VIRTUAL SKELETONS AND DIGITAL MUSCLES: AN EXPERIMENTAL BIOARCHAEOLOGICAL APPROACH TO THE PRE-HISPANIC PRODUCTION OF MILLSTONES (TENERIFE, CANARY ISLANDS)

ESQUELETOS VIRTUALES Y MÚSCULOS DIGITALES: UNA APROXIMACIÓN EXPERIMENTAL BIOARQUEOLÓGICA DE LA PRODUCCIÓN PREHISPÁNICA DE MOLINOS DE PIEDRA (TENERIFE, ISLAS CANARIAS)

Jared Carballo-Pérez[a],* ⓘ, Norberto Marrero-Gordillo[b] ⓘ, Alberto Lacave-Hernández[c] ⓘ, Matilde Arnay-de-la-Rosa[a] ⓘ

[a] Departamento de Geografía e Historia. Universidad de La Laguna. C/ Prof. José Luis Moreno Becerra, s/n. Facultad de Humanidades. Planta 2. Apartado 456. 38200. San Cristóbal de La Laguna, Santa Cruz de Tenerife. jcarbalp@ull.edu.es, matarnay@ull.es

[b] Centro de Estudios de Ciencias Deportivas (CECIDE), Universidad de La Laguna. Campus de Ofra, s/n, 38071 San Cristóbal de La Laguna, Santa Cruz de Tenerife. nmarrero@ull.edu.es

[c] Departamento de Ciencias Históricas, Universidad de Las Palmas de Gran Canaria. C/ Pérez Toro, 1. Edificio de Humanidades. 35001, Las Palmas de Gran Canaria. albertolacave@hotmail.com

Highlights:

- The combination of biomechanical analysis and open-access Kinovea software enables the study of musculoskeletal and articular wear of experimentally reproduced tasks.

- The repeated use of the right arm during indirect percussion and abrasion in lithic production could increase the changes in bone robusticity of specific muscle attachments observed in the osteoarchaeological record.

- Motion ranges and postural angles analysis can generate more accurate representations of "virtual humans" in their archaeological context.

Abstract:

Understanding the physical impact of ancient labours has become an important experimental bioarchaeology area. Complex motion capture systems and digital tools have been used in biomechanical analysis during the reproduction of manual tasks. However, these systems are costly, so the researchers have explored alternative digital solutions. Therefore, the open-access Kinovea software was checked to confirm its reliability in characterizing the physical loads associated with particular works of ancient times. In this case study, the authors have analyzed the central postural angles and muscle chains involved in the indigenous manufacturing process of rotary stone mills, in the high mountains of Tenerife. The study included a virtual motion capture analysis carried out during the different phases of the experimental reproduction of this process; it was defined from the archaeological record of the quarries-workshops of Las Cañadas del Teide National Park (Canary Islands, Spain) volcanic millstones. The results of this study have demonstrated the software's effectiveness to virtually analyze the significant differences in posture between work techniques, observing a predominance of the use of *m. biceps brachii*, the *m. brachioradialis*, and the elbow joint during the manufacture of stone mills. On the other hand, Kinovea also has excellent potential in virtual archaeology, giving users tools to generate the average postural angles. As a result, building "virtual skeletons" in more precise work postures has been possible. This may serve as the base element to create complete body representations in virtual environments.

Keywords: open-access software; virtual archaeology; biomechanics; experimental archaeology; indigenous people

Resumen:

La comprensión del impacto físico de las labores del pasado se ha convertido en una importante área de la bioarqueología experimental. En el análisis biomecánico de la reproducción de tareas manuales se han venido utilizando frecuentemente complejos sistemas de captura de movimiento y marcadores reflectantes. Sin embargo, estos sistemas son muy caros, así que se han explorado soluciones digitales alternativas. De esta forma, hemos querido comprobar la fiabilidad del software de open-access Kinovea en la caracterización de las cargas físicas asociadas con ciertos trabajos del pasado. En este caso de estudio, se han analizado los principales ángulos posturales y las cadenas musculares involucradas en la manufactura indígena de los bloques de molino rotatorio en la alta montaña de Tenerife. El estudio incluyó llevar a cabo un análisis virtual de captura de movimiento en las distintas fases de la reproducción experimental

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de este proceso; éste se definió a partir del registro arqueológico de las canteras-taller de piedra de molino volcánica, halladas en el Parque Nacional de Las Cañadas del Teide (Islas Canarias, España). Los resultados de este estudio han demostrado la eficacia del software para analizar virtualmente las diferencias significativas de postura entre técnicas de trabajo; se ha observado un uso predominante del *m. bíceps brachii*, del *m. brachioradialis*, así como de la articulación del codo, durante la fabricación de molinos de piedra. Por otro lado, Kinovea también tiene un gran potencial en el campo de la arqueología virtual, pues ha permitido generar los ángulos posturales promedios. A partir de éstos, se ha podido constituir unos "esqueletos virtuales" en unas posturas de trabajo más precisas, que podrán servir como elemento base para crear representaciones corporales completas en entornos virtuales.

Palabras clave: programa de código fuente abierto; arqueología virtual; biomecánica; arqueología experimental; población indígena

1. Introduction

The daily life of the past communities is one of the essential axes in archaeology. The nexus of quotidian activities is the primary producer of the material world we study (Lightfoot, 2005; Robin, 2013; Schrader, 2019), which is perceptible in settlements, artefacts, and human bodies.

The interaction between these three elements is a central feature in past social practices, informing us about how knowledge is culturally produced and reproduced (Toren, 1999; Sofaer & Sørensen, 2005). Moreover, many of these practices require specific body techniques and skills, which has led the bones to adapt themselves in variable physical ways according to the objects' productions and uses (Ingold, 2001).

Thus, the constant dialogue between bodies and objects has become one of osteoarchaeology's leading questions, seeking to characterize the impact of past practices on the bone markers of physical activity (Hawkey & Merbs, 1994; Sofaer, 2006; Villotte et al., 2010; Cardoso & Henderson, 2013; Carballo et al., 2021). In this sense, combining experimental archaeology, biomechanics, digital archaeology and virtual archaeology has proven helpful in analyzing everyday physical activity patterns in the past (Pfleging et al., 2015).

1.1. Digital innovation in experimental bioarchaeology

Experimental archaeology has had its central objective in understanding material culture's use to elaborate new hypotheses (Binford, 1980). Although experimental comparisons have been criticized (Wylie, 1985; Lyman and O'Brien, 2001), the use of these analogies have been a valuable tool to explain and propose different behaviours from the past. However, most experimental archaeological studies have explicitly been fixed on material culture. Still, there are lines of research focused on the corporal impact generated by this materiality, which could be framed under the term "experimental bioarchaeology" (Walters, 2017).

Experimental archaeology's interest in gestures during tools production and use techniques began to have a notable development throughout the 20th century (Leroi-Gourhan, 1945; Roux & Corbetta, 1990; Chenorkian et al., 1990; de Beaune, 2000).

In recent decades, digital techniques have substantially impacted the "archaeology of gesture" (Mulliez, 2020), especially in experimental studies of lithic production and human evolutionary adaptation to the use of specific tools (Rolian et al., 2011; Key & Lycett, 2011).

These innovations have their origins in incorporating biomechanics' knowledge and techniques into osteoarchaeological research. This discipline applies mechanical principles to musculoskeletal systems (Ruff, 2008). For instance, bone tissue responds in various hypertrophic ways to the muscular loads exerted throughout the individual's life (Ruff et al., 2006). Muscle contraction occurs through signals from the nervous system, which generate electromagnetic responses (Robertson et al., 2014, Walters, 2017). These electric signals have facilitated the application of tools such as electromyography (Fig. 1a). During the experimental reproduction of archaeologically documented behaviours, electromyography can measure muscles' electrical performance (Shaw et al., 2012; Sládek et al., 2016; Walters, 2017). In addition to electromyographic documentation, bioarchaeological experimental studies of the last two decades have incorporated a whole series of virtual techniques and digital devices that we could group into three categories.

