses a well-documented Early Pleistocene lithic record with established chronologies that span from the Oldowan to the appearance of the Acheulean (Fig. 3; Table 1; Isaac and Isaac, 1997). The vast majority of the artifacts across these three assemblage groups were produced on basalt cobbles that were transported by ancient rivers to the center of the east side of the Turkana Basin (Braun et al., 2009). Whole and split river cobbles were the primary blanks used in core reduction throughout the Oldowan in the Koobi Fora Formation (Toth, 1985). During the Acheulean, large flakes and elongated cobbles were predominantly used in large cutting tool production (Isaac and Isaac, 1997; Presnyakova et al., 2018).

The 12 Early Pleistocene assemblages studied here are curated in the National Museum in Nairobi, Kenya. The assemblages are categorized into three groups based on the geological members to which they belong. The first group (henceforth the Upper Burgi/KBS Members group) includes localities FwJj 20, FxJj 1, FxJj 3, FxJj 10, and FxJj 82 (Isaac and Isaac, 1997; Braun and Harris, 2003, 2009; Braun et al., 2010; Archer et al., 2014). FwJj 20 is dated to about 1.95 Ma and is from the Upper Burgi Member (Mbr.; Braun et al., 2010; Archer et al., 2014). FxJj 1, FxJj 3, FxJj 10, and FxJj 82 are from the KbS Mbr. in the Karari region (Braun and Harris, 2003, 2009), and are dated between 1.87 and 1.6 Ma (Toth, 1985; Isaac and Behrensmeyer, 1997; Brown et al., 2006; Braun and Harris, 2009; Lepre and Kent, 2010; Fig. 3). The Koobi Fora Formation is divided into paleontological areas that serve as a generalized description of geographical and geological context. FwJj 20 is located in Area 41 of the Koobi Fora Formation (Braun et al., 2010). Both FxJj 1 and FxJj 3 are located in Area 105, FxJj 10 is located in Area 118, and FxJj 82 is located in Area 130 of the Koobi Fora Formation (Fig. 3; Braun and Harris, 2009). Artifacts from the Upper Burgi/KBS Members show a dominance of simple cores and flakes with an emphasis on the least-effort production of sharp edges, representing a classic Oldowan technology (Toth, 1985; Schick and Toth, 1994, 2006).

The second group are all derived from sediments in the older part of the Okote Mbr. (henceforth referred to as Lower Okote group). This group includes localities FxJj 16, FxJj 18 IHS, FxJj 20 E, and FxJj 50 (Harris, 1978; Kaufulu, 1983; Isaac and Harris, 1997). These are from the Lower Okote Mbr. and are dated to between around 1.6 and 1.5 Ma (Bunn, 1997; Isaac and Behrensmeyer, 1997). FxJj 18 IHS (Ingrid Herbich Site) is the youngest location of the FxJj 18 site complex (Harris, 1978; Kaufulu, 1983). FxJj 20 E (East) belongs to the FxJj 20 site complex (Harris, 1978; Isaac and Harris, 1997; Hlubik et al., 2017). FxJj 16 and FxJj 18 are from Area 130, and FxJj 20 E and FxJj 50 are from Area 131 of the Koobi Fora

