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ORIGINAL PAPER

Technological adaptations of early humans at the Lower Pleistocene Nihewan Basin, North China: the case of the bipolar technique

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Abstract

The Nihewan Basin in North China has proved to be a key area for the study of human evolution outside of Africa due to its continuous record of hominin occupation since the Early Pleistocene. Lower Paleolithic lithic assemblages at Nihewan are attributed to the East Asian Mode 1 techno-complex, which is often defined by the widespread use of freehand knapping techniques. However, our ongoing investigation of several early Pleistocene archaeological sites at Nihewan has revealed a higher prevalence of bipolar stone artifacts than previously considered, which may have been underestimated in the past due to the disparity of analytical techniques applied to Early Stone Age assemblages and the poor quality of the Nihewan Basin raw materials. This has constrained the identification of bipolar attributes and their differentiation from freehand knapping products. This study aims to investigate technological and economical differences between the two techniques based on experimental results of chert from the Nihewan Basin, creating a referential framework for the study of bipolar artifacts that we apply, to the Early Pleistocene assemblages of Xiaochangliang and Cenjiawan. Our results not only highlight morphological and technological differences between bipolar and freehand products but also demonstrate that both techniques share significant similarities in terms of dimensions and productivity. Overall, our results help to contextualize the technological flexibility of East Asian Mode 1 assemblages in the Nihewan Basin, where early hominins employed alternative flaking techniques, often in the same assemblage, to overcome constrains imposed by the poor quality of most of the raw materials available.

Keywords Nihewan Basin · North China · Early Pleistocene · Bipolar technique · Experimental Paleolithic archaeology

Introduction

The bipolar technique, in which a core is placed on an anvil stone and struck with a stone percussor, is one of the most important lithic techniques from the earliest archaeological sites to the ethnographic present (Leakey 1967; Bordes 1968; S Bordaz 1970; Schick and Toth 1993). The occurrence of bipolar knapping in Oldowan sites such as Omo (de la Torre 2004; Boisserie et al. 2008), Fejej FJ-1a (Barsky et al. 2011), FxJj3 (Ludwig and Harris 1998), and others shows it was one of the earliest knapping techniques used to obtain sharp stone tools (Schick et al., 1999; Wynn et al., 2011). While bipolar knapping has often been considered an expedient knapping technique used to overcome poor flaking quality of raw materials, new evidence indicates that this technique can be applied to produce even bladelet-like products or Levallois cores (Tabrett 2017), and archaeologists have long sought to understand the technological characteristics and variability of human behavior associated with bipolar knapping (Teilhard de Chardin and Pei 1932; Hayden 1979; Shott 1989, 1999; de la Torre, 2004; de la Peña and Wadley 2014; de la Peña 2015; Byrne et al. 2016; Arroyo and de la Torre, 2018).

Bipolar knapping involves three elements, i.e., a hammer, a core, and an anvil (Patterson and Sollberger 1976). Flaking experiments have shown that striking force rebound causes damage to the distal end of the core that is characteristically different from freehand knapping (Patterson and Sollberger 1976; de Lombera-Hermida et al. 2016), but it is unlikely that

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all strikes produce cores with identifiable bipolar features on both proximal and distal ends. Vergès and Ollé (2011) argued that the spatial relation between the impact point and the counterstrike can vary in the bipolar knapping process, and typical bipolar fracture depends on the core morphology and delineation of the resting surface of the anvil. Since not every bipolar flake will be initiated with equivalent forces in the proximal and distal ends, a significant proportion of bipolar products may possess attributes similar to those obtained during freehand knapping (Bordes 1968; Barham 1987; Bradbury 2010; Byrne et al. 2016), which will largely depend on the type and quality of raw materials (Jeske and Lurie 1993). Thus, assessing the extent of bipolar flaking in archaeological assemblages faces the challenges of both correctly identifying the characteristic attributes of this technology, and accounting for the invisibility of this technique among the "non-textbook" products that lack distal damage. Various experiments (de la Peña and Wadley 2014; de la Peña 2015; Byrne et al. 2016) have been applied to explore the constrains of bipolar identification in lithic assemblages. However, theses are often site-specific and therefore fail to establish universal criteria that can be applied to Paleolithic sites in other regions such as Asia, or more specifically, the Nihewan Basin, the case study discussed here.

In this paper, we present the results of a series of bipolar and freehand knapping experiments with local chert collected in Nihewan Basin, compare such experimental results with the Early Pleistocene assemblages of Xiaochangliang and Cenjiawan, and we discuss the technological and economical differences between the two knapping techniques in the context of the Paleolithic in China. Our primary goal is to develop analytical protocols for the identification of bipolar artifacts in the Early Paleolithic of the Nihewan Basin, and to establish the proportion of bipolar pieces that can be expected in Early Stone Age assemblages in this area. Additionally, we aim to compare the productivity of freehand and bipolar techniques using Nihewan chert, and thus contribute new insights into the benefits and constraints involved in the choice of each technique during the East Asian Early Paleolithic.

Materials and methods

Geographic and archaeological context

The Nihewan Basin, located in the transition zone between the North China Plain and the Inner Mongolian Plateau (Zhou et al. 1991; Zhu et al. 2001, 2004; Deng et al. 2008), is a key area for the study of human behavioral evolution worldwide. Most of the Early Pleistocene archaeological sites from East Asia have been excavated in this basin (Wei and Xie 1989; Zhu et al. 2001, 2003, 2004; Wang et al. 2005; Deng et al. 2006, 2007; Xie et al. 2006; Ao et al. 2010, 2013a,b; Liu et al. 2010; Pei et al. 2019; Yang et al. 2019) (Fig. 1), yielding important materials for the study of human origins and dispersal during "Out of Africa I" (Schick et al. 1991; Zhu et al. 2001, 2004; Gao et al. 2005; Deng et al. 2008; Braun et al. 2010; Dennell 2010, 2013; Pei et al. 2017).

It is widely accepted that the technological characteristics of the Nihewan Basin sites fall within the East Asian Mode 1 techno-complex, characterized by core and flake assemblages (Pei et al., 2017, 2019). Most studies have emphasized the predominance of freehand knapping of poor-quality chert local outcrops (Schick et al. 1991; Keates 2000; Shen and Wei 2004; Gao et al. 2005; Dennell 2008; Liu et al. 2013; Guan et al. 2016; Yang et al. 2016; Pei et al. 2017) (see Table 1). In recent years, however, re-analyses of previously excavated assemblages from Xiaochangliang and Donggutuo have identified higher frequencies of bipolar artifacts than originally reported (Yang et al. 2016, 2017); Yang et al. (2016) attributed the underrepresentation of bipolar products in earlier studies to a lack of systematic definitions of bipolar attributes and the particularities of the Nihewan raw materials. Chert nodules primarily selected for tool manufacture in the Nihewan Basin contain abundant internal flaws that lead to unpredictability during knapping and the shattering of products (Shen and Wei 2004; Liu et al. 2013; Pei et al. 2013, 2019; Guan et al. 2016; Yang et al. 2016), thus complicating recognition of bipolar artifacts.

In other Nihewan sites (Table 1), a reconsideration of flaking techniques is still pending, and divergent interpretation of the same lithic assemblages exists. This highlights some of the problems of current research in the region, which are compounded by a lack of experimental referential frameworks. Using criteria identified from our experimental replications, we present a re-evaluation of available results published in earlier studies, along with a preliminary re-examination of archaeological samples from the Cenjiawan site, both of which illustrate how variable proportions of bipolar products are identified depending on the attributes that are used.

Most studies of sites in the Nihewan Basin regard bipolar knapping as a cultural marker of these sites but have not considered its broader implications. However, as a reduction technology, bipolar flaking could be employed by early knappers for a variety of reasons, including ecological or economic constrains, cultural traditions, and/or, cognitive abilities. Therefore, the traditional typological studies of bipolar knapping limit our understanding of human behavioral variability and adaptations in each particular context, and they should be complemented by technological studies aimed at understanding similarities and differences in the reduction processes involved in freehand and bipolar flaking.

