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War Clubs in Southern California: an Interdisciplinary Study of Blunt Force Weapons and Their Impact

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Abstract
Previous studies on violence have focused on patterns of trauma based on bioarchaeological studies of human remains or on architectural features such as palisades, towers, and protected locations. Artifacts used as weapons in conflict have received less attention. Most weapons, particularly war clubs, were made wholly of organic materials that decompose, resulting in low visibility in the archaeological record that creates a challenge for reconstructing their form and potential specialized role in conflict. Using an interdisciplinary approach, historically recorded use of clubs was linked with precontact evidence of blunt force trauma to better understand the usage of different types of war clubs found in southern California. War clubs were recreated with replicative experimentation and then tested in biomechanical experiments to measure lethality and to record likely patterns of associated trauma. Patterns of trauma recorded in experiments were representative of trauma patterns seen in pre-contact/proto-historic case studies. As the presence of war clubs in warfare is well-documented across Indigenous North America, this framework for testing tactics and types of weapons permits cross-cultural comparisons to better inform the practices and impact of weapons in human conflict and violence.

Keywords California · Proto-historic · Multi-disciplinary · Experimental archaeology · Violence

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> *The war chiefs stood between the lines. Each armed with a club only. The Yuma chief said to his opponent: "I am ready to have you strike first if you can." The Maricopa chief answered: "It is for me to let you try your club on me, because you want to kill me, and you have traveled far to satisfy your heart."*
> - O'odham annals stick, Autumn 1842 (Forbes 1965: 76)

Anthropological studies of conflict in the past frequently discuss the use of violence and its implications (Keeley 1996; Kelly 2000; Whitehead 2004; Otterbein 2004; Guilaine and Zammit 2005; Gat 2006; Arkush and Allen 2006; Fry 2013; Allen and Jones 2014). Within the last 20 years, research has focused on the results of bioarchaeological evidence (Martin and Frayer 1997; Milner 1999; Walker 2001; Schulting and Fibiger 2012; Martin *et al.* 2012; Knüsel and Smith 2014; Martin and Harrod 2015), preventive measures for defense (Wilcox and Haas 1994; Wilcox *et al.* 2001; Tuggle and Reid 2001; Allen and Arkush 2006; Reid 2014), and motivations for conflict (Gat 2009; Nielsen and Walker 2009; Kuckelman 2015; Smith 2014). Experimental archaeology has proven to be a productive method for studying weapon systems, particularly projectiles (Dohrenwend 2002; Smith *et al.* 2007; Brown and Craig 2009; Yeshurun and Yaroshevich 2014; Gordón and Bosio 2012; Forsom and Smith 2017). Yet little analysis has centered upon shock weapons. War clubs, in particular, have received scant attention beyond basic recording of measurements (see Dyer and Fibiger 2017 for a notable exception). The global presence of war clubs and similar weaponry indicates that they are cross-culturally significant (Keeley 1996; Martin and Frayer 1997; Kelly 2000; Jones 2004; Otterbein 2004). The questions then are why and how were they utilized? To answer these questions, an interdisciplinary approach is needed to measure lethality within the context of multiple records of violence and connect these various records with each other. This work applies this interdisciplinary approach to investigate war club use during violent conflict in Indigenous precolonial southern California.

Ethnohistoric accounts document multiple instances of warfare among Indigenous groups in southern California (Stewart 1947; Fages 1951; Font 1951; Heizer and Whipple 1951; Fathauer 1954; Forbes 1965; Kroeber and Kroeber 1973; Kroeber 1976; James and Graziani 1992). Shock weapons, such as lances, knives, and clubs, were used in hand-to-hand combat. Clubs appear to be the most prevalent weapon shock weapon and were primarily made of hardwoods or other organics. Consequently, weapons used for warfare can be difficult to distinguish in the archaeological record as many of them, especially war clubs, are made wholly of organic materials that do not preserve well. This new approach builds a framework for determining types of shock weapons (in this case, war clubs) used to inflict blunt force trauma in Indigenous warfare in southern California.

We take an interdisciplinary approach to understand how war clubs were used, how lethal trauma was inflicted, and what types of wounds these weapons potentially caused. Ethnohistoric documents, such as ethnographies and primary accounts, provide details on the use of these weapons, while prehistoric bioarchaeological case studies document the traumatic skeletal injuries. To connect historically recorded use of clubs to prehistoric evidence of blunt force trauma, we use multiple approaches that include replicative experimentation to recreate the war clubs, biomechanical experiments to measure lethality, and biomechanical indices to record likely resultant patterns of trauma. As the use of war clubs is well-documented across Indigenous North America, this framework for testing tactics and types of weapons permits cross-cultural comparisons to further inform the other scholars of human conflict and violence.

Background

Numerous ethnohistoric accounts report that war clubs were used in close quarters by Indigenous warriors throughout southern California (see Fig. 1) (Coronel and Coronel 1824; Ives 1861; Sparkman 1908; Hooper 1920; Stewart 1947; Fages 1951; Font 1951; Heizer and Whipple 1951; Forbes 1965; Heizer 1968; Kroeber and Kroeber 1973; Kroeber 1976; Kroeber and Fontana 1986; James and Graziani 1992; Campbell 2009). The primary weapons used by these groups were mallet-shaped or truncheon-style clubs carved from hardwoods. These styles of clubs are mentioned in ethnographic records of the Cahuilla (Bean 1972), Gabrieleño (McCawley 1952; Heizer 1968), Chumash (Hudson and Blackburn 1980), Quechan (Forde 1931: Forbes 1965), Mohave (Stewart 1947: Fathauer 1954), and many others (Heizer and Whipple 1951; Kroeber 1976).

Records indicate extensive use of war clubs by the Yuman groups such as the Mohave, Quechan, Halchidoma, and Cocopa (see Fig. 2 for examples). Among the Mohave, these two types of specialized club are called *halyawhai* (*i.e.*, mallet) and *tokyeta* (*i.e.*, truncheon) *Halyawhai* are described as one- or two-handed clubs with either rounded or cylindrical heads. Occasionally, ridges were burnt into the top to provide a sharp edge to inflict more damage to the face (Forbes 1965; Forde 1931;

