ABSTRACT

Although it is well established that Hertzian fracture characterizes stone knapping mechanics, its in-depth features on lithic products remain unclear. Observations on a basic component of the Hertzian fracture manifestation, the cone of percussion ‘system’, has previously considered to reveal knappers’ hand preference, yet offering contradictory predicting results within the context of blind tests conducted on experimental lithic products. In this study, basic features of the cone of percussion on stone flakes are re-approached in an effort to determine their exact relation to handedness manifestation during stone knapping. Experimental data analysis suggests that under certain circumstances stone knappers’ hand preference is strongly, but not absolutely, connected with the cone of percussion ‘system’ various geometrics. The pilot implementation of the suggested methodology on lithic artefacts produced by Neanderthals at Kalamakia cave-southern Greece, indicates that right-handers predominate among the flintknappers of the site.
INTRODUCTION

Assessment of hominins’ handedness rates through lithic technology has been a widely considered topic during the last 50 years (e.g. Bargalló & Mosquera 2013; Ruck, Broadfield & Brown 2015; Rugg & Mullane 2001; Semenov 1964; Toth 1985), mainly due to its plausible neurophysiological and cognitive relation to language origins and the organization of the ‘modern’ human brain (e.g. Corballis 2010; Meguerditchian, Vauclair & Hopkins 2013). Despite these efforts, which in their majority evaluated data resulting from experimental knapping simulations of modern left- and right-handers, there is no general agreement on whether specific features of the lithic products can safely reveal hand preference of their producers (see e.g. Dominguez-Ballesteros & Arrizabalaga 2015; Ruck et al. 2020; Uomini & Ruck 2018). As a result, indications of experimental flaking approaches have been barely applied on real archaeological samples (e.g. Bargalló, Mosquera & Lozano 2017; Dominguez-Ballesteros 2016). This is not strange, since the full range of factors contributing to the expression of handedness during stone knapping and its ‘imprinting’ on lithic products, remains largely unknown. These factors can well include the physical laws governing the mechanics of lithic production, as well as the richness of human kinematics being involved to such a complex technical procedure. Some of these points have directly or indirectly been addressed by previous works (e.g. Ruck, Broadfield & Brown 2015; Uomini 2009).

In the exploration of handedness evolution through millennia and its cognitive implications, one of the phenomena that could potentially be indicative of handedness manifestation during lithic production, is the Hertzian fracture characteristics, featuring brittle materials breakage (e.g. Andrefsky 1998). Specific human kinematics -such as the inclination with which a dominant hand, handling a hammerstone, strikes a core surface- have been considered during the past (e.g. Dominguez-Ballesteros & Arrizabalaga 2015; Rugg & Mullane 2001) to affect certain features of that physical mechanism. Such a phenomenon, leads to the appearance of distinct marks on lithic products, the observation of which might reveal their producers’ hand preference.

In this paper, I review the contribution of the so-called ‘cone of percussion’s features -a basic component of the Hertzian fracture’s results on lithic products- to the hominins’ handedness exploration through lithic technology. A new method is proposed here that uses the merits of digital technology to evaluate the geometrical features of the cone of percussion on knapped stone implements, which in turn could be used to identify the hand preference of the knappers. Results from a series of experiments testing the validity of such an approach are presented and the potential benefits and restrictions emerging from its application are discussed, also in comparison with other proposed methodologies (e.g. Dominguez-Ballesteros & Arrizabalaga 2015). Finally, the data occurring from the pilot implementation of the proposed methodology on lithic artefacts of Middle Palaeolithic age, clearly associated with Neanderthals, from Kalamakia cave-southern Greece (Darlas 2007; Harvati et al. 2013; Koleidonianou et al. 2020) are reported to evaluate handedness rates of these hominins.

BACKGROUND RESEARCH

Hertzian fracture occurs during the breakage of brittle materials (e.g. Frank & Lawn 1967), being the result of the pressure distribution, produced between two violently contacting surfaces. The exact mechanisms of this physical phenomenon remain unknown, yet a lot of its manifestation details, mainly from experimental studies on glass or ceramics, have been understood (e.g. Ball 1996; Gogotsi 2013; Quin 2007). In theory, and within a simplistic consideration, the major visible manifestation of a Hertzian fracture on a material consists of a conical or subconical crack, evolving from the point of impact and penetrating the surface of the battered object. For this reason, Hertzian fracture is also referred as ‘conchooidal’ or ‘cone’ fracture (Figure 1a).

In lithic studies, the Hertzian fracture phenomenon is generally used to explain the way that percussion or pressure mechanics function to produce lithic blanks from a core. Hertzian fracture traces are more often visible on the butts and ventral faces of the blanks, reflecting in essence a plane imprint of a ‘perfect’, more or less, cone fracture. The largest part of this component is invisible, since it is formed on the internal structure of the lithic material (Figure 1b). Hertzian fracture effects are in most cases reasonably ignored in traditional lithic analysis since they are not the result of a deliberate human intervention on a stone tool implement. Yet, in a series of studies exploring prehistoric handedness through lithic technology, the character of some of the cone fracture components are considered to be indicative of knappers’ hand preference.

Roug and Mullane (2001) were the first to propose that the examination of the cone of percussion geometry could indicate the hand preference of a lithic artefact producer. The potential skewness of this feature in relation to the striking platform of a blank has been hypothesised to reflect a corresponding inclination to knappers’ blows on a core.

Given the general human kinematics, right-skewed cones (related to the observer eye with a blank grounded to its butt) have been associated with left-handed knappers and vice versa (Figure 2a, b). Testing this hypothesis, Roug and Mullane (2001) refer a nearly 75% success on defining the handedness of modern
left- and right-handed knappers, within the context of blind examinations of experimentally produced lithic blanks. Rugg’s and Mullane’s (2001) observations have been made by ‘eye’ and only a small proportion of their experimental sample (75 flakes over 299–25.1%) showed clear evidence of the cone skewness.

