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RESEARCH

New Approaches to the Bipolar Flaking Technique: Qualitative, Quantitative, and Kinematic Perspectives

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Abstract

The bipolar technique is a flaking strategy that has been identified from 3.3 Ma until the twentieth century, with no geographical or chronological homogeneous distribution. It is represented by the intentional contact of an active percussive element against a core rested on an anvil. This tool composite has been described by some researchers as a sign of low-skill of hominins, unable to perform successfully free-hand flaking or for flaking low-quality raw materials. Based on this premise, our research focused on the following question: Are there any quantitative and qualitative differences in terms of both kinematic parameters and technical skills between knappers with different levels of expertise when flaking using the bipolar technique? To get an answer, we developed a systematic experimental program with 12 volunteer participants with different levels of expertise. Then, to assess potential quantifiable differences and to understand the mechanics of bipolar technology, we did a video motion analysis based on kinematic parameters (including position, velocity, acceleration, and kinetic energy of the hammerstone). In addition, we performed a technological analysis of the experimental lithic assemblages to assess the technological differences between knappers based on their levels of expertise. In kinematic parameters, both statistical analysis and observations from the experiment clearly show that there are differences between the levels of expertise in this technique. Intermediate knappers have been observed to apply more velocity and kinetic energy than experts and novices. Also, differences were observed in the flaking strategies. Expert knappers show a longer reduction sequence, while intermediates show shorter one. Moreover, some of the novice knappers did not even obtain a single flake. The results of our experiment stress the complexity of bipolar flaking and that previous assumptions about it might be reconsidered, especially in terms of reconsidering the negative connotations attributed to this flaking technique.

Keywords Bipolar technique · Experimental archaeology · Video motion analysis · Lithic technology

Extended author information available on the last page of the article

Introduction

Though the bipolar technique has been an important topic in lithic studies in terms of geography and chronology, technology, and behavior of the hominins since 3.3 Ma, it is a phenomenon that is currently not much thought about. Although its simple application has been perceived as an indicator of low-skill of hominins (Patterson, 1979; Patterson & Sollberger, 1976, 1977), this idea has been refuted by several researchers (Cresson, 1977; Haynes, 1977; Stafford, 1977; White, 1977a, 1977b). However, there are still current studies supporting this negative view today (Conesa *et al.*, 2023). Ethnographic studies have noted the prolonged learning period associated with bipolar flaking (Arthur, 2010). The bipolar technique has been described by several researchers in lithic studies. Its composition requires the presence of passive (an anvil) and active (a hammerstone) elements along with a core (Arroyo & de la Torre, 2018; Callahan, 1987; Chavaillon, 1979; Crabtree, 1982; de la Torre & Mora, 2010; Hardaker, 1979; Tsirk, 2014; Whittaker, 1994). The bipolar phenomenon has been discussed intensely in the last two decades, especially in terms of the confusion associated with the identification of *pièces esquillées* and cores (Bardon *et al.*, 1906; de la Peña, 2011, 2015a, 2015b; de la Peña & Toscano, 2013; Goodyear, 1993; Hayden, 1973, 1980; Hays & Lucas, 2007; Hiscock, 2015; Kamminga, 1978; Keeley, 1980; Knight, 1991; LeBlanc, 1992; Lothrop & Gramly, 1982; Shott, 1999; Shott, 1989; White, 1968). Due to both ethnographic and archaeological observations, previous works have sought to address these issues through a combination of functional and typological analyses. For the detection of differences between the cores and wedge/chisel pieces, experimental studies have played an important role (Jeske & Sterner-Miller, 2015). De la Peña's experimental studies (2011, 2015a, b) highlighted the technological and functional differences of bipolar mechanics. Cores present more symmetrical macro traces than splintered pieces. This is because the cores are actively and passively in contact with the stone.

The chronological and geographical distribution of bipolar reduction shows it is a complementary flaking technique that can be found in the Pleistocene and Holocene periods (Horta *et al.*, 2022). In terms of the Early, Middle, Late Pleistocene, and Holocene contexts of Africa (de la Torre, 2004; Gallotti *et al.*, 2020; Harmand *et al.*, 2015; Semaw, 2000; Tabrett, 2017; Van Riet Lowe, 1946), Asia (Güleç *et al.*, 2009; Huan et al., 2024; Keates, 2000; Li, 2016, 2023; Lin, 1987; Liu *et al.*, 2020; Ma *et al.*, 2020; Moore & Brumm, 2009; Naumenko, 2021; Picin *et al.*, 2022; Shen *et al.*, 2011; Yanagida & Kajiwara, 2018; Yang *et al.*, 2016, 2017; Zaidner, 2013, 2014), and Europe (Arzarello & Peretto, 2010; Barsky *et al.*, 2019; Capellari *et al.*, 2021; de la Peña & Toscano, 2013; de Lombera-Hermida *et al.*, 2016; Despriée *et al.*, 2018; Donnart *et al.*, 2009; Grimaldi *et al.*, 2020; Horta *et al.*, 2019; Kot *et al.*, 2022; Khrustaleva & Kriiska, 2022; Kuhn, 1995; Mourre *et al.*, 2011; Ollé *et al.*, 2016; Roda Gilabert *et al.*, 2012, 2015; Rodríguez-Álvarez, 2016; Rossini *et al.*, 2022; Ryssaert, 2005; Sánchez-Yustos *et al.*, 2017; Titton *et al.*, 2021; Soriano & Villa, 2017; Yeşilova *et al.*, 2021), bipolar flaking has been reported from several significant sites. This technique is not only present in Afro-Eurasia but also it is widely presented in The Americas (Berman *et al.*, 1999; Binford & Quimby, 1963; Bradbury, 2010; Eren, 2010; Forsman, 1976; Goodyear, 1993; Hayden, 2022; Honea, 1965; Jeske & Lurie, 1993; Leaf, 1979; Lothrop & Gramly, 1982; Lourdeau *et al*., 2023; Morgan *et al*., 2015; Pargeter & Tweedie, 2018). Likewise, several past and recent ethnographic studies demonstrate its wide variabilities in all over the world (Albright, 1982, 1984; Arthur, 2010; Emmons, 1911; Hampton, 1999; Hardy & Sillitoe, 2003; Hayden, 1979; Holmes, 1919; Kosambi, 1967; Kozák *et al*., 1979; MacCalman & Grobbelaar, 1965; McCall, 2012; McCarthy, 1947; Miller, 1979; Pétrequin & Pétrequin, 2020; Robinson, 1938; Roth, 1924; Shackley & Kerr, 1985; Shott, 1989; Sillitoe, 2017; Sillitoe & Hardy, 2003; Strathern, 1970; Teit, 1900; Vanderwal, 1977; Watson, 1995; White & Thomas, 1972; White, 1977a, 1977b, 1979). The use of this technique has been reported from different geographical areas, with no gender bias, particularly in the light of ethnographic and ethnoarchaeological studies (Albright, 1982, 1984; Arthur, 2010; Belkin *et al*., 2006; Brandt & Weedman, 2002; Bird, 1993; Flenniken, 1981; Masao, 1982; Roth, 1924; Sillitoe & Hardy, 2003; Weedman, 2006).

Comparative analyses, both qualitative and quantitative, among the different raw materials and techniques have been tested by numerous experiments for various purposes such as identification of the technology (Amick & Mauldin, 1997; Arroyo & de la Torre, 2020; Arroyo *et al*., 2020; Barham, 1987; Bradbury, 2010; Byrne *et al*., 2016 de la Torre *et al*., 2013; Diez-Martín *et al*., 2011; Douglass *et al*., 2021; Gurtov *et al*., 2015; Gurtov & Eren, 2014; Kobayashi, 1975; Kuijt *et al*., 1995; Li, 2016; Li *et al*., 2017; Low, 1997; Ma *et al*., 2020; Morgan *et al*., 2015; Muller & Clarkson, 2023; Pargeter *et al*., 2019; Pargeter & de la Peña, 2017; Pargeter & Eren, 2017; Roda Gilabert *et al*., 2012; Sánchez-Yustos *et al*., 2017), residue and technical microwear (Vergès & Ollé, 2011), comparative spatial analysis between freehand and bipolar flaking (de la Torre *et al*., 2019) or functional aspects (Arrighi *et al*., 2020; de la Peña, 2011, 2015a; Flenniken, 1981; Jeske & Sterner-Miller, 2015; Kamminga, 1978; Keeley, 1980). Even though bipolar reduction can be undertaken on many different materials, the relationship between this technique and quartz is often highlighted. It has been suggested that this technique allows for efficient reduction when the raw material is small or the quality is poor, such as in the case of quartz (Dickson, 1977; Driscoll, 2010, 2011, 2016; Flenniken, 1981; Hiscock, 1982; Tallavaara *et al*., 2010), and has been interpreted as the solution to overcome the dimension or quality obstacle of the raw material. As an example, Xiaochangliang (1.36 Ma), an early Pleistocene site situated in the Nihewan basin (northern China), showcases a substantial proportion of lithic artifacts obtained by the bipolar technique. Within this site's chert raw material assemblage, discernible internal flaws are apparent. The application of the bipolar technique within the Nihewan area has been construed as a strategic adaptation employed by hominin groups to optimize the utilization of low-quality raw materials (Yang *et al*., 2016).

In addition, there are cognitive comparative studies with different flaking techniques that examine the bipolar reduction (Delagnes *et al*., 2023; Macchi *et al*., 2021). Although controversial, the materials obtained in survey have also been tested through the bipolar window (Özçelik & Karahan, 2023).

In the current global context, we have elected to investigate the correlation between technical expertise and bipolar percussion conducted on an anvil through experimental methodologies.

This experiment was conducted to find an answer to the question: Are there any quantitative and qualitative differences between knappers with different levels of expertise, in terms of application of bipolar reduction? To address our experimental question, we adhered to a systematic experimental protocol aimed at reevaluating the negative connotations of the bipolar technique in light of the results obtained from the technological analysis of both kinematic parameters and experimental materials. Also, by discussing in detail the complex variants of bipolar technology from an ethnographic and ethnoarchaeological perspectives, we aim to show that this technique is more than just bashing the pebbles.

Materials and Methods

Experimental Setup

For the experimental program, twelve small quartzite pebbles were procured from the Francolí river basin (Tarragona, Spain). In terms of geological formation, quartz and quartzite pebbles are related to the *Buntsandstein* formation. In general, the morphology of the raw materials selected was round and elliptic with some samples being slightly flat. The mean of the raw materials was 58.7 mm in length (SD = 13.8 mm), 44.5 mm (SD = 11.1 mm) in width, 33.8 mm (SD = 7.5 mm) in thickness, and 128.4 g (SD = 71.2 g) in weight. Additionally, a granite nodule (*L*, 270 mm; *W*, 222 mm; *T*, 85 mm; *W*, 9520 g) was selected as an anvil, while a quartzite cobble (*L*, 100 mm; *W*, 60 mm; *T*, 51 mm; *W*, 389.5 g) was selected as a hammerstone (Table 1). These tools were used throughout the experimental program to maintain consistency. Before the experiments, we documented the metrics of each cobble and pebble (Wentworth, 1922), and they were photographed from three perspectives (Fig. 1).

Flaking with bipolar technique has a very different fracture mechanism compared to other flaking systems (Tsirk, 2014, pp. 25, 199; Whittaker, 1994, pp. 113–114-115). So, general knowledge of fracture mechanics may not be readily adapted to this specific technique. Therefore, the knowledge of bipolar technique differs for each subject in terms of its definition. We therefore indicate how each subject perceived the bipolar action (Online Resource 1).

We worked with twelve volunteer knappers with different levels of expertise. A consent form was approved and signed by all participants explaining both the experimental process and that ethical values related to the experiments. A categorization between the knappers was done based on their experience in the knapping activity. Three categories were specified in terms of flaking skills such as novice (no flaking experience), intermediate (2 to 5 years of flaking experience), and expert (> 5 years of flaking experience). Each group included two female and male participants (Table 2).

Two-Dimensional Video Motion Analysis

There are two different methods for quantitative analysis of a moving object, two- and three-dimensional video analyses. The bipolar technique differs from freehand flaking in its mechanics of motion, even though other stone flaking techniques show

Table 1 Metrics of experimental raw materials units

Code	Blank	Raw Material	Aim	Length (mm)	Width (mm)	Thickness (mm)	Weight (g)
Exp. Fr-RMU-14	Cobble	Quartzite	Core	68	59	43	202.2
Exp. Fr-RMU-10	Pebble	Quartzite	Core	48	38	26	65.6
Exp. Fr-RMU-17	Pebble	Quartzite	Core	58	31	25	63.1
Exp. Fr-RMU-04	Cobble	Quartzite	Core	66	54	39	165.9
Exp. Fr-RMU-03	Cobble	Quartzite	Core	72	50	35	171.8
Exp. Fr-RMU-15	Cobble	Quartzite	Core	75	41	40	174.7
Exp. Fr-RMU-18	Pebble	Quartzite	Core	57	41	38	117.8
Exp. Fr-RMU-02	Pebble	Quartzite	Core	44	38	36	85.4
Exp. Fr-RMU-16	Cobble	Quartzite	Core	78	61	45	267.1
Exp. Fr-RMU-09	Pebble	Quartzite	Core	60	57	28	144.6
Exp. Fr-RMU-06	Pebble	Quartzite	Core	43	32	28	46.5
Exp. Fr-RMU-12	Pebble	Quartzite	Core	35	32	23	36.2
Exp. Fr-RMU-13	Pebble	Quartzite	Hammerstone	100	60	51	389.5
Exp. Fr-RMU-19	Nodule	Granite	Anvil	270	222	85	9520

high dynamic in three-dimension (xyz). The bipolar technique has a two-dimensional mechanics. Although three-dimensional video motion analysis provides a high degree of accuracy in terms of spatial motion (Williams *et al.*, 2010, 2012), publications in human biomechanics have demonstrated that a well-organized two-dimensional motion experiment can provide accurate results or reduce the margin of error to very minimal levels, thanks to detailed methodological guidelines (Dingenen *et al.*, 2018; Hensley *et al.*, 2022; Miller & Nelson, 1973; Murray *et al.*, 2018; Payton, 2008; Peebles *et al.*, 2021; Pipkin *et al.*, 2016; Schurr *et al.*, 2017). Therefore, we based our work on Payton's guide to eliminating errors that can occur in two-dimensional video analysis in his study *Motion Analysis Using Video* (2008, p.18).