In the first place, we can highlight the force measurement systems (Fig. 1b), which connect tools to computers to measure their force and trajectory (Key, 2013; Pfleging et al., 2015). Some authors have even developed mechanized robots to monitor computer-guided lithic tools' processes (Calandra et al., 2020).

Secondly, manual pressure sensors like dynamometers (Key & Lycett, 2011; Key, 2013) or Novel Pliance® gloves also stand out to examine the distribution of pressure exerted with the hands during the reproduction of archaeological tasks (Putti et al., 2007; Williams et al., 2012; Price et al., 2016; Williams-Hatala et al., 2020) (Fig. 1c).
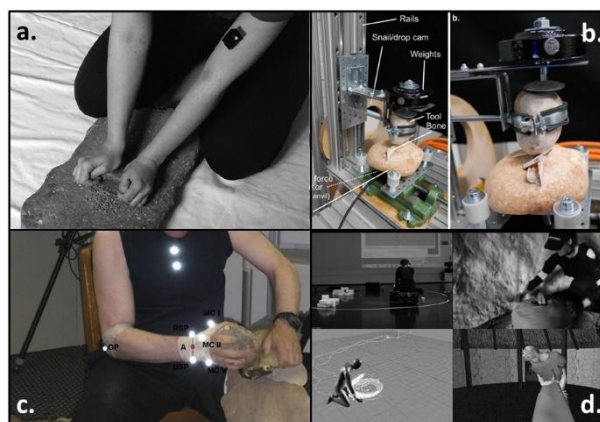

Figure 1: a) Electromyography applied to grind impact (Sládek et al., 2016); b) monitorized robot that measures the impact strength from lithic tools (Calandra et al., 2020); c) kinematic analysis of stone tool production using reflective markers (Price et al., 2014); d) motion analysis integrated into virtual reality (Dunn et al., 2012).

The last category belongs to a line of research closer to the one we propose in this study, motion capture systems. In these analyses, metric data is processed virtually and statistically from video documentation, taking reference points in tools (Geribàs et al., 2010) or joint anatomical points in the human body with the help of reflective markers (Schmitt & Churchill, 2003; Rolian et al., 2011; Williams et al., 2014). The study carried out by Dunn and colleagues (2012) on the Iron Age round huts from Hampshire (United Kingdom) shows this system's applicability to incorporate specific experimental modelling motions in virtual archaeological environments (Fig. 1d).

1.2. Kinovea: an open-access alternative

Most previous methods require a high investment in devices and expensive software, making their reproducibility quite difficult. However, the criteria for open science in archaeology recommend using more transparent and easily reproducible methods (Marwick et al., 2017). Therefore, we have decided to apply Kinovea v. 0.8.27 as an alternative for the first time in "bioarchaeological experimentation".

Kinovea is an open-access video analysis software, available online (https://www.kinovea.org), used in recent years for motion analysis (Guzmán et al., 2013; Elwardany et al., 2015). Although it has been frequently used in investigations related to sports medicine (Abd-El-Raheem et al., 2015; Hisham et al., 2017; Nor-Adnan et al., 2018) and occupational biomechanics (Cândido et al., 2012; Dabholkar et al., 2019), it has not yet been applied to study movements and gestures in experimentally reproduced archaeological tasks.

This programme measures passive and active ranges of motion by sampling images extracted at intervals from a video. This feature also makes it possible to observe and compare different video sections since it can export the data to a database with the movement analysis results (Balsalobre-Fernández et al., 2014; Abd-el-Raheem et al., 2015). One of the primary potentialities of Kinovea is its ability to be a reliable software that can perform analysis without the need to use physical sensors or reflective markers (Nor-Adnan et al., 2018). That is why it can be a perfectly adapted tool for the biomechanical study of works observed in experimental archaeology and ethnoarchaeology (Carballo & Moreno, 2021).

1.3. The indigenous production of millstones in Las Cañadas del Teide (Tenerife): a case study

We have applied the Kinovea software to understand the physical impact of indigenous lithic production from its experimental reproduction.

Tenerife is the main island of the Canary Archipelago, which emerged 7.5-11.5 million years ago after a series of submarine eruptions. This intense volcanic activity generated a landscape marked by a central *caldera* called Las Cañadas, raised by the peak of Teide at 3718 m of altitude (Ancochea et al., 1990; Anguita et al., 2002).

The high central mountains of Tenerife (2000-2300 m above sea level) constitute a unique environment of sparse vegetation and numerous lava flows, which the Guanche natives of the island visited for centuries (4th-16th c. AD), as revealed by radiocarbon dating (Arnay et al., 2011). Given that the southern and

northern slopes at lower levels of the island presented better conditions for agriculture and settlements, archaeological studies have suggested a seasonal occupation of the high mountains (Arnay et al., 2019), which has been reinforced by the descriptions of the chroniclers who arrived with the Castilian conquerors in the 16th century (Espinosa, 1980(1590); Frutuoso, 2004(1590)).

In addition to burying themselves in funerary caves and carrying out activities related to goat-herding, the material remains indicate an occupation related to lithic tools production and provisioning (Arnay & González, 2006), taking advantage of the volcanic raw materials richness in the area. Among the archaeological elements observed in Las Cañadas del Teide, the rotary millstones are relatively abundant (Diego-Cuscoy, 2008), used both by this aboriginal population of Tenerife and later by the modern rural population.

In contrast to Gran Canaria, where the raw material to produce these artefacts was lapilli tufa (Mangas et al., 2008), or sometimes with basalt extracted from vertical walls (Naranjo et al., 2016), in Tenerife, the millstones were manufactured in various porous magmatic rocks, especially in cones with large pyroclastic blocks. Although numerous processed pieces have been found in coastal areas and mid-altitude areas, only a small indigenous "workshop" known in Pedro Méndez was discovered in 1950 (Serra-Ràfols and Diego-Cuscoy, 1950).

The archaeological survey and excavation work carried out in recent years in Las Cañadas del Teide has allowed documenting in detail two quern quarries-workshops (Fig. 2): Cruz de Tea and Los Corrales. In these spaces, characterized by a similar composition of volcanic cones but with different lava formations, many fragmented and complete pieces of these millstones were found (Fig. 3), present in open provisioning areas and associated structures of habitat and production (Arnay et al., 2019).

The interdisciplinary study of aboriginal querns workshops has focused on the same extraction and manufacturing processes. On the one hand, chemical analysis has made it possible to deepen the distribution of materials and the mobility of the population (Arnay et al., 2019). For their part, technological studies indicate that millstone production was a much more specialized and organized activity than previously believed, identifying the different phases of the operational chain (Lacave et al., 2017; Marrero et al., 2021).
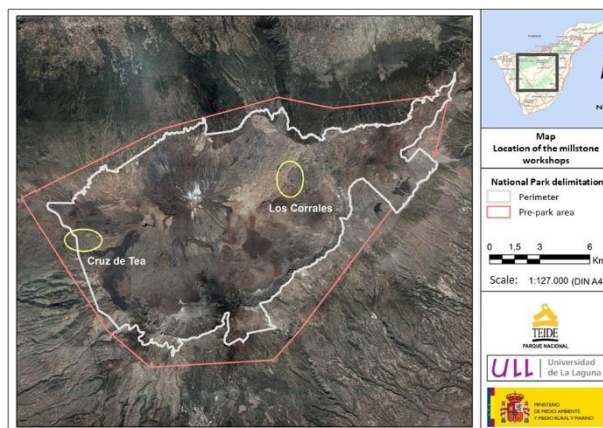

Figure 2: Map with the two quarries-workshops intervened in Las Cañadas del Teide (Arnay et al., 2016).

Figure 3: a) Millstone piece that presents flaking in situ in a single carving event (Arnay et al., 2016); b) pre-hispanic portable rotary quern found near Cruz de Tea (Arnay et al., 2019); c) millstone fragment with an associated basalt tool, recovered in a settlement in Cruz de Tea (Arnay et al., 2019).

This investigation of grinding objects includes an experimental program that seeks to reproduce the operational phases necessary for manufacturing rotary millstone, both from a technological and bioarchaeological perspective (Marrero et al., 2021) present work is framed.