Despite Rugg’s and Mullane’s (2001) promising results in predicting knappers’ hand preference, further attempts on confirming the validity of their method’s principles offered negative outcomes. Consecutive efforts by Uomini (2001), Bargalló and Mosquera (2013) and Ruck et al. (2015, 2020) on experimentally produced artefact samples, failed to repeat the high proximity predicting scores presented in the original publication of the method. Yet in these studies, observations were focused not on the cone of percussion itself but at its ‘ridge’. This ‘ridge’ was described as an elongated, relative rectilinear stigma, on flakes’ ventral side, considered to start at the cone genesis point and running along a large bit of its part. A right oriented cone ridge in relation to the striking platform of a flake (related to the observer eye with a blank grounded to its butt) was considered as the result

**Figure 1** Formation of a Hertzian cone on a brittle material (a) and basic features of a Hertzian fracture imprinted on the ventral side of a flake (b).
of a left-hander’s knapping procedure and vice versa (Figure 2b).

In all the aforementioned studies, observations on lithics were once again made macroscopically. Bargalló and Mosquera (2013) report that 60% of their sample showed clear traces of the cone ridge, and so this feature could be evaluated. In contrast, Ruck, Broadfield and Brown (2015) mention that only 7.7% of their sample was appropriate for such an analysis. Negative results of the above efforts, led to the abandonment of the cone of percussion skewness as a criterion for approaching knappers’ handedness and the method has never been applied to actual archaeological material. Nevertheless, it should be noted that at Rugg’s & Mullane’s (2001) original study, the criterion of hand preference distinction was not the skewness of the ‘cone ridge’, but the skewness of the cone of percussion itself.

To determine hand preference of prehistoric stone knappers, a new method, grounded, in essence, on the Hertzian fracture’s physicalities, has been recently
focused on a feature of the blanks’ butts, caused by hammerstone blows. It is a parabolic in shape distinct scar created around the blow impact point, which is the starting point of a cone of percussion formation, also known as a Hertzian ring crack (e.g. Matsuda & Takada 2018) (Figure 2c). Experimental data have shown that the orientation of this parabola, to the left or to the right, in relation to the blank plane of percussion, is dependent on the inclination of the blows delivered. Taking again in consideration human kinematics, it was proposed that left- and right-handers would produce mirroring parabolic cracks. Therefore, by examining the orientation of the parabolic cracks on individual flakes, the hand preference of their manufacturers could be revealed.

Following these principles, and within the context of a blind test, Dominquez-Ballesteros and Arrizabalaga (2015) report an over of 90% success for predicting knappers’ handedness on experimentally produced lithic assemblages. Furthermore, Dominquez-Ballesteros (2016) applied that method to the archaeological record and reported a result of 3–7 ratio for left- and right-handers within Neanderthal populations. Such an approach was never re-evaluated, and despite its referred high reliability, was proved to have a major limitation: its relative low applicability on lithic flakes. Dominquez-Ballesteros and Arrizabalaga (2015) report that only 34% of their experimentally produced sample (102 out of 300 flakes) preserved distinct parabolic cracks, leaving a big proportion of potential data out of study.

STUDY OBJECTIVES, MATERIALS AND METHODS

Given the contradictory outcomes that previous work has offered concerning the potential association of handedness with the Hertzian fracture’s features on lithic flakes, the study presented here aimed to re-evaluate the soundness of such a methodological approach, but also to bound its restrictions and potentials. Another objective was to apply the principles of such a study approach— if proven reliable—to the real archaeological record, in order to evaluate how hominins’ handedness could be identified in real conditions.

To do so, at a first stage, a closer look into the ‘structural’ features of the cone of percussion has been attempted, focusing on the cone (of percussion) crack paths geometrics, which were placed under detailed investigation. At the same time, a correlation was attempted between these traits and another Hertzian fracture component, the parabolic crack, which was previously considered as indicative of the determination of knappers’ hand preference and an evaluation of the potential association.

In essence, what in lithic studies is described as a cone of percussion, in fracture mechanics is referred as a cone crack, structurally bordered by specific flaws (e.g. Frank & Lawn 1967). These flaws, produced by impact loading, are usually mentioned as the cone crack paths. In a perfect Hertzian fracture two different cone cracks are produced: an inner one, occurring simultaneously with the impact loading of the ballistic implement, and an outer one, produced shortly after, during impact unloading (e.g. Ball 1996) (Figure 3a). A series of studies have dealt with the understanding, but also with the predictability of the cone cracks phenomenon on brittle materials, like glass and ceramics, to use that knowledge on industrial applications (e.g. Huang et al. 2021; Miyamoto & Murakami 2000; Tumbajoy-Spinel et al. 2013; Quinn 2007).

On laboratory conditions, these studies have shown that when impact loading is perpendicular to a striking surface, then both the inner and outer cone crack-bordered by the inner and outer cone crack paths—shape an isosceles triangle or trapezoid. Other studies have examined the way that cone cracks manifest, when contact between the blast instrument (in these cases hard spheres) and battered surfaces is not perpendicular, but inclined. Results of these studies show that according to the blows trajectory inclination—below or above 90°—the triangular or trapezoid in shape imprint of the inner and outer cone crack manifestation has a distinct left or right orientation in relation to the plane surface of impact (e.g. Akimune 1990; Aydelotte et al. 2016; Chaudhri & Lianghui 1989) (Figure 3b). Such a phenomenon, can be metrically documented through the distinct, different angles that the proximal inner and outer cone crack paths doublets form—departing from the impact point and dissipating to the upper part of the blasted object, in relation to a ‘striking surface’.

