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BALLISTIC STUDY TACKLES KINETIC ENERGY VALUES OF PALAEOLITHIC WEAPONRY*

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The appearance of new projectile propulsion modes is viewed as an important element for understanding human behaviour during the Palaeolithic. Because the organic components of hunting weapons (the bow, spear-thrower and arrow, and spear shaft) are only rarely preserved archaeologically, some effort has been invested in experiments to explore how the projecting modes could be identified through the analysis of stone points. The kinetic energy developed by each mode of propulsion has been considered a key variable in these experiments. However, the data used in these studies generally come from a few ballistic studies, with varied results. We present the results of a systematic study conducted with a ballistic pendulum and combined with a classic ballistic analysis. We quantified and compared the kinetic energy developed by the four standard modes of propulsion known for the Palaeolithic. The kinetic energy values that we attained, especially those measured for thrusting spears, clearly differ from what has been assumed up to now, and thus challenge current models on the evolution of hunting technology.

KEYWORDS: PROJECTILES, PALAEOLITHIC, BALLISTICS, KE, BOW, SPEAR-THROWER, SPEARS

INTRODUCTION

Over the past decade, the focus in debates on hunting technology has shifted from projectile identification to the detection of different propulsion modes in the Palaeolithic (Geneste and Plisson 1990; Cattelain 1997; Shea 2006; Iovita *et al*. 2014, 2016; Sano and Oba 2014, 2015; Clarkson 2016; Pargeter *et al*. 2016). In this context, it has been examined whether certain projecting modes such as the bow and arrow or the spear-thrower are exclusively associated with modern humans (Shea and Sisk 2010). Such reflections rely heavily on a model of linear evolution of the invention of different propulsion modes, starting from 'simple' non-assisted projection techniques such as spear thrusting and throwing and advancing towards more 'complex' assisted hunting with spear-throwers or bows (Shea and Sisk 2010; Iovita *et al*. 2016). This model is largely based on a few important discoveries of organic remains in Europe, namely the Lower and Middle Palaeolithic wooden spears or spear fragments from Schöningen (Thieme 1997), Clacton-on-Sea (Oakley *et al*. 1977) and Lehringen (Movius and Hallam 1950), the spear-thrower hook from Combe-Saunière attributed to the Solutrean

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(Cattelain 1989), and the arrows from Stellmoor and the bow from Holmegaard (Junkmanns 2013), both attributed to the Mesolithic period. This model is also based on four assumptions. The linear model proposes a gradual increase in the complexity of tool production and in the effective range and precision of weapons. These are argued to lead to growing efficiency from one weapon type to the next (Shea and Sisk 2010). Recently, impact energy has been added as an argument for explaining the increase of efficiency between different modes of propulsion (Sano and Oba 2015; Clarkson 2016). Verification of the validity of this model and its independence of preservation issues requires an alternative method for the identification of propulsion modes based on the analysis of stone points. Researchers have proposed methods relying on point morphology (Hughes 1998; Sisk and Shea 2011), Wallner lines (Hutchings 2015), impact fracture size (Clarkson 2016; Pargeter *et al.* 2016; Sano 2016), frequencies of 'diagnostic impact fractures'(Pargeter *et al.* 2016) and descriptive attributes of impact-related fractures (Coppe and Rots 2017). At present, none of these attempts has yet been translated into a commonly shared and formalized method.

Most attempts to identify propulsion modes rely on experimentation with stone projectiles launched with replicas of prehistoric weapons or with mechanically assisted propulsion. They generally aim to understand the causal relationship between a propulsion mode and specific fracture phenomena, but an essential prerequisite is accurate measurement of the range of kinetic energy (KE) associated with each mode of propulsion, which is needed to choose suitable raw materials for the replicas or to calibrate modern equipment. It has been problematic to obtain accurate data for the KE, in spite of its importance for understanding changes and variability in hunting technology. We present the results of a systematic study with a ballistic pendulum in combination with a classic ballistic analysis in order to quantify and compare the amounts of KE developed by the four standard weapon systems known to have been used in the Palaeolithic, namely thrusting and hand-thrown spears, the spear-thrower and the bow.

THE ROLE OF KINETIC ENERGY IN CURRENT RESEARCH ON PALAEOLITHIC WEAPONRY

Many experiments have been undertaken over the past decade to clarify what kind of evidence is needed for reliable identification of projectiles and propulsion modes. The main difficulty is the variable nature of projectile impact in comparison to other, more repetitive, tool uses (e.g., scraping and/or cutting), which makes projectiles significantly more complex to identify than other uses (Rots and Plisson 2014). Several authors have tried to isolate the influence of specific parameters on the fracturing process of stone points; in particular, the KE (Iovita *et al.* 2014, 2016; Sano and Oba 2015; Clarkson 2016) and the angle of contact (Iovita *et al.* 2014, 2016). In most cases, the experimental set-up opted for (e.g., an airgun or crossbow) has permitted the use of predefined values for the KE of the projectile and a certain degree of reproducibility. In spite of some differences among the experimental set-ups, the results generally suggest a direct link between KE and fracture development (Iovita *et al.* 2014, 2016; Sano and Oba 2015; Clarkson 2016). More specifically, an increase in KE results in an increase in the size of the fracture if the impact is at 90° (Iovita *et al.* 2014, 2016). At the same time, an acute impact angle has been noted to significantly influence the size of the fracture up to the point of removing or inverting the effect of the impact energy, as observed at 90° (Iovita *et al.* 2014, fig. 6). Also, a relationship between the KE and the number of fractures created during impact has been suggested (Sano and Oba 2015).

If KE indeed determines the development of the fracture path and if there is significant variation in KE among the propulsion modes, the identification of different modes of propulsion may be possible on the basis of fracture patterns on stone points. In this context, knowledge of the values of KE developed by each propulsion mode is crucial. After all, these values are used as basic input for calibrating machine-assisted experiments and will thus determine the fracture patterns obtained. Available data for the KE developed by each of the four standard propulsion modes (thrusting, throwing and the spear-thrower and bow) are highly variable, as they derive from experiments that vary significantly in terms of the weapon characteristics, the propulsion mechanisms, the measurement systems and the metric units used (Table 1). Detailed ballistic studies have been performed only for the bow (Bourke and Whetham 2007; Park 2011). Few reliable data therefore exist that would allow for testing of the influence of the propulsion mode and, in particular, the KE involved, on fracture formation on stone points.

We present the results of a study conducted with a ballistic pendulum associated with a traditional external ballistic analysis.[1] This study intended to quantify the KE that is developed by each of the four standard modes of propulsion within a single measurement system, allowing for the first time the proposition of reliable reference values for all four propulsion modes that can be compared with the literature. An exterior ballistic study was used to verify the consistency of the results obtained with the pendulum. For spear thrusting, the study was complemented with an analysis of the variation introduced by different participants and their level of expertise in order to compensate for the limited data that are currently available for this projecting mode. The results of this ballistic study (1) shed new light on the KE developed by each weapon system, (2) provide reference values for each propulsion mode that can be used in future experiments and (3) help to critically assess how to identify propulsion modes in prehistoric assemblages.