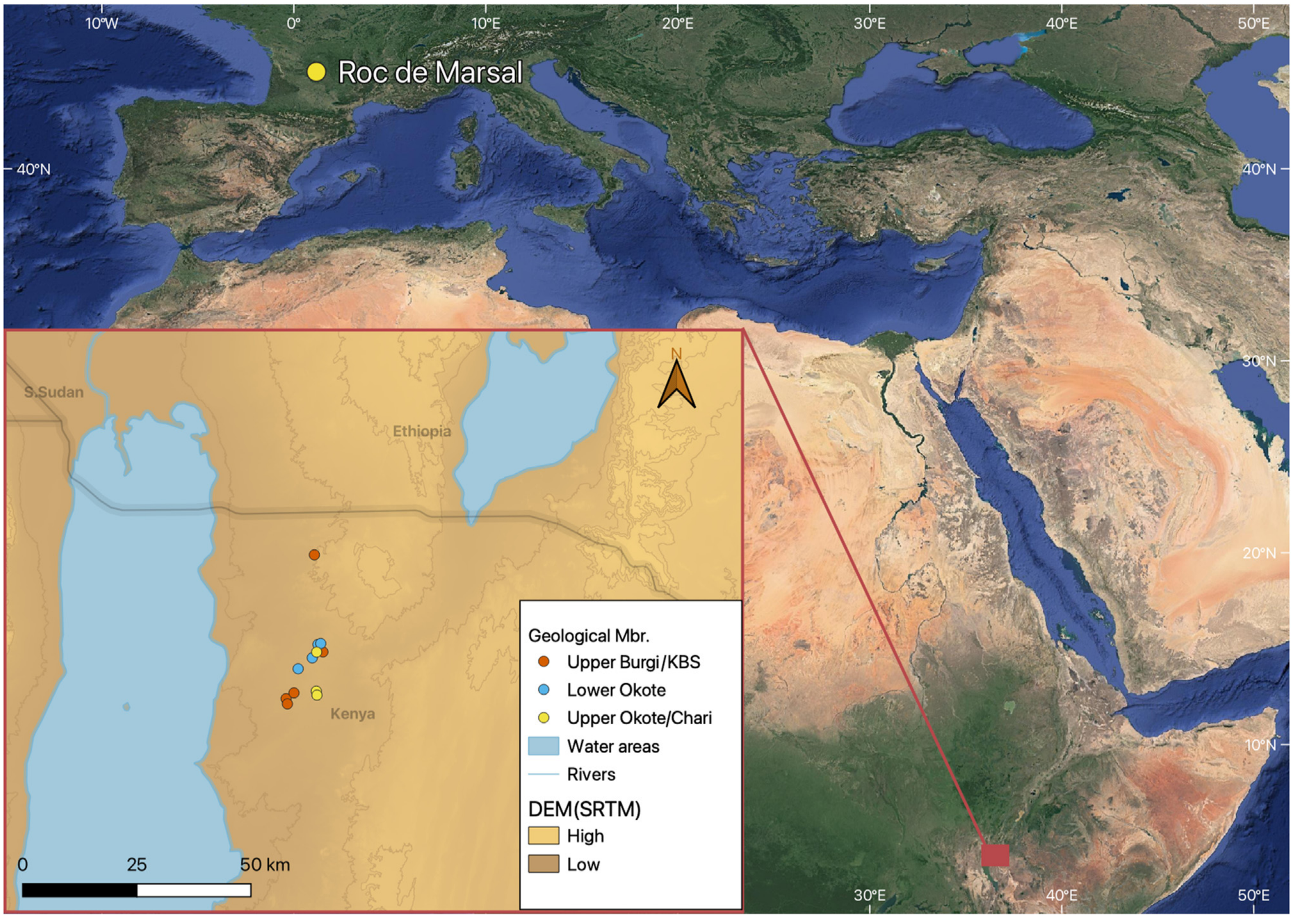

Figure 3. Map showing the locations of the study sites, incorporating data from Natural Earth (naturalearthdata.com), SRTM 90m (Jarvis et al., 2008; available from srtm.csi.cgiar.org), Digital Chart of the World (via diva-gis.org/gdata), and Google satellite imagery, accessed on January 06, 2023.

Formation (Fig. 3; Harris, 1978; Bunn et al., 1980; Isaac and Harris, 1997; Braun et al., 2008b). Artifacts from the Lower Okote group have been attributed to the Karari Industry and are characterized by the predominance of single platform cores (also known as the Karari Scrapers; Harris and Isaac, 1976; Harris, 1978; Isaac and Isaac, 1997).

The third group (henceforth the Upper Okote/Chari group) includes localities FxJj 37, FxJj 63, and FxJj 65 (Liljestrand, unpublished thesis; Isaac and Harris, 1997; Presnyakova et al., 2018; Presnyakova, 2019). FxJj 37 is situated toward the top of the Okote Mbr. and FxJj 63 and FxJj 65 are situated at the base of the Chari Mbr. They are dated to around 1.36 Ma (Isaac and Harris, 1997; Presnyakova et al., 2018; Presnyakova, 2019). Artifacts from the Upper Okote/Chari group are characterized by the dominance of early Acheulean large cutting tools (Isaac and Isaac, 1997; Presnyakova et al., 2018; Presnyakova, 2019; Phillips et al., 2023).

As with the Middle Paleolithic sample, for the Koobi Fora assemblages we only analyzed flakes from a single raw material (i.e., basalt) with unlipped platforms and unambiguous bulbs of percussion (Li et al., 2022). As a result of this selection, the sample sizes reported here are far lower than the total number of whole flakes available at these localities (Isaac and Isaac, 1997). Due to the relatively small size of these Early Pleistocene flake assemblages, we were able to study all of the flakes that fulfil our selection criteria among the various assemblages except for FxJj 18 IHS. Due to its large assemblage size, we randomly sampled 40 flakes from FxJj 18 IHS that meet the selection criteria.

2.2. Attribute measurements

Attributes that were measured included the bulb angle, the EPA, the PD, and flake mass. Bulb angle is defined as the angle between a flake's platform and the protruding side of the Hertzian cone on the interior surface before it extends to form the rest of the bulb of percussion (Li et al., 2022). This is measured using a goniometer to the nearest one degree. A smaller bulb angle indicates that an oblique hammer striking angle (i.e., higher angle of blow) was used to remove the flake; a larger bulb angle indicates a more perpendicular striking angle (i.e., lower angle of blow) was used to remove the flake (Fig. 2; Li et al., 2022). Bulb angle was measured by a single individual (L.L.) on all flakes from both the Early Pleistocene assemblages and Roc de Marsal.

Measuring the bulb angle on flakes can be challenging due to the small size of the features measured, as noted in Li et al. (2022). The difficulty of measuring small features such as edge angles and other attributes on lithic artifacts has been a subject of increasing discussion and improvement, including the introduction of three-dimensional scanning and measuring methods in recent studies (Valletta et al., 2020; Göldner et al., 2022; Yezzi-Woodley et al., 2021; Falcucci and Peresani, 2022). While digital methods offer the advantage of greater accuracy and standardization, these approaches were not feasible during the time of data collection. As such, we implemented a step-wise approach to minimize measurement error using a manual goniometer. First, we measured the attribute of each flake on two separate occasions and used the average in the analysis. Second, we calculated the distribution of values of differences between two measures of a single flake to determine the error in the measurement of a single flake. We then removed any flake where the difference between the repeat measures was above the 95th percentile of differences. This 95% threshold in our data is a difference of five degrees between measurements (see Supplementary Online Material [SOM] Fig. S1).