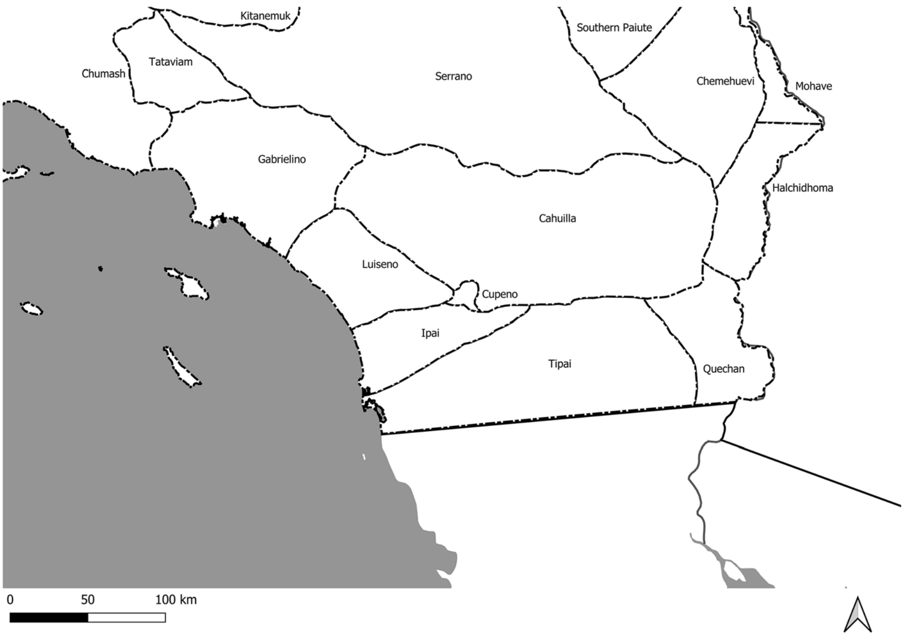

Fig. 1 Map of Indigenous southern California and region of interest. Created by Joseph Curran

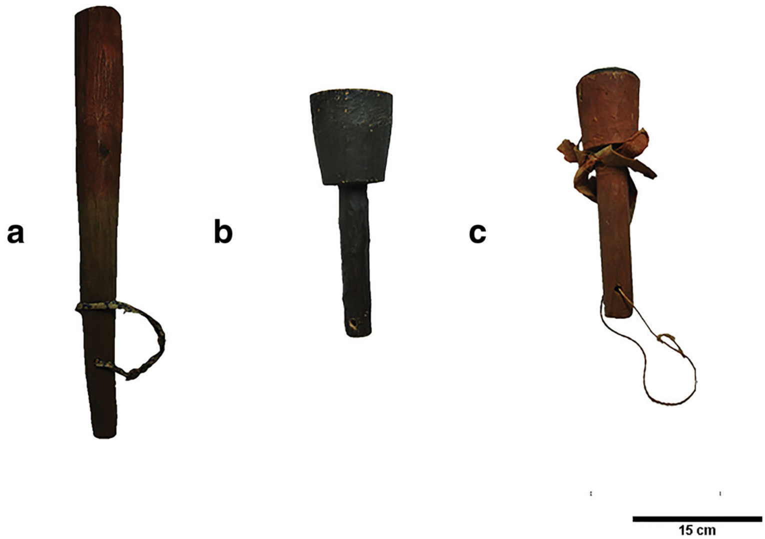

Fig. 2 Examples of Mohave war clubs. (**a**) Red-painted *tokyeta*; (**b**) black-painted *halyawhai*; (**c**) red-painted *halyawhai*. Courtesy of © Phoebe A. Hearst Museum of Anthropology and the Regents of the University of California. Photograph: Joseph Curran (Catalog No. 1-1743, 1-4290, 1-4291)

Fathauer 1954; Stewart 1947; Sweeney and Woodward 1956). Forde notes, "The upper surface was slightly hollowed and its edge was kept sharp so that maximum damage might inflicted" (Forde 1931, p. 170). There are regional cultural differences in club morphology, such as the sharpened-handled Cocopa and Quechan clubs. The *tokyeta* is a 2-ft. rod-like club with a triangular-shaped striking end. These clubs were made primarily from dense hardwoods like mesquite, although ironwood and oak were also carved. As Stewart notes:

> The club was grasped near the cylinder rather than at the end of the handle, and it was usually smashed into the chin or face with an upward stroke. Occasionally the warrior struck downward at the enemy's temple. A warrior might seize an enemy by the hair and club him, then throwing the foe over his shoulder to men armed with heavy straight clubs (tokyeta), with which they cracked his skull (Stewart 1947, p. 262).

From these accounts, it is clear Yumans wielded weapons designed to kill enemies. The presence of similar club types across southern California indicates that the use of the truncheon and mallet types spread beyond the Colorado River. Even though these clubs were critical tools of conflict and violence, this type of artifact is not generally recovered in the archaeological record because wood decomposes quickly in the dry environments of southern California. Therefore, this has created a critical knowledge gap in our knowledge as, necessarily, most research on pre-historic conflict has necessarily focused on skeletal evidence of trauma.

Bioarchaeological evidence of trauma in prehistoric Indigenous populations has been extensively studied in California and elsewhere. The California data primarily comes from the Channel Islands (Walker 1989; Lambert 1997, 2002), Central California (Jurmain and Bellifemine 1997; Bartelink *et al*. 2014; Pilloud *et al*. 2014; Schwitalla *et al*. 2014), and Playa Vista (Stanton 2016). Across California, evidence for blunt force trauma presents primarily in the frontal, parietal, and facial regions of the cranium. Within this body of studies, cranial depression fractures are diagnosed by depressed spherical or ellipsoid shapes, indicating the use of club-like weapons. In a few cases in the Channel Islands, the lesions had an irregular (15.0%; $N = 21$) or linear (5.0%; $N = 7$) shapes (Walker 1989).

In all case studies, cranial depression fractures also appear to be more common on the victim's left side than on the right side of the cranium. Most of the injuries were in the parietal and frontal regions. Facial trauma was also present in all areas.

Differences between regions appear in the dimensions of cranial trauma, with Channel Islands (Walker 1989; Lambert 1997) cases having the smallest wound dimensions with an average diameter of 12.39 mm for parietal wounds and 11.05 mm for frontal trauma and Playa Vista (Stanton 2016) the largest, at nearly twice those of the other two regions with an average diameter of 17 mm for frontal trauma.

An interesting observation is that instances of trauma were similar between sexes. Among younger males and older females, especially, the wounds are mostly in the frontal region. Walker (1996) and Schwitalla *et al.* (2014) indicate that this may be because older women participate in conflict. Other studies from multiple regions have found similar results (Burbank 1994, 1999; Harrod and Stone 2018). However, the violence among women may also be attributed to other forms of violence such as domestic abuse (Walker 1997; Harrod *et al.* 2012; Tung 2012; Martin and Tegtmeyer 2017). Investigating the presence of women in warfare deserves more in-depth study that cannot be given justice in this current research. Yet, more investigations into this topic are needed.