2. Objectives

The study presented in this paper addresses experimental bioarchaeology from a digital approach, examining whether Kinovea software is reliable to analyze the biomechanical impact of certain tasks on the human body. For this specific case, we have employed the reproduction of the manufacturing phases of the rotary mills, identified from the archaeological remains found in Las Cañadas del Teide. Thus, using this software, the main points of joint wear and muscle impact will be characterized. The ultimate objective of this case study will be to verify the value of this digital resource in the interpretation and virtual representation of the body modifications in the aboriginal population from Tenerife, especially those associated with the specialized production of these grinding elements.

3. Materials and methods

3.1. System validation

Initially, to evaluate the effectiveness of Kinovea in the monitoring and analysis of traditional tasks, we followed a motion capture system for traditional textile activities previously developed and tested. Within the framework of two ethnoarchaeological studies, several analyses were carried out on the videos obtained in the textile works of the Cooperativa do Tecelagem (Alentejo, Portugal) and the high mountain domestic areas in Jbel Sirwa (Morocco), made by ten healthy adult women.

The digital outputs (video recordings) were processed by the authors with Kinovea so that the pattern of movements in the different looms was followed and analyzed. The data obtained from the various videos were compared so that the biomechanical differences (Fig. 4) between the use of the vertical loom and the horizontal loom could be successfully characterized (Carballo et al., 2022).

Figure 4: Differences in muscle impact between a) the horizontal loom and b) the vertical loom use based on preliminary ethnoarchaeological analyzes carried out with Kinovea (Carballo et al., 2022).

Finally, we also followed the model of Hisham and collaborators (2017) used for the statistical analysis, which has shown its effectiveness in studying the average angular values in the walking gait activities.

3.2. Experimental setup

According to the recommendations of previous works (Hisham et al., 2017; Nor Adnan et al., 2018; Dabholkar et al., 2019), the camera placement system was explored before reaching an optimal setup. On the one hand, the subject area, the position of the cameras, and the focal length were tested; on the other hand, elements such as the focal point, the capture speed, or the shutter were checked. In this way, the best video quality and viewing angle conditions were achieved (Bujang et al., 2015; Yusuf et al., 2015).

During the experimental reproduction activities of the basalt rotary mills, a Canon SX620 was placed frontally on a tripod (0.30 m high) at about 2.50 m of distance. A Denver AC-5000WMK2 was used to cover the lateral planes broadly at about 2.00 m from the subject and 0.20 cm above ground level, alternating between left or right depending on the predominantly used arm. This field of vision completely covered the anatomical areas of the subject during the experimental work. The focus and shutter of the camera were adjusted to be able to produce images with two-dimensional planes. Figure 5 shows how the cameras and the subject were positioned in the experimental setup.
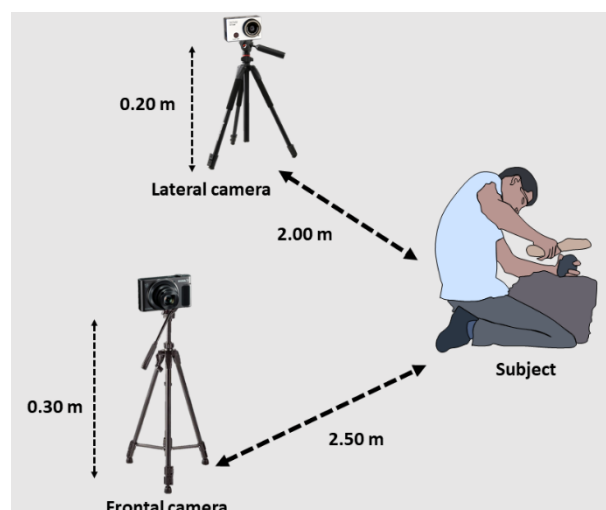

Figure 5: Illustration representing the experimental setup with the subject, camera positions, and distances.

3.3. Experimental protocols

Only one subject was used for this case study. The subject is a healthy juvenile individual with experience in lithic knapping, without any muscle disorders or diseases. In addition, the individual is the co-author of this study (ALH), with which we have his consent and ethical approval.

The design of an experimental program must be based on hypotheses made from previous studies, in this case, carried out from both lithic analysis (Pelegrin, 2011) and experimental bioarchaeology (Walters, 2017).

Based on the technical analysis of the millstone preforms and the associated flakes found in the archaeological contexts of Las Cañadas del Teide, ALH hypothetically reconstructed the production process of the rotary querns in 4 phases (Lacave et al., 2017; Arnay et al., 2022):

- Phase 1: Transformation of the natural block of vacuolar basalt with the first debitage in multidirectional knapping.
- Phase 2: Debitage of the block with another process of centripetal knapping, leaving a reserve in the middle to start the central perforation.
- Phase 3: Process of roughing the preform by debitage and abrasion until giving it a morphology with a clear circular tendency. Sometimes it includes the beginning of the central perforation.
- Phase 4: Final of the operating chain where the piece is worn out to its final morphology, with regularized faces and edges, including the finishing of the central perforation.

Thus, the graphic material obtained during experimental programme sessions was divided and classified among these phases of the operative chain to examine biomechanical differences between the different technological procedures (Table 1). In this way, throughout the 12 sessions that were performed, a total of 107 videos have been processed, collecting 576 minutes of experimentation, in which ALH successfully obtained several active and passive pieces of rotary millstones (Fig. 6).

Table 1: Temporality and quantity of video material analyzed with Kinovea from the 12 experimentation sessions.

Operating chain phases	Number of videos	Minutes	Total time percentage
Phase 1	28	143.03	25%
Phase 2	32	153.40	27%
Phase 3	24	163.90	28%
Phase 4	23	115.85	20%
Total	107	576.18	100%

(a)   (b)   (c)

(d)   (e)   (f)

Figure 6: Two of the finished querns after the experimental process: active pieces (a,d), passive pieces (c,f), an ensemble with a woodstick through its perforation (b,e).

During these sessions, no marker was added in the joint areas since Kinovea is considered a motion capture system that does not need reflective markers. However, other previous studies have used them to provide an excellent focal point during motion tracking analysis (Abd-El-Raheem et al., 2015; Hisham et al., 2017; Nor Adnan et al., 2018).

At the same time, the selection of variables was a crucial aspect of the programme's design since it requires systematic planning of the work and the observation criteria. Given that the planning was carried out jointly with lithic and bioarchaeological objectives, for this case study, only the independent variables were considered, those that are under the control of the authors of the experimental programme (González & Ibáñez, 1994; Gutiérrez, 1994). In this case, qualitative information regarding the raw materials used (vacuolar basalt blocks obtained from the quarries of Las Cañadas) and the tools (coarse-grained basalt picks or wooden hammers, among others) were recorded for each video, as well as the knapping techniques, gestures (force exerted, work angles and postures).

3.4. Motion tracking using Kinovea

For this case study, Kinovea was used to recover and analyze all the visual output obtained with the Canon SX620 and Denver AC-5000WMK2 cameras during the experimentation sessions. In the first place, all the videos were reproduced to check the absence of errors so that those that did not meet sufficient visual quality conditions were discarded. Then, among the 107 videos accepted, we used this software to locate and specify the primary markers in the selected joint areas (Fig. 7), following a protocol similar to that used with cases in which the software tracked the markers using the infrared motion capture system (Hisham et al., 2017; Nor Adnan et al., 2018).

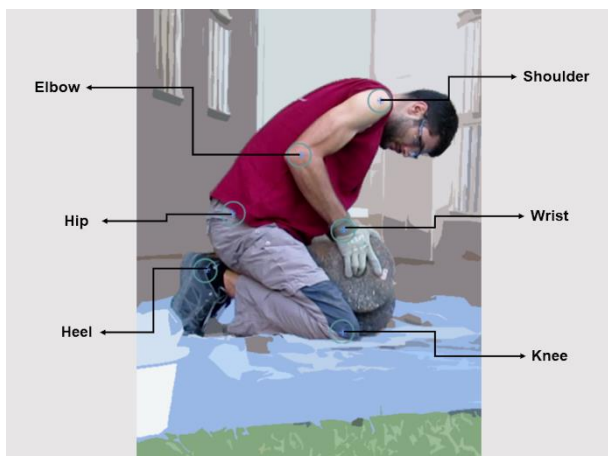**Figure 7:** Selected markers in the joint areas of the subject, located using Kinovea on one of the experimentation videos.