WHAT INFLUENCES THE KINETIC ENERGY DEVELOPED BY A PROJECTILE?

The KE of a projectile depends on its mass (*m*) and its velocity (*v*), expressed as

$$\mathrm{KE} = \frac{1}{2} m.\boldsymbol{v}^2.$$

Its velocity depends on the time (*t*) during which the projectile is subjected to a specific acceleration (*a*) generated by the shooter, expressed as

$$\mathbf{V} = \mathbf{a}.\mathrm{t}.$$

Each of the four standard modes of projection has its own characteristics with regard to mass, acceleration and the distance travelled by the projectile during its propulsion phase. The mass (*m*) is the mass of the projectile in the case of hand-thrown spears, the bow and the spear-thrower, but for thrusting spears, a significant but non-measurable part of the body mass of the spear user also needs to be added. The acceleration (*a*) depends on the muscular strength of the spear user for thrusting spears (Bottoms *et al*. 2013; Chen *et al*. 2017) and on the relationship between his or her strength and the mass of the projectile for hand-thrown spears (Gregor and Pink 1985) and the spear-thrower. In the case of the latter, the length of the spear-thrower also plays a role (Baugh 2003; Lepers 2010). For the bow, the acceleration is only determined by the velocity with which the bow limbs return to their original position (Lepers 2010; Clarenne 2017). This velocity depends on the draw weight of the bow, its raw material, its morphology and the mass of the

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[1] External ballistics is the discipline that deals with the behaviour of the projectile after its propulsion and before its impact.

Table 1 *An overview of the published ballistic experiments with the available details on the experimental set-up and on the measurements of velocity, force and KE*

Bow

Reference	*Type*	*Draw weight range (lb)*	*Draw length (in)*	*Speed range* ($m\ s^{-1}$)	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Speed measurement device*	*Kinetic energy range (J)*	*Spear-thrower length (cm)*	*Spear-thrower mass (g)*	*Type of grip*	*Force range (N)*
English (1930)	Three-ply composite Osage bow, yew, whalebone	46–51	–	40.05–47.37	27.9–38.6	–	–	–	Ballistic pendulum	30.96–31.31	–	–	–	–
Bergman *et al.* (1988)	Replica of Sioux bow	55	–	30	30	58	–	*Cornus stolonifera* or *stricta*	Two photoelectric gates	13.5	–	–	–	–
Bergman *et al.* (1988)	African bow	53	–	35	40	–	–	*Arundinaria japonica*	Two photoelectric gates	24.5	–	–	–	–
Bergman *et al.* (1988)	Yew longbow	80	–	37–53	50–90	–	–	*Betula* sp.	Two photoelectric gates	47.92–84.54	–	–	–	–
Bergman *et al.* (1988)	Replica of Apache bow	38	–	43	28	–	–	*Phragmites* (reed)	Two photoelectric gates	25.89	–	–	–	–
Bergman *et al.* (1988)	Replica of Egyptian composite bow	63.5	–	32–52	25–90	–	–	*Arundinaria japonica*	Two photoelectric gates	33.81–46.08	–	–	–	–
Bergman *et al.* (1988)	Replica of Crimean composite bow	60	–	51–60	25–50	–	–	*Pinus* sp.	Two photoelectric gates	45–65.03	–	–	–	–

(*Continues*)

Table 1 *(Continued)*

Bow

Reference	*Type*	*Draw weight range (lb)*	*Draw length (in)*	*Speed range* ($m\ s^{-1}$)	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Speed measurement device*	*Kinetic energy range (J)*	*Spear-thrower length (cm)*	*Spear-thrower mass (g)*	*Type of grip*	*Force range (N)*
Strickland and Hardy (2005)	Replica of Mary Rose bow	150	32	52.28–73.85	53.6–95.9	–	10–12.7	Birch/ poplar/ash	Doppler radar	110.77–136.53	–	–	–	–
Bourke and Whetham (2007)	Replica of Mary Rose bow	140	32	46–49.68	70–87	31.5	–	Ash	–	75–92	–	–	–	–
Karpowicz (2007)	Ottoman composite bow	110	–	69–91	20–40	–	–	–	–	81–95	–	–	–	–
Karpowicz (2007)	Ottoman composite bow	180	–	85	40	–	–	–	–	147	–	–	–	–
Whittaker *et al.* (2017)	Primitive bow	20	–	35.8	20	–	–	–	–	12.8	–	–	–	–
Whittaker *et al.* (2017)	Catawba bow	30	–	41.6	30	–	–	–	–	26	–	–	–	–

(*Continues*)

Table 1 *(Continued)*

Bow

Reference	*Type*	*Draw weight range (lb)*	*Draw length (in)*	*Speed range* (*m s*$^{-1}$)	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Speed measurement device*	*Kinetic energy range (J)*	*Spear-thrower length (cm)*	*Spear-thrower mass (g)*	*Type of grip*	*Force range (N)*
Whittaker *et al.* (2017)	Modern recurve bow	29	–	45.1	29	–	–	–	–	29.5	–	–	–	–
Hamm (2000)	Hickory bow	40	27	39.9	32.4	–	–	–	Chronograph	25.8	–	–	–	–
Hamm (2000)	Pecan bow	71	28	56	32.4	–	–	–	Chronograph	50.81	–	–	–	–

Spear-thrower

Reference	*Type*	*Speed range* (*m s*$^{-1}$)	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Speed measurement device*	*Kinetic energy range (J)*	*Spear-thrower length (cm)*	*Spear-thrower mass (g)*	*Type of grip*	*Force range (N)*
Raymond (1986)	Basketmaker	19.5–22.5	52–91	142–165	7–15	Willow/spruce	Radar gun	9.78–22.35	53–57	117–122	–	–
Hutchings and Bruchert (1997)	Basketmaker	27.4–64	81.9–545.3	183	12–13	Dry hemlock	Camera	52.49–771.67	65.4	149.5	–	–
Pettigrew (2015)	Basketmaker	20–27	84.2–225	152–208	8–16	*Salix exigua*	High-speed video camera	19.01	–	–	–	–
Baugh (2003)	Basketmaker	21–25.5	71	–	–	–	Radar gun/high-speed video camera	15.26–22.78	61	135	–	–

(*Continues*)