The presence of more cases of antemortem (nonlethal trauma that has healed or is healing) than perimortem trauma (lethal unhealed fractures likely reflecting manner and mode of death) indicates that violence was pervasive, but only lethal in certain cases (Walker 1989; Lambert 1997; Bartelink *et al.* 2014; Pilloud *et al.* 2014; Schwitalla *et al*. 2014). This data indicates that there likely existed differential applications of force depending on whether the opponents were participating in dueling or more lethal battle. Yet, all authors conclude that the trauma indicates purposeful, face-to-face striking from primarily right-handed opponents. This indicates a tactical doctrine of opponents fighting face to face in close quarters. Taken together, this data is evidence for purposeful trauma by blunt weapons and excludes accidental wounding.

The bioarchaeological data appears to correlate with tactics of thrusting the club into the victim's face as described previously (Ives 1861; Stewart 1947; Sweeney and Woodward 1956; Forbes 1965; Kroeber and Kroeber 1973; Kroeber 1976; Kroeber and Fontana 1986; Campbell 2009). By looking at skeletal remains, the results of violent action can be observed, but the techniques of combat, the type of weapons used, and motivations for conflict remain obscured. Complementary interdisciplinary methods using biomechanical engineering allow for connecting the technology of conflict with osteological patterns of trauma.

The analysis of the biomechanics of trauma can be productively used to connect osteological evidence of trauma to the weaponry used by Indigenous warriors in the study region. For example, experiments have utilized a drop tower to impact porcine crania using weights that simulate the density of objects (Powell *et al*. 2012). Porcine models are ineffective at recording frontal/facial trauma of adults because of differing cranial morphology, and other tests are needed to create a comprehensive model for the biomechanics of trauma to the entire cranium (Powell *et al*. 2012; Raymond and Bir 2015). Surrogate materials consisting of a polyurethane skull, gelatin brain substitute, and rubber periosteum (skin-skull-brain model) have been successfully used as proxies in anthropological studies of skull fractures and have demonstrated promise as a trauma-indicating model (Dyer and Fibiger 2017). However, frangible (breakable) skull surrogates have limitations, namely, they have not been extensively validated in terms of their biomechanical response. In addition, no viable method to replicate facial trauma currently exists beyond human cadaver models (Raymond and Bir 2015).

While studies have shown similarities in fracture patterns to case studies of cranial trauma, laboratory-controlled postmortem human subject (PMHS) testing to validate these models is still lacking. An important aspect of validating any biomechanical surrogate is the biofidelity of biomechanical response (force, deflection, acceleration) and fracture threshold. Previous attempts to validate frangible surrogates within the automotive safety industry were abandoned in favor of non-frangible surrogates (Brinn 1969; McLeod and Gadd 1973). These non-frangible anthropomorphic test devices (ATD) are used in conjunction with sensors and injury criterion which are then statistically connected to the likelihood of sustaining various types of fractures, given the biomechanical response recorded by the headform. While frangible, trauma-indicating surrogates hold promise for future biomechanical evaluation, this investigation utilized traditional biomechanical methods for recording force and pressure exerted by weapons and compared results to biomechanical tolerances for types of fractures.

Methods and Materials

The interdisciplinary model use for this study includes a detailed reconstruction of weapons that were then tested using biomechanical engineering experimentation. Results from these experimental studies were compared with ethnohistoric documentation and bioarchaeological case studies of blunt force trauma from human remains in California to connect data from experiments to observations in the historic and prehistoric past.

For the replicative studies, examples from ethnohistoric records (Forde 1931; Stewart 1947; Heizer 1968; Kroeber 1976; Kroeber and Fontana 1986; Campbell 2009) and from museum collections at the Phoebe Anne Hearst Museum of Anthropology (PAHMA) and the Natural History Museum of Los Angeles County (NHMLA) were analyzed for the proper dimensions, material types, and usage (see Fig. 2 for the specimens). Specimens from PAHMA were analysed in person, and artifacts from NHMLA were analyzed from photographs. It was noted by NHMLA staff that the Gabrieleño specimens date to the Mission era, as they had metal saw marks.

Using collected specimens as templates, along with other ethnohistoric information, we recreated clubs using modern tools for expediency. All weapons were measured using inches to keep data uniform with historic records and original measurements (see Table 1 for measurements). Three types of war clubs were replicated following measurements recorded from museum specimens: (1) mallet type, (2) stick type (2 ft. and 1.5 ft. in length), (3) ball-type. Clubs were constructed using either oak or mesquite. In addition, several types of informal tools (tree limb, horn billet, and hammerstone) were used as a control. Eight artifacts were tested as described below (see Fig. 3).

Biomechanical experiments to measure the amount of force exerted by the weapons were conducted at the Applied Injury Biomechanics Laboratory at California State University, Los Angeles. Previous collaborations between anthropologists and mechanical engineers have contributed to understanding of the material characteristics of ceramics (Harry *et al.* 2009) and general patterns of forensic trauma (Powell *et al.* 2012). A previous study used forensic methods to test the efficacy of a Neolithic war club (Dyer and Fibiger 2017). This investigation builds upon previous examples to analyze trauma from prehistoric contexts using reconstructed weaponry. We conducted two different biomechanical tests. The first used an anthropomorphic testing device to measure peak impact force and Head Injury Criterion (HIC) of each club strike. The second used Fujifilm Prescale pressure-sensitive paper to measure club strike psi and contact areas.

The first test consisted of wielding blunt objects on a 50th percentile male, Hybrid III anthropomorphic testing device to measure the amount force inflicted by the weapons (see Fig. 4). The 50th percentile Hybrid III represents an approximate 175 cm tall (69 in.), 78-kg (172 lb) male (Mertz and Irwin 2015). Three linear accelerometers (Endevco, model 7264, 2000 g range) were mounted at the center of gravity of the headform in an orthogonal orientation. Data were sampled at a rate of 20,000 Hz and filtered per SAE J211/1 standards. The anthropomorphic testing device was struck on either the parietal region with an overhand strike or frontal region with a thrusting strike. Three repeat tests were conducted for each club. Overall, 36 tests were conducted. All clubs were swung by one individual who is 196 cm tall (77 in.), 250 lb. with an athletic build. The anthropomorphic testing device was suspended by a winch and chain attached to the thoracic spine box of the anthropomorphic testing device and

Table 1 Measurements and materials of replicated war clubs. See Fig. 2 for pictures of clubs

