The propulsion phase of spear-throwers and its implications for understanding prehistoric weaponry

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Highlights

- We present a revised model for the functioning of the spear-thrower.
- A spear-thrower is more than a lever or arm extender.
- The displacement and the acceleration of its hook is the key point of the spear-thrower functioning.
- The flight of the dart is conditioned by the shaft characteristics, the useful length of the spear-thrower and the shooter's propulsion movement.

Abstract

Understanding the appearance and evolution of prehistoric weaponry is a key topic in archaeological research. While stone or osseous projectile points are identified archaeologically based on damage patterns and other wear traces, identifying how these weapons were propelled requires a more thorough understanding of the ballistic behaviour of each weapon system. Even if the spear-thrower and dart is a commonly known weapon system that is often used in projectile experiments, its functioning is still not yet fully understood. In this article, we contribute to its understanding with a detailed analysis of the propulsion phase of the dart. We use high-speed video recordings and show that the propulsion of a dart has a complexity that goes beyond a simple lever effect or an arm extender provided by the spear-thrower. We argue that the focus should not only lie on the rotation of the spear-thrower but also on the displacement of the spear-thrower hook and the dart's butt during the entire propulsion phase. We demonstrate that the gestures of the user and the specific characteristics of both the spear-thrower and the dart represent three inseparable elements that determine a dart's flight and its ballistic behaviour. Knowledge on the propulsion phase of the dart is therefore a prerequisite for insights into the impact phenomenon, for an adequate understanding of impact fractures on projectile points, and for the recognition of weapon propulsion modes on an archaeological level.

Keywords
spear-thrower, propulsion phase, motion analysis, projectile behaviour, experiments

1. Introduction

Projectile technology used in hunting is a major innovation in human evolution (Ambrose 2001). Projectile points are considered to signal planning abilities and possibly complex cognition and to mark identity (e.g., Hughes, 1998; McBrearty et al., 2000; Rots et al., 2017; Brooks et al., 2006; Shea, 2006, 2009; Shea and Sisk, 2010) In spite of rich literature on projectiles (e.g., Knecht, 1997; Iovita and Sano, 2016) and studies that claim to have identified propulsion modes (e.g., Metz et al., 2023; Sano, 2016; Sano and Oba, 2014, 2015; Sano et al., 2019), little is actually known about Palaeolithic hunting technology and how it evolved through time, even though it is vital for discussions on technological evolution, subsistence strategies, group identity and human behaviour. Traditionally, four main propulsion modes are considered: thrusting spears, throwing spears, spear-throwers and darts, and bows and arrows. In evolutionary terms, a separation is often made between the former two being weapons used at short distance and the latter two being weapons permitting hunting at a longer distance, which is frequently regarded as a significant advance (Sisk and Shea, 2009, 2011; Sahle and Brooks, 2019; Lombard and Shea, 2021; Lombard 2022a, b; Metz et al., 2023). There are indeed important advantages at being able to hunt from a distance, but the view is generally oversimplified, as the selection of what weapon to use in a complex activity such as hunting is not solely based on the potential range of the weapon. Multiple factors may influence the choice, such as the goal and desired precision, amongst several others. Organic remains that document the earliest existence of these weapon systems are few and restricted to 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 (Cattelain, 1989; Stodiek, 1993), and the arrows from Stellmoor and the bow from Holmegaard (Junkmanns, 2013; Rust, 1943), both attributed to the Mesolithic period. All these discoveries were made in Europe, and despite the exceptional importance of these finds, they are too scattered and incomplete to permit an understanding of the appearance and evolution of prehistoric weaponry through time and space.