Table 1 *(Continued)*

Spear-thrower

Reference	*Type*	*Speed range* $(m\ s^{-1})$	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Speed measurement device*	*Kinetic energy range (J)*	*Spear-thrower length (cm)*	*Spear-thrower mass (g)*	*Type of grip*	*Force range (N)*
Carrère (1990)	European Magdalenian wooden hook	21–25.5	150	1.5	15	–	Two photoelectric gates	32.45–48.77	72	280	–	–
Butler (1979)	–	23.21	166	–	–	–	Calculation based on distance	44.72	–	150	–	–
Whittaker *et al*. (2017)	Basketmaker	21–22	84.2–93.1	–	–	Willow	Radar gun	19–23	–	–	–	–
Whittaker *et al*. (2017)	Basketmaker	20–26	107–145	–	–	Cane	Radar gun	22–42	–	–	–	–
Whittaker *et al*. (2017)	Basketmaker	20–23	191–225	–	–	–	Radar gun	39–60	–	–	–	–
Whittaker *et al*. (2017)	Basketmaker	15.6	116	–	–	–	High-speed video camera	14.1	–	–	–	–
Whittaker *et al*. (2017)	Basketmaker	26.6–30	195	–	–	–	High-speed video camera	69.3–87.9	–	–	–	–

Hand-thrown spear

Reference	*Type*	*Speed range* $(m\ s^{-1})$	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Material of speed measurement*	*Kinetic energy range (J)*
Butler (1979)	Dart	17.7	166	–	–	–	Calculation based on distance	26
Vassilios and Iraklis (2013)	Olympic javelin	20–24	600	–	–	–	High-speed camera	120–172.8

(Continues)

Table 1 *(Continued)*

Hand-thrown spear

Reference	*Type*	*Speed range ($m\ s^{-1}$)*	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Material of speed measurement*	*Kinetic energy range (J)*
Jung *et al.* (2012)	Olympic javelin	23.96–27.49	600	–	–	–	High-speed camera	172.2–226.7
Gregor and Pink (1985)	Olympic javelin	32.3	800	–	–	–	High-speed camera	417.32

Thrusting spear

Reference	*Type*	*Speed range ($m\ s^{-1}$)*	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Force and speed measurement device*	*Kinetic energy range (J)*	*Type of grip*	*Force range (N)*
Schmitt *et al.* (2003)	Aluminium tube	–	–	180	25.6 (inner diameter 22.47)	Aluminium	Strain gauge	–	–	1660–3430
Milks *et al.* (2016)	Wooden spear	2.8–6.26	1204–1258	230	36	*Picea abies*	Load cell	–	–	362–1120
Horsfall *et al.* (1999)	Stabbing knife	10.1	600	–	–	–	Piezoelectric load washer and single-axis accelerometer	63.4	Underarm	1000
Horsfall *et al.* (1999)	Stabbing knife	11.6	600	–	–	–	Piezoelectric load washer and single-axis accelerometer	114.9	Overarm	1000
Chadwick *et al.* (1999)	Stabbing knife	2.6–9.2	–	–	–	–	High-speed camera and strain gauge	7–103	–	474–2261
Connolly *et al.* (2001)	Wood–aluminium spear	5.8–6.7	1350	164	–	Wood–aluminium	Transducer and accelerometer	35–42	Overarm	926–1069

(*Continues*)

Table 1 *(Continued)*

Thrusting spear

Reference	*Type*	*Speed range (m s^{-1})*	*Projectile mass range (g)*	*Shaft length range (cm)*	*Shaft diameter range (mm)*	*Shaft material*	*Force and speed measurement device*	*Kinetic energy range (J)*	*Type of grip*	*Force range (N)*
Connolly *et al.* (2001)	Wood–aluminium spear	3.7–3.8	1350	164	–	Wood–aluminium	Transducer and accelerometer	6.5–7.5	Shoulder level, right arm	493–507
Connolly *et al.* (2001)	Wood–aluminium spear	3.3	1350	164	–	Wood–aluminium	Transducer and accelerometer	6	Shoulder level, left arm	556
Connolly *et al.* (2001)	Wood–aluminium spear	4.3–4.8	1350	164	–	Wood–aluminium	Transducer and accelerometer	12.5–14	Underarm	472–711
Bleetman *et al.* (2003)	Stabbing knife	5.94–14.88	–	–	–	Instrumented blade	Calculation, instrumented blade	–	–	97–212

arrow (Baker 2001). The time during which a projectile will be subjected to its acceleration is determined by the length of the propulsion movement made by the shooter in the case of the spear-thrower, hand-thrown and thrusting spears, and by the draw length of the shooter in the case of the bow.

PROPULSION TECHNIQUES AND EXISTING KINETIC ENERGY DATA

Learning the technical gestures

The key challenge in projectile experiments is the use of a suitable gesture for launching the armature. This gesture is specific for each mode of propulsion and requires know-how and experience. As in all sports, practice is required in order to learn an adequate and effective gesture. Depending on the complexity of the body movements involved, some techniques are easier to learn than others, but they all require a certain level of teaching. While weapons and hunting techniques may have changed through time, the gestures compatible with prehistoric hunting are not lost. Throwing a spear by hand, for instance, is little used in present-day hunting, but spear throwing as a discipline exists even though it is now aimed at maximal distance instead of precision in reaching a target (Vassilios and Iraklis 2013). Experiments on prehistoric hunting technology can thus draw inspiration from existing sports in order to understand the gestures needed to make the technique effective for hunting purposes. Similarly, spear thrusting is still used in certain hunting events (e.g., hunting of wild boars, hunting with hounds—'*chasse à courre*' in France) or in traditional events (e.g., El Toro Vega in Spain). By contrast, the spear-thrower is still in use among indigenous populations in Australia and South America and it is also used in recreational events (e.g., the 'World Open Atlatl Contest', 'Championnat européen de tir aux armes de jet préhistoriques'). Despite their recreational nature, such events are helpful for understanding the suitability of raw materials and the possible diversity in appropriate gestures, which has resulted in useful feedback relevant to archaeological experimentation (Whittaker *et al*. 2017). It is essential that this existing knowledge on the gestures linked with each propulsion mode is utilized to improve the reliability of projectile experiments.

The bow

Effective use of the bow involves mainly upper limb gestures. Details of bow-shooting techniques (i.e., anchor points, the finger grip on the string and the position of the arms) vary to a great extent, and abundant literature is dedicated to the topic (for details, see Fredéric 1985; Asbell 1991; Asbell 1993; Roth 2004; Rousseau and Nicolier 2005; Bickerstaffe 2008). In our experiments, we opted for the European string grip and release and for an anchor point located at the corner of the mouth. The experimenter (CL) has 15 years of experience with bow shooting.

Data available from previous experiments on the KE developed by the bow are highly variable due to variation in the bow models used (Table 1). The most powerful traditional bow used in experiments (i.e., the Ottoman bow, 180 lb, or ~81.6 kg) has a maximum energy value of 150 J (Table 1). However, it is generally estimated that an arrow of 30 g launched with a 50-lb (~22.7 kg) bow (approx. 30 J) is the minimum to obtain an effective bleeding wound on middle-sized game (Lecaille and Menu 1985; Mailly 2010; Tomka 2013). The draw weight of Neolithic adult bows is currently estimated between 24 lb (~10.9 kg) and 84 lb (~38.1 kg) (Junkmanns 2013), which corresponds to energy values between 13 and 90 J. Most measurements of KE have been performed with a chronograph, a Doppler radar, photoelectric gates or a ballistic pendulum (English 1930; Bergman *et al*. 1988; Hamm 2000; Strickland and Hardy 2005). These different systems measure the velocity of the projectile in flight at a given moment (chronograph or photoelectric gates) or upon impact (ballistic pendulum). By contrast, a Doppler radar allows measurements throughout the flight of the projectile, but a metallic component has to be added to the projectile in order to track it.