Preparation of Experiment Area

For the experiment, we chose earthen ground so that the flaking process could take in natural conditions (Fig. 2). Video motion analysis is based on testing the

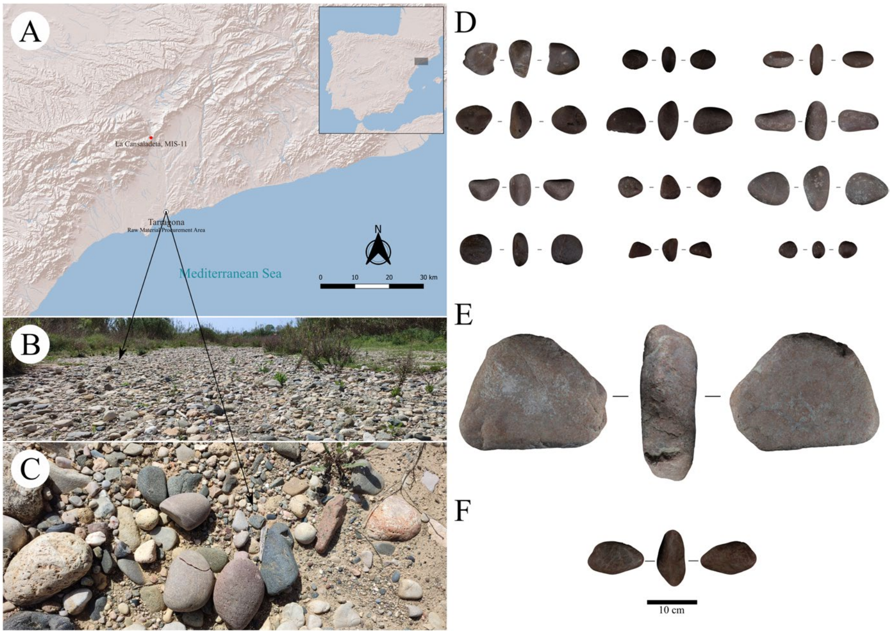

Fig. 1 **A** The map of Tarragona shows raw material procurement area for the experiment; **B-C** The view of fluvial materials from Francolí; **D** Experimental raw material units (quartzite); **E** Anvil (granite); **F** Hammerstone (quartzite)

Table 2 Information of participants before experiment

Participants	Sex	Levels of Expertise	Age	Height (cm)	Weight (kg)	Laterality
Knapper 01	Male	Expert	52	1.70	84	Left
Knapper 02	Female	Intermediate	60	1.57	52	Right
Knapper 03	Male	Intermediate	30	1.78	70	Right
Knapper 04	Female	Novice	32	1.62	60	Right
Knapper 05	Male	Novice	30	1.77	70	Right
Knapper 06	Male	Expert	32	1.77	84	Right
Knapper 07	Female	Intermediate	33	1.65	60	Right
Knapper 08	Female	Novice	51	1.73	88	Right
Knapper 09	Male	Intermediate	37	1.73	91	Right
Knapper 10	Female	Expert	57	1.70	70	Right
Knapper 11	Male	Novice	29	1.65	69	Right
Knapper 12	Female	Expert	44	1.69	61	Right

quantitative values of moving objects in the light of physical parameters. Therefore, in order to obtain precise numerical data, the calibration of the recorded video is crucial for the validity of the results. To ensure the reliability of the calibration of the videos, a one-square meter was created with the help of nails and rope in the area where the flaking process was carried out. In addition, two-meter

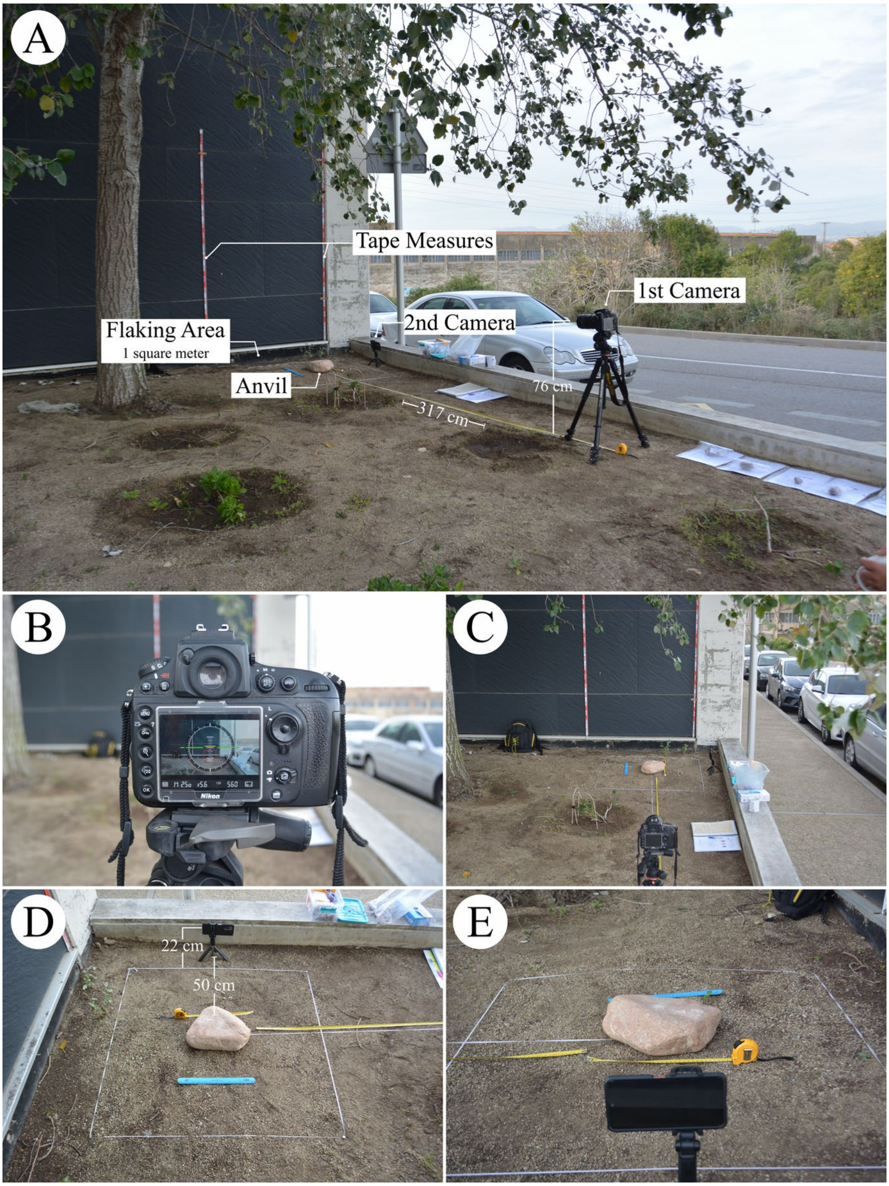

Fig. 2 **A** General view of experimental flaking area; **B** The view of flaking point from the screen of the first camera; **C** Horizontal view of flaking area behind the first camera; **D** Anvil and the second camera; **E** View of anvil behind the second camera

tape measure (×2) were vertically mounted to the wall to calibrate the videos during the analysis process. The reason for using two tape measures is that there were left-handed subjects. Subjects who used their left hand for flaking had to change their position so that the moving object (hammerstone) could be accurately tracked by the camera. If a single tape measure had been used, the tapes would not have been fully visible in the camera, depending on the changed position. However, the two tapes we used made it easy for both left-handed and right-handed subjects to change their positions without disturbing the camera angle and position. The anvil was fixed at the central point of the square meter for the flaking process.

We used two cameras for this experiment. The first camera was used for raw video recording regarding motion analysis. The entire experiment was recorded with a Nikon D800 reflex camera and AF-S NIKKOR 28–300 mm 1:3.5 56 G lens. This camera was fixed at a height of 76 cm, 317 cm behind the point where the flaking activity took place. The focal length was set at 28 mm (75.38° view of angle). The distance, height, and focal length of the camera were kept constant for all 12 subjects to avoid parallax (perspective) error (Martin *et al.*, 2020; Miller & Nelson, 1973; Payton, 2008, p. 18; Stephens *et al.*, 2019; Tian *et al.*, 2002). This camera was set up east of the anvil, at a distance ensuring that the camera framed the whole flaking area, as well as the measure tapes, at a perpendicular angle (Fig. 3).

The flaking activity was carried out against a black background, and participants were provided green nitrile gloves to wear on their hammerstone-wielding hands. The goal of this process was to create a color contrast so that the moving object could be seen more clearly, allowing for a more precise tracking (see details in section *Point mass track*). The second camera was used for slow-motion recording. The slow-motion mode of the Redmi Note Pro 10 was used for this. The videos were recorded at 240 FPS in 720p quality. The smartphone was fixed 50 cm north of the anvil for a clear and close view of the flaking process. Slow motion was used to better analyze the gestures of each participant and to better observe the mechanics of the bipolar technique for the post-experiment process.

Knapping Procedure

Participants were informed with a simple instruction before starting the flaking process:

- Each subject was allowed to reduce only one core.
- Each subject was given 2 min, and all of them used the same hammerstone.
- They had to obtain as many flakes as possible.
- No verbal or physical intervention was made to the subject during the flaking.

Although this is a small sample size, it is more in line with the purpose of our study because the aim is to evaluate the kinematic parameters of knappers' motions according to the levels of expertise rather than detailed technological analysis. Therefore, the focus was on the control of the hammerstone and the velocity, acceleration, and kinetic energy applied to the hammerstone by the knappers when reducing a single raw material unit. When the two minutes were over, the video recordings and flaking process were finalized. All the impacts of each participant were recorded. When the flaking was completed, all the pieces were labeled and individually stored in ziplock plastic bags for technological analysis.

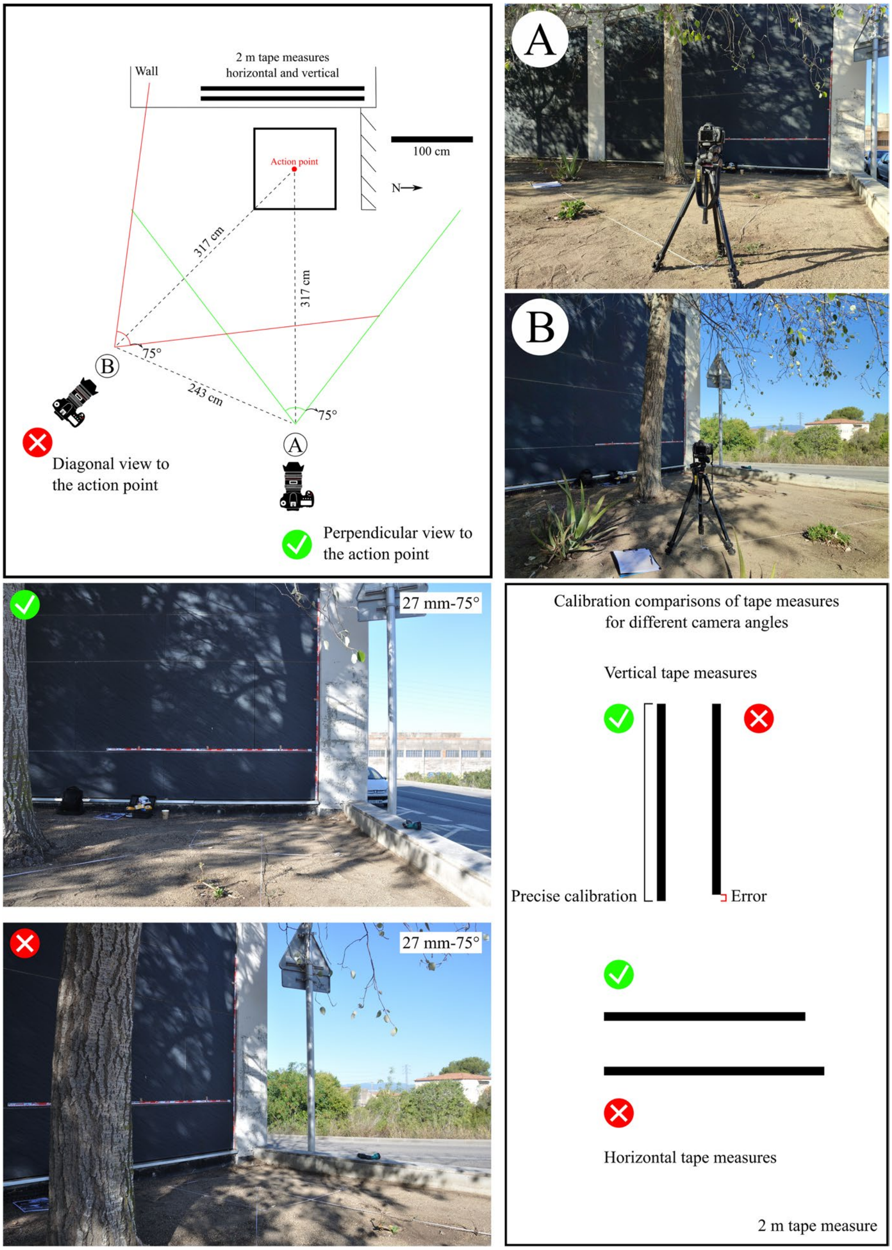

Fig. 3 Spatial plan of experiment area and comparison between wrong and correct camera position. **A** General view (Correct camera position); **B** General view (Wrong camera position). Calibration of tape measures according to the different camera angles

Kinematic Data Collection Protocol

To analyze the videos, we used *Tracker* (Tracker Video Analysis and Modeling Tool. (2023). https://physlets.org/tracker/), an open-source video analysis software (Brown & Cox, 2009; Claessens, 2017; de Jesus, 2017). It is designed to analyze the mechanics of moving objects and individuals through certain kinematic parameters. For this experiment, it was used to assess the quantitative differences in the mechanics of bipolar technique performed by participants with different levels of expertise.