The above verify that theoretically the initial hypothesis of Rugg and Mullane (2001) about the skewness of the cone of percussion on lithic flakes, according to the inclination of the blow has a stable scientific basis. Yet, it would be useful to actually prove that during a stone flaking procedure, impact mechanics act with a similar way concerning the cone of percussion (cone crack) mode of manifestation, in analogy to what it has been observed in glass and ceramics, in laboratory conditions. That would correspond to the creation of distinct and observable cone crack paths, which form deterministic angles in relation to the striking surface of the flake, depending on the inclination of percussion. As a result of flaking procedures, distinct angles would be created due to the hypothesised mirroring kinetic behaviour of the left- and right-handed knappers (Figure 2a). Consequently, accurate measurements of the angles of the cone crack paths—in relation to the striking surface of the flakes—could objectively show a potential skewness of the cone of percussion, in contrast to by ‘eye’ evaluations made in previous studies.
Indeed, primary close-range observations on experimentally produced glass and flint flakes, created through direct percussion with the use of a limestone hammerstone, showed that during flaking procedures distinct crack paths bordering the cone of percussion (inner or outer) are also formed. The most distinct paths are these bordering the inner cone crack. Yet the upper path, the base of an invert cone, is usually not clearly visible, particularly on the stone flakes (Figure 4).

These primary, successful efforts permitted to investigate further the causal relationship between the geometrical features of the cone crack paths and the knappers’ handedness. An investigation was also attempted on the factors and particularities (e.g. basic human kinematics), that would have affected

Figure 3 Schematic diagram of inner- and outer-cone crack geometries according to a perpendicular blow (a) and formation of cone cracks on soda lime glass when a blow is inclined according to Chaudri & Liangyi 1989 (b).
the geometry of the cone crack paths, during the flaking procedures, and how the manifestation of this phenomenon is related to another feature of the Hertzian fracture, the parabolic crack. The latter, as mentioned earlier, has been suggested before (Domínguez-Ballesteros & Arrizabalaga 2015) as another feature appropriate to study handedness of prehistoric knappers, having produced positive results. This is because according to Hertzian theory, it would be logical to assume that the parabolic crack orientation and the potential cone of percussion skewness on lithic blanks should be related interdependently.

To address these issues, a methodological protocol combining the conduction of controlled knapping experiments and a close, multifactor, study of their results was designed. The study’s experiments could be divided in two different types: an ‘open observation’ and a blind one. The ‘open observation’ experiment included the production of the major part of the lithic material for this study. In total 11 knappers (six right- and five left-handers) participated. Three knappers (two right- and one left-handed) could be considered as experienced. For the conduction of these experiments, flint collected from the region of Varathi at Epirus-NW Greece has been used. This is a fine-grained material occurring in various forms (nodules and cobbles) and it was flaked using limestone hammerstones.

Knappers were asked to produce blanks with a way and style comfortable to them. Novice flintknappers were introduced, in an elementary level, to the methods and techniques of knapping, through oral instructions and by observing the expert flintknappers. The largest part of these experimental sessions has been recorded with the use of two high-frame cameras (120fps–1080p). The first camera was placed in front of the knappers, and the second one at the side of the non-dominant hand each time, with which the core has been handled. In such a way, an attempt was made to investigate the inclination with which the hammerstone-handled by the dominant hand-got in touch with the core, each time.

During these knapping sessions over 500 flint blanks of various sizes and forms (flakes, blades) have been produced. Given that one of the study’s aims was the exploration of the cone crack paths’ geometry of the flakes in relation to the orientation of the parabolic crack, the final sample under study included blanks preserving their butt and a significant proportion of their proximal part. On the latter and on the ventral face of the flakes, the cone of percussion formation (cone crack) and its individual features are observable. At the same time, within a conventional bordering, only blanks with a minimum length over 15mm. have been kept for further study. By applying these prerequisites, 286 flakes were considered as appropriate for analysis (154 derived from right and 132 from left-handed knappers) (Table 1).

The second type of experiments has taken place during an advanced stage of the study, so that the results produced by the first type of experiments would...
be blindly evaluated. In total six knappers participated (three left- and three right-handed), among them two experienced. Four out of six knappers also took part in the knapping sessions of the first type of experiments. Again, knappers were asked to produce flakes with any way convenient to them. These sessions have not been recorded. This time, a unique big-sized flint cobble from Zakynthos Island was used as raw material, so that the products of each knapper would be impossible to be identified. The properties of the raw material used in the blind experiment resembled those of the ‘open observation’ one, in terms of flaking quality and grain. Limestone hammerstones were again used to extract the lithic flakes.

Using the eligibility criteria of the experiments of the first type, 172 blanks were gathered for a blind evaluation. These products were marked on their upper face with information regarding their producer and his/her hand preference. These notes were then covered by identical stickers, so that the handedness of the flakes’ producers would remain unknown during the examination. The lithic products were mixed, kept together and after an interval of two months they were attributed a serial number on their ventral face, before starting the analysis. It was later proved that 94 of the flakes had been knapped by left- and 78 by right-handers (Tables 1).

According to the study objectives, video recordings of the knapping sessions of the first type of experiments have been analysed using the Kinovea® software. This allowed a detailed frame per frame observation of the knapping procedures, a synchronization of both cameras recording the experimental sessions and a magnification of the footages’ points of interest. At this stage, such a process mainly pointed to the knappers’ blowing trajectories and inclination, in an attempt to evaluate the validity of previous studies’ (Rugg & Mullane 2001; Domínguez-Ballesteros & Arrizabalaga 2015) a priori hypothesis, that left- and right-handers usually bring mirroring blows on the cores. In addition, the detachment inclination of each extracted flake has been associated with the hand preference of each knapper to investigate how it affects the cone crack paths’ geometry and the parabolic crack orientation.