Club type	Material	Head		Handle		Total		
		Length (cm)	Diameter (cm)	Length (cm)	Diameter (cm)	Length (cm)	Diameter (cm)	Weight (g)
Mallet Club (A)	Ash	12.07	8.89	22.86	3.49	37.47		606.00
Mallet Club (B)	Mesquite	11.11	10.48	28.26	6.35	33.99	10.48	1261.00
Mallet Club (C)	Oak	14.61	12.70	23.50	5.72	38.10		1660.00
Ball Club (D)	Mesquite	16.83	9.84	38.74	4.76	56.83	7.62	1415.00
Truncheon (E)	Mesquite					66.04	5.08	826.00
Tree Limb (F)	Oak	17.46	9.53	37.47	3.49	65.72		947.00
Billet (G)	Horn					36.83	2.86	522.00
Hammer-stone (H)	Stone					12.07	6.99	624.00

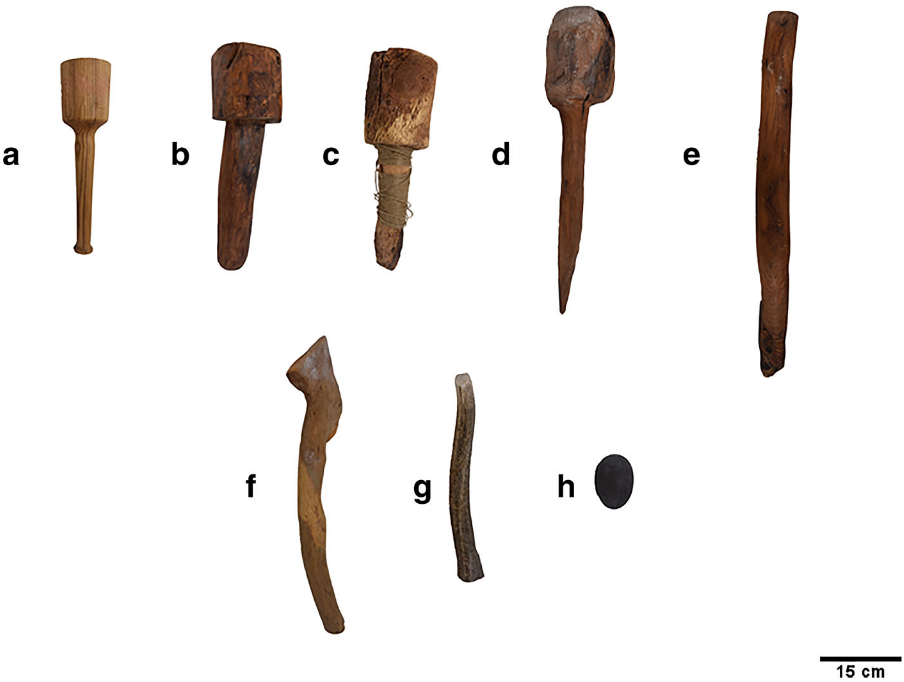

Fig. 3 Weapons tested. (**a**) ash mallet club; (**b**) mesquite mallet club; (**c**) oak mallet club; (**d**) mesquite ball club; (**e**) mesquite stick; (**f**) tree limb; (**g**) elkhorn billet; (**h**) hammerstone. Photograph: Joseph Curran

lowered to the approximate height of the tester. Head acceleration of the anthropomorphic testing device was used to calculate peak resultant head acceleration, the Head Injury Criterion (HIC), and peak impact force. Peak impact force was calculated using $F = ma$, where mass was the weight of the headform (4.54 kg). HIC is an injury criterion developed by the automotive safety industry which measures the likelihood of various severities of head injury arising from blunt head impact. The measurement includes effects and duration of head acceleration. HIC is defined as follows: HIC $= \left[\frac{1}{t_2 - t_1}\int_{t_2}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1)$where t_1 and t_2 are any two points within a 15-ms window

Fig. 4 Examples of ATD testing of frontal thrusts and parietal strikes. Photograph: Joseph Curran

during the impact which maximizes HIC. HIC has been correlated to the Abbreviated Injury Scale (AIS) (see Table 2). The AIS assigns numerical values to different levels of head trauma on a 1-to-6 scale. AIS is an anatomically based injury scoring system originally based on a “threat-to-life” scale. It now includes impairment and functional capacity using a six-point ordinal scale (https://www.aaam.org/).

Since Head Injury Criterion (HIC) is based on resultant acceleration of the head center of gravity, it has been shown to predict head injury risk resulting from head impacts with larger objects with large surface areas that impart rigid body motion to the head. For objects with a smaller, more focused contact area, HIC begins to lose correlation to injury risk prediction due to the deviation from the rigid body assumption. As a result, additional local sensing elements were introduced to capture the local effects on the head.

For the second test, pressure exerted on the headform during club strikes was measured using Fujifilm Prescale pressure-sensitive paper. This product consists of layered laminated sheets with impregnated red ink microbubbles. When the paper is struck, the ink is released at different pressures. Low (350–1400 psi), medium (1400–7100 psi), and high-pressure (7100–18500 psi) films were layered onto the head of the anthropomorphic testing device and struck with each club.

To measure peak pressure taken from the pressure paper, Adobe Photoshop was used to convert the color chart provided by Fujifilm Prescale (see Fig. 5) to the RGB (red, green, blue) color code scale utilized by Photoshop software (see Table 3). Then, the Excel histogram function was employed to calculate and convert values for each shade of red according to the RGB color model (with 0 being red and 255 being white) (see Fig. 6). The x in that equation is the value obtained on the RGB scale from the pressure paper, and the y was the color correlation number that we get from the chart.

Next, the highest point of pressure was found by using the “threshold” function in Excel which found the lowest point on the RGB scale. This threshold number was then compared with the Fujifilm Prescale momentary exposure graph (Sensor Products Inc. 2011 p. 12) to calculate estimated pressure (psi). Thus, the lower the RGB value, the higher the pressure mapped for each strike. With these calculations, charts mapping size and shape of strike patterns caused by weapons were created using Photoshop (Figs. 9 and 10). The data was then compared with previously reported cranial vault fracture tolerance values (Kroman and Symes 2013; Walker 2001; Yoganandan and Pintar 2004).