Hand-thrown spears

For the ballistic experiment with hand-thrown spears, we opted for a gesture inspired by the modern practice of javelin throwing (Vassilios and Iraklis 2013), but without the running phase. The grip on the spear is located at the point of equilibrium of the shaft. The propulsion is a multiple step movement involving the use of several muscles. It begins with a transfer of the body's centre of gravity on to the rear leg (Fig. 1 (a), 1). The propulsion movement itself begins with a push of the rear leg (Fig. 1 (a), 2), followed by a rotation of the hip and the torso of the shooter (Fig. 1 (a), 3) and the movement of the arm (Fig. 1 (a), 4), ending in the release of the spear (Fig. 1 (a), 5). The experimenter (JC) has 6 years of experience with this gesture. The KE developed by elite practitioners of modern javelin throwing reaches values averaging around 200 J, with the world record of 417 J held by Tom Petranoff (1983) (Gregor and Pink 1985). These measurements have been performed using a high-speed camera (Table 1) at the moment of release (Gregor and Pink 1985; Jung *et al*. 2012; Vassilios and Iraklis 2013).

The spear-thrower

The gesture used with a spear-thrower is very similar to the one used for hand-thrown spears as far as the legs, hips and torso are concerned (Fig. 1), but when the hand passes the shoulder, the shooter opens his finger grip on the dart while moving his hand downwards in order to keep the

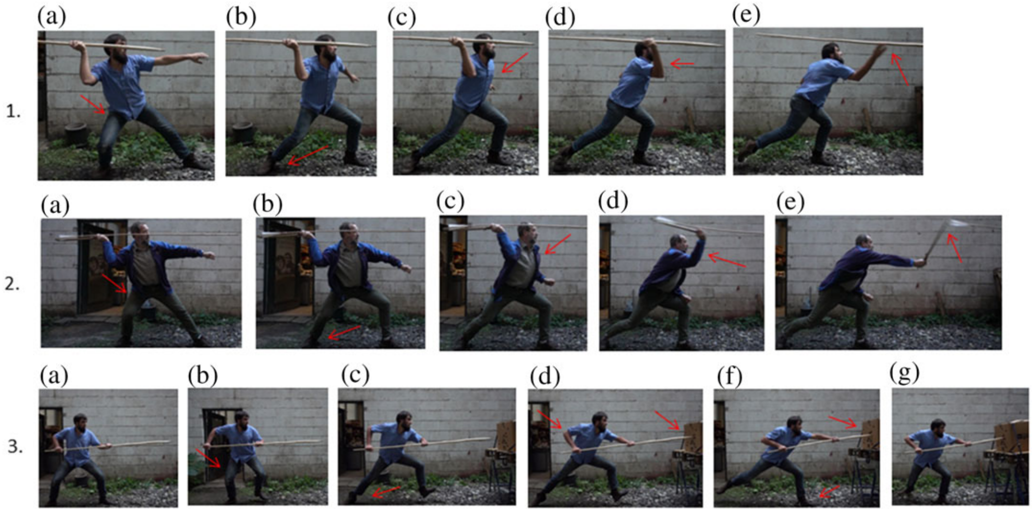

Figure 1 *The different phases in the movement needed for (a) throwing a spear by hand, (b) throwing a dart using a spear-thrower and (c) thrusting a spear. [Colour figure can be viewed at wileyonlinelibrary.com]*

hook of the spear-thrower at the same level all through the movement. The experimenter (CL) has 15 years of experience with this gesture.

The average KE registered in published experiments reaches values between 15 and 90 J. This variation is mainly due to the muscular capacities of the participants and the mass of the darts used (Table 1). One experiment (Hutchings and Bruchert 1997) has intriguing results in comparison to the others: the authors have measured values that range from 52 to 771 J, which significantly exceeds all values recorded in other experiments (Table 1). These values were obtained by calculating the speed based on time and the distance travelled by the projectile between two cameras. The values appear extreme and are clearly outliers with regard to all other measurements, so we suspect errors linked to the measurement device (Whittaker *et al.* 2017). Most other measurements have been performed using a high-speed video camera and speed radar (Table 1).

Thrusting spears

For spear thrusting, a gesture that is well known from ancient Greek hunting iconography was used (Hull 1964; Barringer 2001; Connolly *et al.* 2001). A very similar movement that allows a rapid thrust is still practiced in modern fencing, where it is called the lunge. The experimenter (JC) has 16 years of experience with this movement. The user is positioned perpendicularly to the target, with both legs bent and his centre of gravity in the middle, while holding the spear with both hands. To start, he transfers his centre of gravity to the rear leg (Fig. 1 (c), 2). He then raises his front leg and pushes energetically with his rear leg to propel his body forward (Fig. 1 (c), 3). At the same time, the thrusting movement of the spear, led by both arms, begins and the spear has to touch the target before the user puts his front leg on the ground (Fig. 1 (c), 5). In this movement, the mass of the user has a significant influence on the KE that is developed (see section What influences the kinetic energy developed by a projectile?).

While the velocity of the thrusting movement can be measured, this is not the case for the mass needed to calculate the KE, which consists of the mass of the projectile and a significant part of the body mass of the user. The entire body mass cannot be used, as the user often remains in touch with the ground during the movement. Without knowing what part of the body mass of the user is being transferred, the KE of thrusting spears cannot be calculated. This explains why most previous experiments have systematically focused on measuring the force, with reported values between 362 and 3430 N (Schmitt *et al.* 2003; Milks *et al.* 2016), or on measuring the KE developed by a stabbing movement. Stabbing differs significantly from thrusting since the former does not involve (or only minimally involves) a pushing motion with the legs. The values obtained previously for stabbing are between 7 and 114 J (Chadwick *et al.* 1999; Horsfall *et al.* 1999). Depending on what was being measured in the thrusting experiments, various instruments have been used (e.g., the load cell, strain gauge, transducer, accelerometer and high-speed video camera), resulting in diverse calculations (cf., Table 1).