It is also important to note that the bulb angle values vary by raw material type due to the mechanical properties of the Hertzian cone (Olivi-Tran et al., 2020). That is, the range of variation of a raw material's bulb angle is determined by its Hertzian cone angle (Fig. 2). As a result, raw materials with a larger Hertzian cone angle have a smaller range of variation for bulb angle and vice versa. Fracture mechanics studies show that the Hertzian cone angle of a specific type of raw material is largely affected by its Poisson's ratio (Zeng et al., 1992a, 1992b; Olivi-Tran et al., 2020). Although specific lithologies can vary substantially, we were able to obtain the range of values for Poisson's ratio of both basalt and flint from previously conducted work on the mechanical properties of these rock types studies (Schultz, 1993; Aliyu et al., 2017; Ji et al., 2019) to estimate the Hertzian cone angle associated with each rock type. As a result, we can make estimations about the range of bulb angle variation that we expect to see in the two datasets examined here. Based on the estimated Hertzian cone angles, the theoretical range of bulb angle variation is 108°–144° (±6°) for basalt and 110°–125° (±10°) for flint (Olivi-Tran et al., 2020), indicating that the bulb angle measurements and their relationship with the angle of blow during flake production are not directly comparable between our two archaeological datasets. However, while this raw material variation may complicate inter-assemblage comparisons of absolute bulb angle values, it does not hinder our ability here to examine the relationship between bulb angle and other flake attributes within each of the study assemblages. While the Poisson's ratio of the raw material affects the Hertzian cone angle, the velocity of the hammer strike may also play a role (Chaudhri, 2015). However, studies in fracture mechanics have demonstrated that the range of hammer velocities (greater than 200 m/s; Chaudhri, 2015) that would significantly impact the Hertzian cone angle is well beyond the range of velocities used in knapping activities.

Exterior platform angle was measured as the angle between a flake's platform and its exterior surface using a goniometer (Dibble and Bernard, 1980; Dibble and Whittaker, 1981; Dibble and Rezek, 2009). Platform depth was measured as the distance between the point of percussion and the exterior edge of the platform using a digital caliper to the nearest 0.1 mm (Dibble and Whittaker, 1981; Dibble and Rezek, 2009). Flake mass was measured using a digital scale to the nearest 0.1 gram. We recognize that measures of some of these variables, especially EPA, can suffer from observer inconsistencies (Dibble and Bernard, 1980; Pargeter et al., 2023). To minimize inter-observer variation, these attributes were collected from the Early Pleistocene assemblages by L.L. and J.S.R., who were both trained to measure the variables using the same approach. The same set of variables from Roc de Marsal was collected by different individuals (including S.C.L. and S.P.M.) over several years by following the same analytical system and protocols as a part of the analysis of the site. To further mitigate the impact of inter-observer error we implemented an interval-based estimation method that separates the flake attributes into groups of measures. While doing so results in some loss of precision (Gnaden and Holdaway, 2000; Lin et al., 2013), it helps minimize inter-observer variation in these measures.

2.3. Statistical comparisons

Our analysis consists of two general steps. First, we examined the distribution of the bulb angle values measured across the archaeological assemblages. For the three Early Pleistocene assemblage groups, we further conducted a one-way analysis of variance (ANOVA) and a post hoc Tukey's test to examine for any difference in bulb angle (at an alpha level of 0.05) among the three geological members.

Second, we examined the relationship between bulb angle and the other flake attributes—EPA, PD and flake mass—using ordinary least squares linear regression. Two sets of models were constructed. The first set investigated the relationship between bulb angle and the platform variables by inputting bulb angle as the response variable and EPA and PD as the predictor variables (formula: bulb angle ~ EPA + PD). The second set examined the effect of bulb angle on flake size by inputting flake mass as the response variable and bulb angle as the predictor variable in the linear regression model (formula: flake mass ~ bulb angle). We conducted the Breusch–Pagan test to test for heteroscedasticity in the models and used Cook's distance to identify influential cases (see SOM File S1 3.1.3 and 3.2.2). If influential cases were present, we compared the models with and without the influential cases to determine the degree to which these cases affect the model output. If the impact was not significant, we opted for the models that utilize all the data (see see SOM File S1 3.1.3 and 3.2.2). All data analyses in this study were conducted in R v. 4.1.1 (R Core Team, 2020). To mitigate inter-observer error concerning the Middle Paleolithic assemblage, we conducted ANOVA tests to examine the relationship between groups of PD with 5 mm intervals, EPA with 10-degree intervals, and bulb angle. All data are given in SOM Tables S1 and S2 and the code is given in HTML (SOM File S1) and Rmd file (SOM File S2).