Table 2 Abbreviated Injury Scale (AIS) 2015 coding

AIS level	Injury description
1	n/a
2	Closed; simple; non-displaced; diastatic; linear
3	Comminuted; open but dura intact; depressed ≤ 2 cm; displaced; minor penetrating injury with ≤ 2 cm of penetration
4	Complex; open with torn dura; exposed or loss of brain tissue; large area of skull depressed > 2 cm
5	Major penetrating injury with > 2 cm penetration into brain
6	Penetrating injury involving brain stem; crush injury or massive skull destruction

Fig. 5 Fujifilm Prescale color correlation chart. Adapted from Sensor Products Inc. 2011

Table 3 Correlation of Fujifilm Prescale color correlation chart to RGB scale

Values from chart	RGB value
1.5	159
1.3	164
1.1	173
0.9	180
0.7	189
0.5	210
0.3	240

Digitized strike patterns were analyzed, measured, and processed using Adobe Photoshop and Fiji ImageJ. In Photoshop, images were first cropped to remove any outlying pressure zones and then the object selection tool was utilized to select the strike pattern. Using the measurement log tool, the total area, width, and height of the strike zone were recorded in pixels. It is important to note that measurements only comprised colored extents and white portions were not included in analysis of area. In addition, the high-pressure zones were also measured using the same method. Measurements were then converted to imperial and metric units. Images were then imported to ImageJ for final processing, such as inserting scale bars. The result can be seen in Figs. 9 and 10. Although both low-pressure film and medium-pressure film results were recorded, all figures and tables reference the medium-pressure film as the psi measurements were taken from these strike patterns.

Results

By using the Head Injury Criterion (HIC) to predict the Abbreviated Injury Scale (AIS), the likelihood and scale of cranial trauma can be predicted. The highest average HIC resulted from the Oak Mallet Parietal Test 1 with a score of 1766. The data predicts a

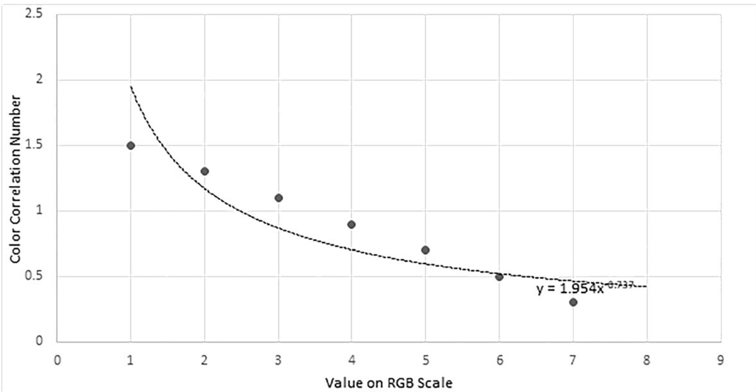

Fig. 6 Momentary exposure graph provided by Fujifilm Prescale

41% likelihood of a major penetrating head injury (AIS 5) and 77% likelihood of a complex fracture (AIS 4) (Table 4). The AIS for other large surface clubs (*i.e.*, all mallets and Mesquite Ball) predicts a high risk for comminuted injury (AIS 3) (73%). The recorded HIC indicates that receiving parietal strikes from most of the clubs would result in a high likelihood of sustaining closed, simple, non-displaced, diastatic, linear, or comminuted fracture (AIS 2-3).

FujiFilm Prescale results permit validation of previous results and comparisons of measurements for lethality. As per Table 5,

the clubs with the highest-pressure readings were the mesquite mallet and tree limb parietal strikes at 5617 psi. The range of pressure readings was 2489–5617 for parietal strikes and 2915–4799 for frontal strikes. The club with the largest contact area was the ash mallet parietal strike at 2.90 in.^{2} (18.71 cm^2). For the parietal strikes, the average values were 4225 psi with a maximum contact area of 1.57 in.^{2} (10.13 cm^2). Averages for frontal strikes were 3812 psi with a maximum contact area of 1.14 in.^{2} (7.35 cm^2). Even though the psi is similar for both parietal and frontal strikes, the distribution of maximum force zones should be noted (see Figs. 9 and 10). Maximum force zones are the areas of highest pressure. Parietal strike maximum force zones are evenly distributed throughout the strike surface while frontal strikes are focused into much smaller areas of the club strikes.

When compared with known measurements of dynamic fracture forces for cranial bones, these values fall well within, or were significantly higher than, the range of force required for cranial fracture using multiple types of impact surfaces on both the frontal and parietal regions (Yoganandan and Pintar 2004). In addition, the contact area was compared with known studies on mechanics of bone fracture. McElhaney *et al.* (1970) had a contact area of less than 1 in.^{2} while Raymond and Bir (2015) had a contact area of approximately 1.5 in.^{2}. Hodgson and Thomas (1971) used flat rigid surfaces (*i.e.*, the ground) (see Figs. 7 and 8).

Dimensions, such as area, height, and width of each strike, were also calculated for both the total strike pattern and the high-pressure zones (see Figs. 9 and 10). Maximum force zones (the area with the highest pressure) predict where cranial fracture is most likely to occur (see insets of Figs. 9 and 10).

For the parietal strikes (see Fig. 9), measurements for total strike patterns were from 0.49–2.23 in.^{2} (318.97–1441.72 mm^2) with an average of 0.92 in.^{2} (595.54 mm^2) for area, 0.95–1.98 in. (24.21–50.29 mm) with an average of 1.44 in. (36.47 mm) for height, and 1.33–3.05 in. (33.78–77.43 mm) with an average of 1.95 in. (49.40 mm) for width. Maximum force zone data were significantly less at 0.11–1.21 in.^{2} (70.42–557.87 mm^2) with an average of 0.26 in.^{2} (168.88 mm^2) for area, 0.22–1.21 in. (5.50–30.61 mm) with an average of 0.72 in. (18.29 mm) for height, and 0.36–2.05 in. (9.02–52.12 mm) with an average of 1.12 in. (28.33 mm). One note is that linear strike patterns were partial and overall measurements were likely greater, but measurements of maximum force zones appear to be complete.

For the frontal strikes (see Fig. 10), measurements for total strike patterns were from 0.11–0.17 in.^{2} (26.00–106.67 mm^2) with an average of 0.11 in.^{2} (73.38 mm^2) for area, 1.21–2.75 in. (30.73–69.72 mm) with an average of 1.89 in. (48.10 mm) for height, and 0.17–2.14 in. (4.32–61.17 mm) with an average of 1.47 in. (37.26 mm) for width. Maximum force zone data were also significantly less at 0.00–0.17 in.^{2} (2.69–71.32 mm^2) with an average of 0.11 in.^{2} (0.07 mm^2) for area, 0.59–2.39 in. (15.03–60.62

Table 4 Average (1st dev.) peak force and Head Injury Criteria (HIC) compared with the Abbreviated Injury Scale (AIS)