Raw materials

The central area of the Cenjiawan Platform (Barbour 1924; Barbour et al., 1927) in the eastern part of the Nihewan Basin

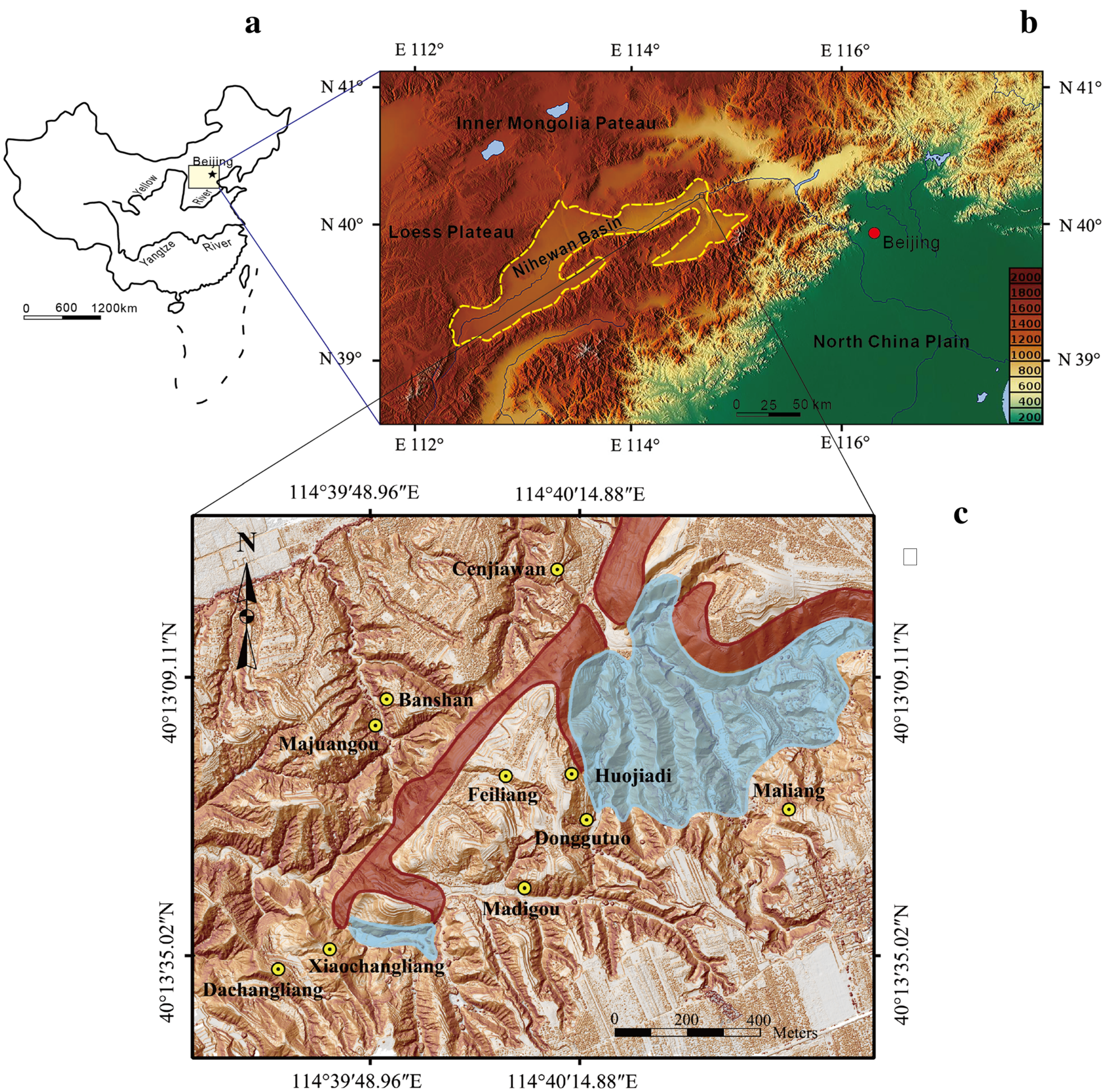

Fig. 1 Position of Nihewan Basin, showing the location of early Pleistocene sites. (**a** and **b**) Nihewan basin in North China. (**c**) Relevant sites in the eastern part of the Nihewan Basin. The area marked with dark brown color represents the Sinian rock system where chert was formed; the area outlined with light blue color refers to the Jurassic system from which volcanic rocks derive

contains outcrops of Precambrian rocks and Jurassic volcanic rocks (Fig. 1c). Precambrian rocks (Sinian rock system) were formed in a lagoon environment where siliceous dolomite was developed. Chert usually appears within the Sinian rock system in bands and as irregular, dense, and homogeneous nodules (with a thin outer layer of cemented silica) (Pei and Hou 2002). Due to tectonic movement and Jurassic volcano eruptions, the Sinian rock system underwent secondary fracture transformations that created a brecciated structure for chert and siliceous dolomite (Pei and Hou 2002; Pei et al. 2017).

The chert is fine-grained silica-rich microcrystalline or microfibrous, and while it varies greatly in color, it is often brown, gray, grayish brown, or rusty red (Pei et al. 2017). The chert often exhibits internal flaws, fractures, and a brecciated structure, which decrease its flaking quality (Guan et al. 2016; Yang et al. 2016, 2017; Pei et al. 2017). Despite these flaws, chert is generally the most suitable rock for flaking in the area. It was locally abundant around the archaeological sites across the Cenjiawan Platform from two sources: most derives from Sinian rock outcrops where chert is usually available as blocks

Table 1 Age and main technological attributes of early Pleistocene sites in the Nihewan Basin

Site	Dating (Ma)	Dating references	Raw material[1] (%)		Artifacts (*n*)		Archaeological references
			Chert	Dolomite	Total	Bipolar	
Majuangou III	1.66	(Zhu et al. 2004)	Main		111	0	(Gao et al. 2005)
Majuangou II	1.64	(Zhu et al. 2004)	Main		226	0	(Xie et al. 2006)
Majuangou I	1.55	(Zhu et al. 2004)	Main		215	0	(Xie et al. 2006)
Xiaochangliang	1.36	(Zhu et al. 2001)	96.4		1468	439	(Yang et al. 2016)
			Main		901	48	(Chen et al. 1999)
			98.2		804	0	(You et al. 1980)
Dachangliang	1.36	(Deng et al. 2006)	Main		33	0	(Pei 2002)
Banshan	1.32	(Zhu et al. 2004)	63.2		95	0	(Wei 1994)
Feiliang	1.2	(Deng et al. 2007)	Main		982	0	(Pei et al. 2017)
Madigou	1.2	(Pei et al. 2019)	44.7	33.4	1517	213	(Pei et al. 2019)
Donggutuo	1.1	(Wang et al. 2005)	96		2315	269	(Yang et al. 2017)
			97.85		1667	9	(Wei 2014)
			Main		702	0	(Hou et al. 1999)
			85.81		1442	1	(Wei et al. 1985)
Cenjiawan	1.1	(Wang et al. 2006)	92.7		1625	0	(Guan et al. 2016)
			94.6		891	6	(Xie and Cheng 1990)
			89.09	5.56	486	0	(Xie and Li 1993)
Huojiadi	1	(Liu et al. 2010)	78.3	6.7	60	1	(Feng and Hou 1998)
Maliang	0.8–0.9	(Wang et al. 2005)	54		197	0	(Liu et al. 2018)

[1] Where no quantitative data is available, predominance is noted

that usually weathered into smaller pieces suitable for human collection, and some were available as cobbles from the braided channels where Sinian lithologies (in contact with Jurassic volcanics) are transported by water (Yang et al. 2016; Pei et al. 2017).

The chert blocks and cobbles used in our experiments were collected from the Cenjiawan Platform fluvio-lacustrine deposits, where most of the Early Pleistocene archaeological sites at Nihewan are clustered. Samples were collected on the basis of their shape and size suitability for flaking. We selected chert with quadrangular or tabular morphology for BO1 experiments (Fig. 2a) and rounded blanks for BS experiments (Fig. 2b), while for the freehand experiments, blanks with an adequate platform angle were preferred. In addition, one 134 × 124 × 62 mm quartzite block with a flat surface was selected as the anvil for the bipolar experiments.

Bipolar and freehand experiments

Variability of gestures potentially involved in bipolar flaking, in which the striking angle plays an essential role (Fig. 3), has long been recognized (see review in Byrne et al. 2016). When cores are made from quadrangular or tabular blanks, flaking can be initiated from one of the core ends, a flaking motion that was in our experiments named as "bipolar knapping with orthogonal hammer (BO1)" (Fig. 2a); when blanks had an elliptical shape, cores were struck on their halving axis and named here as "bipolar splitting (BS)" (Fig. 2b). We chose not to replicate flaking motions in which the core rests obliquely on the anvil (BO2) (Fig. 2c), or where the hammer is used with an oblique trajectory (BOB) (Fig. 2d), as in such cases, fracture mechanisms are similar to those operating in freehand techniques (Duke and Pargeter 2015; Hiscock 2015).