3.5. Angle measurement

Through Kinovea, we selected the three markers that configure each of the previously mentioned joints' relative angles (Fig. 7), as shown in the sample instance (Fig. 8). A primary marker is located at the joint point whose angle is analyzed. The other two angle markers are placed at the adjacent joint points (Ab Patar et al., 2015; Hisham et al., 2017). From these three points, the

software determines the relative angle of each of the joint movements. Instead of recording these data by fixed time ranges (e.g., taking angles every 5 s) the parameters determined in this study are angle changes within the same movement phase (Ab Patar et al., 2014, Nor Adnan et al., 2018). Thus, elbow flexion in a particular video would be evaluated by placing the primary marker on the elbow joint and the two adjacent ones on the wrist and the shoulder, taking the frames corresponding to the maximum flexion and minimal flexion moments. The data were stored in a database exported by Kinovea, differentiating the angles, work phases, postures, techniques, and the laterality of each assessed joint. This last element is vital to characterize the predominance of certain body members in certain activities, which has been a highly studied element in bioarchaeology.

Additionally, we used the "track path" tool of this software to evaluate the mobility of specific body joints during the different phases (Fig. 9).

Figure 8: Sample instance for angle measurement of knee flexion and elbow extension using Kinovea software.

Figure 9: Sample instance of the track path tool with the elbow and wrist markers while drilling the quern's centre hole.

3.6. Statistical analysis

We performed data analysis for all phases (a total of 107 videos) with SPSS version 20.0 for Windows. We also carried out descriptive statistics to compute the mean, standard deviation (SD), and variance values. In the same way, the Kruskal-Wallis and Mann-Whitney's tests were used to evaluate the statistically significant differences between lateralities and phases of the

operative chain. These types of non-parametric tests are frequently used in archaeology to check the heterogeneity of the data distribution between independent samples, since they are the ones with the most statistical resilience in those cases with abnormal distributions (Ostertagova et al., 2014; Auerbach, 2018).

3.7. Biomechanical descriptive analysis

Finally, with the help of the co-author NGM, a descriptive analysis of the central neuromuscular systems identified in each production phase from the videos was also carried out at the Center for Sports Science Studies. The neuromuscular areas are composed of the nervous and musculoskeletal systems, whose unions are functional because muscle is an electrically innervable tissue attached to the bone through tendons (Izquierdo & Redín, 2008).

While the analysis with Kinovea is key to assessing the mobility and impact of joint changes, the correct identification of muscle chains in traditional activities is essential to understanding the musculoskeletal changes in the osteoarchaeological record (Ruff, 2008; Schrader, 2019).

4. Results

As we observed in Table 1, the four phases are balanced in the total experimentation time. Nevertheless, phase 3 seems to be the one that requires the most work time, in which a total of 163.90 minutes were invested (28% of the total).

4.1. Motion tracking analysis

We have analyzed a total of 313 frames that met the ideal conditions to perform motion tracking analysis from the relative angles of the six joints. Through this analysis, 1878 measurements have been obtained thanks to the Kinovea software. Table 2 shows the general results of each joint analysis, classifying the data between those taken from frontal and lateral planes. According to the Kruskal-Wallis test performed, the joints in which statistically significant differences were observed according to the planes were the elbow ($p = 0.00$), the wrist ($p = 0.01$), and the hip ($p = 0.00$).

On the other hand, according to the SD values, the knee variable is where the data is more dispersed, with an average value of 58.92. For its part, the shoulder variable is where there seems to be a lower data dispersion, with an average value of 26.42. Roughly, the average values indicate that the data are slightly more dispersed (38.12) in the variable of frontal view compared to the lateral view (33.31).

In Figure 10, the average values of the SD for Phase 1 (35.33) and Phase 2 (34.84) are mostly regular. However, the lowest dispersion values (31.01) are concentrated in Phase 3, while the highest average values are in Phase 4 (38.83). According to the Kruskal-Wallis test that we performed, the variables of the elbow ($p = 0.00$), the knee ($p = 0.005$), and the ankle ($p = 0.00$) show statistically significant differences between the four work phases.

The SD lines present comparable data for all joint areas, except the knee variable, which shows more dispersed data in all work phases, especially in Phase 4 (70.94).

Thus, it should be noted that the hip and knee variables present similar data trends. There is an increase in dispersion in Phases 2 and 4, while there is a marked decrease in distribution for both variables during Phase 3.

Table 2: Motion tracking analysis results classified by joints and camera view and p-value for significant differences between the front and lateral views.

Joint & View		Min	Max	Aver.	SD	Kruskal-Wallis test	
						Z	p-value
S	FV	90	220	128.23	21.54	0.57	0.56
	SV	48	213	124.51	31.30		
E	FV	8	185	84.35	43.88	5.18	0.00
	SV	37	176	103.41	26.10		
W	FV	70	295	175.05	31.54	2.48	0.01
	SV	68	222	166.28	26.47		
HI	FV	14	187	97.91	37.69	7.25	0.00
	SV	3	117	66.55	26.12		
K	FV	10	202	106.80	53.83	0.21	0.83
	SV	14	191	103.44	64.02		
HE	FV	24	196	120.94	40.28	1.99	0.04
	SV	53	162	114.73	25.86		

Abbreviation: S: Shoulder / E: Elbow / W: Wrist / HI: Hip / K: Knee / HE: Ankle / FV: Frontal view / SV: Side view / SD: Standard deviation.
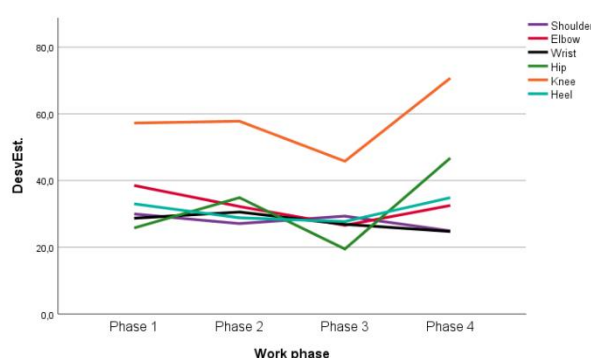
Figure 10: Graphic of multiple lines representing the SD values of each joint along with the different work phases.

Figure 11 shows the dispersion values of the relative angles of the shoulder, elbow, and wrist, classified by the type of techniques and the laterality of the arm. Mann-Whitney test showed significant differences between lateralities for the shoulder ($p = 0.00$) and the elbow ($p = 0.00$). In the case of the shoulder, the mean values of the angles are higher in the right laterality (129.45) than in the left (119.28), while the SD values show that the data are more dispersed in the left
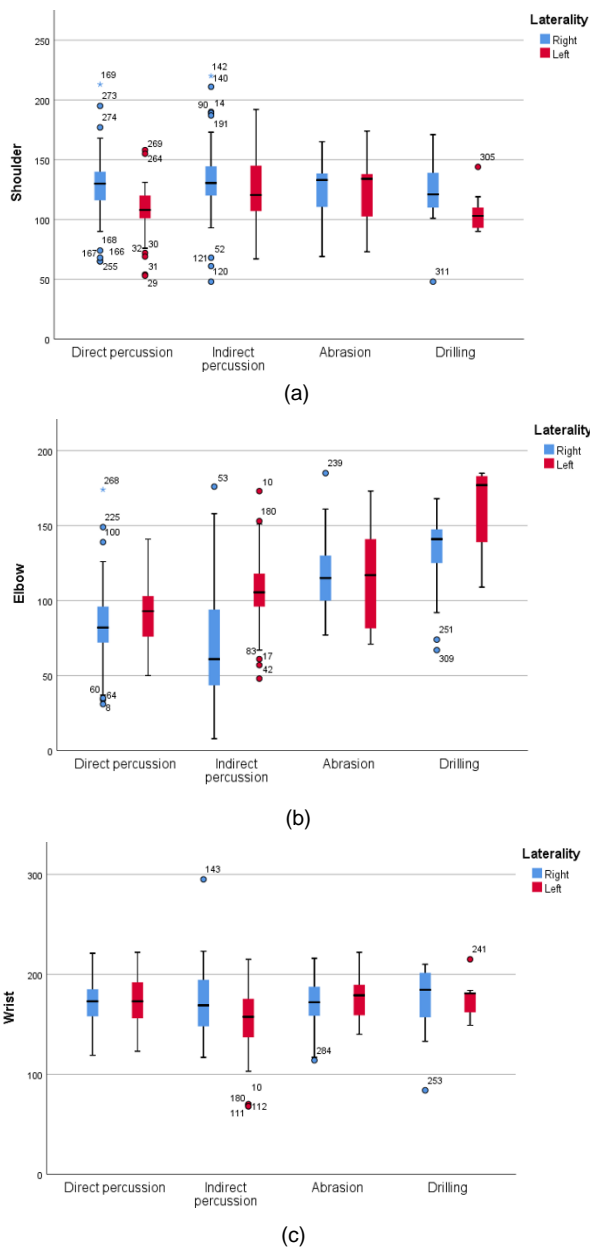
(a)