	Strike region	Pk. res. head accel[1] (g)	HIC	Pk. impact force[2] (lbf)	AIS1	AIS2	AIS3	AIS4	AIS5	AIS6
Ash Mallet Club	Parietal	397	943 (176)	3981 (512)	99%	86%	48%	14%	2%	0%
Mesquite Mallet Club		305	811 (426)	3056 (637)	97%	76%	35%	9%	1%	0%
Oak Mallet Club		437	1766 (1164)	4379 (1744)	100%	100%	96%	77%	41%	9%
Mesquite Ball Club		394	1224 (712)	3951 (1020)	100%	96%	73%	32%	6%	0%
Oak Tree Limb		230	368 (269)	2302 (395)	58%	22%	7%	2%	0%	0%
Mesquite Truncheon		280	493 (24)	2808 (61)	78%	37%	12%	3%	0%	0%
Hammer-stone		88	40 (15)	877 (179)	0%	0%	0%	0%	0%	0%
Elk Horn Billet		263	379 (163)	2635 (310)	60%	23%	8%	2%	1%	0%
Ash Mallet Club	Frontal	58	18 (6)	585 (91)	0%	0%	0%	0%	0%	0%
Mesquite Mallet Club		64	32 (22)	637 (352)	0%	0%	0%	0%	0%	0%
Oak Mallet Club		108	78 (19)	1080 (141)	3%	1%	0%	0%	0%	0%
Mesquite Ball Club		112	88 (15)	1126 (105)	4%	1%	0%	0%	0%	0%
Ash Mallet Club		58	18 (6)	585 (91)	0%	0%	0%	0%	0%	0%

[1] Peak resultant head acceleration

[2] Peak impact force

Table 5 Results of pressure paper tests measuring peak pressure and size of the maximum contact area

		Contact Region	Shape of Pattern	Pk. Pr.[2] (psi)	CA[3] (in^2)	CA[3] (mm^2)	Height (in)	Height (mm)	Width (in)	Width (mm)
Ash Mallet Club	Total	Parietal	Ellipsoid	2489.00	2.23	1441.72	1.98	50.29	3.05	77.43
	MFZ[1]				0.86	557.87	1.21	30.61	2.05	52.15
Mesquite Mallet Club	Total		Spherical	5617.00	0.61	390.96	1.92	48.73	1.43	36.32
	MFZ[1]				0.17	111.57	1.13	28.79	0.36	9.02
Oak Mallet Club	Total		Ellipsoid	4799.00	0.67	429.10	1.64	41.66	1.48	37.59
	MFZ[1]				0.15	97.32	0.76	19.30	0.66	16.85
Mesquite Ball Club	Total		Spherical	3982.00	0.56	358.88	1.32	33.53	1.36	34.46
	MFZ[1]				0.22	143.13	0.68	17.31	1.03	26.04
Oak Tree Limb	Total		Spherical	5617.00	0.82	529.20	1.57	39.84	1.50	38.10
	MFZ[1]				0.19	123.14	0.60	15.11	0.62	15.71
Mesquite Truncheon	Total		Linear	2489.00	1.50	967.44	0.96	24.38	2.73	69.34
	MFZ[1]				0.11	70.42	0.22	5.50	1.61	40.89
Hammerstone	Total		Spherical	4764.00	0.51	328.08	1.15	29.13	1.33	33.78
	MFZ[1]				0.14	91.51	0.54	13.76	0.79	20.02
Elk Horn Billet	Total		Linear	3555.00	0.49	318.97	0.95	24.21	2.69	68.20
	MFZ[1]				0.24	156.04	0.63	15.96	1.81	45.97
	Total Average			*4164.00*	*0.92*	*595.54*	*1.44*	*36.47*	*1.95*	*49.40*
	MFZ[1] Average				*0.26*	*168.88*	*0.72*	*18.29*	*1.12*	*28.33*
Ash Mallet Club	Total	Frontal	Undetermined	4373.00	0.17	106.67	2.75	69.72	2.41	61.17
	MFZ[1]				0.11	71.32	2.39	60.62	2.20	55.88
Mesquite Mallet Club	Total		Undetermined	3164.00	0.10	63.58	1.21	30.73	1.45	36.70

Table 5 (continued)

	Contact Region	Shape of Pattern	Pk. Pr.[2] (psi)	CA[3] (in^2)	CA[3] (mm^2)	Height (in)	Height (mm)	Width (in)	Width (mm)
	MFZ[1]			0.10	63.58	1.21	30.73	1.45	36.70
Oak Mallet Club	Total	Undetermined	2915.00	0.04	26.00	1.89	47.96	1.85	46.86
	MFZ[1]			N/A	N/A	N/A	N/A	N/A	N/A
Mesquite Ball Club	Total	Undetermined	4799.00	0.15	97.25	1.73	43.98	0.17	4.32
	MFZ[1]			0.00	2.69	0.59	15.03	0.69	17.53
	Total Average		*3812.75*	*0.11*	*73.38*	*1.89*	*48.10*	*1.47*	*37.26*
	MFZ[1] Average			*0.07*	*45.86*	*1.40*	*35.46*	*1.45*	*36.70*

[1] Maximum Force Zone

[2] Peak Pressure

[3] Contact Area

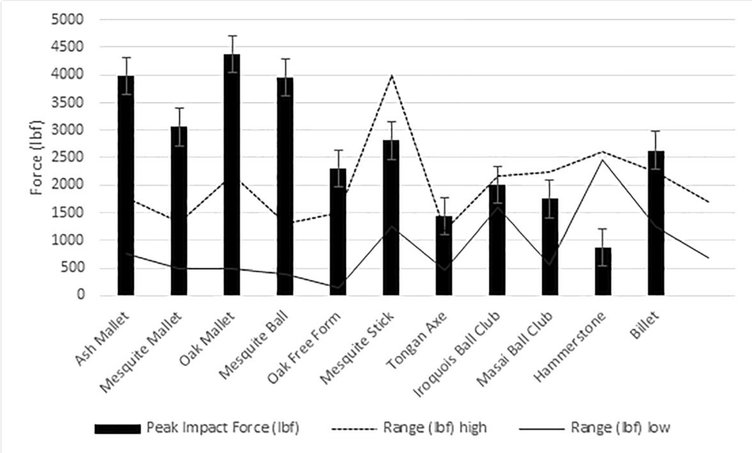

Fig. 7 Average peak impact force (lb) results for parietal strikes compared with ranges for skull fractures from known fracture studies (Messerer 1880; Nahum *et al.* 1968; McElhaney *et al.* 1970; Hodgson and Thomas 1971; Schneider and Nahum 1972; Stalnaker *et al*. 1977; Allsop *et al*. 1991; McIntosh *et al*. 1993; Yoganadan *et al*. 2003; Raymond and Bir 2015)

mm) with an average of 1.40 in. (35.46 mm) for height, and 0.69–2.20 in. (17.53–55.88 mm) with an average of 1.45 in. (36.70 mm).