The inclination of the knappers’ blows was evaluated macroscopically, at the moment when the hammerstone struck the core surface, and it was divided in three broad categories: ‘expected’, if it was in accordance with the hypothesis of its depended kinematic relationship with the hand preference of every knapper (Figure 5a); ‘invert’, if it was contrary to the expected one (Figure 5c); and ‘perpendicular’, if the blow inclination was nearly vertical to a striking surface (Figure 5b). Blowing inclination has been calculated at an ideal position, where the core is handled at a straight level right in front of the knappers’ eyes and always related with the inclinations that also striking surfaces might have represented, due to the cores’ way of handling. It should also be noted that knappers’ blows were coded by a single observer and their evaluation may be susceptible to individual perceptual biases. A more detailed kinematic analysis would have a lot to offer as a logical next step in future research.

Observations on the geometry of the cone crack paths have been made with the use of digital tools, permitting accurate measurements. In this manner, a maximum

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>EXPERTISE LEVEL</th>
<th>NUM. OF FLAKES (OPEN OBSERVATION EXP.)</th>
<th>NUM. OF FLAKES (BLIND EXP.)</th>
</tr>
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<tbody>
<tr>
<td>R1</td>
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<td>20</td>
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</tr>
<tr>
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<td>Expert</td>
<td>33</td>
<td>21</td>
</tr>
<tr>
<td>R3</td>
<td>Median</td>
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<tr>
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<td>Median</td>
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</tr>
<tr>
<td>R5</td>
<td>Novice</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>R6</td>
<td>Novice</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
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<td>Novice</td>
<td>0</td>
<td>31</td>
</tr>
<tr>
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<td>37</td>
</tr>
<tr>
<td>L2</td>
<td>Median</td>
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<td>27</td>
</tr>
<tr>
<td>L3</td>
<td>Novice</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>L4</td>
<td>Novice</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>L5</td>
<td>Novice</td>
<td>31</td>
<td>0</td>
</tr>
<tr>
<td>L6</td>
<td>Novice</td>
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<tr>
<td>Total</td>
<td></td>
<td>286</td>
<td>172</td>
</tr>
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</table>

Table 1 Handedness, level of expertise and products number of the participants in the ‘open observation’ and the blind experimental session (R=Right-hander. L=Left-hander).
reduction of subjectivity and personal bias was attempted, concerning the evaluation of the features under study—a major issue addressed by previous research (e.g. Ruck et al. 2020). These processes aimed to highlight the cone crack paths of the flakes and to objectively measure the potential skew of the cone of percussion that these paths might imprint.

After exhaustive tests, the following procedures proved to be the most effective concerning the objectives of the current study, but also relative low-cost and simple regarding their application, offering, at the same time, constant, high-quality results: the ventral faces of the flakes produced during the ‘open observation’ experiment have been recorded with digital photography, placed under single directional, low angle, cold lighting and a stable camera. The light was set so that it originates in the bottom of the frame. The camera (in the case of the current study a Mirrorless Canon® EOS M100-24.2 MP with a standard lens 15–45mm) was manually set to a low ISO (100 or 200), to reduce noise, and photographs were shoot in a RAW format. Usually, a f-stop of around 8 and a shutter speed of 1/15 were efficient to capture clear, sharp, enlightening images. Subsequent procedures of images processing in Adobe Photoshop®, such as strong magnification, adjustments of sharpen, contrast and brightness, but also the application of appropriate filters (e.g. inversion of the photos’ colours, grayscale mode) gave very good results concerning the uncovering of the cone cracks’ structural details (Figure 6).

Figure 5 Examples of blows’ inclination during the experimental flaking sessions from left and right-handers: a: ‘expected’, b: ‘perpendicular’, c: ‘invert’.
Nevertheless, it should be noted that the procedure and settings described here should be considered as only one plausible way for highlighting the cone crack paths on the flakes, since this is the first study to target these features (for similar techniques used to lithics’ digital photography and processing, yet for other analysis purposes, see Dryer & Mazierski 2009, Plisson & Lompre 2008). Future ‘digital’ experimentation could reveal a series of other modes, appropriate for the purposes of analogous studies (e.g. application of micro CT techniques—see e.g. Abel et al. 2011).

Following such a process, it turned out that the most clearly defined cone crack paths are these that border the inner cone crack. This observation led to the decision to focus measurements on this specific element. Digital measurements have been made using the Adobe Photoshop® rule tool. To determine a specific value that would reveal the skewness of an inner cone of percussion, measurements were focused on the exterior angles of the two proximal inner cone crack paths (the two sides of the triangle or the trapeze being in touch with the striking surface), in relation to a specific reference point. This reference point is the straight line passing through the origins of the inner cone crack paths at the striking platform of the blank. In essence, the part of the straight line, which conjoins the two inner cone crack paths, represents the impact surface of the hammerstone into the striking surface (Figures 6b, 7a). Hence, measurements were possible on blanks with convex or concave striking surfaces, which previous studies were struggling to evaluate (see e.g. Ruck, Broadfield and Brown 2015), since an absolute reference point, used as the ideal straight line was absent.

In practical terms, the difference occurring from the subtraction of left to the right angle measured (related to the observer eye with a blank grounded to its butt), could theoretically define the skewness of a cone, but also the inclination of the impact blow. Within such a consideration and by adopting contact mechanics principles, the following hypothesis has been examined: quotients with negative signs should be in agreement with a blow of a left-hander, whereas quotients with positive signs with that of a right-hander. For the needs of this research, and in order to eliminate potential mistakes on measurements, quotients on the −5, +5 region were considered to reveal unskewed cones.