All the videos were individually uploaded to the software for analysis. First, the videos were calibrated with the tape measures used during the experiment to obtain precise numerical data. Second, the x and y axis were determined. The purpose of x–y plane was to define a coordinate system and analyze the position and acceleration of the hammerstone. The position of the pebble placed on the anvil was considered as the zero point, and the x–y plane was created with reference to the zero point. Once the calibration process was complete, a specific analysis frame was selected from each video. The analysis frame was set at 569 (22.760 s). However, the moment at which this frame is determined was different for each video (Fig. 4). The importance of the frame analyzed here is that it includes the impacts recorded until the first flake was obtained. For example, 569 frames were set at the beginning of the video while for another video, they were set in the middle or at the end of the video due to the different flaking performance of the participants (Table 3).

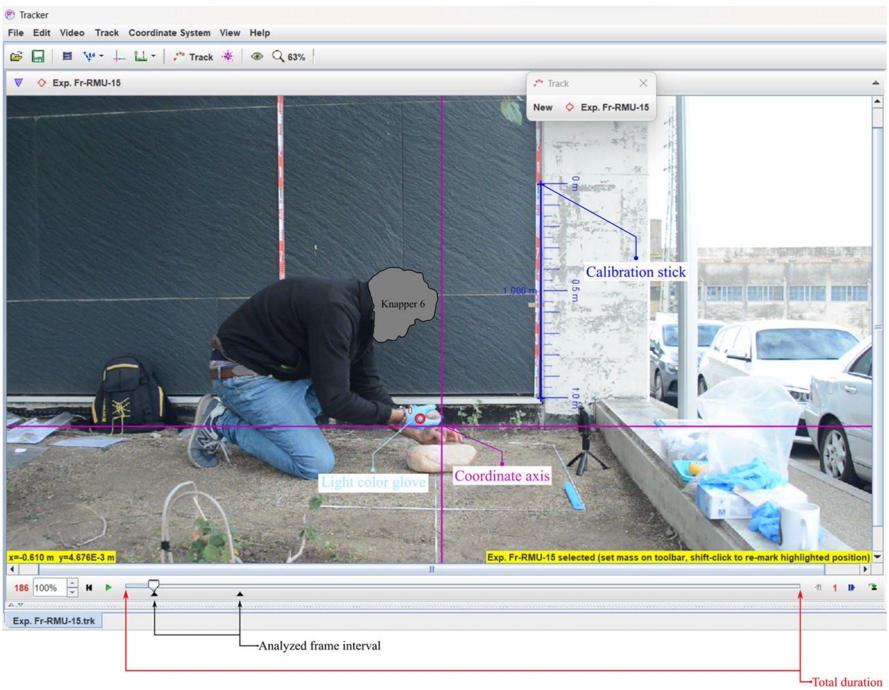

Fig. 4 Analysis window of Tracker. Demonstration of calibration tools, total duration of video and analyzed frame interval

Table 3 Frame and strike counts of each experiment set

Participant ID	Experience	Raw material	Total frame	Start frame	End frame	Analyzed frame	Total strike	Analyzed strike
Knapper 01	Expert	Exp. Fr-RMU-14	3011	128	697	569	45	9
Knapper 02	Intermediate	Exp. Fr-RMU-10	1643	677	1246	569	21	11
Knapper 03	Intermediate	Exp. Fr-RMU-17	3029	66	635	569	58	9
Knapper 04	Novice	Exp. Fr-RMU-04	3041	68	637	569	118	22
Knapper 05	Novice	Exp. Fr-RMU-03	3065	581	1150	569	51	9
Knapper 06	Expert	Exp. Fr-RMU-15	4481	186	755	569	95	9
Knapper 07	Intermediate	Exp. Fr-RMU-18	3044	1818	2387	569	77	16
Knapper 08	Novice	Exp. Fr-RMU-02	3011	34	603	569	53	10
Knapper 09	Intermediate	Exp. Fr-RMU-16	3035	1927	2496	569	59	11
Knapper 10	Expert	Exp. Fr-RMU-09	3072	294	863	569	55	9
Knapper 11	Novice	Exp. Fr-RMU-06	689	63	632	569	8	8
Knapper 12	Expert	Exp. Fr-RMU-12	3024	2182	2751	569	45	5

Kinematic Analysis

Point Mass Track

After determining the analysis frame, the process of point mass tracking (PM) began. PM is a method for determining the kinematic parameters of a moving object over time. The important point is that the object to be tracked must have a mass. Once a moving object was identified in the video, its mass was registered (389.5 g). In this study, PM was done manually as it allows higher precision in the measurements. During this process, a fixed point was set on the object in each frame. To ensure the accuracy of the fixed point, each participant performed the flaking process wearing light green nitrile gloves. Once tracking was complete, four important kinematic parameters were considered in terms of understanding the mechanics of the bipolar technique (Bril et al., 2010, 2012, 2015).

Kinematic Parameters

The continuous development of technology enables innovative approaches to obtain very different results and interpretations in scientific studies. There are various methods, devices, and software to analyze and understand the quantitative values of moving objects (Beichner, 1996; Laws & Pfister, 1998; Payton *et al*., 2008). We can see how biomechanical gloves and clothing can digitize and analyze real human body movement (Caeiro-Rodríguez *et al*., 2021). In addition, many open- or closed-source software that allow researchers to detect and analyze moving objects in videos are also preferred by researchers. Not only in physics and engineering but also in different fields of archaeology and primatology, the analysis of moving objects or individuals has been the main subject of many studies, regarding kinematic parameters such as position of hammerstone, velocity, acceleration, and kinematic (Bril *et al*., 2012, 2015; Macchi *et al*., 2021).

The testing of motion mechanics of the bipolar technique was based on these four kinematic parameters (Miller & Nelson, 1973). These parameters represent the quantitative values of the position, velocity, acceleration, and kinetic energy of a moving object (see the details in Online Resource 2).

y: position-component, y (m) displays the position of the moving object relative to the y-axis over time. In bipolar reduction, the moving object is the hammerstone. The point where the hammerstone meets the core is defined as the zero point. The hammerstone moves away from the zero point, i.e., the core, with the upward movement of the hand of the knapper. It moves closer to the core, i.e., the zero point when the impact is attempted to obtain a flake from the core.

v: velocity magnitude, v (m/s) displays the velocity of the moving object over time. Velocity is the rate of the displacement of an object (Atkins & Escudier, 2013; Rennie & Law, 2019). The velocity of the hammerstone depends on the force applied by knapper and the mass of the hammerstone. The peak point on the graph shows the moment when the velocity is highest. This point is just before the hammerstone meets the core.

ay: acceleration y: component, a_y (m/s^2) displays the acceleration of the moving object relative to the y-axis over time. Acceleration shows the change in the velocity of the moving object over time (Atkins & Escudier, 2013; Rennie & Law, 2019). When the velocity of an object decreases due to a force, it is defined as negative acceleration, and when the velocity increases, it is defined as positive acceleration. In the graph, the negative acceleration was recorded during the upward movement of the hammerstone. This is because at this time the hammerstone was ready to contact the core. Therefore, it is when the moving object is at its slowest moment. The positive acceleration was recorded just before the hammerstone meets the core. This is when the moving object is at its fastest.

K: kinetic energy, K ($g \cdot m^2/s^2$) displays the energy of the moving object over time (Atkins & Escudier, 2013; Rennie & Law, 2019). It also shows how much force is applied by the knapper during the flaking process. The peak point on the graph shows the point where kinetic energy is the highest. This point is reached just before the contact of the hammerstone with the core. In addition, the lowest point recorded immediately after the highest point indicates the contact of the hammerstone with the core. At this point, the kinetic energy of the hammerstone is almost zero due to the contact of a moving object with a stationary object.

Technological Analysis

All the pieces obtained during the flaking process were categorized into five technological categories core, complete flake, broken flake (with proximal part), flake fragment (distal/medial part), and fragment. For the technological analysis of experimental materials, key attributes were considered to cover the characteristics of the bipolar technique. In the case of cores, the type of platform, bipolar scar, the intensity of crushing on the platform, and the presence or absence of battering marks were considered. In the case of flakes, in addition to the attributes listed above, the presence of functional edge, flake terminations, the profile, and the element form with a citrus-section were also considered (Byrne *et al*., 2016; Cotterell & Kamminga, 1987; Low, 1997; Ma *et al*., 2020; Odell, 2004, p. 57).

A small explanation of the citrus-section phenomenon would be an important action. Such pieces can be the result of sequential flaking or an initial blow. In lithic terminology, these pieces are called by different names: lemon slice (Białowarczuk, 2015), orange segment (Ballin, 1999, 2021; Crabtree, 1982; Pargeter & Tweedie, 2018), citrus-section (Low, 1997), orange section (Whittaker, 1994: 115), pie-shaped cobble cores (Barham, 1987; Flenniken, 1981), compression-controlled fracture (Cotterell & Kamminga, 1987), *quartier d'orange* (Guyodo & Marchand, 2005), and quartier (Donnart *et al*., 2009). Morphologically, these pieces have two ventral faces. One part of the piece contains the cortex. The part with the cortex shows part of the morphology of the pebble or cobble before blow. They have a triangular cross-section. To avoid terminological confusion, we refer to such pieces as citrus-section. Citrus-section was defined by Low in his experimental work on bipolar technique. Low (1997, p. 135) describes this type of pieces in detail as follows:

> "This class of bipolar fracture is directly related to the overall body form of the material being worked, which is to say that these flakes derive from a pebble or cobble that is fairly round with a width to thickness ratio being nearly equal. I have previously noted that with an ellipsoid-shaped body the spherical waves pass through a larger portion of a specimen creating a highly variable area of central pressure within the material as the force waves emanate through the material".

For the dimensional analysis of the materials, only their length, width, thickness, and weight were taken into account. The lengths are measured along the technological axis where this can be determined and along the morphological axis in other cases (Inizan *et al.*, 1999, p. 107). The proximal, medial, and distal widths and thicknesses were not measured due to the raw materials were small-sized pebbles (Table 4; Fig. 5).

Graphic Representation

Both modern and traditional graphic representation methods are used in combination to describe the technological indicators for the analysis of experimental materials. Experimental and some archaeological samples photographed with Nikon D780, 40-mm lens. Traditional lithic material illustration was made by manual drawing (Addington, 1986; Inizan *et al.*, 1999, p. 118; Raczynski-Henk, 2017). In our study, we have illustrated fine-grained quartzite with outline hatching and dotting in an ultra-realistic style with tips of different sizes. We performed microscopic documentation of some experimental and archaeological samples with the 3D digital microscope Hirox-KH8700 (low-range, × 35).

Statistical Analysis

Statistical analyses were applied to understand whether there were any differences in kinematic parameters between participants, levels of expertise, and sex. All the statistical analysis was performed in IBM SPSS Version 29.0 (Pallant, 2020). Our statistical analysis aimed to test the null hypothesis (H_0).

$\boldsymbol{H_0}$**:** There is no significant difference between the levels of expertise and sex regarding kinematic parameters.

Data Distribution and Normality Test

A normality test was applied to determine how the data was distributed. It is possible to determine whether the data are normally distributed using two different tests such as Kolmogorov–Smirnov and Shapiro–Wilk. In our study, Kolmogorov–Smirnov was applied as a normality test. This is because Shapiro–Wilk is a more appropriate test for the small-sized samples (< 50) while Kolmogorov–Smirnov is used for large-sized samples (≥ 50) (Mishra *et al.*, 2019).

Table 4 Technological categories

Technological categories	Definitions of technological categories	Technological attributes	Attribute type
Core	A piece that is intentionally flaked to produce a flake	Crushing	Absent, slight, medium, heavy
		Platform	Punctiform, linear, plain
		Scar	Scar with one impact, bipolar scar
		Battering marks	Yes, no
Flake	Pieces obtained as a result of intentional flaking from the core and bearing the characteristic indicators of the flaking mechanism such as platform, dorsal, and ventral faces	Platform	Punctiform, linear, plain
		Bulb	No bulb, only one bulb, double bulb
		Crushing	Absent, slight, medium, heavy
		Profile	Convex, concave, irregular, straight
		Termination	Feather, step, hinge, *outrepassé*
		Cutting edge	Sharp profile less than 60°
		Battering marks	Yes, no
		Citrus-section	Yes, no
		Scar	Scar with one impact, bipolar scar
Broken flake	This term is used for flakes with fractured distal parts. These pieces, completely or partially, include platform and bulb	Fragment type	Longitudinal, transversal, and *siret* fractures (Siret, 1933)
Flake fragment	This term is used for flakes with fractured proximal parts. These pieces do not demonstrate platform	-	
Fragment	These fragments were used to characterize the unintentional, angular fractures that occur during the flaking process	-	