In addition, the general configuration of trauma patterns was noted. Strike patterns were divided into three different types: ellipsoid, spherical, and linear (see Table 5). The ellipsoid pattern was typical of parietal mallet strikes. The largest mallet club can cause up to a major penetrating head injury (AIS 5) but are most ellipsoid strikes are predicted for risk of closed, simple, non-displaced, diastatic, or linear fractures (AIS 2). The spherical pattern was associated with ball strikes which are associated

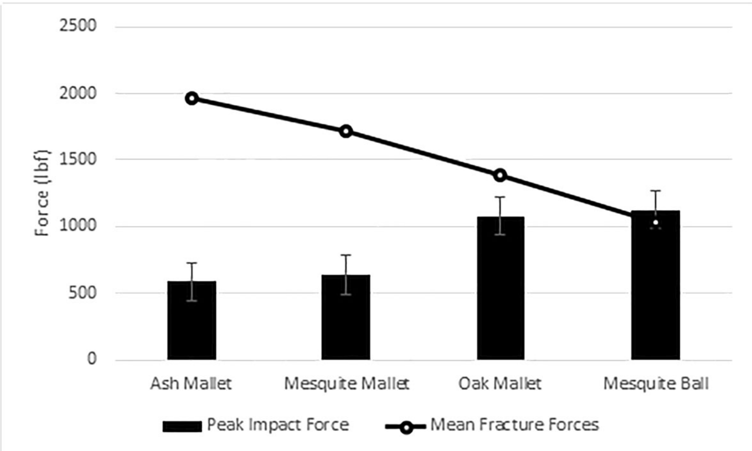

Fig. 8 Average peak impact force (lb) results for frontal strikes compared with studies on mean fracture forces from intact human cadaver impacts (Yoganadan and Pintar 2004; Hodgson 1967). Impact surfaces include 1 in. radius cylinder, flat plate, 8 in. radius hemisphere, and 3 in. radius hemisphere

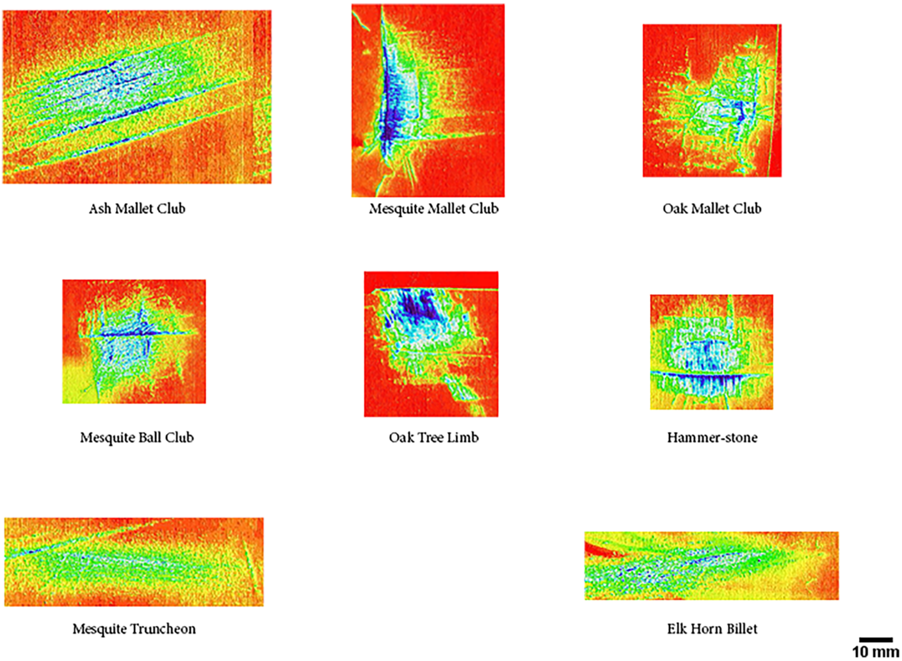

Fig. 9 Analyzed pressure paper test results for parietal strikes. Maximum force zones are represented as dark blue. Patterns were recorded by psi. Results were digitized using Photoshop by Yeachan Lee and Joseph Curran

with a likelihood of comminuted trauma (AIS 3). Linear patterns were found in stick and axe strike tests and are only associated with little to no damage (AIS 1) (see Fig. 9 for images of patterns). In general, frontal patterns were more diffuse with less defined boundaries and were predicted to not cause significant injury (AIS 1) (see Fig. 10).

From this comparison, a few observations can be made. The average parietal strike impacts greater than 1.5 in.^{2} fall within one standard deviation of all studies. Recorded values less than 1.5 in.^{2} do fall within the range recorded by McElhaney *et al.* (1970)

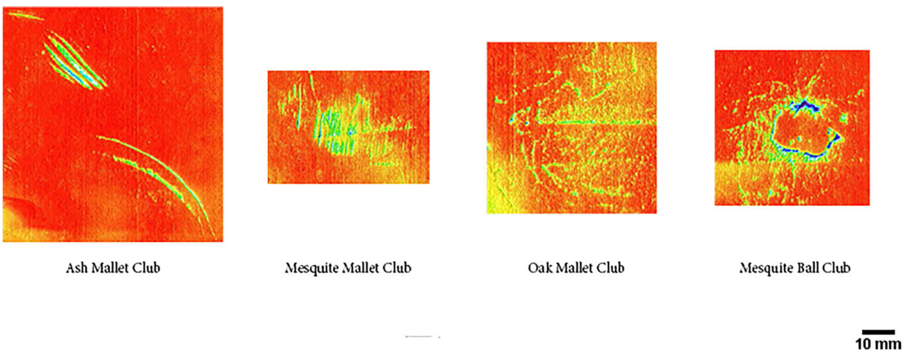

Fig. 10 Analyzed pressure paper test results for frontal strikes. Maximum force zones are represented as dark blue. Patterns were recorded by psi. Results were digitized using Photoshop by Yea Chan and Joseph Curran

Table 6 Comparisons between experiment results and bioarchaeological data (Adapted from Walker 1989; Pilloud *et al.* 2014)

Cranial	Element	Channel Islands			Central California			Experiment TSP[1]			Experiment MFZ[2]		
		N	$\overline{x}$	s	N	$\overline{x}$	s	N	$\overline{x}$	s	N	$\overline{x}$	s
Parietal	Diameter	61	12.39	6.21	18	12.9	6.39	8	49.4	18.68	8	28.33	15.92
Frontal	Diameter	78	11.05	6.01	16	15.17	8.09	4	37.26	24.15	4	36.7	16.46

[1] Total strike pattern

[2] Maximum force zone

but are on the outer limits of other results. However, smaller surface areas of the strikes result in greater risk for bone failure for a given impact force (Melvin and Evans 1971). Thus, the Head Injury Criteria, as compared with the Abbreviated Injury Scale and contact area, shows that clubs with a larger strike area and ellipsoid/spherical contact surface would likely result in comminuted fracture in the parietal region.