The same practices were followed during the evaluation of the flakes produced during the blind test. Yet, in this case independent judgments ‘by eye’ were made in advance and remained unknown until the evaluation of the digital measurements and their success rates in predicting knappers hand preference. In this way, an attempt was made to determine the precision of the macroscopic observations in comparison to the digital...
measurements and the rates of accordance between the two approaches. It should be also noted that the hall procedure of the artefacts’ digitisation and the definition of cone crack geometry through measurements requires a larger amount of time in its implementation (about 15–20 minutes for each flake) in comparison to the ‘traditional’ macroscopic approaches of previous efforts. Yet, such an approach, as mentioned before, was considered able to offer the benefits of accurate observations and objectivity concerning the examination of the cone crack skewness.

Regarding the parabolic crack measurements, the basic methodological protocol proposed by Domííquez-Ballesteros and Arrizabalaga (2015) has been followed: flakes with linear, cortical and punctiform butts have been excluded from the study, along with those with a maximum butt thickness of less than 5mm. Flake butts have been close-up photographed and accordingly processed. Yet, a more simplistic way of measurement has been chosen for the definition of the parabolic crack orientation: the angle of the straight line passing through the parabola centre to another straight line joining the ends of the intersection of the ventral face with the butt of the flakes has been calculated, using again the Adobe Photoshop® rule tool. In theory and by adapting the system proposed by Domííquez-Ballesteros and Arrizabalaga (2015) an angle under 81° would be in agreement with a blow of a right-handed knapper, whereas an angle over 99° with the blow of a left-handed one (Figures 7b, 8). Values between 81–99° were considered as non-determinable, as also Domííquez-Ballesteros and Arrizabalaga (2015) have experimentally shown.

After weighting and evaluating the results obtained through the analysis of the experimental material (see Results section), at a final stage of the study, the pilot implementation of the cone crack paths’ methodology in the actual archaeological record it was decided. As noticed earlier, this was an attempt to evaluate how hominins’ handedness rates could be approached in real conditions, within the available archaeological material of the study from Kalamakia cave, associated with Neanderthals. Although these hominins in Kalamakia cave produced lithic blanks on a variety of raw materials (e.g. flint, andesite, quartzite, quartz) only artefacts manufactured on flint have been examined, for reasons of uniformity with the study’s experimental material. By applying the same sampling criteria as followed for the experimental artefacts of the study (size, intactness), the available sample counted 468 objects in total. This material derives from 9 different occupation levels of the site (Figure 9, Table 5).

Methodologically, the examination of flint flakes from Kalamakia cave followed the same ‘digital’ practices also applied to the experimentally produced flakes of the study.

RESULTS

Following the methodology described in the previous section, it was made possible to clearly identify the angles of the cone crack paths in 275 out of 286 flakes of the ‘open observation’ experiment, reaching a nearly 96.1% rate of determinability. Indeterminate blanks include mainly objects, where eraillure scars had spoiled decisively the geometry of cone crack paths, creating confusion. 69 flakes (24.1% of the sample) showed traces of the parabolic crack and a clear orientation of this feature.

Figure 7 Methodology of digital measurements of cone cracks’ geometry (A) and parabolic cracks’ orientation (B).
Figure 8 Application of digital measurements concerning the parabolic crack orientation on experimentally produced flakes: 1: flake produced by a left-hander. 2: flake produced by a right-hander.

Figure 9 Locality and stratigraphy of Kalamakia cave, southern Greece.
A strong agreement rate concerning the hypothesis of the relation between the cone crack paths geometry and the subjects’ handedness is evident, as indicated by the values of the digital measurements. By excluding unskewed cones, left-handed knappers as a total showed a slightly stronger agreement signal than right-handed ones. The above tendencies indicate a degree of variation among individual knappers. For the group of left-handers, a maximum of 88% agreement rate between handedness and cone crack geometry is observed for two of the participants (one expert and one novice), whereas the least agreement ratio of 75% is associated with a novice flintknapper.

A similar fluctuation is evident between the members of the right-handers’ group. A maximum 82% of agreement rate between handedness and cone crack geometry concerns one of the expert flintknappers. The lowest percentage of agreement regards an also experienced knapper. By importing and evaluating the factor of unskewed cone cracks, a larger variation can be observed between right-handers. Unskewed cones of percussion on the latter team are ranging between 4% and 26%. The corresponding rate among left-handers is 13% to 23% (Figure 10, Table 2).

**Figure 10** Difference of cone crack path angles (a) and rates of cone crack skewness (unskewed cones excluded) (b) on the lithic flakes produced during the ‘open observation’ experiment, according to subjects’ hand-preference. L1, L2: Left-hander 1, 2…R1, R2: Right-hander 1,2…LT: Left-handers total. RT: Right-handers total. Agr.: In agreement with hypothesis. Dsgr.: in disagreement with hypothesis. Rcp.: Right crack path. Lcp.: Left crack path.

### Table 2 Results of cone crack skewness and parabolic crack orientation on the lithic flakes of the ‘open observation’ experiment, according to subjects’ hand-preference. L1, L2: Left-hander 1, 2…R1, R2: Right-hander 1,2…LT: Left-handers total. RT: Right-handers total. Agr.: In agreement with hypothesis. Dsgr.: in disagreement with hypothesis. Ind.: indeterminable.