Given that the search for suitable angles is not a priority in bipolar knapping, and to facilitate the morphological and technological analysis of resulting products, all bipolar cores in our experiments were reduced using only a single platform. Conversely, no constraints were imposed in the positioning and rotation of cores during freehand knapping, which were manipulated freely to find appropriate striking platforms. Two quartzite hammerstones (93 × 68 × 55 mm and 111 × 83 × 47 mm) were used in the experiments, weighing 506 g and 717 g respectively. One quartzite anvil was used during the bipolar experiments.

The primary goal in each experiment was to produce as many flakes as possible; when the core became too small to hold or when no debitage was produced after 20 consecutive strikes, the experiment was deemed as completed. As

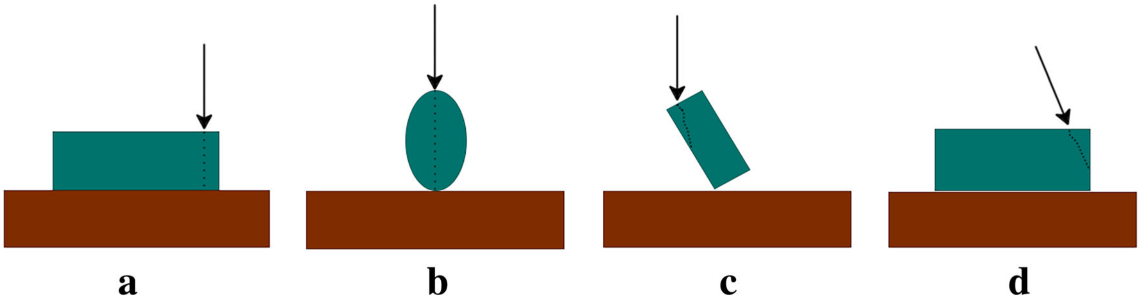

Fig. 2 Different motions potentially employed in bipolar knapping. (**a**) Bipolar knapping with orthogonal hammer (BO1). (**b**) Bipolar splitting (BS). (**c**) Bipolar knapping with orthogonal hammer, but obliquely- placed core (BO2). (**d**) Bipolar knapping with oblique hammer (BOB)

discussed above, Nihewan chert is riddled with internal flaws, which led some cores to split during the experiments; when a fragment was large enough to be handheld, it was regarded as a core and knapping continued, while the smaller core fragments were categorized as part of the resulting debitage.

Two intermediate-skilled knappers (Yingshuai Jin and the first author of this paper) participated in the experiments. A total of 25 sets, comprising eight BO1, six BS, and eleven freehand cores, were produced (Table 2). Experiments were conducted at the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences (Fig. 3), where the experimental assemblages are currently housed. All sessions were video recorded, and all materials produced in each experiment were collected; shatter less than 20 mm was not studied for this paper, while all materials at or above 20 mm were analyzed.

Measured variables and statistical analysis

In order to compare bipolar and freehand artifacts produced with Nihewan chert, we measured the same attributes in all assemblages. Table 3 compiles all the attributes considered in our study, which encompass standard variables widely used in the analysis of bipolar products (Kobayashi 1975; Byrne et al. 2016), and some less-commonly used attributes that we hoped could provide further insights in the differentiation between freehand and bipolar flaking.

Fig. 3 (**a**) Bipolar core (right) and refitted set after the BO1 experiment (left). (**b**) Bipolar core before and after the BS experiment. (**c**) Bipolar knapping. (**d**) Freehand knapping

Table 2 Original dimensions (mm) and weight (g) of cores used in the experiments

Experiment	Blanks	Length	Width	Thickness	Weight
BO1 1	Block	107	82	60	536
BO1 2	Block	96	72	53	621
BO1 3	Block	91	84	48	588
BO1 4	Block	107	94	69	1078
BO1 5	Block	97	89	56	782
BO1 6	Cobble	91	85	64	687
BO1 7	Block	81	76	47	585
BO1 8	Block	85	67.4	34.2	276.4
BS 1	Cobble	100	58	44	370
BS 2	Cobble	87	51	49	387
BS 3	Block	105	58	55	467
BS 4	Cobble	88.2	55.4	47.3	296
BS 5	Cobble	69.4	51.3	46.7	243
BS 6	Cobble	80	78	60	382
FH 1	Block	125	124	60	1096.7
FH 2	Block	165	151	54	2011.2
FH 3	Cobble	103	86	62	757.9
FH 4	Block	134	91	53	883
FH 5	Cobble	141	91	76	1221
FH 6	Block	97	69	65	818
FH 7	Block	134	73	59	791
FH 8	Block	106	105	77	1535
FH 9	Cobble	98	88	71	676
FH 10	Block	100	80	55	491
FH 11	Block	94	86	63	718

Normality tests were conducted to determine adequacy of the sample. Independent sample *t* tests and Mann-Whitney *U* tests were performed to compare metric variables. Chi-square tests were used to compare categorical variables of bipolar and freehand cores and flakes. Fisher's exact tests were used in variables where the sample was less than five. The Kruskal-Wallis test was used to compare ratios of length to width of BO1, BS, and freehand flakes. All statistics were computed using SPSS.

Results

Techno-typological analysis

Types of artifacts

Apart from cores, all detached pieces can be classified into four categories: complete flake (abbreviated here to flake), flakes with transversal fractures (incomplete flakes with missing distal ends), Siret flakes (split along the long axis through the bulb of percussion), and shatter (products with no identifiable attributes). Table 4 shows the distribution of artifacts produced in bipolar and freehand experiments. Bipolar experiments yielded 123 flakes, 35 transverse fracture flakes, 35 Siret flakes, and 105 shatter pieces, while freehand experiments produced 107 flakes, 28 transverse fracture pieces, 33 Siret fractures, and 111 shatter pieces. The chi-square test shows no statistically significant differences in the proportion of products between bipolar and freehand knapping ($\chi^2(3) = 1.492$, $p = 0.684$).

Cores

In the bipolar experiments, BO1 and BS motions show significant differences in the resulting cores. Proximal and distal ends of most BS cores show conspicuous battering and crushing, whereas BO1 cores are considerably less damaged. Even more significantly, all BS cores present heavily battered striking platforms, which is always absent in BO1 cores and becomes the most obvious difference between the two core types (Figs. 4, 5).

Clear differences are also observed in crushing between bipolar and freehand cores, which are statistically significant (Fisher's test: $p = 0.000$). As shown in Table 5, all BO1 and BS experiments present medium or heavy crushing, while no freehand cores show heavy crushing. Fifty-nine percent of bipolar cores possess bipolar scars (as defined in Fig. 4), which are absent in all freehand experiments and constitute the most distinctive attribute in identifying bipolar cores.

Flakes

A total of 56.1% bipolar and 85% freehand flakes show no dorsal battering or crushing in the proximal end (Fig. 6). The proportion of slight crushing in bipolar flakes (30.9%) is larger than in freehand flakes (12.2%). Medium crushing also occurs more frequently in bipolar (7.3%) than in freehand (2.8%) flakes, and heavy crushing is only observed in 5.7% of bipolar flakes (Fig. 7a). The chi-square test shows ($\chi^2(3) = 24.284$, $p = 0.000$) statistically significant differences between the two samples, with bipolar flakes being more likely to present crushing in their proximal ends.

Feathered terminations dominate in both bipolar and freehand flakes (Fig. 7b). Hinged, plunge, and axial terminations (i.e., where fracture proceeds directly through the core to its opposite end, and often roughly bisects the core (Cotterell and Kamminga, 1987)) all account for small proportions in the two samples. Flakes with impact points at the opposite ends are often regarded as typical bipolar flakes (Shott 1989; Bradbury 2010; Gurtov and Eren 2014). In our experiments, however, only 13.8% percent ($n = 17$) of bipolar flakes possess this feature. With the exception of flakes with two opposite impact points (only present in bipolar knapping), there are no

Table 3 Technological and morphological variables considered in this study

Category	Attribute	Variable[1]
Core	Size	Length; width; thickness
	Weight	(Grams)
	Crushing	Absent; slight; medium; heavy (Fig. 4c)
	Platform	Punctiform or linear; plain
	Scar	Bipolar scar; scar with one impact point
	Axial length	(mm)
Flake	Size	Length; width (proximal, medial and distal); thickness (proximal medial and distal
	Weight	(Grams)
	Platform	Punctiform; linear; plain
	Bulb[2]	Absent; present
	Profile[3]	Concave; straight; convex; irregular (Fig. 4b)
	Crushing	Absent; slight; medium; heavy
	Cutting edge[4]	Number of cutting edges; cutting length
	Termination	Feather; axial; plunge
	Axial length	(mm)
Fragments	Type	Transversal fragment; Siret; shatter
	Size	Length; width; thickness
	Weight	(Grams)

[1] All dimensions in mm

[2] Bulbs with a prominent convexity fall into the "present" category, and flakes with inconspicuous/flat bulbs are grouped within the "absent" category

[3] The profile shape considered the morphology of the overall ventral face of the flake

[4] Cutting edges are considered here as those with a sharp profile and an angle lower than 60°

statistically significant differences in the termination of flakes obtained through the two techniques (Fisher test $p = 0.439$).