(b)

(c)

Figure 11: Boxplots showing the spread and mean values of the data sets for shoulder (a), elbow (b), and wrist (c) relative angles, classified by lateralities and techniques.

(a)

(b)

(c)

Figure 12: Boxplots showing the spread and mean values of the data sets for hip (a), knee (b), and ankle (c) relative angles, classified by postures exerted by the lower limbs.

In general terms, both tests show that in the wrist there are hardly any statistically significant differences due to laterality or technique in the average and dispersion values, as can be seen in Figure 11c.

In Figure 12, we show the distribution of the average and dispersion values of the hip, knee, and ankle, classified between the postures exerted by the lower extremities. According to the Kruskal-Wallis test, statistically significant differences were only found in the ranges of values of the knee ($p = 0.00$) and the ankle ($p = 0.00$). For the first case, we observe through the standard deviation that they are considerably concentrated as in the "genuflected" posture (9.72), although the "sitting on top" posture (40.25) and "sitting on the floor" (50.48) show a higher dispersion by many outliers. Averages of angles reveal that the high values are concentrated in "sitting on the floor" (151.90) and "standing up" (155.32), while the "genuflected" position shows a lower average (28.09).

Regarding the ankle, data are much more dispersed in the "sitting on top" posture, while again, values are more concentrated in the genuflection (29.57) than with the rest of the variables. The averages here are more regular than in the previous case, ranging from 126.58 to 98.70.

laterality (28.39) than on the right (26.46). For the elbow variable, it is observed that the angle averages are higher on the left side (107.80) than on the right (89.10), although the SD shows a more significant dispersion in the data from the right laterality (36.63) than on the left (31.22).

For its part, the Kruskal-Wallis test performed between the different techniques again showed significant differences only in the shoulder ($p = 0.02$) and the elbow ($p = 0.00$). In the first case, we can observe that the highest relative angle values are concentrated in "abrasion" (125.72), although there is a more considerable dispersion of data in "indirect percussion" (28.48). The highest average values are concentrated in the "drilling" variable (141.88). At the same time, the SD shows a more extensive data dispersion in indirect percussion (31.74), especially in the right laterality.
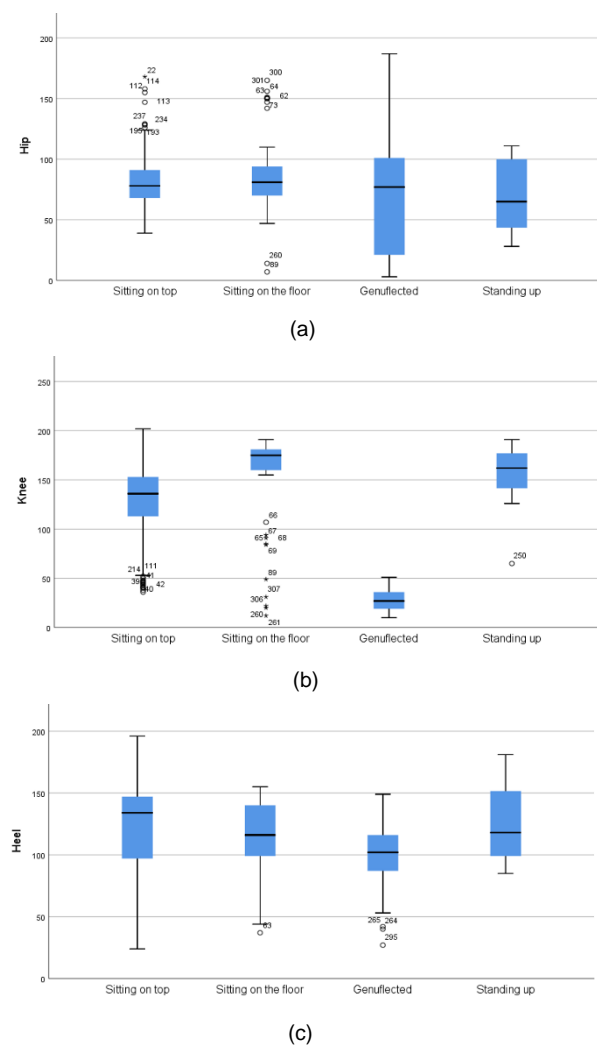
4.2. Biomechanical analysis

According to the visual analysis of the 107 videos combined with the Kinovea track path tool, below, we describe the main anatomical areas involved in each of the techniques.

Table 3: Crossed table of frames analyzed with Kinovea, classified by technique and posture.

	Direct percussion	Indirect percussion	Abrasion	Drilling	Total
ST	53	96	11	0	160
SF	36	3	3	7	49
GF	12	27	33	13	85
SU	1	4	9	5	19
Total	102	130	56	25	313

Abbreviations. ST: Sitting on top / SF: Sitting on the floor / GF: Genuflected / SU: Standing up.

As we can see in Table 3, indirect percussion is the most widely used technique, frequently performed on a seat. The repetition of the rotation of the right arm is mainly observed. In this process, the *latissimus dorsi* and *pectoralis major* muscles are activated in their internal rotation phase and the spinous and subscapular muscles in external rotation. Since the forearm and wrist are fixed, most of the impact is absorbed by the elbow. This technique requires using both arms. The analyzed individual usually grasps the size block with both legs in a forced hyperflexion posture, which overloads the *adductor* muscles and the lumbar plexus.

Second, direct percussion is usually performed on a seat or sitting on the floor (Table 3). We see a repetitive arm use during this technique that activates the flexor muscles (*biceps brachialis* and *brachioradialis*) and extensors (*triceps brachialis* and *anconeus*). In addition, the individual frequently supports the elbow to unload the back during this technique, thereby reducing spinal injuries.

Third, the abrasion is carried out primarily on the knees or a seat (Table 3). It requires a firm grip on the object with the hand, using the radial neuromuscular system that activates muscles such as the *extensor digitorum* and the *supinator brevis*. On the other hand, the continuous movement with the elbow involves the musculocutaneous nerve, which activates the *biceps brachii* and *coracobrachialis* muscles. In addition, the continued hyperflexion with the head lowered could imply the wear of the cervical and lumbar plexuses, and the knee and elbow joints can be affected.

Finally, the drilling work is performed by genuflecting (bending the knees) or sitting on the ground (Table 3). It requires a firm fixation of the arm to lock the elbow and thus generate a continuously flexed pronosupination. This movement, which combines the actions of rotating the forearm so that the palm is turned down or back, requires the median and radial nerves. Therefore, it activates muscles such as the *supinator brevis* and the *pronator quadratus*. If this activity is prolonged too long, a heavy load on the humeral head can be generated.

It should be noted that throughout almost all these techniques, the individual used the right arm as an active member, while the left arm was a passive one. As an exception, we can point out that both arms were actively used during abrasion.