The relevance of a ballistic pendulum

While the ranges of energy developed by the bow and the spear-thrower can be estimated and while a maximum value for hand-thrown spears can be deduced from the world record in modern javelin-throwing, we have less knowledge about the KE of hand-thrown spears in a hunting context. For spear thrusting, no KE values are yet available, given that current data come either from experiments involving a completely different gesture (stabbing) (Chadwick *et al.* 1999; Horsfall *et al.* 1999; Bleetman *et al.* 2003) or from experiments in which only the force (in newtons) has been measured (Connolly *et al.* 2001; Schmitt *et al.* 2003; Milks *et al.* 2016), which prevents a comparison with other modes of propulsion. In addition, most measurements of KE have been taken either at the release of the projectile or during its flight, instead of when the weapon hits the target, which is the value of interest when studying hunting technology. Several measurement systems have been used to calculate the KE for different propulsion modes, including the high-speed camera and the Doppler radar for flying projectiles and the accelerometer for thrusting spears. Even though these systems are perfectly suitable for the applications mentioned above, the camera and the radar are not adapted to measuring the energy involved in thrusting. Unidirectional accelerometers, in turn, are not suitable for flying projectiles, which have complex trajectories, and the use of three-dimensional accelerometers seriously complicates data processing. The advantage of the ballistic pendulum is that all modes of propulsion can be compared using a single measuring device and that the kinetic energies at the moment of impact can be calculated and easily compared.

MATERIALS AND METHODS

The ballistic pendulum

The ballistic pendulum was invented in the 18th century by Benjamin Robins to measure the velocity of musket bullets (Robins *et al.* 1805). It is based on the principle of conservation of momentum during an inelastic collision. When the projectile hits the pendulum at its centre of mass, it starts to move and reaches a certain height corresponding to the impact energy received (Fig. 2 (c)). Based on this height and the mass of the pendulum, the impact energy is calculated (using textbook physics of inelastic collisions in one dimension):

$$\mathrm{KE(i)} = \Big((m_1 + m_2)^2 gh\Big)/m_1,$$

where KE(i) is the KE of the impact, m_1 is the mass of the projectile, m_2 is the mass of the pendulum, g is the terrestrial acceleration and h is the height reached by the pendulum.

To allow the detection of low energy values, we constructed a pendulum that is as light as possible, which resulted in a device weighing 7.74 kg (Fig. 2; see also Figs 1 (a) and 1 (c)). Reliable measurements can only be produced when the movement of the pendulum does not exceed 45° and, therefore, the pendulum is able to receive an additional 40 kg when needed. An increase in the mass of the pendulum reduces the angle that may be reached with a given amount of energy, and thus allows an increase in the measurement range of the device. The device is suspended by four iron cables and the cage receiving the impact is placed at 1 m from the pivoting point. A system was added to register the angle reached by the pendulum after each shot (Fig. 2 (a)) with a precision up to a quarter of a degree. The height of the pendulum was calculated using the following angle:

$$h = L(1 - \cos\alpha),$$

where h is the height reached by the pendulum, L is the length between the centre of mass of the pendulum and the pivoting point (1 m) and $\cos\alpha$ is the cosine of the angle reached by the pendulum.

A piece of foam was used as an impact plate for the three projected weapons to retain the projectile in the pendulum and to avoid disruptive movements or a rebound of the projectile after the

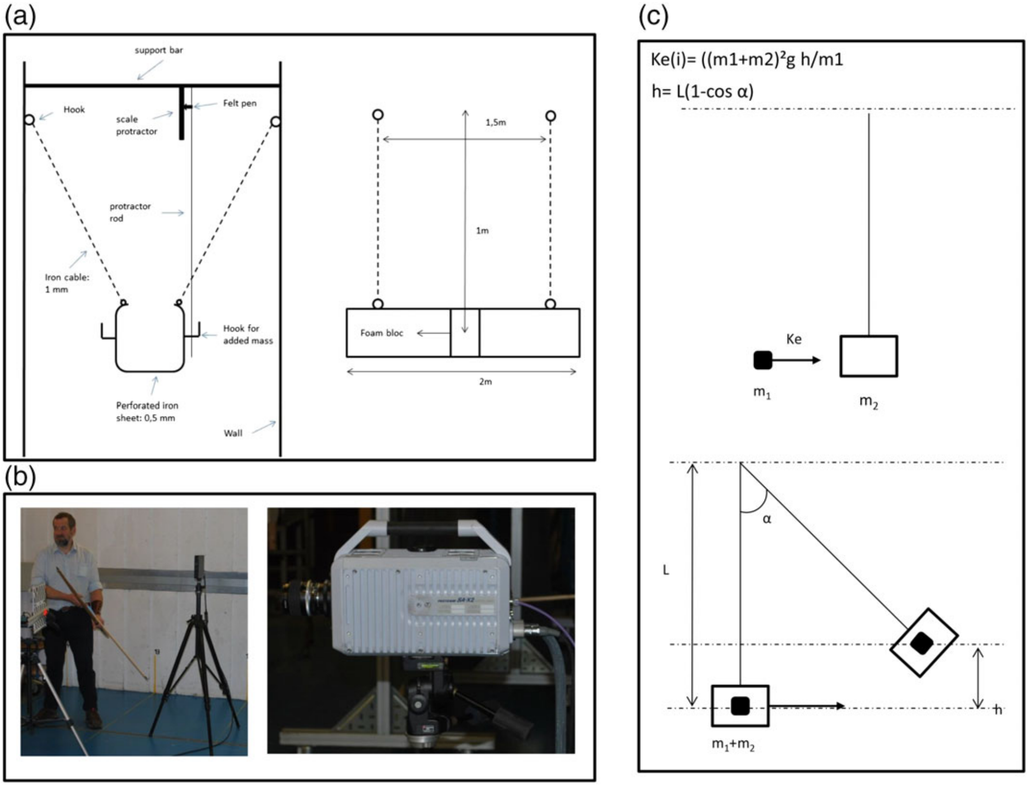

Figure 2 *(a) A schematic drawing of a ballistic pendulum. (b) Left, the WEIBEL SL520 Doppler radar (Ballistic Measurements Ltd); right, the Fastcam SA-X2 high-speed video camera (Photron). (c) The operating principle of a ballistic pendulum. [Colour figure can be viewed at wileyonlinelibrary.com]*

impact. For the thrusting weapon, a 4-mm iron plate was used to receive the impact as the foam was not resistant enough. The effect of this iron plate in comparison to foam was tested and found to be negligible (for detailed information, see the online Supplementary Material).

Experiments

Three experiments were performed: (1) a general experiment with the ballistic pendulum, aimed at quantifying the KE developed by each of the four modes of propulsion; (2) a classic exterior ballistic study to evaluate the validity and precision of the results obtained with the ballistic pendulum; and, finally, (3) an experiment dedicated to spear thrusting, to understand the variation introduced by different participants and their varied skill levels and body masses. This was done to compensate for the sparse data that are currently available for this propulsion mode. The physical characteristics of each projectile and mode of propulsion are detailed in Table 2.