Bulbs are absent in 74% of bipolar flakes ($n = 91$), and the proportion (68%) is similar in freehand flakes ($n = 73$), with the chi-square test ($\chi^2(1) = 0.928$, $p = 0.335$) confirming that no statistic differences exist between the two techniques.

Regarding flake profile shape (Fig. 7c), straight patterns dominate in both bipolar (47.5%) and freehand (49.5%) flakes, and convex profiles are at least represented in both techniques. Again, no statistically significant differences ($\chi^2(3) = 0.662$, $p = 0.882$) are observed for this attribute between bipolar and freehand knapping. In bipolar and freehand experimental results with quartz collected from Zhoukoudian, Li (2016) described that the curvature of blanks is generally straight for bipolar flakes (62/74 = 83.8%), while freehand flakes have more curved profiles (10/20 = 50%). De la Peña (2015) also reported similar experimental results (where the profile of bipolar blanks tends to be rectilinear) on quartz collected from Johannesburg, Limpopo, and Namibia.

The high ratio of punctiform or linear striking platforms (Fig. 7d) is regarded as an important attribute of bipolar flakes (52%), and in fact, this becomes fully dominant in the BS experiments, where such platform types reached 81%. In contrast, only 18.7% of freehand flakes possess punctiform or linear platforms, and statistically significant differences exist between both techniques ($\chi^2(1) = 27.437$, $p = 0.000$).

Dimensional analysis

Since size of original cores varies greatly, and in order to ensure that there is no statistical difference in experimental data between bipolar and freehand knapping products, those

Table 4 Distribution of debitage categories produced during the experiments

Technique	Experiment	Products	Flake		Transverse fracture		Split fracture		Shatter	
	n	*n*	*n*	Weight (g)	*n*	Weight (g)	*n*	Weight (g)	*n*	Weight (g)
Bipolar	14	298	123	2078.6	35	347.3	35	281.3	105	961.2
Freehand	11	279	107	2991.1	28	139	33	260	111	1522.2

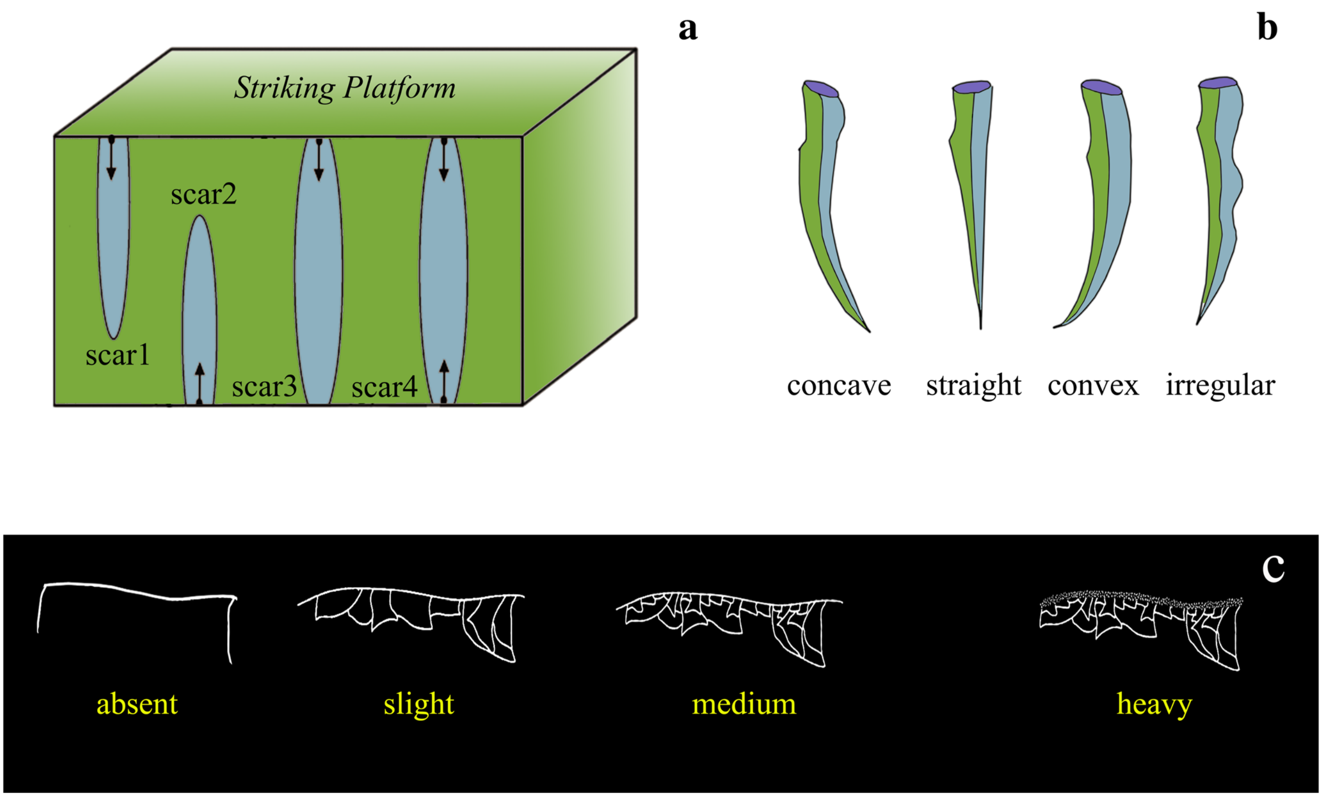

Fig. 4 Relevant attributes in bipolar and freehand experimental sets. (**a**) Impact points on scars. **car1**: impact point on the striking platform; **scar2**: distal impact point resulting from rebound against the anvil; **scar3**: proximal impact point on a scar that travels across the core face; **scar4**: bipolar scar containing 2 bipolar impact points on a scar that travels across the core face. (**b**) Flake profile shapes according to ventral faces (right side) (after Peng 2012). (**c**) Crushing intensity on the striking platform of flake or core (after de la Peña 2015). **absent**: pieces with no scars shorter than 1 cm. **slight**: pieces with 1 ~ 2 layers of scars shorter than 1 cm. **medium**: pieces with 3 or more layers of scars shorter than 1 cm. **heavy**: pieces with crushed edges and abundant microfractures

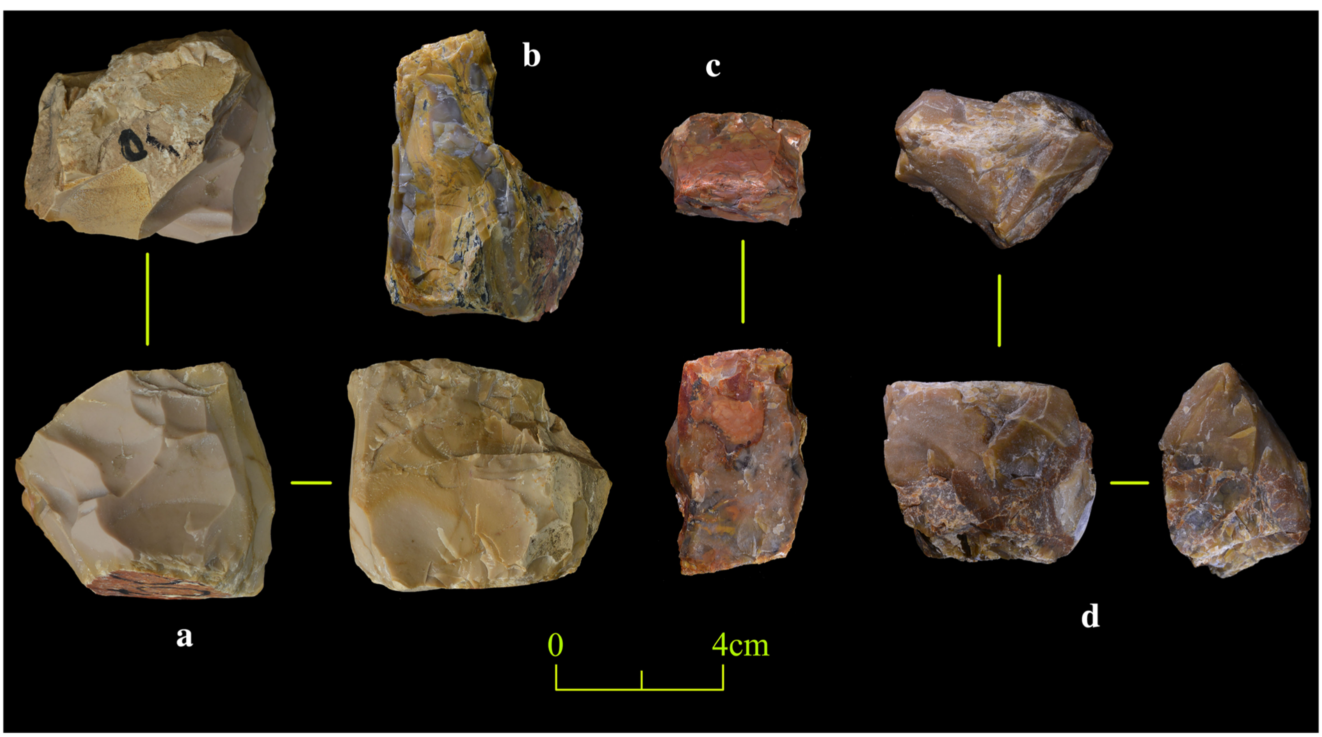

Fig. 5 BO1 (**a** and **b**) and BS (**c** and **d**) cores produced in bipolar experiments