<table>
<thead>
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<th>SUBJECT</th>
<th>CONE CRACK SKEWNESS</th>
<th>PARABOLIC CRACK ORIENTATION</th>
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<td>L1</td>
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<tr>
<td>L2</td>
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<td>5</td>
</tr>
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<td>L5</td>
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</tr>
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<td>LT</td>
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<tr>
<td>R3</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>R4</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>R5</td>
<td>23</td>
<td>5</td>
</tr>
<tr>
<td>R6</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>RT</td>
<td>93</td>
<td>23</td>
</tr>
<tr>
<td>Total</td>
<td>180</td>
<td>45</td>
</tr>
</tbody>
</table>
Concerning the parabolic crack orientation, this feature was independently connected with the cone crack geometry of the flakes, as hypothesised. In this context, wherever present, a parabolic crack, showing a measurement value less than $81^\circ$, was always combined with a cone crack paths’ difference value more than $+5$. Consequently, a parabolic crack showing a measurement value more than $99^\circ$, was always combined with a cone crack paths’ difference value less than $-5$. Evaluating independently the values of the parabolic cracks, again left-handers show a stronger agreement rate between this feature and their hand preference. In contrast, two of the right-handed knappers show almost equal separated agreement and disagreement results. Concerning the cone cracks geometry, these two subjects show ‘normal’ agreement rates’ results. (Figure 11, Table 2).

Regarding the evaluation of the knappers’ kinetic behaviour (observations on the blows inclination through the experiments’ video recordings) in association with their hand preference, blow inclination data have been extracted from 175 of the experimental lithic flakes. For 172 of these objects the crack paths’ geometry was made also possible to be evaluated. The examination of blows trajectories with which the latter group of objects has been produced, show that in general both left- and right-handers tend to bring on flaking angles, which confirm to a great extent the a priori hypotheses of previous studies (e.g. Domínguez-Ballesteros & Arrizabalaga 2015; Rugg & Mullane 2001). ‘Expected’ blowing inclination rate is 50% for left- and 61.7% for right-handers. The ‘invert’ blows percentage is relatively larger for left- than for right-handers (28.2% versus 14.8% respectively). Knapping experience does not seem to affect these results.

An examination of the flaking angles in relation to the cone crack paths’ geometry shows that, although there is a general agreement between blows inclination and the cone of percussion skewness, disagreement rates are not negligible. In this context, in some cases, ‘expected’ or ‘invert’ blows were found to correspond to a cone crack geometry opposite to the theoretically expected one. This remark concerns both left- and right-handed knappers in almost equal rates (Figure 12, Table 3). The number of the experimental flakes for which the parabolic crack could be determined, and at the same time a blow inclination was made possible to be extracted through the experiments’ recordings, was too low (42) to permit an analogously valid evaluation.

The results of the blind experiment (Table 5) confirm, at first, the general picture of the analyses carried out through ‘open observations’. Excluding unskewed cones (16% to 24% for all subjects), the prediction success rates for knappers’ handedness is just over 72%, with a determinability rate approaching 90%. However, the latter percentage for three of the experiment’s subjects, one left-hander and two right-handers, is below 90% but exceeds 80%. Concerning individual knappers, the agreement between handedness and expected cone geometry is ranging from 69% to 78%.

Of particular interest, however, are the success prediction rates of the macroscopic, ‘by eye’, observations. Excluding objects for which the cone skewness was indeterminate (25%), test results show a prediction success of just over 50%. Although this percentage shows a particularly large variation between the subjects, the maximum success rate is not exceeding in any case 60%.

The results from the study of the parabolic cracks orientation made on the blanks of the blind experiment show that in all cases such a trait agrees with the cone crack geometry. Yet, again, the determinability of this feature among flakes is particularly low, since only 22.6% of the sample bore this distinctive trait. Additionally, the application of that method in the sample examined proved unreliable, since its predictability success rate is just over 47%.

The results of the cone crack geometry digital evaluation on the flint flakes from Kalamakia cave shows that determinability of the method reached a percentage of 90%, comparable with that of the
study’s experimental material. Excluding objects in which the angles of inner cone crack paths identifying an unskewed inner cone crack (20.1%), the results of this pilot study demonstrate that, in their great majority (over than 75%) the flint stone products from Kalamakia bore cone crack geometries, which, at first glance and according to the study’s primary hypotheses should theoretically be associated with right-handers. Using as main reference the occupation level eight, which contained most of the objects studied, this rate reaches 73.5% (Figure 12, Table 3).

**DISCUSSION**

The results produced by the experimental data analysis, indicate that during knapping tasks the inclination of blows delivered to core striking platforms seem to be consequently connected to an important extent with the imprints of certain Hertzian fracture features on the produced blanks’ ventral faces, and butts. It seems, thus, that specific angles of detachment predetermine the lithic products’ inner cone cracks geometry and the parabolic cracks orientation. On this issue it should be noted that the observable low inconsistency (Figure 12, Table 3), between the blow inclinations and the resulted cone crack geometries (e.g. cases that an ‘expected’ blow of a right-hander results to a cone crack geometry, which in theory should be attributed to an ‘expected’ blow of a right-hander) could be attributed to a certain degree to the misjudging of the angle of detachment for some of the flakes, evaluated through the videos analysis. This aspect might not be depended only on the blow inclination and core handling, but also on other factors (e.g. torque forces.

![Cone Crack Skewness & Blow Inclination](image)

**Figure 12** Correlation between blow inclination and cone crack skewness on the experimentally produced flakes among left- and right-handers. LH: Left-handers. RH: Right-handers. Agr.: In agreement with hypothesis. Dsgr.: in disagreement with hypothesis. Unsk.: Unskewed. Exp.: Expected. Inv.: Invert. Perp.: Perpendicular.