3. Results

3.1. Roc de Marsal

The bulb angle values of the Middle Paleolithic Levallois flakes range from 110° to 147°, which exceeds the theoretical range of variation determined for flint as mentioned earlier (110°–125° ± 10°). This discrepancy may indicate that the Poisson's Ratio of the flint material used at the site is different to the published values of flint that we used in the theoretical calculation. Results from the linear models show that there is a significant relationship between bulb angle and PD ($r^2 = 0.06$, $p = 0.007$), as well as a significant inverse relationship between bulb angle and EPA ($r^2 = 0.29$, $p = 0.004$; Fig. 4B) such that as bulb angle decreases, EPA increases. Results from the ANOVA tests also show significant differences in bulb angle among the PD groups ($F = 2.605$; $p = 0.041$; Fig. 4A) and the EPA groups ($F = 4.886$; $p = 0.001$). Given that bulb angle is negatively correlated with the angle of blow, this finding suggests that, as PD increases, the Neanderthal knappers at Roc de Marsal tended to strike the core more perpendicularly. As EPA increases, they tended to strike the core obliquely. Flakes with an EPA of 80° or above are especially associated with much lower bulb angles, reflecting more oblique hammer strikes (Fig. 4B).

3.2. The Early Pleistocene assemblages

Figure 5 shows the bulb angle distributions of the Early Pleistocene assemblages grouped by the geological members (see also Table 2). Comparisons between Early Pleistocene groups show significant differences in bulb angle among the three members ($F = 9.744$, $p < 0.001$). However, this difference is driven largely by the Lower Okote assemblages having lower bulb angle values than those of the Upper Burgi/KBS and Upper Okote assemblages (Tukey HSD, Lower Okote–Upper Okote/Chari, $p < 0.001$; Lower Okote –Upper Burgi/KBS, $p = 0.011$; see also SOM).

Results of the linear regression models (bulb angle ~ EPA + PD) show that there is a significant positive relationship between bulb angle and EPA and PD among the flakes from the Upper Okote/Chari assemblages ($r^2 = 0.15$, p[EPA] = 0.015, p[PD] < 0.001; Fig. 6C). For the Lower Okote flakes, there is a significant relationship between bulb angle and PD only ($r^2 = 0.06$, p[PD] = 0.014, p[EPA] = 0.286, Fig. 6B). For the oldest Upper Burgi/KBS assemblages, there is no significant relationship between bulb angle and either EPA or PD (Fig. 6A).

We examined more closely the relationship between bulb angle and PD across the three groups of Early Pleistocene assemblages by constructing linear regression models that include PD as the sole predictor of bulb angle. Results of this analysis show that there is a significant positive relationship between PD and bulb angle among the flakes in the Upper Okote/Chari ($r^2 = 0.13$, $p < 0.001$) and the Lower Okote ($r^2 = 0.06$, $p = 0.002$) assemblages, but not for the flakes in the earlier Upper Burgi/KBS (Fig. 7). These findings indicate that the hominin toolmakers associated with the Upper Okote/Chari and the Lower Okote tended to apply more oblique hammer strikes (i.e., smaller bulb angle) to remove flakes with smaller PD and more perpendicular hammer strikes (i.e., larger bulb angle) to detach flakes with larger PD. To verify if this observed pattern is biased by differences in the PD values represented among the assemblages, we applied a 15 mm upper cutoff to standardize the PD range across the three assemblage groups. The Upper Burgi/KBS Mbr. assemblages tend to have smaller flakes than the younger assemblages, so the 15 mm cutoff removes the extremely large flakes in the younger assemblages. The resulting linear model output shows the same relationships observed without the upper cutoff: the relationship between PD and bulb angle remains significant for flakes from the Upper Okote/Chari ($r^2 = 0.08$, $p = 0.007$) and the Lower Okote assemblages ($r^2 = 0.05$, $p = 0.004$), while the relationship between PD and bulb angle remains nonsignificant for flakes from the Upper Burgi/KBS (see also SOM Fig. S2).

In terms of the relationship between bulb angle and flake mass, both the average and the range of variation of flake mass increase with bulb angle among the Upper Okote/Chari and Lower Okote flake assemblages, while no obvious pattern can be observed for the Upper Burgi/KBS flakes (Fig. 8). This observation is confirmed by the linear model results which show that there is a significant relationship between bulb angle and flake mass for flakes from the Upper Okote/Chari ($r^2 = 0.15$, $p < 0.001$) and Lower Okote ($r^2 = 0.17$, $p < 0.001$) assemblages but not for the flakes in the earlier Upper Burgi/KBS. In other words, for the Upper Okote/Chari and Lower Okote assemblages, a more oblique hammer strike (i.e., smaller bulb angle) tends to be associated with the production of smaller and lighter flakes, while the size of flakes becomes larger and more variable as the hammer striking angle becomes more perpendicular to the platform (i.e., larger bulb angle). Using 100 g as the upper cutoff value to remove extreme cases and to standardize the range of flake mass represented across the three assemblage groups, we still observe the same significant relationship between bulb angle and flake mass in the Upper Okote/Chari ($r^2 = 0.15$, $p < 0.001$) and Lower Okote ($r^2 = 0.13$, $p < 0.001$) assemblages. In addition, we also see a potential trend toward a significant relationship between bulb angle and flake mass ($r^2 = 0.02$, $p = 0.04$) in the Upper Burgi/KBS assemblages (see also SOM Fig. S3).