5. Discussion

5.1. From muscle to the bone: an osteoarchaeological perspective

The results of the motion tracking analysis show the effectiveness of Kinovea in studying the variability of postures and movements exercised during specific tasks, providing more refined statistical evidence of the differences between techniques, productive phases, and anatomical areas. In addition, it has the enormous potential of being an open access measurement system that does not need sensors on the body (Faro, 2009). However, as other studies have pointed out, there is little literature on Kinovea (Abd El-Raheem et al., 2015), so it would be convenient to advance in analyzing inter and intra-observer error applied to experimental bioarchaeology.

Nevertheless, several physiotherapist researchers have established the validity and reliability of range of motion (ROM) measurements to analyze physiological movements (Boone et al., 1978; James and Parker, 1989; Van der Wurff et al., 2000; Glasgow et al., 2003; Cleland et al., 2006; Faro and Rui, 2016). Furthermore, according to authors such as Salmon & Wright (2014) and De la Vega et al. (2007), open-source technology is the best way to learn about the physical principles applied to biomechanical studies of human movement. Therefore, its application in experimental bioarchaeology allows us to reflect on how past bodies acted in specific physical tasks. This study can help us better understand the bone markers of physical activity in the osteoarchaeological record.

We offer a proposal to interpret the results obtained from the digital study of the rotary millstones experimentation. First, the ROM analysis shows the importance of the plans used during the audiovisual documentation process. A priori, it seems that the most reliable view is the side, so in future studies, we recommend positioning the cameras on the left and right sides to document the entire body correctly.

Secondly, the statistical processing of the data obtained with the obtained software indicates that during Phase 3, the range of movements is much shorter compared to Phase 4, where there is more significant ROM variability. The drilling technique is prioritized in Phase 4, which requires much wider movement ranges.

Concerning the ROM differences between techniques applied during the lithic production, we have focused mainly on the upper extremities since the reliability is usually higher than in the analysis of the lower extremities (Boone et al., 1978). According to the results, higher ranges of motion are concentrated in the elbow, especially in using the right side as an active arm during indirect percussion. However, the left arm has a wide range of postural positions. The preference for the right directional asymmetry is because the subject of study is right-handed. Thus, he performs active tasks more efficiently with the right muscles. The predominance of the right arm is a phenomenon of genetic influence studied in both modern and archaeological populations (Ruff & Jones, 1981; Refai, 2019; Carballo et al., 2021).
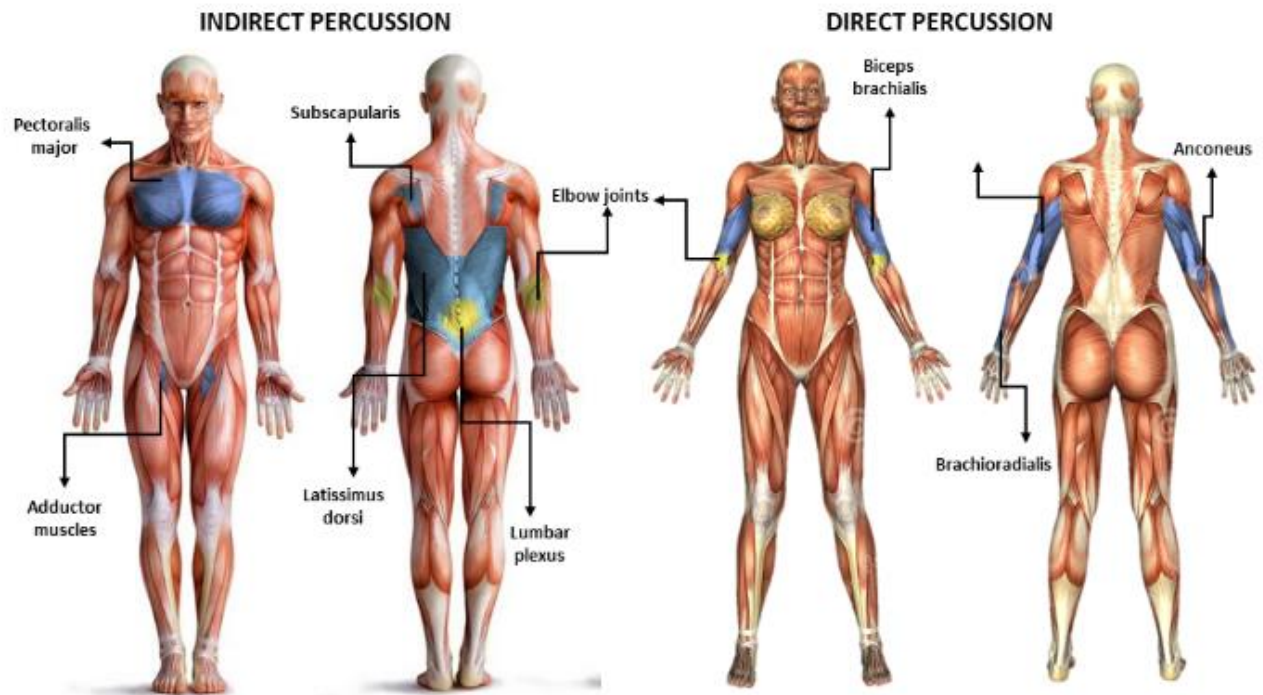
Figure 13: Anatomical model showing the areas with the highest muscular (blue) and joint (yellow) impact during direct and indirect percussion.
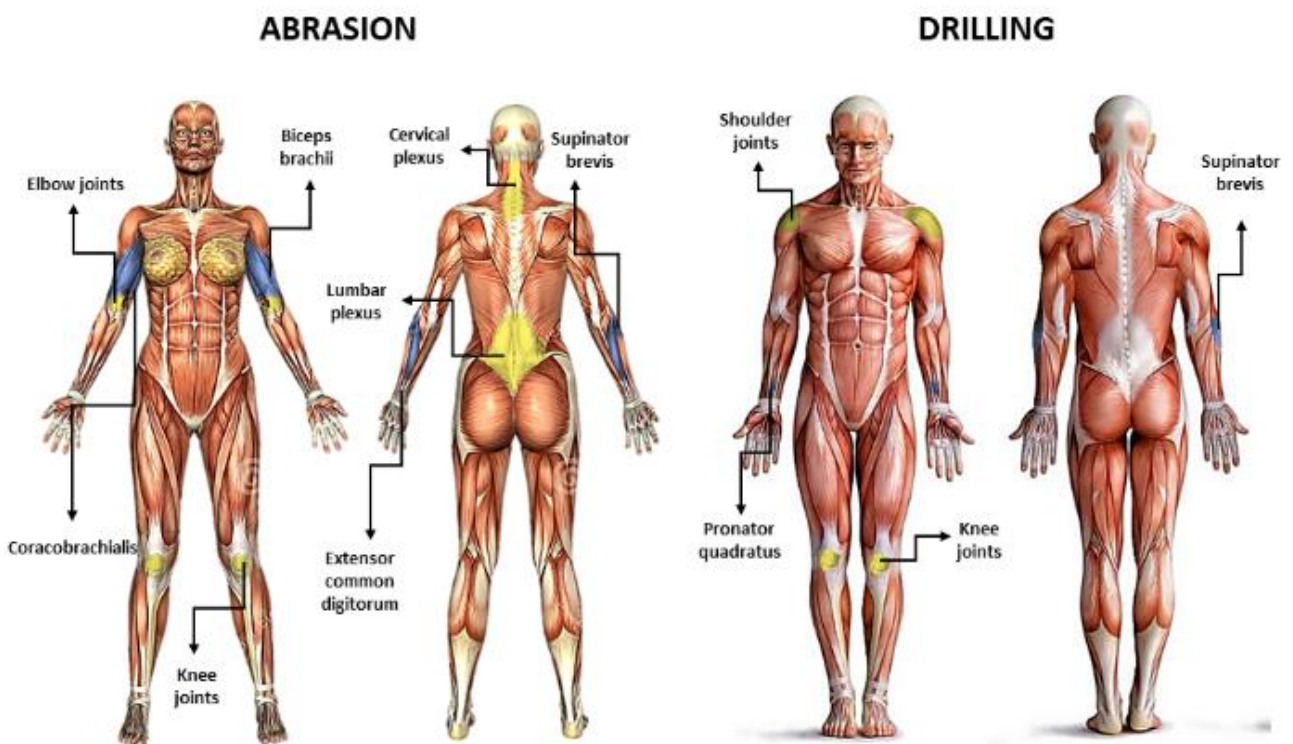

Figure 14: Anatomical model showing the areas with the highest muscular (blue) and articular (yellow) impact during abrasion and drilling.