<table>
<thead>
<tr>
<th>BLOW INCLINATION</th>
<th>CONE CRACK SKEWNESS</th>
<th>AGR.</th>
<th>UNSKEWED</th>
<th>DSGR.</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LH</td>
<td>RH</td>
<td>LH</td>
<td>RH</td>
<td>LH</td>
</tr>
<tr>
<td>Exp.</td>
<td>32</td>
<td>50</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Perp.</td>
<td>14</td>
<td>13</td>
<td>0</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Inv.</td>
<td>10</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>56</td>
<td>67</td>
<td>8</td>
<td>10</td>
<td>14</td>
</tr>
</tbody>
</table>

**Table 3** Correlation between blow inclination and cone crack skewness on the experimentally produced flakes among left- and right-handers. LH: Left-handers. RH: Right-handers. Agr.: In agreement with hypothesis. Dsgr.: In disagreement with hypothesis. Exp.: Expected. Perp.: Perpendicular. Inv.: Invert.
created during flakes detachment), which remained ‘invisible’ in the macroscopic observations made on the video recordings.

Nevertheless, the current study’s empirical data suggest that the low determinability of the parabolic crack method (Figure 11, Tables 2, 4) seems to affect to a decisive degree its reliability (but not its objectivity), which can prove to be stochastic depending on the sample that is examined each time, but also on the ability of the researcher applying the method. For this reason, the parabolic crack method has not been applied to the archaeological material of the current study. In contrast, it seems that the methodology for the determination of the cone of percussion skewness, through its quantified digital evaluation proves to be a method that can be applied to a larger artefact sample than the approaches previously proposed, leading to more comprehensive and large-scale results (Figure 10, Tables 2, 4). It also became clear that observations made on artefacts using modern and close-range digital techniques and measurements can reveal many more useful information about unknown aspects of technology, than the traditional macroscopic approaches. Concerning this remark, it is worth noting that the successful handedness judgments rate, based on the macroscopic evaluations conducted during the blind test of the current study, is in agreement with corresponding rates reported by older similar efforts which used ‘by eye’ approaches of the artefacts (e.g. Ruck, Broadfield & Brown 2015; Ruck et al. 2020). This would render once again the basic principles of the cone of percussion’s skewness method for distinguishing handedness through lithic artefacts unreliable (Table 4).

However, a main issue arising from the current, but also from previous studies, is how handedness can be clearly associated with specific blow inclinations among left- and right-handers during knapping procedures, which in their turn seems to strongly determine the properties of the Hertzian fracture features on lithic blanks. As already mentioned, in past studies (e.g. Domínguez-Ballesteros & Arrizabalaga 2015; Rugg & Mullane 2001) such a trait has been considered as a ‘de facto’ principal in order to associate the various characteristics of the Hertzian fracture on flakes, with a formatted and distinct hand preference, and also to evaluate research results on this issue. In contrast, as previous efforts have underlined (e.g. Uomini 2001), individual knapping styles can easily alter in principle the mechanic prerequisites of such an ‘ideal’ scheme. Moreover, other factors such as the core handling position, local anomalies of the core striking surfaces and of the hammerstones’ impact surfaces can also negatively affect each time the blowing inclinations expected as ‘normal’ for left- and right-handers and alter their effect on the Hertzian fracture features. Such conditions can well lead to contradictory and confusing results concerning the possibility of determining hominin hand preference through the lithic technology.

The results of the current study indicate that individual knapping styles are not proven to be a decisive factor for the overall knappers’ handedness successful distinction through the evaluation of cone cracks geometry. For example, observations on knappers blowing angles (Figure 12, Table 3) indicate that in general left-handers tend to bring on ‘invert’ or ‘perpendicular’ blows in a larger degree than right-handers do. Such an observation could be correlated with a series of known data which indicate

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>NUM. OF FLAKES</th>
<th>CONE CRACK SKEW-BY EYE EVALUATION</th>
<th>CONE CRACK SKEW-DIGITAL EVALUATION</th>
<th>PARABOLIC CRACK EVALUATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IND.</td>
<td>SUC. JUDG.</td>
<td>IND.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>%</td>
<td>N</td>
</tr>
<tr>
<td>L1</td>
<td>37</td>
<td>11</td>
<td>29.7</td>
<td>12</td>
</tr>
<tr>
<td>L2</td>
<td>27</td>
<td>10</td>
<td>37</td>
<td>10</td>
</tr>
<tr>
<td>L3</td>
<td>25</td>
<td>5</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>LT</td>
<td>89</td>
<td>26</td>
<td>29.2</td>
<td>30</td>
</tr>
<tr>
<td>R1</td>
<td>21</td>
<td>4</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>R2</td>
<td>31</td>
<td>4</td>
<td>12.9</td>
<td>16</td>
</tr>
<tr>
<td>R3</td>
<td>31</td>
<td>8</td>
<td>25.8</td>
<td>12</td>
</tr>
<tr>
<td>RT</td>
<td>83</td>
<td>16</td>
<td>19.2</td>
<td>38</td>
</tr>
<tr>
<td>TOTAL</td>
<td>172</td>
<td>42</td>
<td>24.4</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 4 Results of the blind evaluation of cone crack skewness and parabolic crack orientation on experimentally produced lithic flakes according to subject’s hand-preference. L1, L2: Left-hander 1, 2...R1, R2: Right-hander 1,2...LT: Left-handers total. RT: Right-handers total. Ind.: indeterminable, Suc. Judg.: Successful judgments.

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that left-handers tend to have more ambilateral behaviors in comparison to right-handers (e.g. McManus, Van Horn & Bryden 2016). In consequence, this phenomenon might create an in-principle difficulty of left-handers’ recognition. Yet, such a potential ‘anomaly’ does not seem to be imprinted on the experimental material of the current study. According to the experimental data, left-handers, in overall, produce flakes with cone crack geometries, which are in agreement with their hand preference in a similar or larger degree than right-handers (Figure 10, Tables 2, 4).