In the absence of organic materials, detailed studies of stone (and bone/antler) tools have been used to identify projectile points (Fischer, 1981, 1984; Geneste and Plisson, 1990; Pargeter et al., 2016; Shea, 2006) and to explore whether long-distance weaponry could be identified on the basis of the stone tools only (Hutchings, 2015; Iovita et al., 2014; Pargeter et al., 2016; Sano et al., 2019; Sano and Oba, 2015; Shea, 2006; Shea and Sisk, 2010). Several approaches have been proposed, using proxies based on morphometrics such as TCSA/TCSP values (Friss-Hansen, 1990; Hugues, 1998; Salem and Churchill, 2016; Metz et al., 2023; Shea, 2006; Sisk and Shea, 2009), the length of so-called diagnostic impact factures (DIFs) (Iovita et al., 2014; Iovita and Sano 2016a, b; Sano and Oba, 2015; Clarkson, 2016) or Wallner lines (Hutchings, 2011). Critics have highlighted major weaknesses for each of these approaches (for extensive critiques about TCSA/TCSP see: Clarkson, 2016; Coppe, 2020; Rots and Plisson, 2014; Villa and Roebroeks, 2014; for DIF length see Rots and Plisson, 2014; Coppe and Rots, 2017; Salem and Churchill, 2016; and for the application of Wallner lines see Douze et al., 2018). More recently, an alternative approach has been proposed on the basis of macrofractures, other wear traces and extensive experimental programs, following extensive ballistic work (cf. Coppe et al. 2019, 2022). Preliminary applications have permitted to hypothesise the use of the thrusting spear at Hohle Fels (Germany, Middle Palaeolithic) (Rots et al. 2021) and the bow for the Federmessergruppen at Lommel-Maatheide, Belgium) (Tomasso et al. 2021). A large-scale application of the method permitted the identification of spear-thrower use in the Gravettian at Maisières-Canal (Belgium; Coppe et al. 2023).
All approaches mentioned earlier share a focus on the stone armatures to try and identify the mode of propulsion, but at the exception of the newly developed approach, they ignore the weapon itself, in particular how each mode of propulsion works from a physical perspective and what kind of mechanical stress is received by the stone armature upon impact. Spear-throwers are a good case in point: while previous work has resulted in different theories about the physical phenomena behind its functioning (without reaching a consensus), this ballistic work was not incorporated in the study of stone armatures nor in attempts to identify the mode of propulsion.

Spear-throwers have been known to prehistorians and ethnologists since the 19th century (Cattelain, 2000: 60) and their use was described by ethnologists following contact with populations who still used this weapon system (see for example Cundy, 1989; Victor and Robert-Lamblin, 1989). Practical questions about its use have been raised since the second half of the 20th century onwards. Researchers unanimously state that a spear-thrower allows for a better energy transfer to the dart in comparison to throwing a spear by hand, but opinions diverge on how this transfer occurs exactly. Some consider spear-throwers as a system that extends the arm and thus the distance over which the spear is being pushed by the shooter (Howard, 1974: 102; Palter, 1977: 164; Stodiek, 1988: 317; Raymond, 1986: 158). Other users hypothesise that darts and certain types of spear-throwers bend during their propulsion (Cundy, 1989; Perkins, 1993; Baugh, 1998: 38, 40; 2003: 349) and speculate about a spring effect in which both dart and spear-thrower would accumulate energy during the propulsion phase. Most authors converge towards seeing the spear-thrower as a lever, thereby focusing on its rotating movement (Cattelain, 1994: 6, 1997; Cotterell and Kamminga, 1990: 166; Cundy, 1989: 45; Lansac, 2004: 30; VanderHoek, 1998; Whittaker, 2014, 2016: 65; Whittaker and Maginniss, 2006). Finally, purely theoretical models have also been proposed (Baugh, 2003; Denny, 2019), though these are not entirely satisfactory. In our view, most of these studies focus on a specific part of the propulsion phase only (the rotating motion of the hand), instead of on the complete propulsion phase, though the latter determines the phenomena that occur during the flight and how the projectile impacts its target.

In any research that aims to identify the use of a spear-thrower archaeologically, be it on the basis of stone or organic projectile points, an in-depth understanding of how exactly the spear-thrower system functions is an essential first step. More specifically, we need to understand (1) the interaction between the spear-thrower and the dart, (2) the influence of the spin if—of the projectile, the length of the spear-thrower, and the throwing technique employed by the shooter on the ballistic behaviour of the dart during its flight. In this article, we focus on the propulsion phase exclusively and we break it down into its constituent components. A stepwise experimental approach to each of these components permits us to understand how a spear-thrower operates and to evaluate to what extent the gestures of the shooter and the technical characteristics of the spear-thrower and dart influence the dart's propulsion. We argue that our results provide a firm foundation for a method that aims to identify this weapon system archaeologically, for instance by exploiting macro- and microscopic wear data on projectile points.