It should be noted that laterality has been widely studied to understand better the gestural preference in specific activities of ancient populations (Al-Oumaoui et al., 2004). According to bioarchaeological evidence, rotary quern appearance since the Iron Age has influenced an increase in bilateral asymmetry among the upper limbs. In addition, its manufacture facilitated that the grinding was four times more effective than using the saddle quern (Sládek et al., 2016).

For its part, the wrist range of motion seems to be very low in all the applied techniques, although it maintains the most open average angle from all the joints. This characteristic is related to the high degrees of extension of the wrist during lithic knapping, which contributes to greater efficiency and linear velocity of the hand, reducing damage to the carpal bones and ligaments during hyperextension (Williams et al., 2014).

The highest variability is observed between the hip and the knee in lower limbs since their ROM show significant variations depending on the posture. In the case of the knee, it is critical to note that the subject constantly changes position due to the weight of the block. According to osteoarchaeological and clinical studies, the risk of osteoarthritis in the knee is high in those activities that involve repeated flexing, especially if there are mechanical loads applied (Cooper et al., 1994; Eng, 2015).

Figures 13 and 14 show schematically male and female models, which would be the main muscular and joint areas subject to physical wear according to the applied technique, based on the combination of the data obtained with Kinovea and the biomechanical analysis. According to archaeological sources, the lithic production of rotary querns in Las Cañadas del Teide could have been a specialized task for those who temporarily inhabited this high mountain area (Lacave et al., 2017; Arnay et al., 2016; Arnay et al., 2019; Marrero et al., 2021). Based on Ruff and colleagues' (2006) principles, the prolonged execution of these tasks could have remodelled the most affected musculoskeletal attachments in the bones of these aboriginal communities in the form of entheseal changes and osteoarthritis. These first changes refer to bone modifications that occur at muscle attachment (enthesis) as a result of physical stress (Schrader, 2019).

Most of the indicators indicated in Figures 13 and 14 have been widely studied in numerous bioarchaeological studies both internationally (Villotte et al., 2010; Cardoso & Henderson, 2013; Schrader, 2019) and in the specific context of the aboriginal populations of the Canary Islands (Estévez, 2005; Santana et al., 2015; Carballo et al., 2021).

Direct and indirect percussion occupy 70.3% of the total production time. Therefore it could be possible that these repeated activities were carried out for a long time. Therefore there could have been an increase in the entheseal robustness and joint osteoarthritis during the execution of these techniques. Table 4 shows the entheses and joint areas most affected according to the methods and bones, which can serve as a guideline when interpreting entheseal changes (EC) and osteoarthritis (OA) of some of the most studied bones at the level of physical activity in osteoarchaeology.

In order to consult the specific location of the muscle insertions in the bones, it is recommended to use the visual and descriptive atlas of Santana and colleagues (2013) for the upper extremities, as well as the anatomical atlas of Netter (2007) for the lower extremities.

Table 4: Guideline table for most affected enthesis (EC) and joint areas classified by type of bone and technique.

	Markers	Type	IP	DP	AB	DR
Clavicle	*Pectoralis major*	EC	▲			
	Scapular joint	OA				▲
Humerus	*Subscapularis*	EC	▲			
	Pectoralis major	EC	▲			
	Latissimus dorsi	EC	▲			
	Brachioradialis	EC		▲		
	Coracobrachialis	EC			▲	
	Extensor common	EC			▲	
	Proximal joint	OA				▲
	Distal joint	OA	▲	▲	▲	
Ulna	*Triceps brachii*	EC		▲		
	Biceps brachii	EC		▲	▲	
	Anconeus	EC		▲		
	Pronator quadratus	EC				▲
	Proximal joint	OA	▲	▲	▲	
Radius	*Biceps brachii*	EC		▲	▲	
	Supinator brevis	EC			▲	▲
	Pronator quadratus	EC				▲
	Proximal joint	EC	▲	▲	▲	
Vertebral spine	Cervical vertebrae	OA			▲	
	Lumbar vertebrae	OA	▲		▲	
Femur	*Adductor*	EC	▲			
	Distal joint	OA			▲	▲
Tibia	Proximal joint	OA			▲	▲

Abbreviations. IP: Indirect percussion / DP: Direct percussion / AB: Abrasion / DR: Drilling / EC: Entheseal changes / OA: Osteoarthritis.

In the case of the muscular insertions of the *biceps brachii* and *brachioradialis*, their impact had already been previously assessed in the experimental bioarchaeological study of the leatherwork with lithic instruments (Walters, 2017). These muscles are moreover innervated during the squatting position to apply direct force with the tools. Furthermore, the impact of these muscles has also been analyzed for the aboriginal population of Tenerife (Estévez, 2005), interpreted as a derivation of the usual practice of applying force with flexed arms. However, it must be taken into account that the aetiology of EC is quite complex since it is influenced by different influences of genetic, hormonal, degenerative, and metabolic origin (Villotte et al., 2010; Cardoso & Henderson, 2013; Godde et al., 2018; Bakirci et al., 2020; Salega, 2021; Villotte et al., 2021). Thus, we should be cautious when associating the robustness of certain muscular forces with specific activities.

Nevertheless, recent works have proven the impact of occupation on EC (Karakostis et al., 2017; Karakostis et

al., 2019). In addition, it must be considered that these muscles were required to execute other daily activities. In the case of the pre-Hispanic population of Gran Canaria, they have been interpreted within the framework of agricultural practices (Santana et al., 2015).

The application of forces with flexed arms can also be related to joint wear at the elbow, present in most techniques (Table 4). If these processes were executed daily, it could appear osteoarthritis in the distal joint of the humerus and the proximal joint of the radius and ulna. These degenerative bone changes have been observed in different archaeological populations (Becker & Goldstein, 2017), especially those in which there is early incorporation to physical work, as could be the case of the aboriginal population of Tenerife.

It is worth noting other muscles observed in the biomechanical analysis, such as the insertion of the pectoralis major since changes in the entheseal robustness of this muscle have been observed in the clavicles of the Guanche population, also related to other activities that require shoulder rotation, widespread in the south of the island (Estévez, 2005). It is also the case of supinator muscle hypertrophy, observed during abrasion and perforation, which has been analyzed in the aboriginal populations of the Canary Islands (Carballo et al., 2021) related to the practice of specialized artisan activities.

Regarding the spine, the practice of quern knapping in forced posture could lead to a series of pathological signs mainly concentrated in the lumbar vertebrae, such as compression fractures, arthrosis in the vertebral bodies, or Schmörl's nodules. These pathological modifications have also been observed in archaeological populations with intense physical activity (Al-Oumaoui et al., 2010; Carballo & Jiménez, 2020).

In the case of the lower extremities, although osteoarthritis in the knee and the application of forces with the adductor to support the block could lead to a physical impact, it is somewhat more challenging to interpret the daily physical activity patterns of the aboriginals of the Canary Islands. However, both archaeological and anthropological studies have revealed a high level of mobility in these indigenous communities (Arnay et al., 2019) because they are specialized activities carried out temporarily in high mountain areas and that also they would be interwoven in pastoral strategies that require frequent movements between the coast and the mountainous regions (Arnay et al., 2021). Therefore, when interpreting bone changes, the performance of mobility combined with many daily physical practices should be considered. For example, Figure 15 shows different cases of aboriginal bone remains from funerary contexts of Las Cañadas del Teide, which have certain muscles or body areas with high physical stress, probably derived from the constant execution of this type of work.