Discussion

For mallet and ball clubs, results revealed that thrusting to the face and frontal region rarely led to fracture of the frontal bone while overhand strikes to the parietal almost always led to fractures of the cranium and could be lethal. All these clubs were predicted to cause at least closed, simple fractures of the parietal region but could cause comminuted fractures and, in the case of the oak mallet, cause complex, open wounds. As indicated earlier, bioarchaeological studies (Walker 1989; Lambert 1997; Jurmain and Bellifemine 1997; Bartelink *et al.* 2014; Pilloud *et al.* 2014; Schwitalla *et al.* 2014; Stanton 2016) found more antemortem (nonlethal) trauma on the frontal region and more perimortem (lethal) trauma on the parietal region. In addition, mallet and ball clubs produced ellipsoid and spherical trauma patterns like those observed in the bioarchaeological studies (see Table 6).

Truncheon clubs were not conducive to testing on the frontal region and ethnohistoric documentation indicates that they were only used for strikes to the parietal region. Truncheons are described as being angular, but during testing, it became apparent that sharp angled edges would cause structural problems for the club. More rounded edges produced better results. In testing, the truncheon club was predicted to cause some simple wounding. However, the Prescale film results, a more accurate test for smaller surfaces, indicate that parietal truncheon strikes (2489 psi) were well within the range for fracture (140–2200 psi). These results indicate that truncheon clubs would likely cause linear fractures to the parietal region.

By comparing the size of strikes to known dimensions from recorded trauma cases, weapon types and tactics can be connected to the bioarchaeological record. As shown here, the average parietal strike was 12.39 mm σ = 6.21 mm on the Channel Islands (Walker 1989; Lambert 1997) and 12.90 mm σ = 6.39 mm for Central California (Schwitalla *et al.* 2014). In comparison, the average total strike pattern was 49.40 mm σ

= 18.68 which is double but still within one standard deviation of values for parietal trauma recorded in both Coastal and Central California. However, when we look at the high-pressure zones that predict were cranial fracture is likely to occur, the average (28.33 mm σ = 115.92) is within one standard deviation of recorded cases of parietal trauma in the bioarchaeological record. In fact, if we only consider spherical and ellipsoidal patterns, the average is 23.30 σ = 15.19 which falls well within the one standard deviation of all results from California.

In contrast, the average diameter for frontal strikes was 11.05 mm σ = 6.01 mm on the Channel Islands (Walker 1989; Lambert 1997) and 15.17 mm σ = 8.09 mm for Central California (Schwitalla *et al*. 2014). In Playa Vista (Stanton 2016), two individuals displayed cranial vault trauma (specific location is not given) with an average diameter of 17 mm. Average dimensions for frontal total strike patterns (37.26 mm σ = 24.15 mm) and high-pressure zones (36.70 σ = 16.46 mm) fall within the range of measurements found in bioarchaeological records of California, especially the case study from Playa Vista (Stanton 2016). In addition, mallet and ball clubs produced ellipsoid and spherical trauma patterns like those observed by Walker (1989) and Schwitalla *et al.* (2014). Also, thrusting to the face with the Ash Mallet produced a clear pattern of the edge reflecting accounts that edges were purposefully sharpened to produce more wounding to the derma and nose (Forbes 1965; Forde 1931; Fathauer 1954; Stewart 1947; Sweeney and Woodward 1956).

Interestingly, informal weapons included in testing (tree limb, hammerstone, and billet) had mixed results. The tree limb is on the low end of Head Injury Criterion and peak impact force measurements predicted that the object used as a club would still cause some injury. However, the overall shape is not effective for frontal strikes. The hammerstone shares a similar pattern and dimensions to the ball club. However, during testing, the hammerstone was less secure and the shock of the blow was transmitted to the user's hand. Since the other weapons included handles, this shock appears to have been mitigated by purposeful design features, such as an elongated handle. The peak pressure from the billet is within one standard deviation (1129) of average peak pressure results (4225 psi). The overall effectiveness of the elkhorn billet indicates that antler/horn weapons warrant further investigation. One inference from these observations is formal weapons likely developed to compensate for such factors as creating a more effective striking surface, increased grip, and mitigating the effects of shock to the wielder's arm.

One observation is a methodological problem appears to create difficulty in comparisons between bioarchaeological and experimental data. As ellipsoidal fractures have been only measured on one dimensional axis in previous studies, it is difficult to calculate area of trauma patterns for comparison. To more accurately measure bioarchaeological blunt force trauma, future studies will need to record both minor and major axis radii of wounds.

When compared with ethnohistoric and ethnographic accounts, these data mirror recorded tactics of face-thrusting followed by strikes to the side of the head producing the killing blow. This indicates a high likelihood that a class of weapons similar to mallets or ball clubs was used for face-to-face combat throughout Southern California, and truncheon clubs were used solely for parietal strikes (Ives 1861; Sparkman 1908; Hooper 1920; Stewart 1947; Fages 1951; Font 1951;

Heizer and Whipple 1951; Forbes 1965; Heizer 1968; Kroeber and Kroeber 1973; Kroeber 1976; Kroeber and Fontana 1986; Walker 1989; James and Graziani 1992; Campbell 2009). Bioarchaeological data also indicate a high likelihood of continuous war club use from at least the Early Middle Period (1500 cal B.C–A.D. 580) to the historic period (Walker 1989; Lambert 1997; Bartelink *et al.* 2014; Pilloud *et al.* 2014; Schwitalla *et al.* 2014).

Conclusion

This interdisciplinary method for identifying weapons used in precontact California groups has provided useful data for better understanding their use and lethality without locating actual weapons in the archaeological record, precluded by their organic nature. A key finding was that patterns of trauma recorded in experiments are representative of trauma patterns seen in the frontal region of crania in pre-historic/proto-historic case studies. In this study, we demonstrated that war clubs can be connected to osteological evidence of trauma and ethnohistoric documentation of use in warfare in groups such as the Cahuilla, Gabrieleño, Chumash, Quechan, and Mohave. Our method enriches the archaeological, bioarchaeological, and ethnohistorical analytical toolkits through cross-cultural comparison to elucidate the material record of human conflict and violence. Yet, as with any research, this work highlights further questions to investigate beyond of the scope of this study. As the study of trauma is a complex subject, we understand that there are many other directions for research on this topic in California and across the world. However, this study points us to a fruitful interdisciplinary method to better fill in the gap left by preservation issues of the archaeological record.

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Data Availability Data is presented in the article and available upon request.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

Code Availability Not applicable.

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