2. Background

Darts and spear-throwers have been in use since the prehistoric period up until today. No remains of prehistoric spear-thrower handles have ever been found in Europe, but some complete examples are known in the USA (for an extensive list see Pettigrew and Whittaker, 2012). Generally, only the hook or a portion of the distal part have been preserved (Cattelain, 1988, 1989, 2005, 2017; Garrod, 1956). The oldest known evidence is a spear-thrower hook found at the site of Combe-Saunière (France) and dated to 17,500 BP (Ly-3329 17,470 +/- 249 BP; 21,807–20,511 cal BP (Ly-3329 conventional); Cattelain, 2005: 307; 2018: 154) though its attribution to the Solutrean or early Magdalenian has been questioned on stratigraphic grounds (Cattelain and Pétillon, 2015: 22; Cattelain, 2018). Finds of hooks are significantly more abundant for the Magdalenian (Cattelain, 1994: 7; 2005: 313), suggesting that this weapon system was commonly used in Europe until the beginning of the upper Magdalenian (most recent finds date to 11,220 +/- 120 BP (B-3327) at Kesslerloch; Cattelain, 2005: 311). Whether the spear-thrower was used in Europe before 17,500 BP is uncertain (Cattelain, 1994: 20). Some prehistoric hooks show elaborate decorations testifying to a significant investment in their manufacture. These objects likely had important lives (Cattelain, 1991; Cattelain and Bellier, 2002) and may have marked social ties or identities (Cattelain, 2005; Stodiek, 1988).

While organic remains are rare and do not permit researchers to truly pinpoint the appearance and distribution of this weapon system, ethnographic data for different continents allude to the fact that its use in prehistory may have been widespread. The spear-thrower and dart are attested in multiple cultures, including the Basketmaker Culture in the Southwest USA, cultures in Central America, and in South America (Brazil, Peru, Chile) (Donnan, 2016; Groshmeyer, 2017a, b; Pettigrew, 2015a; Prins, 2010; Whittaker, 2009, 2015, 2016b, 2017; Whittaker and Kamp, 2011). It was also frequently used in Australia and Papua New Guinea up until the first half of the 20th century (Cundy, 1989; Davidson, 1936; Palter, 1977). Its use is also documented among the Inuit where a decline can be noted around the same time (Drieux, 2016; Hall, 2007; Victor and Robert-Lamblin, 1989, 2016), but the spear-thrower remained in use with certain arctic communities for hunting marine mammals (Hall, 2007; Drieux, 2016). The use of darts and spear-throwers has commonly been assumed to be linked with open ecosystems, but likely a mixture of cultural, technical, and environmental factors explain its choice, and these are difficult to disentangle. Sizes and shapes of ethnographically known spear-throwers vary significantly. For example, Australian spear-throwers have variable shapes and their size ranges between 54.3–114.1 cm (mean: 76.73 cm). Inuit spear-throwers also vary in shape, but they are generally shorter (between 33–63 cm, mean: 48.53 cm). The size of pre-Colombian spear-throwers varies between 43–75 cm (mean: 59.08 cm) and those from Papua New Guinea between 63–120 cm (mean: 82.8 cm) (Cattelain, 2000: 62).

No darts have been preserved from Europe, but some rare prehistoric examples have been found in North America (Groshmeyer, 2017a, b; Hare et al., 2004, 2012; Pettigrew, 2015a, b; Pettigrew and Whittaker, 2012), while many other examples exist in ethnographic collections and museums (e.g., Cundy, 1989; Davidson, 1936). The dimensions and weights of darts show an important cultural and regional variation and the same goes for the presence of fletching. All darts share the fact that the energy for their propulsion is transferred through the dart's butt end, similar to arrows, with the exception of some ethnographic examples (e.g., some Inuit darts are propelled by a peg located near their centre; VanderHoek, 1998: 20).

3. Materials and methods

Ballistically speaking, firing a dart with a spear-thrower can be divided into three successive phases, as is the case for other propelled weapons (Bell, 2012; Pirlot, 2014: 4): a propulsion phase (internal ballistics) before the projectile leaves its propulsion device, an intermediate phase (external ballistics) when the projectile is in flight, and a final phase (terminal ballistics) when the projectile impacts its target. Here, we focus exclusively on the propulsion phase, during which the projectile is provided with the necessary kinetic energy to reach its target. Three autonomous entities work in synergy during the propulsion phase: the user, the spear-thrower and the dart. In this study, we focus on the influence of each of these entities on the propulsion phase. The results of a set of four experiments are discussed. In the first experiment, we address to what extent the use of a spear-thrower differs from using a hand-cast spear. In subsequent experiments, we study the impact of different variables: the influence of the dart, more precisely its spine (experiment 2), the influence of the length of the spear-thrower (experiment 3) and the influence of the shooter and the shooting technique used (experiment 4). The combination of these experiments permits an in-depth understanding of the weapon system. The experimental set-up benefitted from experiences gained during previous experiments performed in collaboration with the ballistics lab of the Royal Military School in Brussels (Abal, E.R.M. Brussels) (cf. Coppe et al., 2019, 2022). These first experiments were filmed with a Photron S12 high-speed camera (7000 frames per second) and the detailed study of these videos provided some initial insights (Clarenne, 2017: 41; Coppe and Rots, 2017: 11). All experiments presented here were filmed using a Sony RX100mIV camera (500 frames/second) that was set up at 6 m, perpendicular to the flight trajectory.