Table 5 Percentages of different crushing stages in cores

	Absent	Slight	Medium	Heavy
BO1	0	9.1	36.4	54.5
BS	0	0	33.3	66.7
Freehand	25	50	25	0

with an initial weight between 400 and 2000 g were considered in the dimensional analysis, which included 8 bipolar and 9 freehand experiments. The mean weight of bipolar original blanks is 668 g, and 876 g for those employed in freehand knapping. A t test ($t(16) = 1.594$, $p = 0.081$) comparison shows no significant differences between bipolar and freehand blanks, which produced 82 flakes in the case of bipolar cores and 94 flakes in freehand experiments.

The mean size and weight of bipolar flakes are 33.6 × 25.7 × 9.6 mm and 15 g, and 37 × 30 × 10.3 mm and 21.6 g in the case of freehand flakes (Table 6). Results of the Mann-Whitney U test indicate that differences in proximal width ($U = 3400.5$, $p = 0.022$) and mesial width ($U = 3321$, $p = 0.012$) of bipolar and freehand flakes are statistically significant, while other variables such as length ($U = 3852$, $p = 0.303$), distal width ($U = 3945$, $p = 0.439$), proximal thickness ($U = 4130.5$, $p = 0.796$), mesial thickness ($U = 3973.5$, $p = 0.488$), distal thickness ($U = 4051.5$, $p = 0.633$), and weight ($U = 3941$, $p = 0.433$) are similar in both samples.

In order to compare the size of flakes produced in bipolar and freehand experiments, the length × width ratio ($U = 3516$,

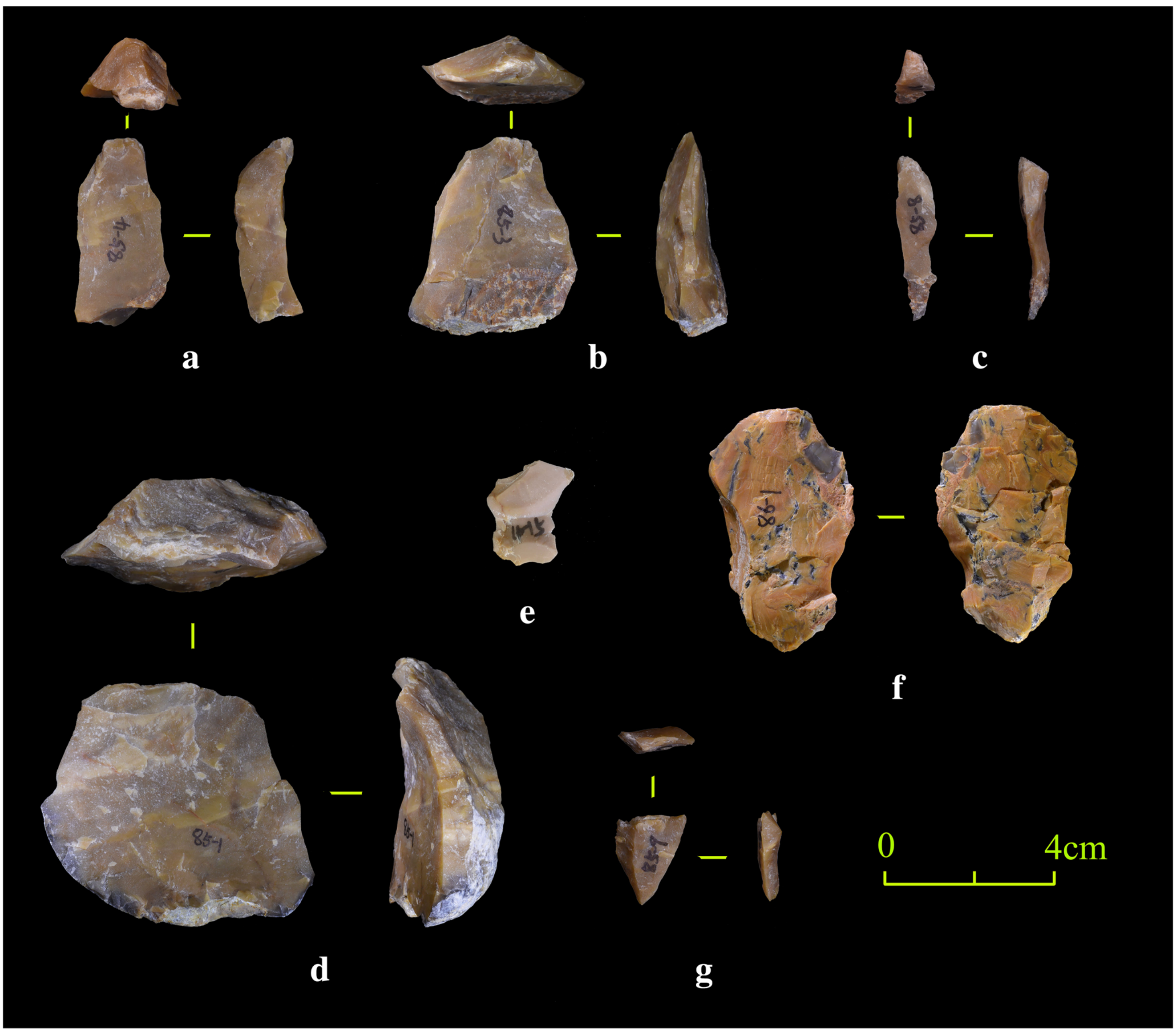

Fig. 6 Bipolar flakes produced in the experiments. (**a**–**d**) and (**g**) are flakes with punctiform or linear striking platforms and heavy crushing on the platform. (**e**) and (**f**) are flakes with impact points in both the proximal and distal ends of ventral surfaces