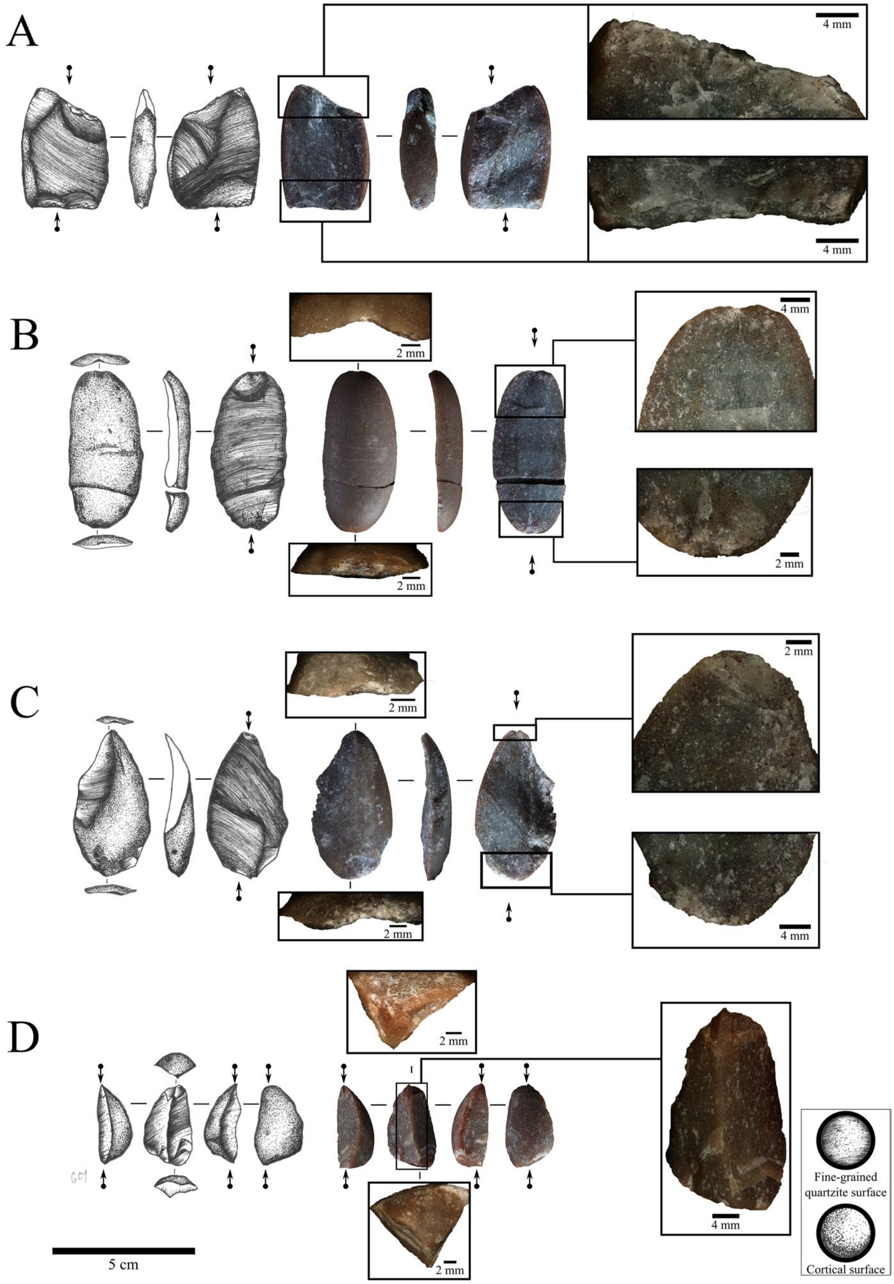

Fig. 5 Manual and microscopic graphic documentations of some technological attributes. **A** Core with opposed crushed striking platform; **B-C** Flake with proximal and distal striking platform; **D** Citrus-section element with triangle cross section. Technical illustration: Görkem Cenk Yeşilova. 3D digital microscope: Hirox-KH8700 (low-range, x35)

Non-parametric Tests

According to the results of normality distribution, non-parametric tests were performed Kruskal–Wallis and Mann–Whitney *U* (Pallant, 2020). Kruskal–Wallis (for continuous variables more than two groups) and Mann–Whitney *U* (for continuous variables between two groups) tests are non-parametric versions of the *t* test and one-way ANOVA. In this study, the Kruskal–Wallis test was used to compare kinematic parameters (position, velocity magnitude, acceleration and kinetic energy of hammerstone) between the 12 participants and knappers with 3 different levels of expertise, while the Mann–Whitney *U* test was used to compare these parameters between the female and male groups. One-way ANOVA (Tamhane) was performed to see the differences between 12 participants and 3 different levels of expertise. Even though One-way ANOVA is a parametric test, Tamhane post-hoc is used for non-normal distributed data. Also, in cases where statistically significant differences were identified, Pairwise Comparison was performed. This type of comparison shows which groups are significantly different and which are not (Pallant, 2020, p. 278). The significance level of the tests was set up at $p<0.05$. Significance values were adjusted by Bonferroni correction for the Pairwise Comparison. Median values of kinematic parameters that showed statistically significant differences among participants, levels of expertise, and female / male were taken into account. This is because both Kruskal–Wallis and Mann–Whitney *U* tests compare the median values rather than mean (Pallant, 2020, p. 236, 243). Chi-square test was applied to detect the association in the categorical variables of technological attributes, levels of expertise, and sex (see details of statistical analysis in Online Resource 3).

Results

General Observations from the Experiments

During the experiments, it was observed that expert knappers paid attention to the morphology of the core and the hammerstone before starting the flaking. First, the knappers rehearsed how to orient the blank on the anvil. Then, they determined the point where the hammerstone had the most suitable morphology for the flaking (Fig. 6A). Some knappers systematically, depending on the morphology of the pebble, split the pebble into two and continued flaking with one of the halves of the pebble. In general, the hammerstone was used with a baseball-style grip (Fig. 6D) (Bril *et al.*, 2015). The flat part of the hammerstone was used in the palm of the hand. However, the curved or relatively convergent parts were the point in contact with the blank. The knappers reduced the core by controlling each impact. After each detachment, they quickly checked the final shape of the core and continued until the flaking was finished.

Intermediate and novice knappers did not pay attention to the morphology of the core and hammerstone (Fig. 6B and C). Some novice knappers grasped the hammerstone with cylinder style (Fig. 6C and D). In addition, their impacts were too fast and uncontrolled. The core was never rotated to find a suitable platform or

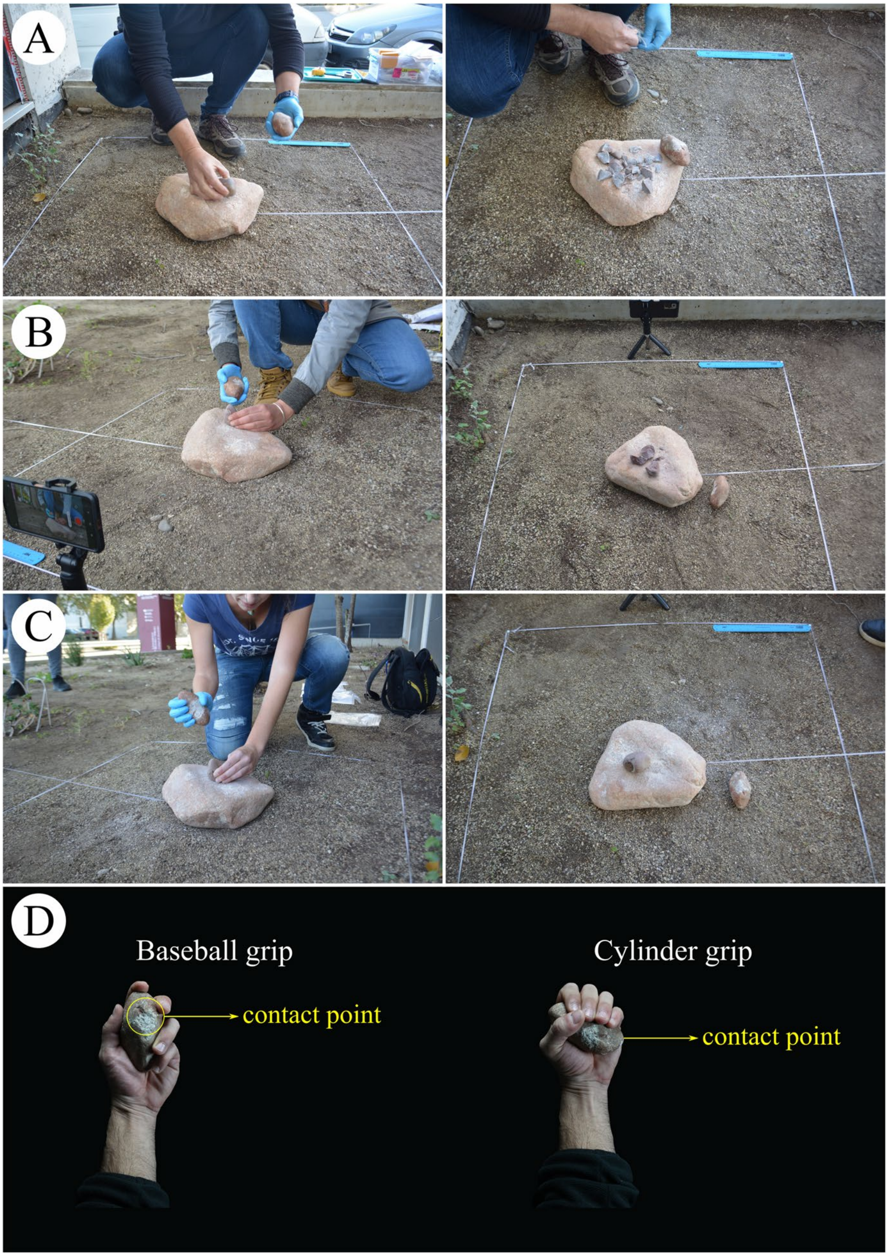

Fig. 6 General view from the experiment. **A** Expert knapper; **B** Intermediate knapper; **C** Novice knapper; **D** Grip types

orientation, and the same area was hit successively. Moreover, some participants were also observed who were unable to obtain any extractions from the pebbles during the experiment (Fig. 6C). The grip style of the hammerstone was almost unchanged. Some knappers involuntarily pulled their fingers back to protect them from the impact of the hammerstone during the flaking (Online Resource 4; 5; 6 include the slow-motion records of each level of expertise).

Figure 7 shows the kinematic parameters measured during the flaking process by the expert, intermediate, and novice knappers. The graph of the expert knapper shows a regular distribution of kinetic energy (Fig. 7A (4)), while the graph of the novice and intermediate knappers shows a much more irregular pattern (Fig. 7B (4) and C (4)). The irregular distributions were also observed in other kinematic parameters. Expert knappers raised the hammerstone very high to get the first extraction. Later, however, the height of the hammerstone was kept at a constant level. This level of height was less than the first one (Fig. 7A (1)). This was not observed in the actions of novice and intermediate knappers (Fig. 7B (1) and C (1)). Likewise, the velocity of the flaking also showed differences. Expert knappers applied an almost constant velocity for each impact (Fig. 7A (2)), whereas this was also not observed in novice and intermediate knappers (Fig. 7B (2) and C (2)). Also, the acceleration of the hammerstone showed differences between the levels of expertise (Fig. 7A (3)–C (3)).

Statistical Analysis of Kinematic Parameters

The results of the Kolmogorov–Smirnov test showed that all the kinematic parameters present non-normal distribution: *y: position-component*: $D(6839) = 0.159, p < 0.001$, *v: velocity magnitude*: $D(6839) = 0.265, p < 0.001$, *ay: acceleration y: component*: $\mathrm{D}(6839) = 0.222, p < 0.001$, *K: kinetic energy*: $\mathrm{D}(6839) = 0.375, p < 0.001$ (George & Mallery, 2019; Tabachnick & Fidell, 2013).

y: Position-Component, y (m) by Each Participant, Levels of Expertise, and Sex

According to the Kruskal–Wallis test, a significant difference was observed in the position of the hammerstone relative to the y-axis between each participant ($x^2(11, n = 6839) = 2309.426, p < 0.001$), while no difference was found between participants with different levels of expertise ($x^2(2, n = 6839) = 1.527, p = 0.466$). On the other hand, the Mann–Whitney U test showed that there was a significant difference between female and male participants ($U = 3753640.000, z = -25.635, p < 0.001$). Female participants raised the hammerstone higher than male participants.

v: Velocity Magnitude, v (m/s) by Each Participant, Levels of Expertise, and Sex

The Kruskal–Wallis test showed a significant difference in the velocity of the hammerstone between each participant ($x^2(11, n = 6839) = 747.599, p < 0.001$) and participants with different levels of expertise ($x^2(2, n = 6839) = 113.264, p < 0.001$).

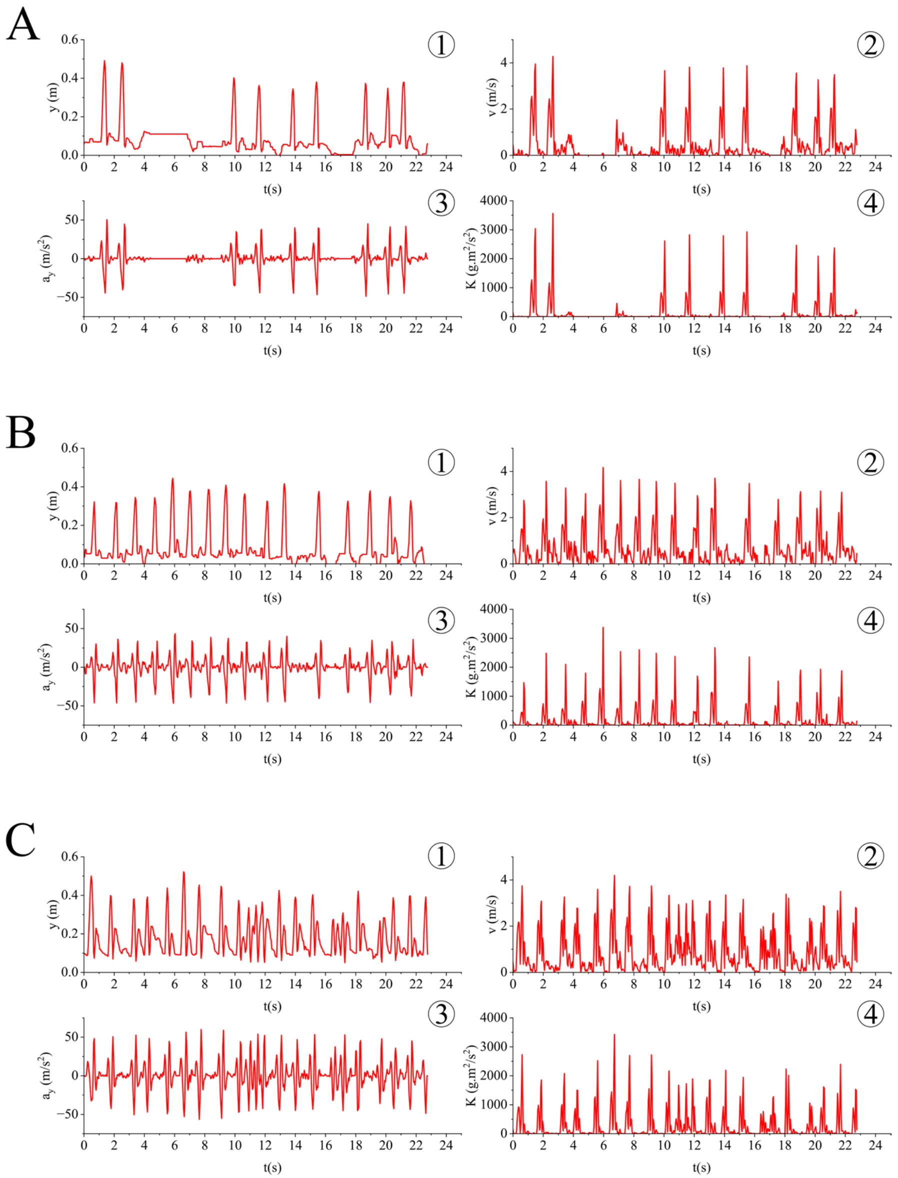

Fig. 7 Representative graphs that show kinematic parameters according to levels of expertise. **A** Expert knapper; **B** Intermediate knapper; **C** Novice knapper. Position of the hammerstone according to the y axis, y: position-component (1); Velocity magnitude, v: velocity magnitude (2); Acceleration of hammerstone, ay: acceleration y: component (3); Kinetic energy, K: kinetic energy (4)

Intermediate knappers used the hammerstone with more velocity than novices and experts. The results of the comparative analysis between female and male participants also confirmed the statistical difference with the results of the Mann–Whitney

U test ($U = 5086521.000, z = -9.393, p < 0.001$). Female knappers present more velocity than male knappers in the flaking activity.

ay: Acceleration y: Component, a_y (m/s^2) by Each Participant, Levels of Expertise, and Sex

The results of the comparative analysis, Kruskal–Wallis and Mann–Whitney *U*, showed that there was no significant difference in the acceleration of the hammerstone between the participants ($x^2(11, n = 6839) = 8.117, p = 0.703$), knappers of different levels of expertise ($x^2(2, n = 6839) = 0.837, p = 0.658$), and the sex ($U = 5752941.500, z = -1.151, p = 0.250$).