4. Discussion

Much of our understanding of early hominins' tool use requires reconstructing the technical decisions they made during the knapping process (e.g., Roche et al., 1999; Delagnes and Roche, 2005; Braun et al., 2008c). In this study, we used bulb angle as a proxy for the angle of blow to investigate Early Pleistocene hominins' control over hammer strike angles during flake production. We did this by studying a number of Early Pleistocene assemblages to evaluate the association between the bulb angle and other independent knapping variables that were under the direct control of hominin knappers (i.e., EPA and PD). We also examined the same variables among a sample of Middle Paleolithic flakes to provide a point of comparison from a more recent period of lithic technological development. We acknowledge the caveat that the range of

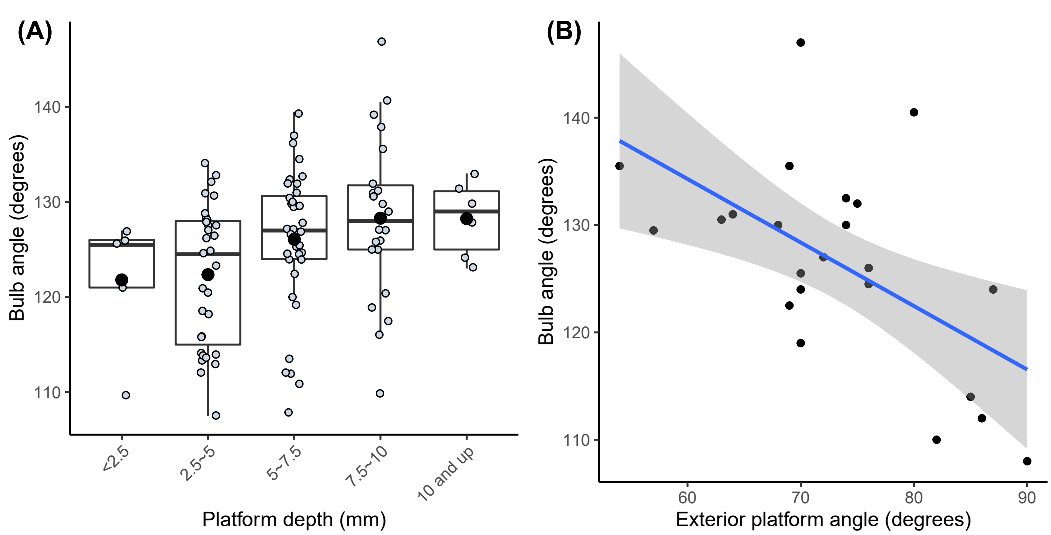

Figure 4. A) Boxplots of the relationship between bulb angle and platform depth for flakes from Roc de Marsal. The box represents the range between the 25th and 75th percentiles of the bulb angle. The average bulb angle within each platform depth interval is represented by the black dot, the solid black line indicates the median value of bulb angle within each platform depth interval; B) Scatterplot of the inverse relationship between bulb angle and exterior platform angle for flakes from Roc de Marsal. The solid blue line represents the ordinary least-squares regression line and they gray shading represents the 95% confidence interval about the regression. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

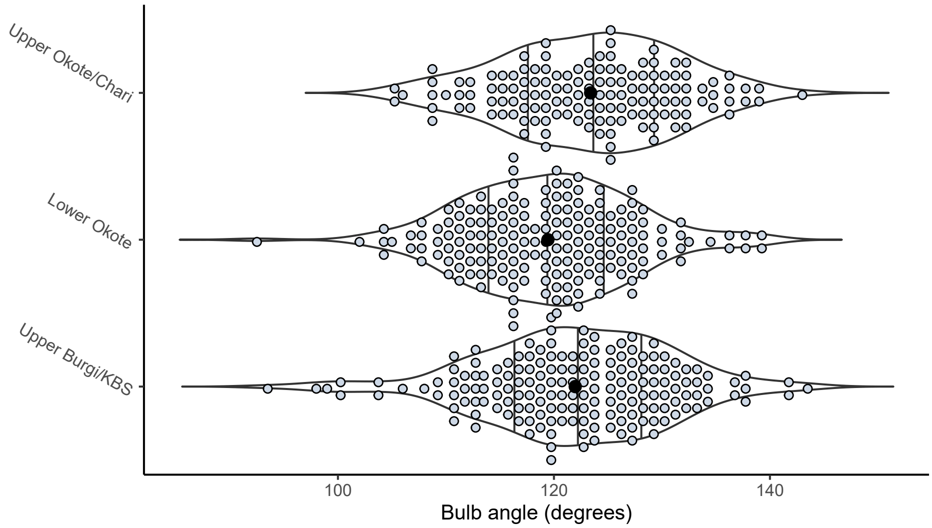

Figure 5. Dotplots and violin plots showing the bulb angle distribution of the three Early Pleistocene groups. The black dot in each dotplot indicates the average bulb angle. The groups on the y-axis are in chronological order from youngest to oldest (top to bottom). The flakes from the Lower Okote Mbr. assemblages have lower bulb angles compared to the flakes from the Upper Burgi/KBS and Upper Okote/Chari assemblages.

Table 2
Summary statistics of the bulb angle distribution for the Early Pleistocene dataset.

Group	Bulb angle (degrees)				
	Mean	SD	Variance	CV	*n*
Upper Burgi/KBS	122.0	8.7	75.3	7.1%	171
Lower Okote	119.4	7.7	59.0	6.4%	177
Upper Okote/Chari	123.4	7.9	62.9	6.4%	138

CV = coefficient of variation.

variation of the bulb angle varies by raw material type (Olivi-Tran et al., 2020). To address this issue, we limited our analysis to single raw material types in the two archaeological datasets studied.