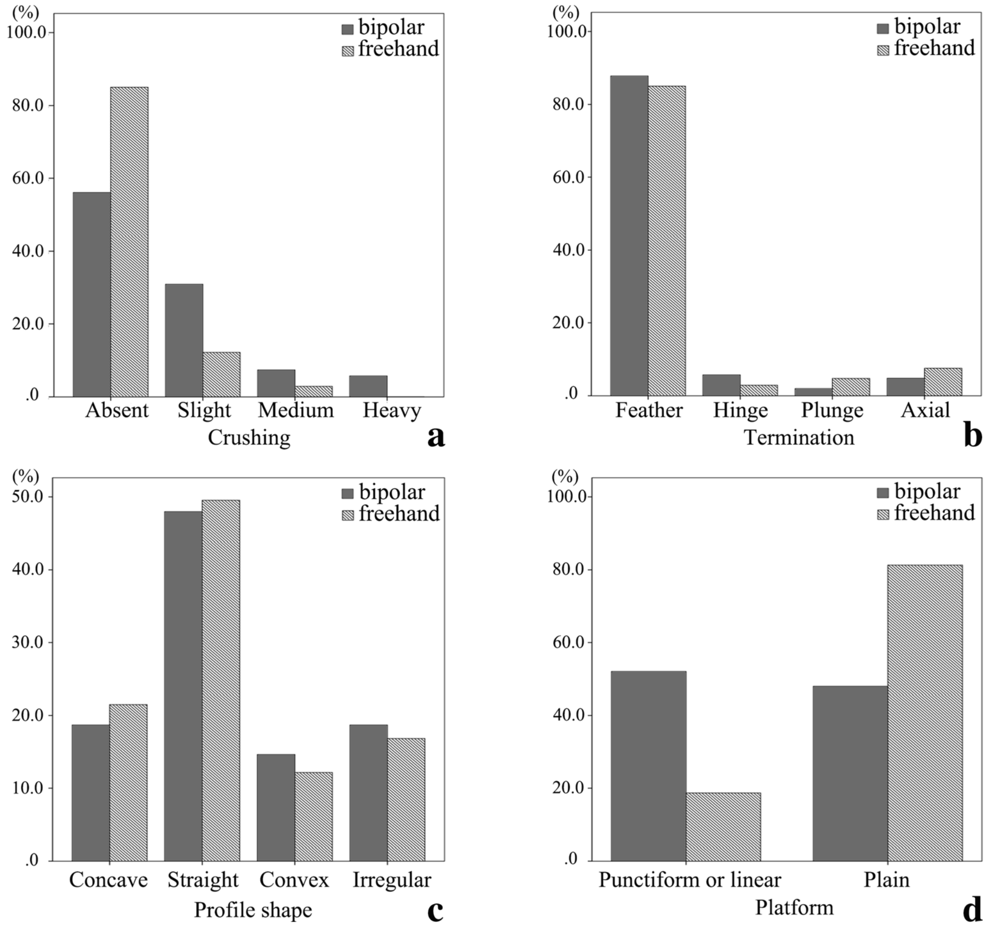

Fig. 7 Technological comparisons between bipolar and freehand flakes. (**a**) Crushing. (**b**) Termination. (**c**) Profile shape. (**d**) Platform

p = 0.05) (Fig. 8a) and length (Fig. 8b) of flakes were also compared and plotted. The results do not seem to significantly segregate bipolar and freehand flakes, even when the latter are normally larger.

The mesial width/length ratio provides information on flake elongation. In our experiments, this ratio is 1.43 in BO1 flakes, 1.59 in BS, and 1.3 in freehand knapping. The Kruskal-Wallis test (H = 9.545, p = 0.008, df = 2) shows there are significant differences between the three groups, whereas a pairwise comparison indicates there are no statistically significant differences between BO1 and BS flakes ($\chi^2(1)$ = 17.478, p = 0.223) or between BO1 and freehand flakes ($\chi^2(1)$ = − 18.701, p = 0.418). Nonetheless, BS flakes are

Table 6 Dimensions (mm and g) of bipolar and freehand flakes

	Bipolar				Freehand			
	Min	Max	Mean	St. dev	Min	Max	Mean	St. dev
Length	13	69.2	33.6	13.2	11.1	78.3	37	16.7
Proximal width	4.7	85.1	21.6	11	8.6	81.9	25.3	11.9
Mesial width	10.5	56.3	25.7	10.3	9.8	80.1	30	13.4
Distal width	3.5	59.9	21.2	12	5.5	82.3	22.8	13.2
Proximal thickness	1.7	30.3	9	5.7	2	27.4	9.4	5.9
Mesial thickness	2.8	32.7	9.6	6.1	1.6	34.2	10.4	6.7
Distal thickness	1.3	34.9	7.3	6.7	1.3	45.4	7	5.8
Weight	1.3	141	15	23.6	0.7	272	21.6	37.8

statistically more elongated than freehand flakes ($\chi^2(1) = 36.178$, $p = 0.008$).

Flake and edge productivity

Bipolar experiments produced an average of 26 debitage pieces (SD = 13.2), 33 cutting edges (SD = 22.7), and 803.6 mm (SD = 510.8) of edge length (Fig. 9a), while freehand experiments yielded an average of 25 debitage pieces (SD = 14), 37.4 cutting edges (SD = 22.1), and 1018 mm (SD = 685.9) of cutting length. The Mann-Whitney U test shows no statistically significant differences between bipolar and freehand knapping in either of these variables (number of detached pieces $U = 39.5$, $p = 0.929$; cutting edges $U = 30$, $p = 0.351$; cutting length $U = 29$, $p = 0.310$).

Only 82.3% of bipolar products presented cutting edges, compared to 91.5% in the freehand sample (Table 7), with the chi-square test indicating statistically significant differences between the two techniques ($\chi^2(1) = 8.528$, $p = 0.004$). Focusing on the flakes, 89% ($n = 73$ out of 82) of bipolar flakes presented cutting edges, whereas 99% ($n = 93$ out of 94) of freehand flakes had cutting edges (Table 7), with the Chi-square test again indicating statistically significant differences between the two samples ($\chi^2(1) = 8.029$, $p = 0.006$).

The mean cutting length of all bipolar products is 37.3 mm (SD = 19), while freehand pieces yield 44.9 mm cutting length in average (SD = 28.3), showing statistically significant differences between the two samples (Mann-Whitney $U = 16{,}927$, $p = 0.03$). Focusing on the flakes, the mean cutting length in bipolar is 46.14 mm (SD = 20), considerably less than in freehand flakes (60.13 mm; SD = 28) (Fig. 9b), again with statistically significant differences between the two techniques (Mann-Whitney $U = 2322.5$, $p = 0.000$).

Analysis of the videotapes enabled counting the number of hammerstone-to-core strikes in each experiment, which can be used as a measure of flaking efficiency and help to evaluate differences in productivity between bipolar and freehand knapping. The quantitative analysis of strikes per experiment (Table 8) and the Mann-Whitney test show that there are no statistically significant differences in the production of flakes ($U = 21$, $p = 0.145$), other detached pieces ($U = 23.5$, $p = 0.228$), number of cutting edges ($U = 17.5$, $p = 0.075$), and cutting length per strike ($U = 18$, $p = 0.083$) between bipolar and freehand experiments. The ratio of core weight loss to number of strikes per experiment indicates that bipolar cores lost 3.8 g per strike (SD = 2.84), and freehand lost 5 g (SD = 3.5), with the Mann-Whitney test showing no statistical differences between the two techniques ($U = 25$, $p = 0.290$).

Discussion

New perspectives on the identification of bipolar products at the Nihewan Basin

In our experiments with Nihewan chert, cores are the most conspicuous proxies to distinguish bipolar from freehand flaking; 59% of bipolar cores presented bipolar scars, and 61% of such cores showed heavy crushing at the proximal or distal ends. BS cores are more prone to present crushing than BO1 cores.

Identification of bipolar flakes has often been considered substantially more difficult than in the case of cores. In our experiments, most bipolar flakes possess a feathered termination and present no bulbs and a straight profile shape, which are all techno-morphological attributes also typical of freehand flakes. Previous experiments have also encountered similar issues when attempting to differentiate bipolar from freehand flakes (e.g., Patterson and Sollberger 1976; Bradbury 2010; Byrne et al. 2016), and often reliable determinations come down to classic bipolar features such as crushing both on the proximal and distal ends of flakes and crushing of

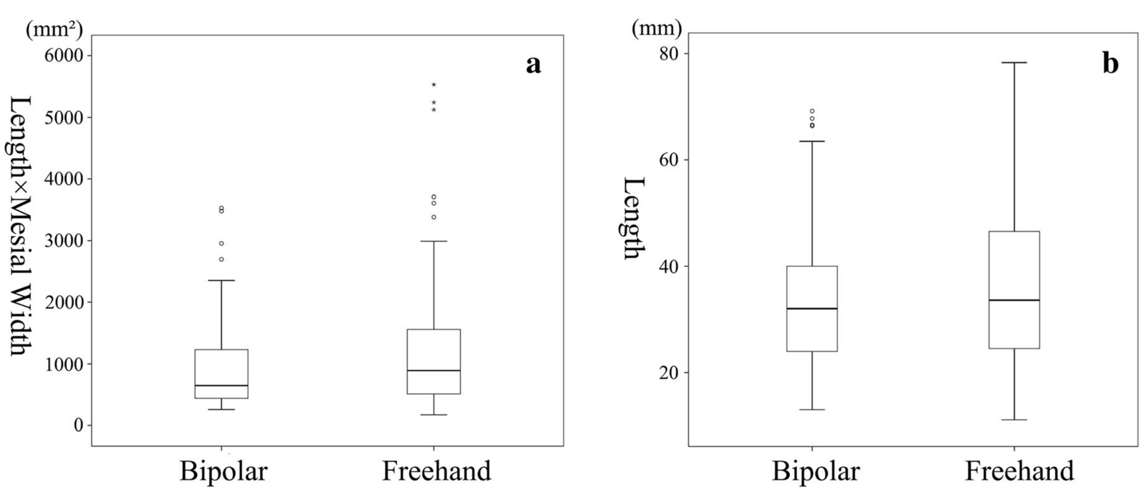

Fig. 8 Dimensional comparison of bipolar and freehand flakes. (**a**) Length × mesial width. (**b**) Length