The pendulum experiment Each projectile was shot into the pendulum 30 times. Half of the shots were performed at a 4-m distance from the pendulum and the other half at a 10-m distance. For the thrusting motion, all 15 trials were performed in direct contact with the

Table 2 *A summary of the experimental details and results of the pendulum experiment performed at TraceoLab and the classic ballistic experiment*

Type	*Draw weight (lb)*	*Draw length (in)*	*Speed range ($m\ s^{-1}$)*	*Projectile mass (g)*	*Shaft length (cm)*	*Spin (cm)*	*Shaft diameter, min.–max. (mm)*	*Shaft material*	*Speed measurement device*	*Measuring distance (m)*
Yew longbow	48	29	44.8–45.5	30	82	1.3	8	Pine	Doppler radar	5
Yew longbow	48	29	–	30	82	1.3	8	Pine	Ballistic pendulum	5
Yew longbow	48	29	–	30	82	1.3	8	Pine	Ballistic pendulum	10
Spear-thrower	–	–	22.1–26.8	167	210	4.6	10.2–17.8	Hazel	High-speed video camera	5
Spear-thrower	–	–	–	167	210	4.6	10.2–17.8	Hazel	Ballistic pendulum	5
Spear-thrower	–	–	–	167	210	4.6	10.2–17.8	Hazel	Ballistic pendulum	10
Hand-thrown spear	–	–	–	740	210	–	15.5–40	Spruce	Ballistic pendulum	5
Hand-thrown spear	–	–	–	740	210	–	15.5–40	Spruce	Ballistic pendulum	10
Thrusting spear	–	–	–	740	210	–	15.5–40	Spruce	Ballistic pendulum	0

Table 2 *A summary of the experimental details and results of the pendulum experiment performed at TraceoLab and the classic ballistic experiment*

Type	*Kinetic energy (KE) range (J)*	*KE average*	*KE standard deviation*	*KE coefficient of variation (%)*	*Spear-thrower length (cm)*	*Spear-thrower mass (g)*	*Number of trials*	*Experimenter*
Yew longbow	30.1–31.1	30.7	0.4	1.4	–	–	3	CL
Yew longbow	27.1–31.8	29.9	2.3	7.7	–	–	15	CL
Yew longbow	27.1–31.8	28.3	2.1	7.3	–	–	15	CL
Spear-thrower	40.6–60.1	51.3	5.9	11.5	60		10	CL
Spear-thrower	45.2–61.5	55.2	4.6	8.3	60		15	CL
Spear-thrower	40.3–50.4	43.9	3.3	7.5	60		15	CL
Hand-thrown spear	63.3–87.6	74.2	7.5	10.2	–	–	15	JC
Hand-thrown spear	60.4–89.3	71.7	8.2	11.5	–	–	15	JC
Thrusting spear	2461.1–3355.9	2910.3	269.4	9.3	–	–	15	JC

target. Importantly, no pushing motion into the pendulum was allowed: the position of the spear user had to be such that only brief contact was made with the pendulum at the end of the gesture. If the user were to maintain contact with the pendulum, it would be the accumulation of energy linked to the pushing motion that would be measured rather than the impact energy.

All shots were performed by two experimenters, CL for the bow and the spear-thrower and JC for the thrusting and hand-thrown spears. The mass of the pendulum was kept at 7.74 kg for the bow, spear-thrower and hand-thrown spears and increased to 37.74 kg for spear thrusting.

The classic ballistic experiment For the classic ballistic experiment, exactly the same weapon elements were used by the same experimenters as in the pendulum experiment. The projectile's velocity was recorded at 4–5 m from the shooter using a WEIBEL SL520 (Ballistic Measurements Ltd) Doppler radar with Remstrack software and a FASTCAM SA-X2 slow-motion camera (Photron, 12 500 fps and 1024 × 1024 pixels for image resolution) (Fig. 2 (b)). The projectile was filmed over a distance of 3 m and its velocity was calculated using the Photron FASTCAM Viewer software, based on the displacement of a reference point placed on the projectile between the frames. Given the characteristics of the measuring devices, this ballistic study only concerned the spear-thrower (10 shots) and the bow (three shots).

The experiment on variability in spear thrusting Experience and an adequate gesture are essential elements in spear thrusting and are bound to affect the KE that is developed. The pendulum is an ideal device for a systematic comparison of the KE developed by a wide range of participants under the exact same conditions. In total, 20 people with different body masses, genders and levels of experience participated; they were divided into four groups on the basis of their existing experience. The first group consisted of people with no experience in thrusting a weapon (nine adults and one child). They were allowed to choose how to perform the thrusting motion without guidance or training. The second group was formed by the people of group 1 after explaining to them how to perform the gesture efficiently and giving them 30–60 min of time for free practice. Each participant in groups 1 and 2 performed three shots into the pendulum. The people in group 3 were familiar with the thrusting gesture as a result of regular training in fencing (six adults with a minimum of 3 years' experience in fencing). Finally, the people in group 4 had a minimum of 8 years of similar experience (four adults). Each participant in groups 3 and 4 performed five shots into the pendulum.

RESULTS

Evaluation of the impact energy

The results of the pendulum experiment are explicit and indicate that the bow is the least powerful system of all four propulsion modes (Table 2 and Fig. 3 (a)). The KE measured for the arrows varied between 27.1 and 31.8 J at 4 m, with an average of 29.9 J, and between 27.1 and 31.8 J at 10 m, with an average of 28.3 J (Table 2 and Fig. 3 (a)). The bow is followed closely by the spear-thrower, with values varying between 45 and 61.5 J at 4 m, with an average of 55.2 J, and between 40.3 and 50.4 J at 10 m, with an average of 43.9 J (Table 2 and Fig. 3 (a)). The hand-thrown spear values vary between 63.3 and 87.6 J at 4 m, with an average of 74.2 J, and between 60.4 and 89.3 J at 10 m, with an average of 71.7 J (Table 2 and Fig. 3 (a)). By contrast, the energy developed by the thrusting spear reaches values between 2461.1 and 3355.9 J, with an average of