K: Kinetic Energy, K ($g \cdot m^2/s^2$) by Each Participant, Levels of Expertise, and Sex

In terms of kinetic energy, Kruskal–Wallis and Mann–Whitney *U* tests showed that there were significant differences between each participant ($x^2(11, n = 6839) = 744.827, p < 0.001$), knappers with different levels of expertise ($x^2(2, n = 6839) = 113.088, p < 0.001$), and

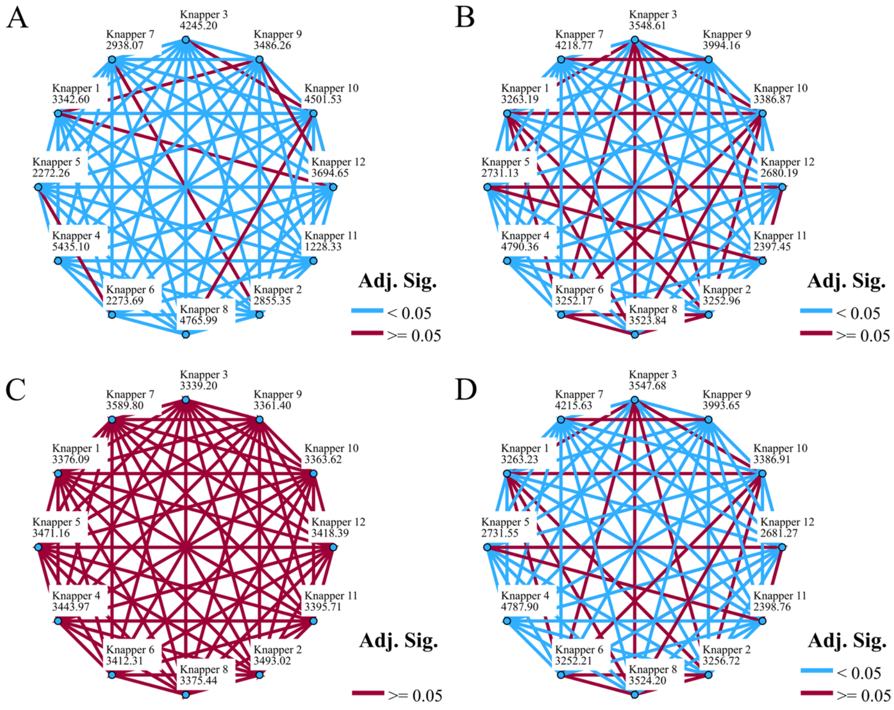

Fig. 8 Pairwise comparison between 12 participants according to the kinematic parameters (Each node demonstrates the sample average rank of participants). **A** Position of the hammerstone according to the y axis, y: position-component; **B** Velocity magnitude, v: velocity magnitude; **C** Acceleration of hammerstone, ay: acceleration y: component; **D** Kinetic energy, K: kinetic energy

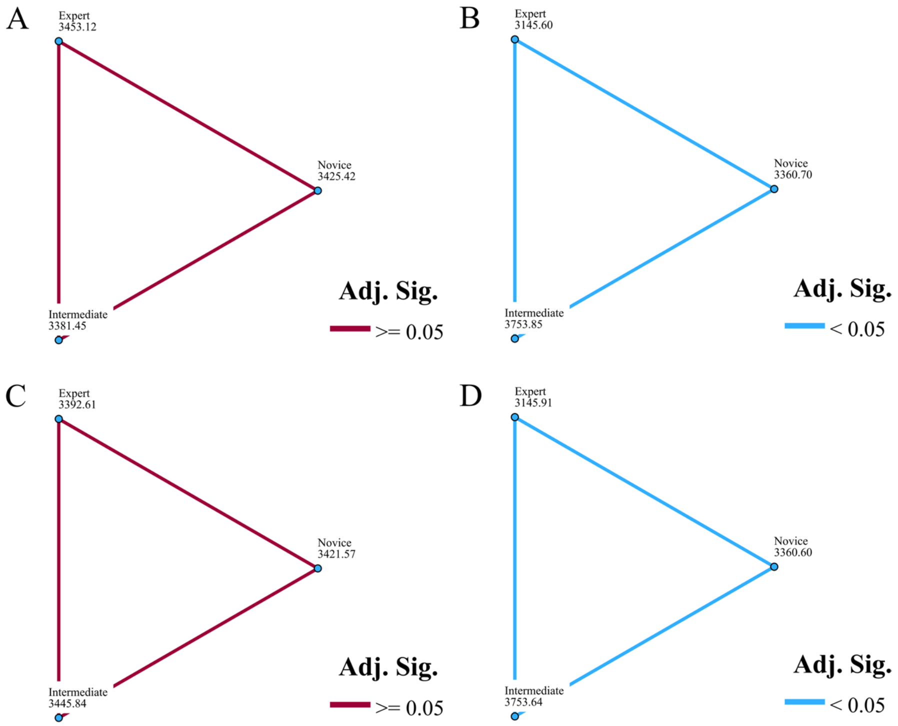

Fig. 9 Pairwise comparison between the levels of expertise according to the kinematic parameters (Each node demonstrates the sample of average rank of participants). **A** Position of the hammerstone according to the y axis, y: position-component; **B** Velocity magnitude, v: velocity magnitude; **C** Acceleration of hammerstone, ay: acceleration y: component; **D** Kinetic energy, K: kinetic energy

between sex ($U = 5086726.000, z = -9.390, p < 0.001$). Intermediate knappers used the hammerstone with more kinetic energy than novices and experts. Also, female knappers performed the flaking activity with more kinetic energy than males.

The results of pairwise comparisons more clearly illustrated the differences between participants, levels of expertise, and sex (Figs. 8, 9, and 10). Intermediate knappers applied more kinetic energy than novice and expert knappers. On the other hand, expert knappers applied less kinetic energy than novice knappers. The statistical difference in kinematic parameters between the sex showed that female participants had higher numerical values in the position of the hammerstone, velocity, and kinetic energy (Fig. 11).

Technological Analysis

General Technological Categories

Tables 5 and 6 show the distribution of technological categories according to levels of expertise and sex. The total lithic elements obtained from the experiment were 86

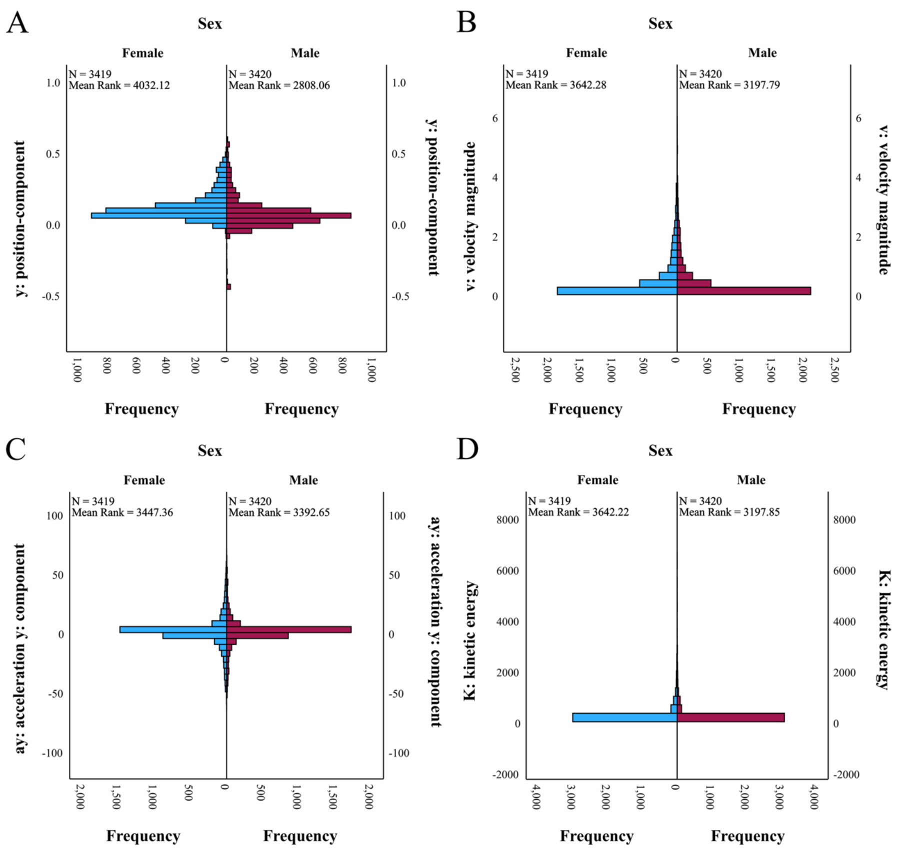

Fig. 10 The results of Mann-Whitney U test between the sex according to the kinematic parameters. **A** Position of the hammerstone according to the y axis, y: position-component; **B** Velocity magnitude, v: velocity magnitude; **C** Acceleration of hammerstone, ay: acceleration y: component; **D** Kinetic energy, K: kinetic energy

flakes (51.5%), 35 fragments (21.0%), 23 broken flakes (13.8%), 12 cores (7.2%), 9 flake fragments (5.4%), and 2 pebbles (1.2%) from which no flakes were extracted. There was no association between knappers with different levels of expertise and technological categories $(x^2(10, n = 167) = 13.253, p = 0.210)$. However, there was an association between female and male in terms of technological categories $(x^2(5, n = 167) = 14.922, p = 0.011)$. Male knappers produced more flakes than females.

Cores

Tables 7 and 8 show the attributes of the cores according to levels of expertise and sex. Overall, the cores had platforms with heavy crushing marks the majority of the cores (41.7%), followed by crushing with a medium (33.3%) and slight (8.3%) incidence, and

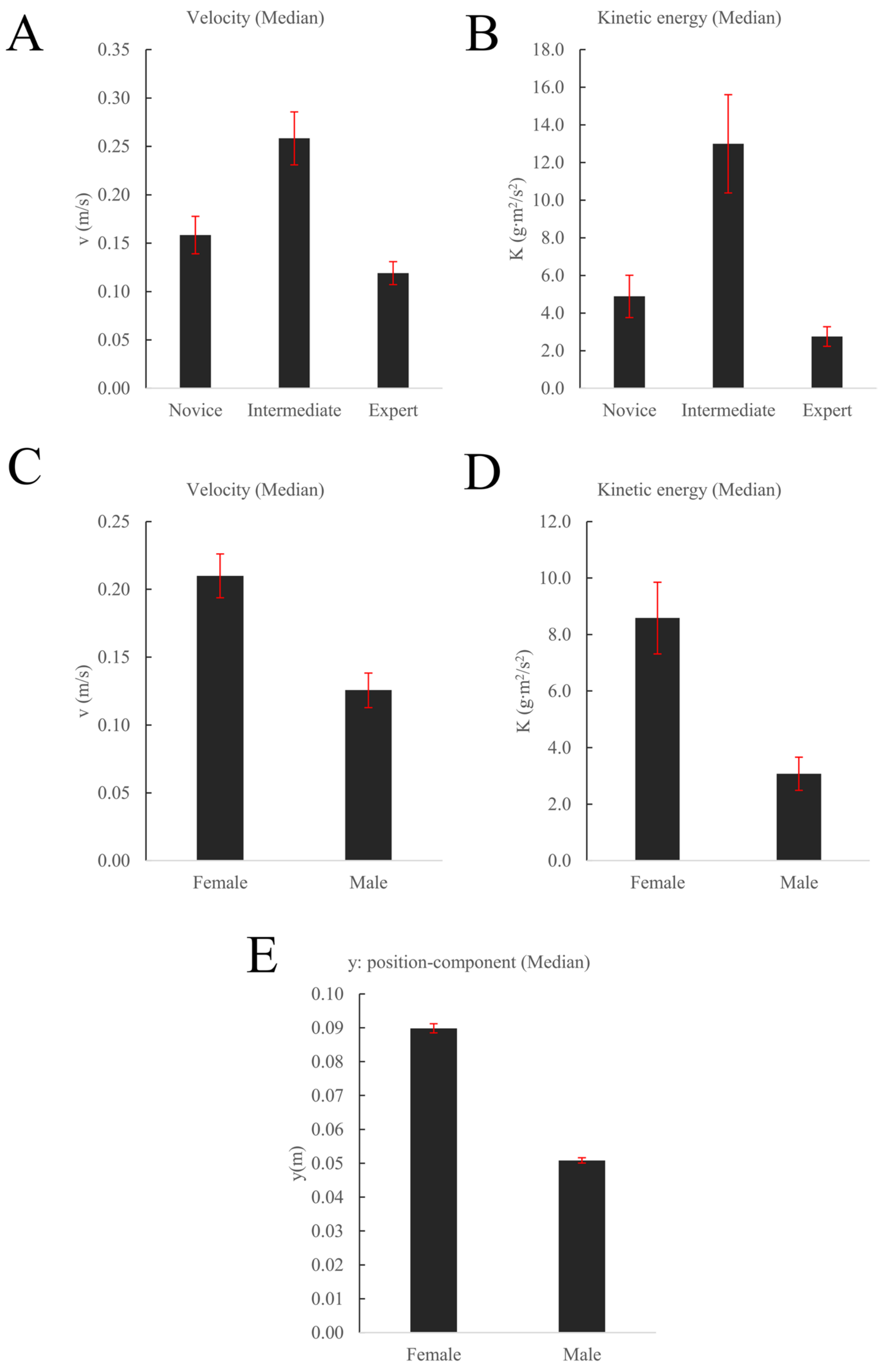

Fig. 11 Median values of kinematic parameters showing statistical differences between sex and different levels of expertise. Between levels of expertise: **A** Velocity; **B** Kinetic energy. Between sex: **C** Velocity; **D** Kinetic energy; **E** Position of hammerstone. Error bars: 95 % confidence interval