Looking only at the bulb angle in the Early Pleistocene dataset, we observed that the Lower Okote hominins employed the most oblique angles of blow on average. However, the difference in bulb angle among the three assemblage groups does not reveal any discernible pattern that may indicate a change in the hominins' control over the angle of blow in flake production. Moreover, the relatively low coefficients of variation of the bulb angle values for all three groups suggest that, in general, the Early Pleistocene hominins applied a similar range of hammer striking angles in flake production.

However, if we examine the bulb angle in relation to EPA and PD, a temporal pattern emerges. In the oldest group of assemblages—the Upper Burgi/KBS group (1.98–1.56 Ma)—there is no significant association between the bulb angle and the two platform variables. This finding does not necessarily indicate a lack of understanding of basic flaking mechanics by the hominins. Instead, it is possible that the hominins employed knapping strategies such that variation in the angle of blow does not correspond to platform parameters. For instance, with a 'least effort' approach to produce sharp flakes irrespective of size and shape (Toth, 1985; Schick and Toth, 1994, 2006), the effect of the angle of blow may in fact be relatively muted in comparison to that of EPA and PD. It is also possible that the hominin toolmakers were not aware of the influence of the angle of blow in the knapping process or could not effectively control the parameter during force delivery due to biomechanical constraints (Susman, 1998; Tocheri et al., 2007; Marzke, 2013).

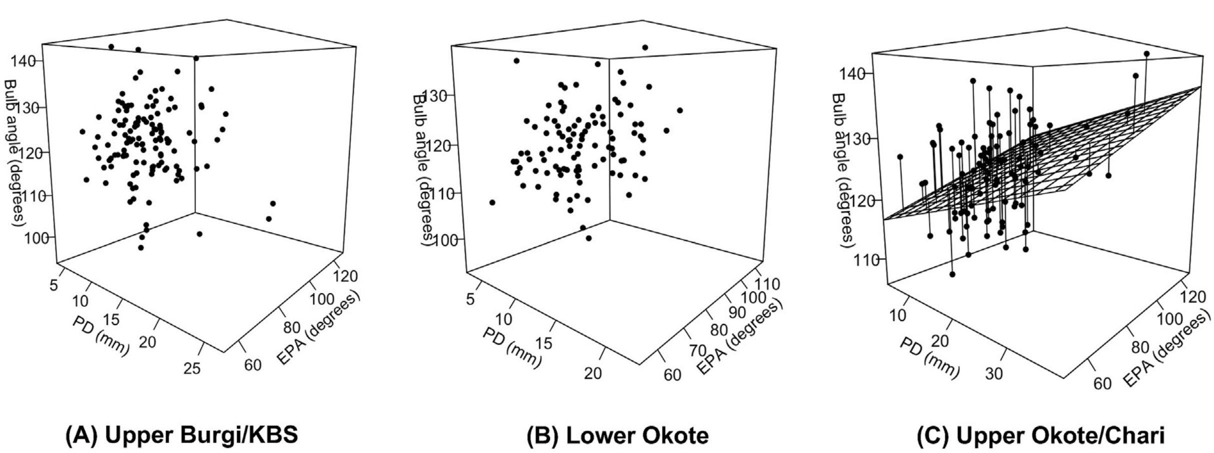

Figure 6. Three-dimensional scatterplots of the ordinary least-squares regression results using exterior platform angle (EPA) and platform depth (PD) to predict bulb angle for flakes from Early Pleistocene assemblages for A) Upper Burgi/KBS, B) Lower Okote, and C) Upper Okote/Chari. The regression plane (C) for flakes from the Upper Okote/Chari assemblages is displayed. The flakes from the Upper Okote/Chari assemblages show a significant relationship between both EPA and PD with bulb angle.