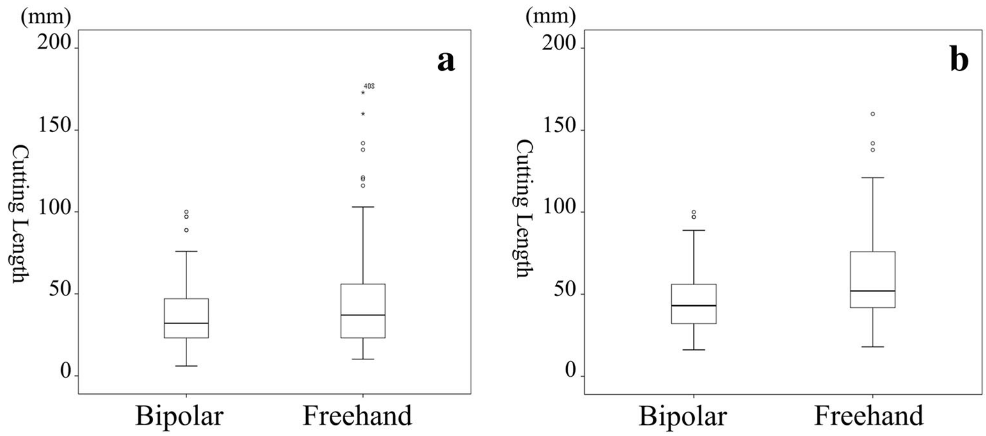

Fig. 9 Cutting length of flakes (**a**) and products excluding flakes (**b**)

platforms. In our experiments, only 5.7% of bipolar flakes show heavy crushing on platforms and 13.8% have impact points both in the proximal and distal ends. Based on these two attributes combined, around 18% of bipolar flakes could be confidently identified for this technique. The absence of bulbs and straight profiles is a common feature in our experimental freehand flakes, which we link to the poor quality of the local chert. Thus, these attributes are not strong indicators of freehand versus bipolar flaking for the raw materials analyzed here, and hence, they cannot be used to distinguish knapping techniques.

Apart from attributes exclusive of bipolar knapping, punctiform or linear striking platforms are often thought to have a strong relationship with bipolar knapping (Binford and Quimby 1963; Hayden 1979; Barham 1987; Bradbury 2010; Berman et al. 2017). In our experiments, not all bipolar products presented punctiform or linear platforms, but 27% of flakes obtained through this technique did show crushing associated to punctiform or linear platforms, which is in stark contrast to freehand flakes (3%). This suggests that the shape of the striking platform is an important discriminatory attribute.

Conversely, attributes such as profile shape, termination, or bulb presence yielded similar proportions in both bipolar and freehand products with Nihewan chert, which reinforces previous observations on other raw materials (e.g., Byrne et al. 2016).

Bipolar and freehand knapping produced similar proportions of flakes, transverse and split fragments, and shatter in our experiments. Thus, the widespread notion that bipolar knapping produces higher percentages of debris and is more wasteful than freehand knapping (Shott 1989; LeBlanc 1992; Jeske and Lurie 1993; Gurtov and Eren 2014) is not supported by our results for Nihewan chert. It is therefore likely that the high proportion of debris in some Nihewan early Pleistocene sites is associated with the poor quality of raw materials, rather than to the predominance of bipolar knapping in the assemblages (Yang et al. 2016, 2020; Pei et al. 2019). As discussed above, Nihewan chert often exhibits internal fractures and a brecciated structure that makes this raw material prone to shattering.

Bipolar flakes are similar to freehand flakes in size, weight, surface area, and the ratio of length to mesial width, whereas distal and mesial width of freehand flakes is larger than in bipolar flakes, with the former also being more elongated. When productivity is considered in terms of number of strikes to obtain a flake, no significant differences exist in the number of cutting edges and total cutting length produced in bipolar and freehand experiments. However, the mean cutting length of debitage and flakes is longer in freehand than in bipolar products, and freehand pieces possess more sharp cutting edges. In addition, this study supports results by de Lombera-Hermida et al. (2016) that higher accuracy can be inferred for freehand knapping than in bipolar.

Our experiments have also shown that, although the overall advantages of productivity of freehand knapping are not entirely evident, this technique is more effective in

Table 7 Flake and length productivity in bipolar and freehand products

		Total	Pieces with cutting edges	Pieces with no cutting edges	Total number of cutting edges	Total length (mm) of cutting edges
Bipolar	Flakes	82	73	9	129	3368.2
	Other debitage	211	173	38	264	6428.7
Freehand	Flakes	94	93	1	181	5591.7
	Other debitage	225	206	19	337	9164.6

Table 8 Knapping efficiency based on flaking strikes involved in the production of debitage and cutting edges

Technique	Flakes per strike		Other debitage per strike		Cutting edges per strikes		Cutting edge length per strike	
	Mean	St. dev	Mean	St. dev	Mean	St. dev	Mean	St. dev
Bipolar	0.08	0.039	0.21	0.086	0.25	0.12	6.15	3.03
Freehand	0.12	0.054	0.3	0.132	0.45	0.211	12.21	6.64

producing cutting edges and cutting length. However, several benefits have been recognized in the use of bipolar knapping as well, such as enabling reduction of round pebbles/cobbles or poor-quality raw materials, increasing productivity in situations of high scarcity by maximizing reduction (Barham 1987; Knight 1988; Shott 1989; Hiscock 2015), and producing particular tools such as microliths (de la Peña 2013). In the Nihewan Basin, however, freehand techniques were the primary choice of Early Pleistocene hominins, and bipolar knapping may have been used essentially as a complementary technique (see Table 1). Given the proximity of Nihewan Early Pleistocene sites to the raw material sources and the large size of some cores in the assemblages, we conclude that bipolar knapping was not employed as a response to raw material scarcity or to maximize return by exploiting miniaturized cores. As a working hypothesis, we propose that the inherent unpredictability of the Nihewan chert may potentially have incentivized the use of poor-accuracy techniques such as bipolar flaking, as knappers would be aware that high-quality flakes were unattainable due to the internal flaws of most of the raw materials locally available. Such expedient methods would have complemented freehand knapping techniques, which predominate at Nihewan but seem to be consistently accompanied by bipolar flaking.

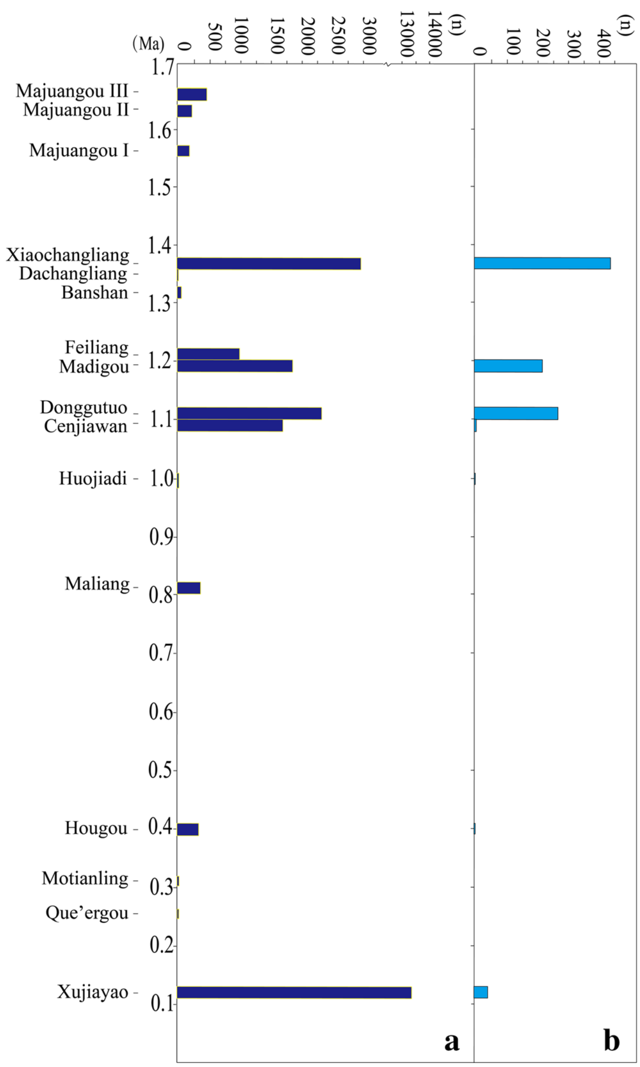

Fig. 10 Summary of Paleolithic sites of early and middle Pleistocene in Nihewan basin. (**a**) Complete lithic assemblages. (**b**) Bipolar products identified in each site

Tracing bipolar technology in the Nihewan Basin Early Pleistocene sites

Bipolar flaking is yet to be widely recognized in the Nihewan assemblages (Fig. 10), yet it is relevant not only to early human technological choices but also to analytical factors and the history of research. For instance, the properties of Nihewan raw materials hamper the identification of bipolar products. As we have shown in our experiments, less than 20% of bipolar flakes show features that would allow them to be recognized in archaeological contexts. Soft raw materials such as wood can be used as anvils for bipolar flaking and would produce flakes with undamaged distal edges (Soriano and Villa 2017). While we have no evidence for wood use in the Early Pleistocene Nihewan sequence, it is worth highlighting that stone anvils are yet to be reported in any of the assemblages, which makes the presence of bipolar flaking at the sites even less conspicuous. Together with the potential "invisibility" of bipolar elements, it should be borne in mind that the sites with higher proportions of bipolar products are those studied in the last few years, which indicates that an awareness of the potential existence of bipolar flaking is a recent analytical trend.