Table 5 Technological categories according to levels of expertise

		Novice		Intermediate		Expert		Total	
		Count	%	Count	%	Count	%	Count	%
Technological categories	Broken flake	4	12.5%	9	15.3%	10	13.2%	23	13.8%
	Core	2	6.3%	5	8.5%	5	6.6%	12	7.2%
	Flake	16	50.0%	27	45.8%	43	56.6%	86	51.5%
	Flake fragment	1	3.1%	2	3.4%	6	7.9%	9	5.4%
	Fragment	7	21.9%	16	27.1%	12	15.8%	35	21.0%
	Pebble	2	6.3%	0	0.0%	0	0.0%	2	1.2%
	Total	32	100.0%	59	100.0%	76	100.0%	167	100.0%

Table 6 Technological categories according to the sex

		Female		Male		Total	
		Count	%	Count	%	Count	%
Technological categories	Broken flake	2	6.3%	21	15.6%	23	13.8%
	Core	5	15.6%	7	5.2%	12	7.2%
	Flake	17	53.1%	69	51.1%	86	51.5%
	Flake fragment	1	3.1%	8	5.9%	9	5.4%
	Fragment	5	15.6%	30	22.2%	35	21.0%
	Pebble	2	6.3%	0	0.0%	2	1.2%
	Total	32	100.0%	135	100.0%	167	100.0%

only 16.7% of the cores with no crushing marks on their platform. Linear platform (66.7%) is one of the most represented attributes, followed by plain (25.0%) and punctiform (8.3%). Almost all the cores (91.7%), regardless of the knapper skill, clearly show bipolar scars developed from the contact with the anvil. The percentage of cores showing scars with one impact point is very low (8.3%). Fifty percent of the cores show battering marks on the cortical part, while the other 50% do not. When comparing the technological attributes of the cores across categories, we found no association between the levels of expertise and the presence of crushing marks on the cores ($x^2(6, n = 12) = 4.440, p = 0.617$), the type of platform ($x^2(4, n = 12) = 8.400, p = 0.078$), the presence of bipolar scar ($x^2(6, n = 12) = 1.527, p = 0.466$), nor association on the presence of battering marks ($x^2(2, n = 12) = 3.600, p = 0.165$). No association were observed either in the comparison between sex and the presence of crushing ($x^2(3, n = 12) = 5.006, p = 0.171$), type of platform $x^2(2, n = 12) = 1.543, p = 0.462$), bipolar scar ($x^2(1, n = 12) = 0.779, p = 0.377$), or battering marks ($x^2(1, n = 12) = 3.086, p = 0.079$).

Table 7 Core attributes according to levels of expertise

		Novice		Intermediate		Expert		Total	
		Count	%	Count	%	Count	%	Count	%
Crushing	Absent	1	50.0%	1	20.0%	0	0.0%	2	16.7%
	Heavy	1	50.0%	2	40.0%	2	40.0%	5	41.7%
	Medium	0	0.0%	2	40.0%	2	40.0%	4	33.3%
	Slight	0	0.0%	0	0.0%	1	20.0%	1	8.3%
	Total	2	100.0%	5	100.0%	5	100.0%	12	100.0%
Platform	Linear	2	100.0%	5	100.0%	1	20.0%	8	66.7%
	Plain	0	0.0%	0	0.0%	3	60.0%	3	25.0%
	Punctiform	0	0.0%	0	0.0%	1	20.0%	1	8.3%
	Total	2	100.0%	5	100.0%	5	100.0%	12	100.0%
Scar	Bipolar scar	2	100.0%	5	100.0%	4	80.0%	11	91.7%
	Scar with one impact point	0	0.0%	0	0.0%	1	20.0%	1	8.3%
	Total	2	100.0%	5	100.0%	5	100.0%	12	100.0%
Battering marks	No	1	50.0%	1	20.0%	4	80.0%	6	50.0%
	Yes	1	50.0%	4	80.0%	1	20.0%	6	50.0%
	Total	2	100.0%	5	100.0%	5	100.0%	12	100.0%

Table 8 Core attributes according to sex

		Female		Male		Total	
		Count	%	Count	%	Count	%
Crushing	Absent	1	20.0%	1	14.3%	2	16.7%
	Heavy	3	60.0%	2	28.6%	5	41.7%
	Medium	0	0.0%	4	57.1%	4	33.3%
	Slight	1	20.0%	0	0.0%	1	8.3%
	Total	5	100.0%	7	100.0%	12	100.0%
Platform	Linear	3	60.0%	5	71.4%	8	66.7%
	Plain	2	40.0%	1	14.3%	3	25.0%
	Punctiform	0	0.0%	1	14.3%	1	8.3%
	Total	5	100.0%	7	100.0%	12	100.0%
Scar	Bipolar scar	5	100.0%	6	85.7%	11	91.7%
	Scar with one impact point	0	0.0%	1	14.3%	1	8.3%
	Total	5	100.0%	7	100.0%	12	100.0%
Battering marks	No	1	20.0%	5	71.4%	6	50.0%
	Yes	4	80.0%	2	28.6%	6	50.0%
	Total	5	100.0%	7	100.0%	12	100.0%

Table 9 Flake attributes according to levels of expertise

		Novice		Intermediate		Expert		Total	
		Count	%	Count	%	Count	%	Count	%
Platform	Linear	9	56.3%	8	29.6%	8	18.6%	25	29.1%
	Plain	1	6.3%	2	7.4%	11	25.6%	14	16.3%
	Punctiform	6	37.5%	17	63.0%	24	55.8%	47	54.7%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%
Bulb	Double bulb	0	0.0%	1	3.7%	0	0.0%	1	1.2%
	No bulb	12	75.0%	19	70.4%	29	67.4%	60	69.8%
	Only one bulb	4	25.0%	7	25.9%	14	32.6%	25	29.1%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%
Profile	Concave	4	25.0%	6	22.2%	13	30.2%	23	26.7%
	Convex	4	25.0%	10	37.0%	7	16.3%	21	24.4%
	Irregular	2	12.5%	9	33.3%	3	7.0%	14	16.3%
	Straight	6	37.5%	2	7.4%	20	46.5%	28	32.6%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%
Crushing	Absent	14	87.5%	21	77.8%	30	69.8%	65	75.6%
	Medium	1	6.3%	3	11.1%	5	11.6%	9	10.5%
	Slight	1	6.3%	3	11.1%	8	18.6%	12	14.0%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%
Cutting edge	No	14	87.5%	26	96.3%	35	81.4%	75	87.2%
	Yes	2	12.5%	1	3.7%	8	18.6%	11	12.8%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%
Termination	Feather	14	87.5%	20	74.1%	39	90.7%	73	84.9%
	Hinge	0	0.0%	0	0.0%	1	2.3%	1	1.2%
	Plunge	0	0.0%	2	7.4%	0	0.0%	2	2.3%
	Step	2	12.5%	5	18.5%	3	7.0%	10	11.6%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%
Battering marks	No	14	87.5%	25	92.6%	42	97.7%	81	94.2%
	Yes	2	12.5%	2	7.4%	1	2.3%	5	5.8%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%
Citrus-section	No	16	100.0%	26	96.3%	36	83.7%	78	90.7%
	Yes	0	0.0%	1	3.7%	7	16.3%	8	9.3%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%
Scar	Bipolar scar	2	12.5%	3	11.1%	16	37.2%	21	24.4%
	Scar with one impact point	14	87.5%	24	88.9%	27	62.8%	65	75.6%
	Total	16	100.0%	27	100.0%	43	100.0%	86	100.0%

Flakes

Tables 9 and 10 show the flake attributes according to levels of expertise and sex. Overall, platform crushing ratio of the flakes is absent in most of the flakes (75.6%), followed by a slight (14.0%) and medium (10.5%) incidence of crushing

Table 10 Flake attributes according to sex

		Female		Male		Total	
		Count	%	Count	%	Count	%
Platform	Linear	4	23.5%	21	30.4%	25	29.1%
	Plain	4	23.5%	10	14.5%	14	16.3%
	Punctiform	9	52.9%	38	55.1%	47	54.7%
	Total	17	100.0%	69	100.0%	86	100.0%
Bulb	Double bulb	0	0.0%	1	1.4%	1	1.2%
	No bulb	14	82.4%	46	66.7%	60	69.8%
	Only one bulb	3	17.6%	22	31.9%	25	29.1%
	Total	17	100.0%	69	100.0%	86	100.0%
Profile	Concave	5	29.4%	18	26.1%	23	26.7%
	Convex	6	35.3%	15	21.7%	21	24.4%
	Irregular	5	29.4%	9	13.0%	14	16.3%
	Straight	1	5.9%	27	39.1%	28	32.6%
	Total	17	100.0%	69	100.0%	86	100.0%
Crushing	Absent	11	64.7%	54	78.3%	65	75.6%
	Medium	2	11.8%	7	10.1%	9	10.5%
	Slight	4	23.5%	8	11.6%	12	14.0%
	Total	17	100.0%	69	100.0%	86	100.0%
Cutting edge	No	16	94.1%	59	85.5%	75	87.2%
	Yes	1	5.9%	10	14.5%	11	12.8%
	Total	17	100.0%	69	100.0%	86	100.0%
Termination	Feather	12	70.6%	61	88.4%	73	84.9%
	Hinge	0	0.0%	1	1.4%	1	1.2%
	Plunge	2	11.8%	0	0.0%	2	2.3%
	Step	3	17.6%	7	10.1%	10	11.6%
	Total	17	100.0%	69	100.0%	86	100.0%
Battering marks	No	15	88.2%	66	95.7%	81	94.2%
	Yes	2	11.8%	3	4.3%	5	5.8%
	Total	17	100.0%	69	100.0%	86	100.0%
Citrus-section	No	15	88.2%	63	91.3%	78	90.7%
	Yes	2	11.8%	6	8.7%	8	9.3%
	Total	17	100.0%	69	100.0%	86	100.0%
Scar	Bipolar scar	4	23.5%	17	24.6%	21	24.4%
	Scar with one impact point	13	76.5%	52	75.4%	65	75.6%
	Total	17	100.0%	69	100.0%	86	100.0%

marks. The punctiform type platform has the highest percentage (54.7%), while linear (29.1%) and plain (16.3%) are represented by a smaller percentage. Most of the flakes are represented by a straight ventral face without a bulb (69.8%), while only 29.1% show only one bulb. Another interesting feature to note is that 1.2% of the flakes shows three bulbs: two in the proximal part and one in the distal part. However, this phenomenon is very low in percentage terms. The profiles of the flakes are represented as straight (32.6%), concave (26.7%), convex (24.4%), and irregular (16.3%). In terms of cutting edge, only 12.8% of flakes show a suitable cutting edge. Eighty-seven percent do not show a functional edge. Most of the flakes show feather termination (84.9%), while step (11.6%), plunge (2.3%), and hinge (1.2%) terminations are less frequent. Most of the flakes are represented by scar with one impact point (75.6%), while only 24.4% show bipolar scars. Most of the dorsal faces of the flakes do not present battering marks (94.2%). Only 5.8% present battering marks. Citrus-section flakes are represented by a very low percentage (9.3%).

As it has also been noted with other technological categories, we found no association between different levels of expertise and in crushing ($x^2(4, n = 86) = 2.352, p = 0.671$). However, there was an association in terms of type of platform ($x^2(4, n = 86) = 11.482, p = 0.022$). Most of the punctiform type of platform associated with the expert knappers. No association was observed in the bulb ($x^2(4, n = 86) = 2.646, p = 0.619$). Presence of bipolar scars show association ($x^2(2, n = 86) = 7.634, p = 0.022$) between levels of expertise. Most of flakes produced by novices, intermediates, and experts present scar with one impact point. Battering marks on flakes do not present association between knappers ($x^2(2, n = 86) = 2.387, p = 0.303$). Additionally, neither flake with a citrus-section ($x^2(2, n = 86) = 5.125, p = 0.077$) nor presence of the cutting edge showed associations ($x^2(2, n = 86) = 3.303, p = 0.192$).

Furthermore, no association were observed between female and male knappers in the presence of crushing ($x^2(2, n = 86) = 1.758, p = 0.415$), type of platform ($x^2(2, n = 86) = 0.919, p = 0.632$), bulb ($x^2(2, n = 86) = 1.678, p = 0.432$), bipolar scars ($x^2(1, n = 86) = 0.009, p = 0.924$), battering marks ($x^2(1, n = 86) = 1.370, p = 0.242$), flake with citrus-section ($x^2(1, n = 86) = 0.152, p = 0.696$), and presence of cutting edge ($x^2(2, n = 86) = 0.907, p = 0.341$). In terms of the flake termination, no association was observed in different levels of expertise ($x^2(6, n = 86) = 7.839, p = 0.250$). However, female and male knappers present an association in the flake termination ($x^2(3, n = 86) = 9.534, p = 0.023$). Flakes of the male knapper present more feather termination than flakes of females.