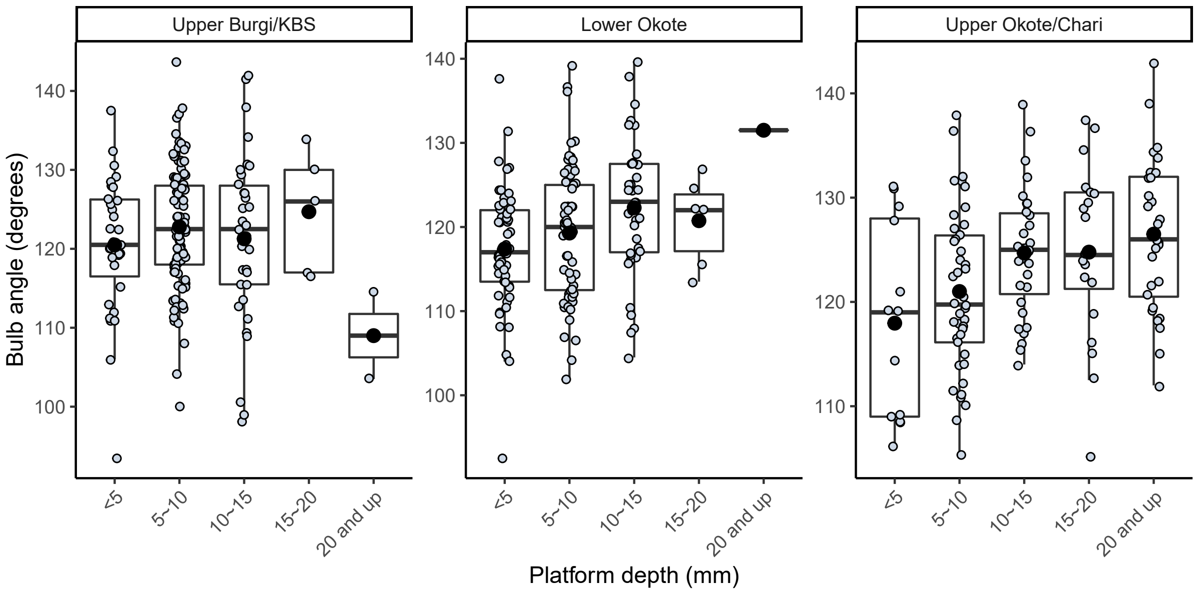

Figure 7. Boxplots of the relationship between bulb angle and platform depth for flakes from the Early Pleistocene assemblages grouped by geological member. The box represents the range between the 25th and 75th percentiles of the bulb angle. The black dot represents the average bulb angle within each platform depth interval, the black solid line in the box indicates the median bulb angle within each platform depth interval. The upper whisker represents the maximum bulb angle within 1.5× the interquartile range above the 75th percentile, and the lower whisker represents the minimum bulb angle within 1.5× the interquartile range below the 25th percentile. The flakes from the Lower Okote and Upper Okote/Chari assemblages show a significant positive relationship between platform depth and bulb angle.

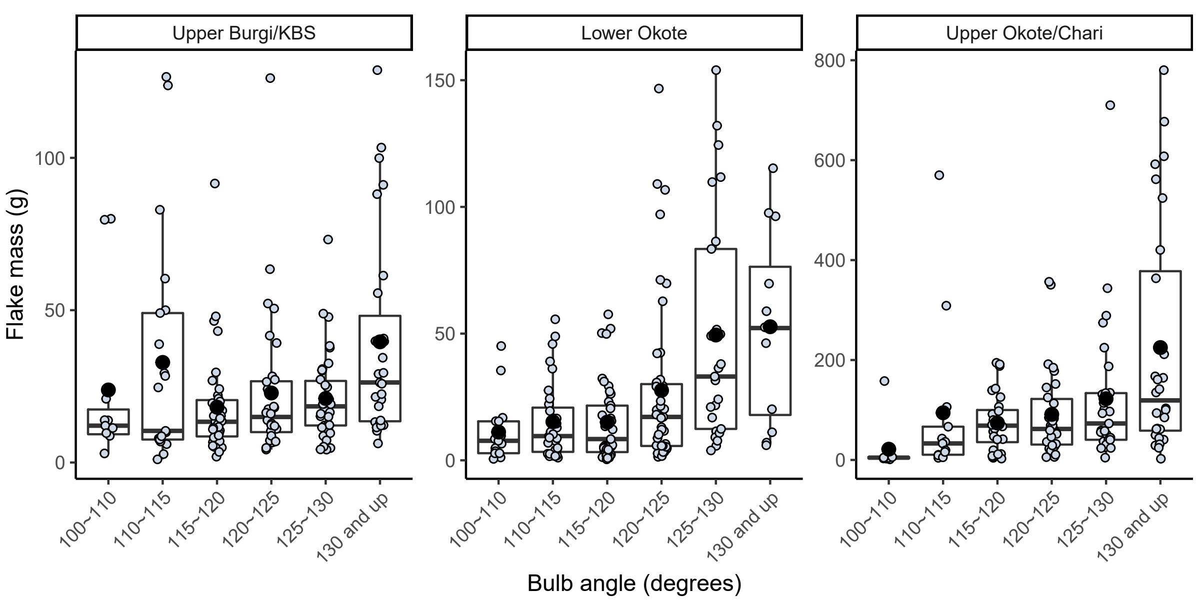

Figure 8. Boxplots of the relationship between flake mass and bulb angle for flakes from the Early Pleistocene assemblages grouped by geological member. The box represents the range between the 25th and 75th percentiles of flake mass. The black dot represents the average flake mass within each bulb angle interval, the black solid line in the box indicates the median flake mass within each bulb angle interval. The upper whisker represents the maximum flake mass within 1.5× the interquartile range above the 75th percentile, and the lower whisker represents the minimum flake mass within 1.5× the interquartile range below the 25th percentile. For flakes from the Upper Okote/Chari and Lower Okote assemblages, both the average flake mass and the range of variation increase with bulb angle.

We found a significant association between the bulb angle and PD in the Lower Okote assemblage group (1.56–1.48 Ma) suggesting that these knappers adjusted their angles of blow to be more perpendicular to the platform as they struck farther away from the core edge (i.e., increasing PD). The same relationship between the bulb angle and PD was also observed in the more recent Upper Okote/Chari assemblage group (1.48–1.38 Ma). Moreover, in addition to the significant association with PD, the bulb angle in the Upper Okote/Chari assemblages also exhibits a significant relationship with EPA whereby flakes with steeper EPAs tend to be struck by more perpendicular hammer blows. These results show that the Upper Okote/Chari hominins had a propensity to change the angle of blow in relation to both platform variables. They would strike more perpendicularly when knapping a larger PD and/or higher EPA. This finding supports the argument that, by 1.5–1.4 Ma, knappers at Koobi Fora systematically adjusted the angles of blow strategically according to specific platform configurations for flake removal.