Therefore, the proposal of this study is not aimed at performing a direct association of these bone markers of physical activity with rotary millstone production. Instead, the primary applicability of this biomechanical analysis lies in its potential to facilitate the interpretation of the muscular forces that intervene in specific technical processes of the past and the physical impact that it could have on the skeletal remains of archaeological communities with similar life patterns.

Figure 15: Different human bones with signs of physical stress from various funerary caves in Las Cañadas del Teide: a) lumbar vertebra with Schmörl's node and spondyloarthrosis (Llano de Maja); b) ulna with a robust m. biceps brachii (Llano de Maja); c) radius with a robust m. biceps brachii (El Portillo); d) humerus with a robust m. pectoralis major (Cañada del Capricho).

5.2. From muscle to computer: potentialities of Kinovea in virtual archaeology

The application of free access software such as Kinovea to this experimental study is a new addition to digital archaeology, a positive factor since it has been growing with improvements in digital technologies (Daly & Evans, 2006).

While digital archaeology encompasses the tools and methods applied to research the past, it must also be considered that this type of embodied technology blurs the physical and virtual boundaries between the human body, the places, and the objects (Morgan, 2019). This digital approach to studying the relationship between bodies and objects can also provide exciting perspectives to virtual archaeology, as Dunn et al. (2012) did for integrating humans with rotary millstones in a virtual environment.

In recent years, the use of "virtual humans" (VH) has been incorporated more frequently in cultural heritage, both with avatars and virtual agents (Thalmann et al., 2014; Machidon et al., 2018; John et al., 2018; Kolivand et al., 2018; Karuzaki et al., 2021). An avatar is a graphic representation of a human, two-dimensional (static or moving images) or three-dimensional (e.g., characters in a video game or virtual reality). Implementing virtual humans is a complex task since it needs a great variety of software and hardware to provide the avatar with realism and consistency (Machidon et al., 2018). Unlike in the biomechanical analysis of the experimental process in which we go from muscle to bone, the construction of 3D models of VH usually begins by creating an invisible "skeleton" that mimics the structure of human bones. In order to capture static and dynamic postures, low-cost depth cameras (Kinect or RealSense, among others) have typically been used on human subjects while they perform the activity that is to be captured virtually (Tong et al., 2012; Zeng et al. 2013). During the reshaping of the virtual human, it is challenging to carry out a consistent reconstruction of body size and muscles (Hasler et al., 2009; Zhang et al., 2013).

In this sense, the biomechanical analysis of experimental archaeological work with Kinovea can provide new solutions to the reconstruction of virtual humans, especially with the invisible skeletal structures, and give greater precision to muscle reshaping. In this way, the track path tool can execute dynamic scenes, and the average angles of the motion track analysis can be applied to two-dimensional static representations.

For this case, we have used Manikin software. It is a three-dimensional presentation app that can be helpful to reproduce a "virtual skeleton" (VS) because it helps to reshape postures straightforward. In this case, we have positioned the VS in a specific posture, and we have placed each of its joints at the average angles observed in the Kinovea motion tracking analysis for each technique. In this way, we can obtain base models of virtual humans in much more precise postures from biomechanical and experimental perspectives.

In Figures 16 and 17, we have inserted these VS in their archaeological sites, positioning their joints in the posture ranges obtained from motion tracking analysis to give them greater realism. Considering the archaeological sources and the phases defined by Lacave et al. colleagues (2017), the aboriginal population would carry out works such as abrasion and drilling more frequently around the habitat structures associated with the workshops, while the direct and indirect percussion of the first phases would indeed be carried out in the quarries since it involved the first knapping of the blocks (Arnay et al., 2016; Arnay et al., 2019). Thus, in Figure 16, we have added a VS positioned according to the postural angles of direct percussion, sitting on the ground with a basalt stone tool and representing the moment when one of the blocks would be working with breaks. This block was located during the Cruz de Tea quarry (Las Cañadas, Tenerife). For its part, in Figure 17, we have placed another VS that is genuflected according to the postural abrasion angles, placing it in the virtual reconstruction of the habitat structure in the site of Chasogo, located near the Cruz de Tea quarry-workshop, and in which the last stages of the production process could also have been carried out.

During the reshaping phase of the virtual human body, it is necessary to integrate pre-existing templates, sets of mesh, and databases of digitalized bodies in different shapes and positions. In this sense, incorporating the data generated with Kinovea may have exciting potential when building the body of virtual humans (Zhang et al., 2013; Machidon et al., 2018). In the same way, when resizing the muscles of these avatars, it would be essential to give a greater dimension to those muscles that are more used during a given physical activity.

However, it must be considered that the integration of the data from this study depends on the type of postures by a single individual, so it would be necessary to integrate data of the postures performed by more people to ensure the validity of the angles, and it would be equally essential to compare with ethnographic studies of similar characteristics. Thus, the inclusion of data from this type of open-access software will have innovative and cheap applicability in virtual archaeology, making increasingly necessary the collaboration between osteoarchaeologists and professionals of the sector in the production of virtual humans.

Figure 16: Virtual skeleton (VS) that has been placed in the archaeological quarry of Cruz de Tea (Tenerife, Spain) in the position of direct percussion with a stone tool and a recently broken block.

Figure 17: VS that has been placed in the reconstruction of the archaeological site of Chasogo (Tenerife, Spain) in a genuflected posture during the abrasion phase.

6. Conclusions

We have proposed throughout this work the use of Kinovea software as an open-access alternative to the expensive digital and virtual methods that have been used in experimental bioarchaeology. Furthermore, to evaluate the physical impact of archaeological works and their physical representation in virtual archaeology, we have taken the experimental reproduction of the indigenous production of rotary mills, archaeologically documented in the Las Cañadas del Teide National Park (Tenerife, Spain).

Following models previously applied in sports medicine, we have proposed an experimental study protocol that combines video documentation, range of motion analysis with Kinovea, statistical processing, and biomechanical study. From the 576 minutes of video processing, a total of 1878 measurements were statistically analyzed according to the work phase, the anatomical area, the applied technique, or the body posture. According to the study of ranges of motion and biomechanical analysis, drilling and indirect percussion performed with the right arm generate the most significant physical impact on the body. Although many hormonal, metabolic, and clinical factors must be considered when interpreting bone markers of physical

activity, this type of task could have increased robustness changes in enthesis such as *m. biceps brachii*, *m. supinator brevis*, or degenerative changes in the elbow joint and the spine.

This study facilitates the interpretation of the physiological forces that intervene in particular works of the past and improves the virtual representation of the bodies that carried out these tasks. Furthermore, since the use of "virtual humans" (VH) is becoming more and more frequent in archaeology, we have used the average ranges obtained from the analysis with Kinovea to insert in their archaeological context some "virtual skeletons" (VS), which could serve for their further development in full-body representations.

It would be convenient for future studies to increase the study sample with different individuals and apply our methodology in various experimental works using different observers. In addition, it must be taken into account that many of the gestures used in experimental studies may be derived from modern lifestyles, since the learning processes vary greatly between cultural groups, generating possible differences between the subjects of the present with those of the past. Similarly, to improve the reliability of Kinovea, it would also be necessary to statistically compare its efficiency with other motion analysis software such as Cortex, which uses reflective markers on the body.

However, even though it is a particular experimental case study, the potential of this work lies in showing the ability of the combination between virtual archaeology and bioarchaeology to increase the precision of analysis in the processes of transformation and representation of the bodies of past people in the field of physical labour.

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Author contributions

Jared Carballo–Pérez: formal analysis, methodology, software, investigation, writing-original draft. Norberto Marrero-Gordillo: methodology, research, software, writing-review. Alberto Lacave-Hernández: methodology, investigation, formal analysis. Matilde Arnay-de-la-Rosa: project administration, supervision, writing review, and editing.

Conflict of interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial or nonfinancial interest in the research and the data supporting it discussed in this manuscript.

Data availability statement

The authors confirm that the data supporting the findings of this study is original and first featured in this study unless stated otherwise, in which case the source is cited. All original data of this study are available within the article and its supplementary materials under request.

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