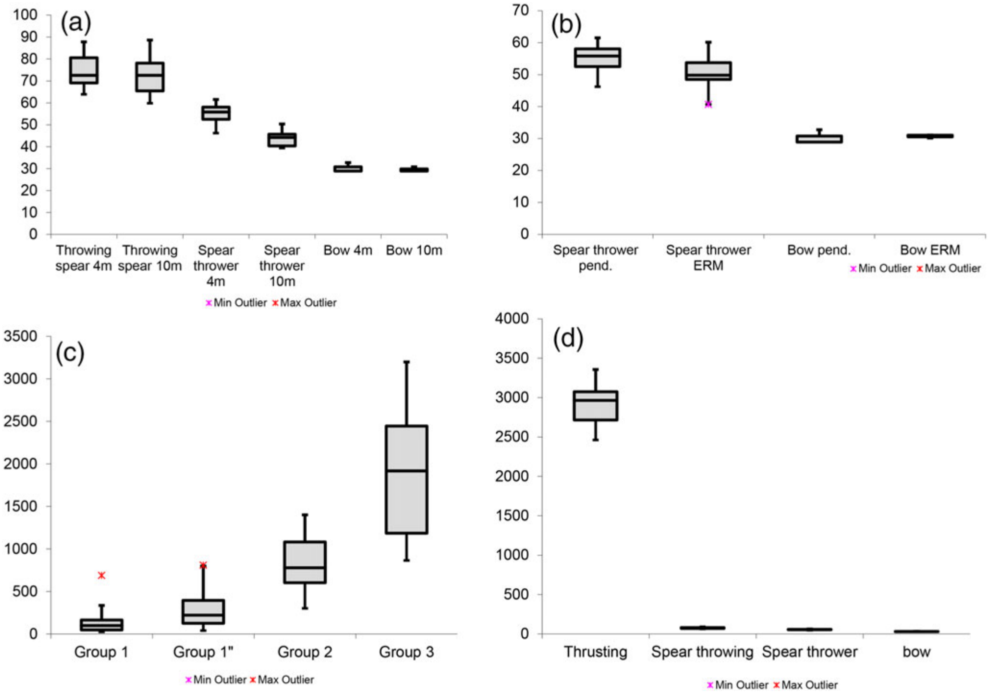

Figure 3 *(a) The ranges of KE (J) measured with the ballistic pendulum for the hand-thrown spear, the spear-thrower and the bow at 4 and 10 m. (b) The ranges of KE (J) measured with the ballistic pendulum ('pend.') and classic ballistic instruments (in the classic ballistic experiment) for the hand-thrown spear, the spear-thrower and the bow. (c) The ranges of KE (J) measured with the ballistic pendulum for the four groups of participants in the spear-thrusting experiments. (d) The ranges of KE (J) measured with the ballistic pendulum for the thrusting spear, the hand-thrown spear, the spear-thrower and the bow. [Colour figure can be viewed at wileyonlinelibrary.com]*

2910.3 J (Table 2 and Fig. 3 (d)), which is extremely high. The coefficients of variation of the measurements with the ballistic pendulum are broadly comparable between the propulsion modes (Table 2). Moreover, the variation in KE recorded for thrusting is also due to some variation in the gesture used; more specifically, whether or not both feet of the experimenter remain on the ground at the moment of impact, which affects the mass involved in the motion. The recorded values differ from what has been previously suggested and used in experimental set-ups; in particular, for the thrusting spear (Table 1), which calls for a revision of the possible causal relationship between KE and fracture formation on stone points, and whether a link exists between impact fractures and propulsion modes.

The classic ballistic study and reproducibility of the results

The classic exterior ballistic study, conducted in a ballistics laboratory, allowed measurement of the KE generated by the bow and the spear-thrower with a higher precision. This study revealed that KE varies between 30.1 and 31.1 J, with an average of 30.7 J, for the arrows and between 40.6 and 60.1 J, with an average of 51.2 J, for the darts (Fig. 3 (a) and Table 2). The values are based on direct measurements of velocity and the results prove to be reproducible, with negligible variation between shots for the bow and a slightly higher variation for the spear-thrower (Fig. 3 (b)) due to the complex body movement involved in the latter technique (see section Spear-thrower).

The averages of the values correspond well to the results obtained with the pendulum (Fig. 3 (b)). The difference between the coefficient of variation calculated for the bow based on measurements with the Doppler radar (1.4%) versus the one for the pendulum (7.7%) is caused by the precision level of the pendulum (see section The ballistic pendulum). For the spear-thrower, the coefficient of variation is 11.5%, which is due to the higher degree of variation between individual shots. The correspondence between the values obtained in the classic ballistic study and those obtained with the pendulum confirms the reliability of the latter, which implies that the very high values of impact energy obtained for the thrusting spear are accurate.

Variation in kinetic energy in spear thrusting

When the KE values obtained by the different participants in the spear-thrusting experiment are compared, it is evident that important differences exist between the participant groups. The dominant variable affecting the KE measured appears to be the level of know-how of the participant. The most experienced group 4 transferred significantly higher amounts of energy into the target than the inexperienced participants in group 1 (Fig. 3 (c)). Participants in group 1 generated kinetic energies between 26 J and 688 J (Fig. 4 (a)). These values clearly increased

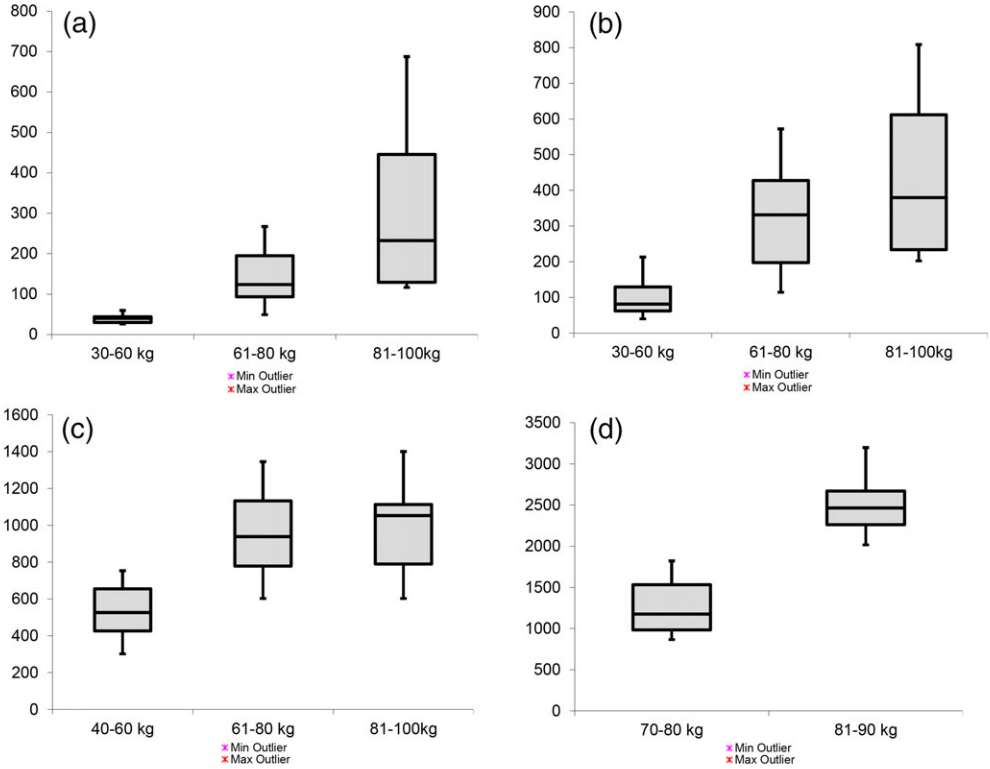

Figure 4 *The ranges of KE (J) in spear-thrusting for different body-mass categories (kg), measured with the ballistic pendulum: (a) group 1; (b) group 2; (c) group 3; (d) group 4. [Colour figure can be viewed at wileyonlinelibrary.com]*

after the short training session: the values for group 2 are between 40 J and 808 J (Fig. 4 (b)). Participants in group 3 reached values between 302 J and 1401 J (Fig. 4 (c)). Participants in group 4 clearly reached the highest KE values, varying between 865 J and 3198 J (Fig. 4 (d)). The mass of the participant also proved to be an important variable: a greater body mass systematically resulted in higher amounts of impact energy (Fig. 4). By contrast, the age and gender of the participants proved irrelevant.