Discussion

In the light of our results, it has been confirmed that knappers with different levels of expertise in stone flaking show remarkable differences in kinematic parameters. In particular, the differences in the kinetic energy and velocity parameters applied to the hammerstone are supported by statistical values that reveal differences at levels of knappers.

The kinematic parameters that form the basis of our study showed a different distribution than usual in terms of levels of expertise. When the kinetic energy and velocity values of the hammerstone were analyzed, intermediate level knappers use more energy and velocity than novices and experts. Reduction sequence analysis have shown that intermediate knappers end the flaking process only by splitting the pebble in two. In other words, even when the instruction given to them was to flake a cobble, the goal of the intermediate knappers seemed to be only to split the pebble. Perhaps this option is influenced by the previous knowledge of the knapper, and the fact that traditionally the bipolar flaking is associated to splitting small size cobbles (Duke & Pargeter, 2015). Experts keep energy and velocity at a certain rate after they split the pebble into two pieces. This is because expert knappers followed two different flaking strategies:

1) **Initial flaking:** splitting the pebble in two (with high kinetic energy)
2) **Sequential flaking:** using one of the split pebbles to obtain the flakes in a regular way (with low kinetic energy)

On the contrary, for intermediate knappers, the flaking strategy does not change. They only aim to split the pebbles with a maximum energy. This is precisely why intermediate level knappers have a higher kinetic energy and velocity values than other levels of expertise.

Furthermore, the fact that novice knappers show more kinetic energy and velocity than experts is due to their lack of knowledge of the flaking mechanics. According to the observations during the experiment, the kinetic energy applied by the novice knappers should be considered as an uncontrolled effort to break the stone rather than a controlled behavior. Because when slow-motion videos were analyzed, it was observed that novices could not fully control the hammerstone. As we mentioned in the "Results" section, the graph of kinetic energy and velocity presents a more irregular pattern compared to experts and intermediates.

The position and acceleration of the hammerstone relative to the x- and y-axis also have differences. Expert knappers usually use the hammerstone at a certain height. The highest height of hammerstone is held just before the first blow. That is the blow which was used to split the pebble in two. The height of the hammerstone is kept at a constant level for subsequent impacts after the first one. However, this shows a more irregular pattern in the other levels of expertise. This is due to the fact that novices and intermediates do not have the skills to use the mass of hammerstone.

In experts, the acceleration of the moving object also shows a regular pattern. However, these two parameters are represented by a completely irregular pattern in both intermediate and novice knappers. This proves how the bipolar technique, which has simple mechanics, varies according to different levels of expertise.

These quantitative data point differences in the skills of the knappers in the application of this technique. This shows that expert knappers are able to make optimal use of the mass and morphology of hammerstone. In the light of different works, it has been observed by expert knappers that kinetic energy is kept at a constant level. Specifically, hammerstones with varying masses were utilized at distinct kinetic energy levels (Bril *et al.*, 2010, 2015).

Duke and Pargeter's study (2015) shows that there are statistical differences between expert and novice knappers, from raw material procurement to flaking. In particular, the cobbles selected for splitting differ morphologically from randomly selected cobbles. Experts prefer thin cobbles with more standardized forms. In terms of time, experts perform the splitting process in a much shorter time and with less impact than novices. The median values in the study show this clearly. In fact, this study supports the results of our experiment from the time perspective.

Our observations during the experiment revealed that experts consider the morphology of the cores when rotating them on the anvil. Additionally, we observed that they carefully choose the contact point of the hammerstone with the core. While in our experiment, subjects did not select the raw materials themselves, had they been given the choice, experts would likely have chosen raw materials with a morphology suitable for applying the bipolar technique, as seen in the case of Duke and Pargeter (2015).

Also, the fact that the experts have the skill of how to use the mass of the hammerstone shows that they apply the flaking process differently from the novices because they preferred to use the mass of the hammerstone rather than hitting the core with extra force.

Nevertheless, it would be an incomplete action to identify the levels of expertise in archaeological materials because kinematic parameters are not a determining factor in the interpretation of archaeological assemblage.

A more complete conclusion can be drawn in tandem with a technological analysis of experimental materials. In the light of the analysis of technological categories, it is difficult to understand the levels of expertise of the knappers who applied this technique. From a statistical point of view, except some attributes, there are no significant differences between the levels of expertise and technological categories as we mentioned above. Also, on the qualitative side, individual technological analysis of the experimental materials is not conclusive in determining the level of knappers. Joslin-Jeske and Lurie's study on the distinguishing of freehand direct percussion and bipolar technique supports this conclusion (1983). Although intermediate and novice knappers use the hammerstone with more kinetic energy than experts, the intensity of these parameters leaves no discernible mark on the lithics in the macroscopic way. However, qualitative technological analysis varies depending on the raw material. This is clearly emphasized in de la Peña's experimental studies comparing different raw materials. In her experimental work on the distinction of splintered pieces and bipolar cores, she mentioned the facility of identification of qualitative indicators of flint (2011, 2015a). Therefore, a new set of experiments on fine-grained raw materials such as flint or obsidian may help to determine levels of expertise through qualitative analysis of individual lithic materials.

Additionally, it is worth noting that bipolar flaking marks exhibit significant contrast between cores and flakes. Nearly all the cores display clear bipolar traces, whereas flakes generally exhibit a lower number of bipolar traces. This difference is attributed to the mechanics of the bipolar technique. When the active impact does not align with the passive one upon returning from the anvil, the flake detachment occurs primarily due to the counterstrike (Vergès & Ollé, 2011).

However, if we focus on the refit analysis of raw material units rather than individual, the differences in levels of expertise are seen in much higher resolution. The analysis of the reduction sequences does indeed play a supporting role in this regard (Fig. 12).

Expert knappers are much more aware of how to use the raw material optimally than novice and intermediate knappers. In particular, re-orienting the vertically split pebbles horizontally on the anvil to obtain more flakes shows that the

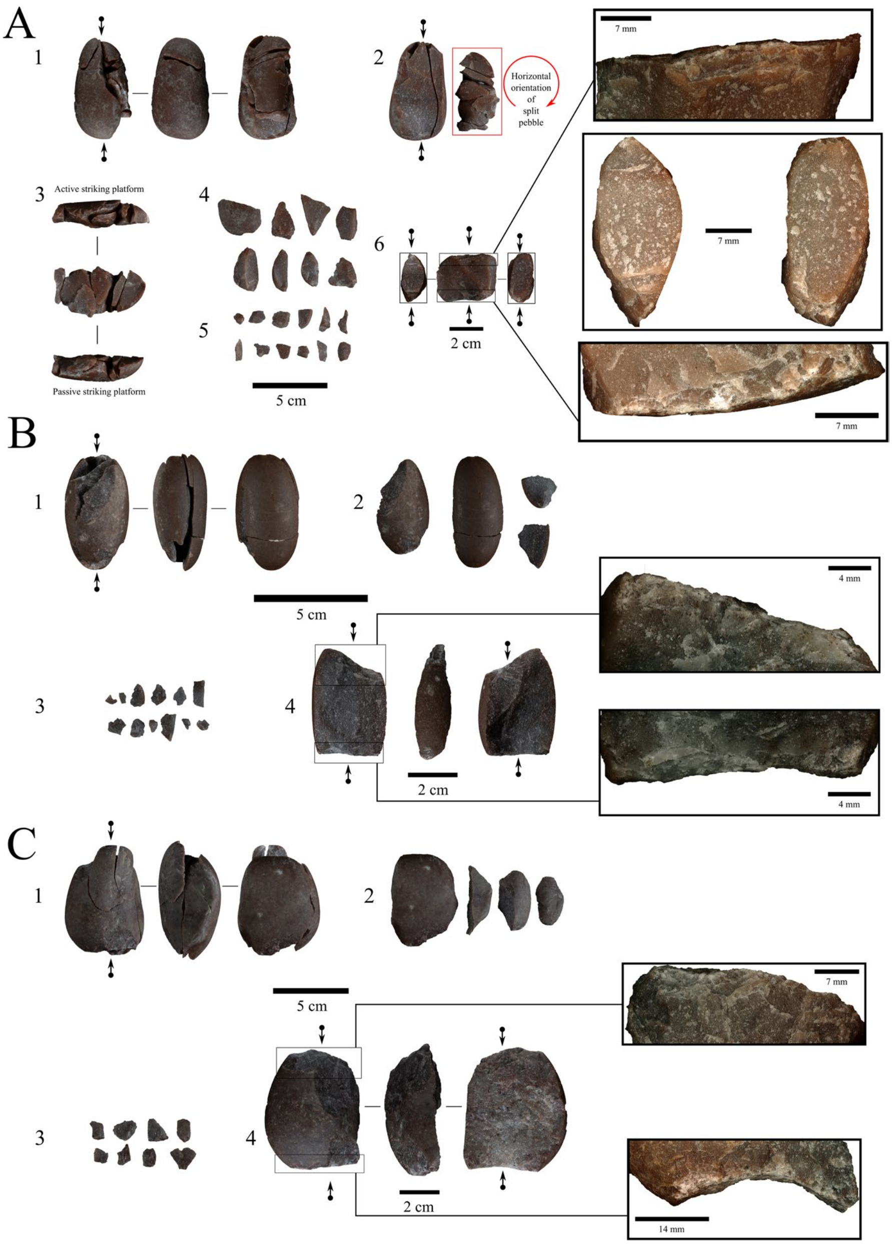

Fig. 12 Refits of experimental raw material units. **A** Expert knapper (1) complete set, (2) splitting sequence, (3) selected half of the pebble, (4) flakes, (5) fragments, (6) core; **B** Intermediate knapper (1) complete set, (2) flakes, (3) fragments, (4) core; **C** Novice knapper (1) complete set, (2) flakes, (3) fragments, (4) core. 3D digital microscope: Hirox-KH8700 (low-range, x35)

knappers prefer a systematic approach. Specifically, citrus-section, which is one of the characteristics of bipolar technique, elements were obtained by flaking a vertically split pebble horizontally on the anvil (Low, 1997). During the experiment, these objects were usually obtained by expert knappers. A few citrus-section samples were obtained by intermediates. In terms of flaking process, knappers at this level followed different strategies. Both metrically and typologically, the differences in the levels of expertise of the citrus-section elements are clearly visible. The main difference between the citrus-sections obtained by knappers of these two levels of expertise is that experts obtain these pieces sequentially during secondary flaking. However, intermediate levels obtained them with an initial blow.

The citrus-sections obtained by intermediate knappers have a much wider and non-standard morphology than those of experts. Their platforms are flat and contain a cortex. The citrus-sections of intermediates are not the products of sequential flaking. The elliptical shaped pebbles are caused by a single impact on their central point, where the pebble is compressed between the active and passive impact, breaking into pieces of almost equal size (Cotterell & Kamminga, 1987, 1990). In fact, technologically, these components do not fully represent the indicators of a flake or a core. These components usually have two ventral faces. One or both ventral faces have marked percussion bulb, while in some cases, this bulb is completely diffused. Ballin mentioned in his works that such orange segments create problems in identification due to lack of indicators (1999, 2021). However, some experimental studies have defined the orange segment phenomenon differently from Ballin's approach. For example, in Flenniken's experimental work on the lithic industry of the Hoko River site, he described the segments as pie-shaped split cobble cores (see the Technological Analysis section for terminological equivalencies). Flenniken describes the fracture mechanics of these pieces as;

> "… the cobble would shatter due to the delivery of an excess amount of force; or 4) the cobble would split into from 2 to 5 pie-shaped pieces or split cobble cores…".(1981, p. 37).

Barham also uses Flenniken's nomenclature for these pieces in his experimental work (1987). A recent example of these type of detachments were observed at La Cansaladeta, a Middle Pleistocene site in northeastern Spain (Tarragona), as a result of intensive refit work (Fig. 13). The local raw material was flaked at the site using the bipolar technique. When we examine these refit sets, we can clearly see that there are indicators in accordance with the definitions we have made above (Ollé *et al.*, 2016; Yeşilova *et al.*, 2021).

One notable aspect of Flenniken's definition is the emphasis on the excessive force applied. The quantitative evidence of intermediate knappers utilizing their hammerstones with maximum kinetic energy further supports Flenniken's interpretation of the citrus-section pieces.