An example of this trend is the recent analysis of the Xiaochangliang assemblage, where chert is the main raw material (96.4%) used in stone knapping. Yang et al. (2016) identified bipolar cores and bipolar splinters. While standards for the identification of bipolar cores were not clarified, bipolar splinters were defined as small pieces with crushing on either the proximal platform or the base, and always without evidence of Hertzian initiation (e.g., bulbs of force, éraillure scars, ripple marks) (Yang et al. 2016). The criteria used by these authors to identify bipolar products were looser when considered in the light of our experimental results. Thus, a great number of "chips" and "chunks" were classified as bipolar products, with 56.92% of artifacts in the assemblage (including 111 bipolar cores and 328 bipolar splinters) attributed to the bipolar technique. This is a much higher proportion than in previous studies (Table 1).

However, according to our experiments, some attributes used by Yang et al. (2016), such as the bulb of force, are also absent in most freehand flakes (68%), and no significant differences can be discerned between bipolar and freehand flakes. Only 20% of the bipolar products could be identified confidently in our experiments, and this ratio would be even lower when considering that in many archaeological assemblages, the use of both freehand and bipolar techniques coexisted. Therefore, in the light of our experiments, we would argue that the actual ratio of bipolar products at the Xiaochangliang site may have been overestimated, and the assemblage needs to be re-examined using standards set in our experimental replications.

In addition to re-examining recently published case studies in the light of our experimental results, we also apply these to our own analysis of the archaeological assemblage of Cenjiawan assemblage. This site has been dated to ca. 1.1 Ma, and is located on the margin of the Cenjiawan platform (Fig. 1), yielding a total of 1996 stone artifacts (81.5% of them on chert). Although bipolar cores retain more identifiable attributes, only two bipolar cores (2 out of 79) with bipolar scars and obvious crushing were identified. In addition, among the 634 flakes in this assemblage, only eight could be confidently identified as bipolar flakes, when our experimental standards are applied.

Regarding the Cenjiawan flakes regarded as freehand products, 16.7% (88 out of 528) present linear or punctiform platforms, 48.9% show no bulbs, and 28.8% present a straight profile shape. Except for the proportion of linear or punctiform striking platforms that is similar to our experiments, the proportions of absent bulbs and straight profiles in flakes interpreted as freehand features are a little lower than in our experimental results. Therefore, we concluded that attributes such as bulb shape, profile shape, and flake termination types cannot be employed to confidently identify bipolar knapping products on chert in the Nihewan Basin, especially when both freehand and bipolar products co-exist in an assemblage.

Bipolar technology and hominin adaptations in Early Paleolithic China

Bipolar knapping has long been recognized in the Early Stone Age of China, starting with the excavations at Zhoukoudian (Breuil 1932; Pei 1932, 1933), where this flaking technique is still its most distinguished feature (Li 2016). However, recent experimental studies have suggested that the proportion of bipolar products might be lower than previously estimated, as 75% of debitage may be attributed to bipolar flaking (Pei and Zhang 1985; Li 2016).

Since the 1970s, bipolar products have been reported in other Early Paleolithic sites in northern China (e.g., Zhang 1998; Gao 2000), although often in very low proportions. Some exceptions exist, however, such as Xiaochangliang (Yang et al. 2016), and Donggutuo (Yang et al. 2017), where the proportion of bipolar products is higher, although always playing a secondary role to freehand knapping.

In south China, cobbles are commonly used as blanks for stone tools, and freehand knapping is also the primary knapping technique. Similar to the situation of north China, very few southern China sites have been reported to contain bipolar products and, where present, the proportion is also significantly low. An interesting pattern, as revealed recently by Li et al. (2017), is that bipolar knapping was also used to obtain large Acheulean flakes at the Danjiangkou Reservoir Region, as a flexible technological adaptation to the local poor-quality raw material of quartz phyllite. In addition, a particular bipolar technique similar to the non-axial bipolar technique described in western Europe (e.g., de Lombera-Hermida et al. 2016) is known in China as Ruileng bipolar knapping (Cao 1978; although see Gao et al. 2008). It involves selection of large cobbles with tabular shapes, which are placed on the anvil obliquely (rather than axially), similar to the motions shown in Fig. 2c except that the cores were exclusively made on cobbles with tabular shapes. Flakes produced via Ruileng bipolar knapping usually have punctiform or linear platforms, and they lack crushing on the distal ends (Cao 1978). Ruileng bipolar products are found extensively across southern China, potentially spanning from the Early to the Late Pleistocene (Xie and Lin, 2017).

To summarize, and following Gao (2000), bipolar knapping in Early Paleolithic China is complementary to freehand knapping at most sites, except for Zhoukoudian Locality 1, where bipolar knapping was reported as the main knapping technology to exploit quartz. Quartz is the most commonly used raw material in bipolar flaking, and bipolar products are normally small and few are retouched. Nonetheless, it also seems clear that the relevance of bipolar knapping has been consistently underestimated for most sites in China, and it is probably not a coincidence that most of the assemblages with a higher proportion of bipolar knapping derive from recent reanalyses of collections. This hints at our incomplete understanding of bipolar attributes across Early Paleolithic sites in China, although new experimental studies have started to consider the impact of local raw material idiosyncrasies in their identification (but see Lin 1987; Li 2016; Li et al. 2017).

While bipolar knapping has long been regarded from a cultural history perspective (e.g., Zhang 1998) that would link culture traditions from the Lower to the Upper Paleolithic in China, emphasis should now be placed on understanding its role in hominin organization and adaptive strategies. Among these, raw material exploitation has proved to be a major factor influencing technical choices of stone tool-makers (Braun, et al., 2009). Shifting perspectives such as those adopted in this paper are considering bipolar knapping as an economical, technological, and/or adaptive response by ancient tool-makers (Li 2016), rather than an evolutionary one, although future efforts should also consider its paleoecological implications.

Conclusions

This paper has explored the role of bipolar flaking in early hominin technological organization in North China. We have analyzed the attributes that can used in the identification of bipolar products in the Nihewan Basin by conducting experiments with the same chert that was used by Early Pleistocene hominins in the area. Our results show that cores are the most reliable indicators to identify bipolar knapping, with most bipolar cores presenting attributes like bipolar scars or heavy crushing of the proximal or distal ends. These are traits that are significantly different from freehand cores. Proportions of flakes confidently attributable to bipolar knapping are consistently low: only attributes like heavy crushing on platforms or impact points both at the proximal and distal ends could confidently be identified as bipolar flakes, while profile shape, termination, or bulb shape cannot be used to distinguish freehand from bipolar techniques.

Freehand knapping materials produced more cutting edges and cutting length than bipolar experiments, which may explain the dominance of freehand assemblages in the Nihewan Basin. Bipolar knapping, however, consistently appears throughout the Early Pleistocene at Nihewan and had a complementary role, which we propose may be associated with the poor quality of raw materials generally available in the basin. This may have restrained the use of more controlled flaking gestures such as those involved in freehand knapping.

Results presented in this paper are intended to explore the specific characteristics of bipolar knapping on chert from Nihewan Basin. We advocate that similar experimental work should be done in other areas of China using raw materials specific to those sites. This will contribute to assessing the technological and economical differences between bipolar and freehand knapping, and it will create a referential framework for the study of bipolar artifacts in each particular research area.

The bipolar technique, which is widely spread across China not only in the Early Pleistocene but also across the Middle Pleistocene, may have been associated with economic and functional constraints that are still poorly understood, and which deserve further in-depth studies on the significance of technological choices in the adaptations of Early Paleolithic hominins in East Asia.

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Authors' contributions SWP, DDM, and IT designed the research. DDM and SWP collected the data. DDM, SWP, IT, ZX, and HL performed the analysis. DDM, SWP, and IT wrote the paper.

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