DISCUSSION

The debates on Palaeolithic hunting technology over the past decade have been influenced by a model of linear evolution for the invention of different propulsion modes. This model assumes a gradual progression from simple to more complex weapon systems and appears to be supported by important though sparse discoveries of organic weapon remains in Europe. Within this model, thrusting and throwing spears are generally viewed as simple weapons that are less efficient in terms of energy, range and precision, while the spear-thrower and the bow are considered complex weapons (i.e., multiple components) that are supposed to be more powerful (Sano and Oba 2015; Clarkson 2016), precise and effective at longer distances (Shea and Sisk 2010; Sisk and Shea 2011; Iovita *et al*. 2016).

In the absence of more organic evidence, a progression in our understanding of Palaeolithic hunting technology has to rely on a detailed analysis of the stone points. The idea that a link exists between the development of the fracture path and the KE that is transferred during impact (Iovita *et al*. 2014, 2016; Clarkson 2016; Pargeter *et al*. 2016; Sano 2016), potentially permitting the recognition of different modes of propulsion in an archaeological context, is understandably attractive. To explore this hypothesis, experimental studies with mechanical devices are important for assessing the relationship between the amount of energy developed by each weapon system and the characteristics, frequency and size of the impact fractures formed on stone points. Such experiments need an input of accurate KE values for each propulsion mode in order to calibrate the mechanical device used to launch the projectile. Up to now, ballistic projectile experiments have been severely hampered by the difficulty of correctly estimating the range of KE developed by each weapon system, especially for thrusting spears (Milks *et al*. 2016). Previous attempts have struggled with what device to use for measuring the energy for both projected and thrusted weapons. Thrusting weapons in particular have raised many issues and in the absence of accurate energy data, these weapons have been assumed to be at the lower end of the range in comparison to other prehistoric propulsion modes.

Through the use of the ballistic pendulum, it has finally been possible to exactly measure the KE of all propulsion modes with a single device, as such permitting a direct comparison of the values. Opposite to what the model of linear evolution predicts, thrusting weapons—assumed to be the oldest weapon type used—develop the highest KE and should thus be considered the most powerful propulsion mode. This result should not surprise us, because the thrusting motion exploits a significant part of the body mass of the spear user. Importantly, our experimental set-up did not permit a true pushing motion, implying that the measured values can be considered minimum values for a real-life thrusting motion, in which case the hunter's body mass plays a role up until the end of the motion into the target. Projected weapons, by contrast, are limited by their mass and although they are propelled at higher velocities, they will never reach the KE values developed in thrusting. In this regard, hand-thrown spears are perhaps an exception, as the maximum kinetic energies registered so far (Gregor and Pink 1985) overlap with the range measured for thrusting spears in our multiple-participants spear-thrusting experiment. This range, however, proved to be largely influenced by the experience level of the participants. The significance of this overlap between thrusting and throwing spears is therefore limited; in particular, considering that the maximum energy value for the throwing spear used here is the release energy value measured for an Olympic champion javelin thrower. The latter value can thus be considered as an absolute maximum value for impact energy in any hunting event and it only overlaps with the lowest energy values measured for the group with little experience in spear thrusting (group 3) and with the range produced by people with no experience at all (groups 1 and 2). Within the category of projected weapons, the hand-thrown spear proved to develop the highest amount of energy, followed by the spear-thrower and finally the bow (Table 2 and Fig. 3). Each of these three modes of propulsion has a specific range of variation in KE and even if these ranges may be in close proximity to each other, no overlap between them was observed. Although the pendulum does not measure the KE of a flying projectile as precisely as the traditional tools used in a ballistic analysis (Doppler radar and high-speed camera), it proved to be a very useful tool for comparing energy levels between the four standard modes of propulsion, including thrusting.

In the absence of exact technical details for the weapons used during the Palaeolithic, we have to exercise caution with regard to the lower and upper limits of the energies developed by each weapon system. Consequently, the possibility of an overlap in the range of kinetic energies developed by all three projected weapons used during the Palaeolithic cannot be excluded and will need to be examined further by integrating weapons with differing technical characteristics in new experiments. Thrusting spears clearly fall outside any potential overlap with other propulsion modes, since the energy range developed by skilled spear users surpasses 500 J, which exceeds the maximum energy developed by a javelin thrown by an Olympic champion (Table 1). Therefore, if the relationship between the KE and the size and frequency of fractures is to be examined through mechanically assisted experiments, preferably only two categories of weapons should be compared: thrusting weapons versus projected weapons.

Mechanically assisted experiments have an undeniable advantage over realistic experiments when exploring a complex phenomenon such as projectile impact, but significant preliminary work is required to understand the influence of each individual variable. Only then can we effectively use and calibrate machines with realistic settings and address questions that involve the combined effect of different variables.

Finally, our results demonstrate that one of the recent assumptions that underlie the model of evolutionary phases in Palaeolithic weaponry, this being the gradual increase in KE from one mode of propulsion to the next, is false. No increase in KE from one system to the next could be established. In addition, each system has its own advantages and constraints, also in terms of precision, and one system does not necessarily outcompete another on all levels. When considering the developments in hunting technology, it is also important to acknowledge that different types of hunting weapons may have coexisted, each potentially responding to different needs. The invention or development of a new weapon system does not necessarily replace the existing system(s). The choice of a particular weapon system or a combination of several systems may further be influenced by cultural, ecological and economic factors. Stone points recovered without their organic shafts at a particular site cannot thus all be assumed to have been used within the same weapon system, even if they can be reliably identified as projectiles. One of the major challenges in the future will be to continue to find new ways to understand this complexity in hunting technology and its variability through space and time on the basis of the most frequently preserved material, namely the stone tools.

CONCLUSION

Ballistic studies are necessary for understanding past hunting technologies. The use of a ballistic pendulum proved to allow an accurate comparison of the KE developed by each weapon type (thrusting spear, hand-thrown spear, spear-thrower and bow). It provides an entirely new insight into weapon systems and demonstrates that thrusting spears are the most powerful weapons used in the Palaeolithic. In addition, our experiments clearly challenge the notion of a gradual increase in KE as weapon systems develop through time. Changes in projectile weaponry do not necessarily reflect a gradual linear evolution, and may instead be an answer to a wide range of changes affecting hunting strategies (environment, prey, social context of hunting, cultural transmission etc.). The shifts between propulsion modes are indubitably complex and may involve the (re-)appearance and (re-)disappearance of systems, as well as the coexistence of several systems. Without representative organic remains for different areas and time periods, the exploitation of a more durable and ubiquitous material such as stone is essential to progress in the study of Palaeolithic hunting practices, thereby continuing the important methodological work on fracture dynamics and ballistic studies that were initiated nearly half a century ago.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data S1:
Supporting Information