An interpretive hypothesis to this phenomenon would be that left-handers have alternative ways to express their handedness in the context of flaking procedures which could not be detected by the methodological protocol of this study. Such an alternative way could concern a high degree of co-ordination between their left (blowing) and right hand (core handling) which in any case results (through the angles of detachment created) to a high expression of left-handedness concerning the cone crack geometry. In any case this is an issue for future research.

Beyond the above discussion, results of the current study indicate that both left- and right-handers produce flakes with cone crack geometries, which in overall are in agreement with their hand preference and only a deviation from the expected handedness expression is observed. Within such a consideration, the data presented suggest that even the ‘high-scoring’ left- and right-handers during knapping procedures produce to some degree flakes, bearing features that refer to knappers with an inverse hand preference, whereas the rates of ‘centred oriented’ features on flakes (e.g. unskewed cone cracks) also vary between individuals. In short, it would be reasonable to assume that the non-absolute agreement rates of knappers’ handedness through the study of the cone cracks’ geometry do not constitute a failure of the method, but a real fact of deviation from the manifestation of an individual’s well-established hand preference.

Although such a phenomenon could well be associated with many technical causes (e.g. experience, raw materials), it could also be related to the degree of hand preference that every individual brings, and the expression of his/her amphidexterity in various expressions of life (e.g. Bryden & Steenhuis 1987; Schachter 2000), independently of his/her broad categorization as left- or right-handed. Thus, this ratio of ‘personal handedness’ is very likely to be imprinted also in lithic production, yet not preventing in any case the handedness recognition. Future research employing cognitive science research protocols concerning the diagnosis of the degree of hand preference expression among knappers would be quite informative, to further advance such an argument.

In this discussion, the issue of how we could approach in practice prehistoric handedness ratings and their cognitive implications among the archaeological record, is inevitably raised, taking into account also the results offered by the present study within the context of the archaeological artefacts’ evaluation (Figure 13, Table 5). As mentioned in the introduction, such efforts are limited (e.g. Bargalló & Mosquera 2017; Dominquez-Ballesteros 2016), mainly due to the negative experimental results of previously suggested methods for predicting knappers hand preference. Yet, even in one of these cases (Bargalló & Mosquera 2017), the objective was the recognition of individuals’ hand preference through refitted assemblages, and not a calculation of the general prehistoric population handedness rates through the study of a big number of artefacts, produced by numerous knappers.

The experimental results of this study along with other recent efforts (e.g. Dominquez-Ballesteros 2016), suggest that the past restrictions, although remaining to a certain degree, could be surpassed. Such an approach, at this stage, would not produce definitive results but only approximate ones. Consequently, we may not be able to determine the exact degree of left- and right-handers.

**Figure 13** a) Difference of cone crack path angles of the flint flakes from Kalamokia cave, in relation to the distinct occupation levels. b) Potential hand-preference attribution of the artefacts based on the rates of determinable cone crack skewness. Rcp: Right crack path. Lcp.: Left crack path. PLH: Possible left-handers. PRH: Possible right-handers.
handers among hominins, but we could detect at least a predominance of right- or left-handers. In such a context, a simple statistical comparison between the values of the cone cracks’ paths difference extracted through the experimental and archaeological data of this study indicates, that at Kalamakia Cave, left-handed knappers could not have predominated. Most probably, thus, the archaeological artefacts examined constitute in their majority the products of individuals with a right-hand preference (Table 6).

In any case, such an argument should be considered as only indicative, concerning only one archaeological case. Thus, a next step to the study of prehistoric handedness and its neurophysiological and cognitive extensions on extinct populations, would be to apply widely on the archaeological material existing methodologies that have proven to be reliable; to create large datasets and databases; and to conduct extensive comparative studies. Moreover, comparisons between assemblages created within a wide temporal spectrum of several millennia might also indicate evolutional trends concerning the ‘dominant hands’ of prehistoric societies.

CONCLUDING REMARKS

Distinguishing hominin hand preference through lithic technology is a particularly complex issue, whose
multifactoriality has rightly troubled researchers in recent years. The current study, at the moment, can only offer approximations and not absolute conclusions, demonstrating the slow pace of progress on issues that cannot be tackled with absolute certainty, due to the lack of control on all components determining them. If such a condition characterises already defined physical laws, it is only amplified when considering the human behaviour, whose manifestation details are far from being tangible. Although such a conclusion might seem pessimistic, the present study offers an encouraging perspective, arguing that careful observation of cone crack paths on lithic artefacts is a proportionately objective methodology, which could function positively towards the diagnosis of a physical law that characterises, in turn, an aspect of human kinetic behavior, but also the conscious or unconscious mind functions.

Undoubtedly, the findings set out here will need to be confirmed within a greater level of certainty by future studies, along with the improvement of the research protocol and the moderation of any limitations currently featuring this research. Future efforts should be also centred around the interpretation of what the results of hand preference would actually mean for a prehistoric population, an objective which exceeds the epistemological capabilities of traditional archaeology. This ‘request’ could only be fulfilled within an interdisciplinary framework, where collaborative research will be invited to interpret the behavioural and neuroscientific dimensions of what the evolution of handedness means even today, beyond a convenient arrangement at the dining table!

DATA ACCESSIBILITY STATEMENT

Datasets related to this article can be found at https://github.com/stligkov/NeandLang-dataset hosted at https://github.com.

ETHICS AND CONSENT

Research has been conducted in accordance with the Declaration of Helsinki. Informed consent has been obtained from the participants to the experimental arrangements and all intended security measures have been met.

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COMPETING INTERESTS

The author has no competing interests to declare.

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