However, our observations from another parallel experiments have shown that the use of excessive force is not only related to the force of knapper but also to how dense the mass of the hammerstone used is. The high compression on the core or blank gives the part an inertia on the anvil. In order to achieve immobility, the core

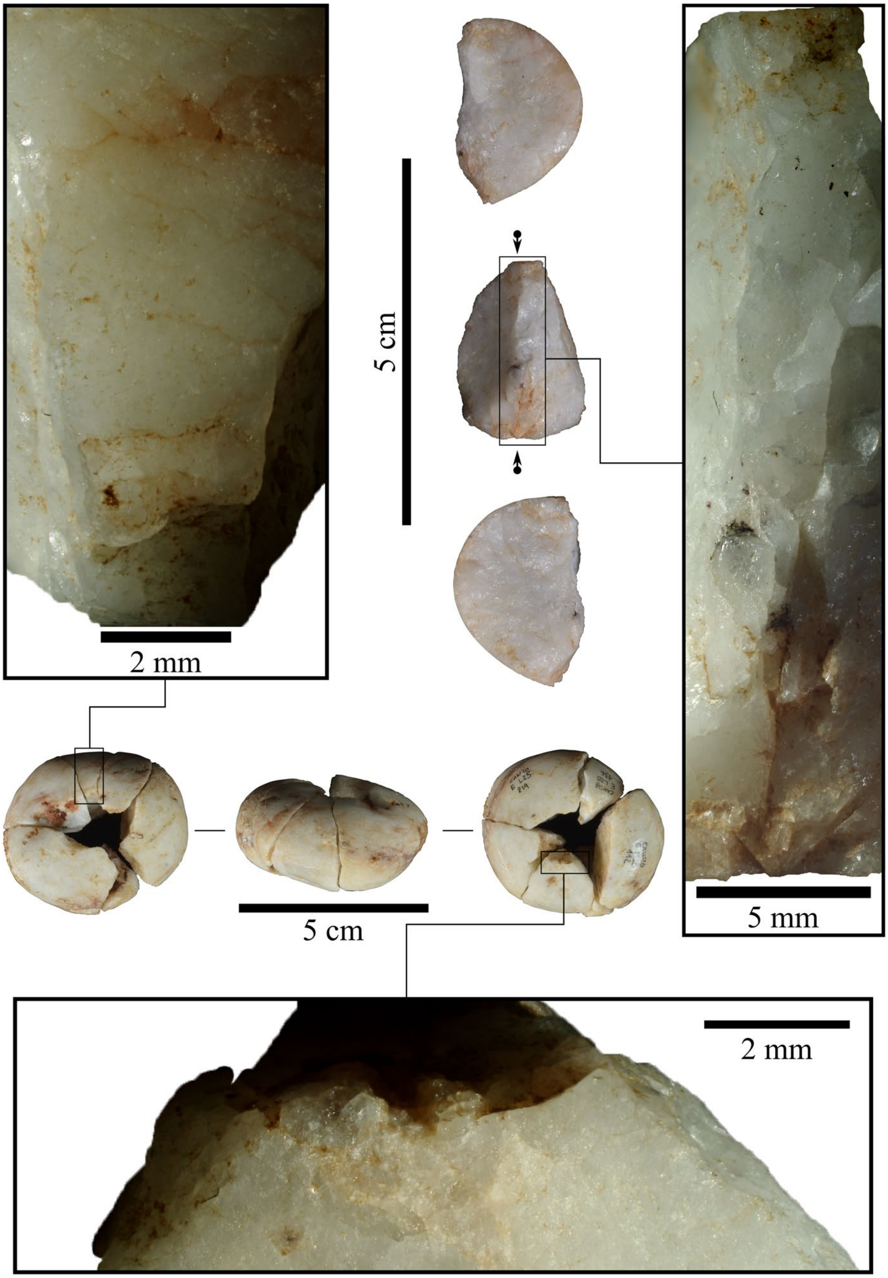

Fig. 13 Microscopic view of the refit set CAN(E)_R_QS-02 of La Cansaladeta (Middle Pleistocene site), level E. 3D digital microscope: Hirox-KH8700 (low-range, x35)

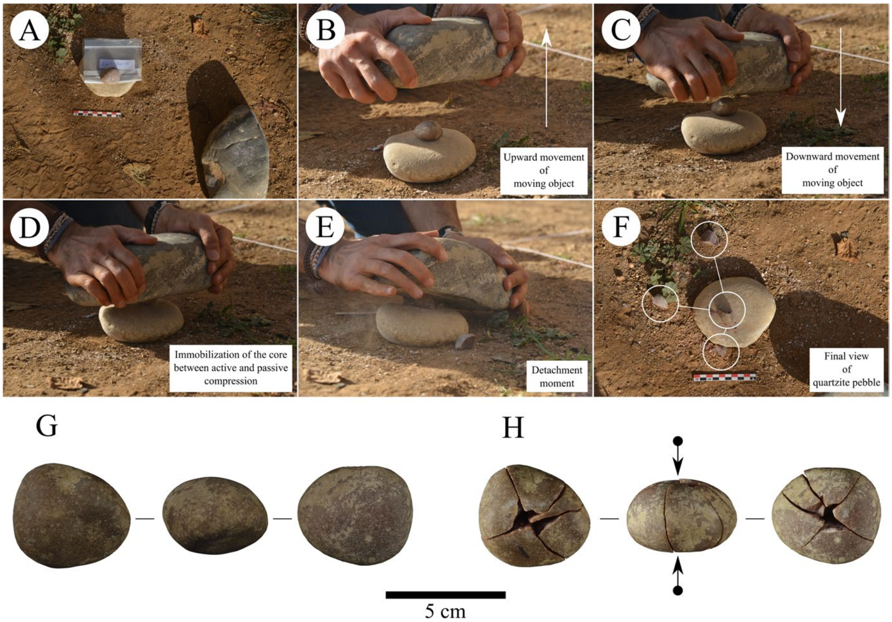

Fig. 14 Production of citrus-section pieces from the parallel experiment. **A** General view of pilot experiment set (Anvil: Limestone (L: 136 mm, W: 120 mm, T: 45 mm, W: 1072 g), Hammerstone: Schist (L: 230 mm, W: 123 mm, T: 80 mm, W: 3450 g), Core/blank: Quartzite (L: 41 mm, W: 37 mm, T: 27 mm, W: 58 g); **B** Upward movement of hammerstone; **C** Downward movement of hammerstone; **D** Immobilization of the core/blank due to compression; **E** Detachment of core/blank; **F** View of pebble after detachment; **G** View of pebble before experiment; **H** View of pebble after experiment

or pebble must be held stationary on the anvil by an external force (hand of knapper) or momentarily immobilized by a moving object with a very dense mass.

Figure 14 illustrates exactly this phenomenon. Heavy schist nodule was used as a moving object to flake a small quartzite pebble. The force applied to the moving object momentarily immobilized the stone on the anvil, allowing the impact to pass through the center of the material. As a result, the pebble, compressed between the passive and active force, broke into almost equal-sized pieces, as in the citrus-section description.

Novices, on the other hand, simply aim to break the pebbles, without adhering to a specific strategy. In fact, the edge of the split pebble was used as a striking platform by experts. In this case, the detached pieces present a punctiform striking platform (see the results of the technological analysis). This is the reason why platform type presents significant differences regarding the levels of expertise. In fact, this kind of flaking activity has been reported as a systematic truncation method in Liang Bua (Flores, Indonesia) (Moore *et al.*, 2009). In addition, there are many studies showing the systematic use of the bipolar technique. The Bizat Ruhama site in Israel presents an important example in this regard. In the light of Zaidner's experimental studies, flint pebbles are split into two pieces, the ventral face is rested on the anvil and the dorsal face is used as a striking platform (Zaidner, 2013, 2014). Thomas

Fig. 15 Some important ethnographic evidence of application of the bipolar technique from Papua New Guinea. All the photos were taken in the Lake Kopiago region in 1967 by Peter White. **A** One of the Hewa speakers (northwest of Lake Kopiago). A wood block was used as an anvil; **B-D**: Duna speakers from Harege parish, the name of the knapper is Hera. Hera was applying a different variant of the bipolar technique. These ethnographic figures were used with permission of Peter White

Quarry I-L1 (Casablanca, Morocco) site provides important examples of the systematic application of this technique. At the site, small-sized flint pebbles were flaked as in the example of Bizat Ruhama. First, the raw material is split into two equal pieces and then a continuous process is applied to one of the halves (Gallotti *et al*., 2020). In addition to these, the Eagles Nest (Mount Sinai Harbour, New York) site from the Middle-Late Holocene are hemispherical quartz stones that were split by the bipolar axial technique and used for sequential flaking (Pargeter & Tweedie, 2018). In fact, this type of flaking demonstrates both the economical use of raw materials and the fact that hominin groups used bipolar technique for more than just bashing the pebbles in different chronologies and geographies.

The association between women and bipolar technique has been proposed through different ethnographic studies in Africa, North America, and Oceania (Albright, 1982, 1984; Arthur, 2010; Belkin *et al*., 2006; Brandt & Weedman, 2002; Bird, 1993; Flenniken, 1981; Masao, 1982; Roth, 1924; Sillitoe & Hardy, 2003; Weedman, 2006). The ethnographic studies, based on live observations (Fig. 15), have provide a valuable information and propose alternative views regarding the use of the bipolar technique.

In terms of concept of sex, our results show that the position of hammerstone, velocity, and kinetic energy also show differences. However, when looking at the technological analysis, it is not possible to determine the sex of knappers based on the attributes that we analyzed, indicating that both can equally successfully perform the activity. Indeed, considering the gender-neutral success observed in the flaking activity, discussing differences would be redundant. Emphasizing the necessity of conducting a future experiment encompassing a larger and more diverse participant pool becomes imperative. Such an undertaking would establish a robust foundation for drawing broader conclusions regarding the bipolar technique and the comprehensive experience of flaking.

To illustrate the relationship between women and the bipolar technique, rooted in ethnographic studies, we can demonstrate some examples from British Columbia. In fact, studies on Tahltan women have shown that bipolar technology has a very different and more complicated structure than the concept of an expedient tool. Albright's fieldwork (1982, 1984) shows that the bipolar technique was used to produce stone tools for hideworking. Long basalt pebbles are split vertically and used without retouch. This is because half of the split pebble presents a suitable convex frontal part for the scraping process (Hayden, 2022). In fact, Albright's work is more important to discuss how a simple fracture mechanism can serve a complex behavior than to discuss the bipolar technique in terms of sex. Moreover, this is not a sex-dependent phenomenon, but one that depends entirely on the skill to perceive the morphology of the raw material. In point of fact, Albright's work, a study in response, sheds light on a very important point regarding techno-functional importance of split pebbles. Because the study of Hrdlička in South America suggested that the split pebbles would not serve any functional purpose without modification (1912).

As a matter of fact, a technique of which so many variants have been observed in ethnographic studies needs to be further examined from an archaeological perspective, in terms of both functional and technological point of view, because the importance of ethnographic studies is that they contribute to the interpretation of archaeological materials and to the development of these interpretations (Hayden, 1979, 2015, 2017, 2022).

According to the results of our experiment, the bipolar technique has an absolutely skillful motion mechanism. Although there is a large body of ethnographic and empirical works to support our study, there are also very recent experimental studies that still oversimplify the bipolar technique, arguing that it is just a matter of randomly bashing stones (Conesa et al., 2023, p. 14):

> "The exploitation is to execute, as evidenced by experimentation, as inexperienced knappers were able to develop it with instinctive postures and gestures (i.e. it does not require the adoption of developed technical knowledge that implies a specific holding of the volume or that requires a specific orientation of the volume.)"

Here, it is clear that the authors make such a conclusion ignoring the difference between stone bashing and flaking.

Unfortunately, experimental work without a detailed experimental protocol and kinematic perspective still argues that this technique does not require knowledge. Although the technique has a simple mechanic, individuals without knowledge of this technique will have difficulty using the components of the bipolar technique effectively.

Patterson and Sollberger (1976, p. 40) may have perceived the bipolar technique in a simplistic way. Or they may have thought that the simple mechanics of the technique were due to the lack of skill because that was exactly their definition of bipolar technique: "True bipolar flaking should be described as the lack of skill in flintknapping, rather than as an alternate desirable technique."

From our perspective, the use of the bipolar technique is not an indicator of lack of technological skill. On the contrary, it is precisely a skilled technique. In order to apply the bipolar technique, the knapper needs raw materials with an appropriate morphology, the correct rotation of that raw material on the anvil and suitable hammerstone. In this process, it is the experience of the knappers that affects the result (Devriendt, 2011; Duke & Pargeter, 2015; Shott & Tostevin, 2015).

With advances in technology, there have been significant improvements in the testing of archaeological materials and human behaviors. Kinematic parameters in the flaking mechanics have been proven, not only by video motion analysis, but also by other methods. Biomechanical or electromagnetic sensor analyses plays an important role in obtaining quantitative data of moving individuals or objects (Bril *et al.*, 2010, 2012, 2015; Macchi *et al.*, 2021). Comparative studies, especially in percussive technologies, play an important role in examining the mechanics of flaking from a cognitive perspective between non-human primates and humans (de la Torre & Hirata, 2015). We acknowledge that our study cannot provide a global conclusion on bipolar technique but is rather a step forward towards a more detailed understanding of this phenomenon, which is very complex both in its definition and interpretation. As such, there is a need for more experimental studies and different comparative methods to further investigate this mechanism from a cognitive perspective.

Conclusion

In our experimental study, we examined whether there is a quantitative difference between knappers with different levels of expertise in the bipolar technique in the light of kinematic parameters. This technique is based on the mechanics of hitting a stationary object with a moving one. The simple mechanics of this technique have led some researcher to associate it with negative connotations. Bipolar reduction is a technique or method, and it has many variations. It is evident from ethnographic field works that this system is used by indigenous people for different functions and by different sex. In fact, when we look at the data from these field studies, it is impossible not to see complex different patterns in bipolar phenomenon.

As a result of the experiments presented in this paper, we can conclude that the bipolar technique is entirely dependent on the individual skill of the knapper. It is evident that expert knappers know how to use the three components of the bipolar technique—anvil, hammerstone, and core—in a more effective way than novice and intermediate knappers. This demonstrates that the bipolar technique necessitates a skill to control its components.

However, qualitative technological analysis of individual materials is not enough to reveal the differences between the levels of knappers and sex. For the time being, we can only rely on the detailed refit analysis to determine the differences between the knappers at different levels. The most important thing to be careful about is the raw material. Fine-grained raw materials may help to make much more reliable conclusions.

Instead of celebrating a triumph, the results of our study underscore the importance of ongoing experimentation using different methods and advanced equipment. An essential parameter to include in future studies is the calculation of the pressure applied by the knapper's hand holding the hammer per unit of force. Incorporating biomechanical equipment alongside frame analysis will provide more comprehensive experimental results (Key & Dunmore, 2015; Key *et al*., 2017).

In summary, the importance of the bipolar technique in our evolutionary history is evident, as it is found in every chronology regardless of time and space, encompassing both primary and secondary flaking techniques (Horta *et al*., 2022). Indeed, the "confusion in the bipolar world" still persists but takes a different direction (Hayden, 1980). Variations observed from an ethnographic standpoint also warrant investigation from an archaeological perspective. Henceforth, future studies should not only aim to define the bipolar technique but also delve into researching its variants. Specifically, testing ethnographic samples and comparing them with archaeological materials may offer new interpretations and help reconsider the negative associations linked to the bipolar technique, such as poor-quality raw materials, dimensional constraints, or the limited skills of early hominins.

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Data Availability The authors confirm that the data supporting the findings of this study are available within the article as supplementary material.

Declarations

Competing interests The authors declare no competing interests.

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