The observed relationships between the bulb angle and flake platform attributes among the study assemblages can be explained by two independent processes in flake formation. First, increasing EPA and/or PD directly results in the production of larger flakes (Dibble and Whittaker, 1981; Dibble and Pelcin, 1995; Dibble and Rezek, 2009). Second, with all else being equal, a more direct hammer strike to the platform produces larger flakes in both linear dimensions and mass (Dibble and Rezek, 2009; Magnani et al., 2014). Therefore, the significant positive relationships between bulb angle and the two platform attributes that we observed in the more recent Early Pleistocene assemblage groups (Lower Okote and Upper Okote/Chari) could reflect the hominins' effort to control flake size. In other words, these knappers were likely aware that not only can larger flakes be produced by striking a steeper core edge (i.e., higher EPA) and/or hitting farther into the platform (i.e., larger PD), but also that by hitting the platform at a more perpendicular angle, they could further increase the size of the detached flake.

Another line of evidence that supports the hypothesis that Upper Okote/Chari hominins had developed control over the angle of blow is that similar associations between the angle of blow and the platform attributes are also observed in the Middle Paleolithic sample from Roc de Marsal. If we can assume that the Neanderthals at Roc de Marsal had a keen understanding of knapping techniques, then we can assume that the bulb angle and platform attributes pattern reflects their aptitude in knapping.

For the Roc de Marsal dataset, we see similar patterns where flakes with larger PD tend to be produced with more perpendicular hammer strike angles (i.e., larger bulb angle), reflecting the possible strategy of maximizing flake size as mentioned above. However, unlike the Upper Okote/Chari hominins who preferred to strike more perpendicularly when given higher EPA, the Neanderthal knappers at Roc de Marsal were inclined to strike more obliquely when given steeper platform edges. The reason why Upper Okote/Chari hominins and Neanderthals applied different approaches to hammer strike angles is currently unclear, although it may be related to variation in knapping strategies and the relative emphasis on EPA in flake production. If Middle Paleolithic technology involved more frequent preparations and utilizations of steeper platform margins, we may expect to see Neanderthal knappers adopting techniques to facilitate flake production under such settings. In fact, the practice of striking steep edged platforms more obliquely aligns with modern knapping observations that emphasize the importance of oblique hammer strikes to facilitate fracture propagation, especially under high EPA settings. This technique prevents platform crushing and the creation of step/hinge terminations (Whittaker, 1994; Clark, 2012). Regardless of the reason, the significant relationship between EPA and the bulb angle in both the Upper Okote/Chari group and Roc de Marsal highlights the role of the angle of blow in facilitating successful flaking under different EPA settings (Callahan, 1979, 1984; Whittaker, 2004).

In addition to the EPA and PD relationships, the Early Pleistocene dataset also revealed a temporal change in the association between the bulb angle and flake mass. Specifically, the two variables have limited detectable association in the earlier Upper Burgi/KBS assemblages but share a significant relationship in the two more recent assemblage groups (Lower Okote and Upper Okote/Chari). In these later assemblages, the hammer strike angle becomes more perpendicular as flake size increases. This finding contradicts our initial expectation that hominin knappers would utilize oblique hammer strikes when detaching larger flakes. Instead, it indicates that by 1.56 Ma hominins at Koobi Fora were systematically applying more perpendicular blows when detaching larger flakes, perhaps as a means of controlling flake size. In other words, the knappers might have understood that using a more direct angle of blow, along with larger EPA and PD, could produce bigger flakes. This pattern could reflect an increasing emphasis on the production of large flake blanks around this time and may be associated with the onset of Acheulean technologies in region (Sharon, 2009; de la Torre, 2016; Presnyakova et al., 2018; Toth and Schick, 2019).

5. Conclusions

We objectively quantified the angle of blow—a previously archaeologically invisible variable—from the lithic record by using bulb angle as a proxy for the angle of blow. We discovered evidence showing that toward the Oldowan–Acheulean transition Early Pleistocene hominins at Koobi Fora began to systematically adjust their hammer strike angles in flake production. Our results indicate that hominins from the Lower Okote and Upper Okote/Chari assemblages applied different angles of blow depending on other knapping variables. This outcome suggests the possibility that these hominins might have developed a more comprehensive understanding of the effect of the angle of blow and its interactions with other platform attributes, such as PD and EPA, in flaking. Importantly, based on our Middle Paleolithic point of comparison, this Early Pleistocene pattern of altering the hammer strike angles in flake production is comparable to that of the Late Pleistocene Neanderthals.

The Early Pleistocene assemblages in our study spread across several hundred thousand years. The timing of the observed changes in hominins' control over the angle of blow overlaps with the Oldowan–Acheulean transition in the study area. At Koobi Fora, the Oldowan–Acheulean transition encompasses changes in many aspects of hominins' lifeways such as their stone tool production and use, dietary breadth, habitat, as well as possible changes of hominin species (Braun and Harris, 2003; Semaw et al., 2009; de la Torre et al., 2012; Uno et al., 2018). Our findings, which demonstrate a gradual shift in the relationship between the angle of blow and other key flake attributes, offer new evidence to the discussion of the Oldowan–Acheulean transition in human evolution. Results from our study shed light on hominins' cognitive and technological capacities, particularly with regard to patterns of force delivery in stone knapping, features that remain difficult to fully reconstruct from the archaeological record. By exploring further research avenues relating to the application of the bulb angle method, we can enhance our understanding of the knapping strategies of hominins and provide valuable insights into the decision-making processes of the prehistoric stone tool makers.

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Appendix A

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