3.1. Spear-thrower

3.1.1. Technical parameters

A spear-thrower is basically a wooden stick with a hook at one end and a grip at the other end. The most complete spear-throwers (archaeological or ethnographic) exhibit actual handles to provide a better grip (Cattelain, 2000: 64), either by carving them into the mass of the handle or by adding parts or materials. The handle can also be made of leather straps into which the user inserts their fingers. These modifications allow a better transfer of the shooter's force and a grip that remains constant between throws.

3.1.2. Spear-throwers used in experiments

Six spear-throwers were used for the experiments. ST1, ST2 and ST3 are made of hazel wood with a hook made of antler glued and bound at their distal end. For a constant grip, their handle is equipped with a leather strap in which the shooter inserts their index finger of the gripping hand. These spear-throwers were used throughout all the experiments. ST4, ST5 and ST6 were only used in experiment 4. These spear-throwers were used by three external shooters we invited to participate in the experiment to be able to compare their shooting technique. These three spear-throwers are also made of wood with an antler hook at their distal end, but spear-thrower ST5 has an additional supporting device at its handle to hold the dart. All spear-throwers used are rigid and do not flex during use.

For each spear-thrower, the rotation point (fulcrum) and the effective length were measured (Table 1). We fix the rotation point of the spear-thrower in the centre of its handle (Fig. 1) (Lepers, 2010: 129). The effective length is the distance between the rotation point in the centre of the handle (fulcrum) and the point of the spear-thrower hook (contact with the dart notch).

Spear-thrower	Ref spear-thrower	Total length (cm)	Effective length (cm)	Experimental use
reference spear-thrower	ST1	60	51	1,2,3,4
spear-thrower 30 CL	ST2	39.5	30	3
spear-thrower 75 CL	ST3	84.5	75	3
spear-thrower A	ST4	58.5	48	4
spear-thrower B	ST5	59	48.5	4
spear-thrower C	ST6	58.5	48.5	4

Table 1 Characteristics of the spear-throwers used in the experiments.

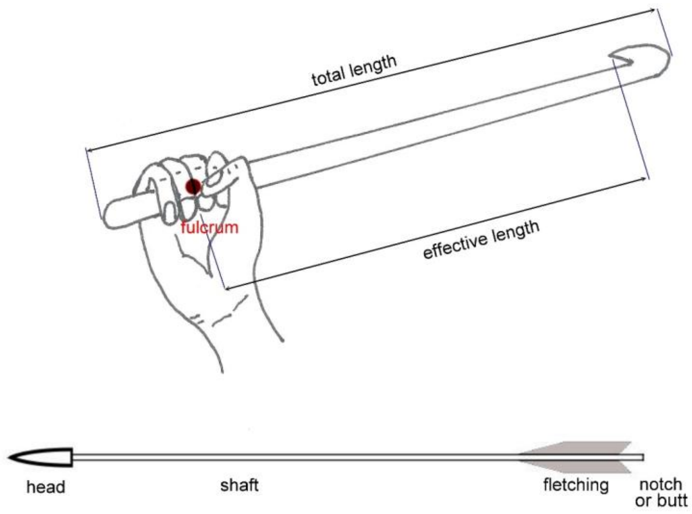

Fig. 1 Spear-thrower and dart.

3.2. Darts

3.2.1. Technical parameters

Darts are made of a wooden shaft with a point at their distal end and fletching and a notch at their base. To launch a dart, the hook of the spear-thrower is inserted into the notch of the dart. For each dart, wood species, length, weight, spine, balance point, FOC and the area of fletching are documented in Table 2.

3.2.1.1. The spine

The spine of a dart is important, as is the case for arrows too (cf. Lepers and Rots 2020). When a dart is shot, the spear-thrower pushes on the butt of the dart and initiates a flexion of the dart's shaft. This phenomenon is well-known and has been studied in detail for arrows (Baugh, 2013; Coppe and Rots, 2017: 115; Frédéric, 1985: 68; Greenland, 2000: 10; Klopsteg, 1943: 187; Lepers, 2005: 129, 2010: 113–119; Lepers and Rots, 2020). While the projectile recovers from the initial flexion, it bends in the opposite direction but with reduced amplitude. These parasitic flexions gradually decrease until the missile straightens and flies with a direction parallel to its theoretical trajectory. In our view, the intensity of this flexion depends on the propulsion characteristics (kinetic energy transmitted to the dart and distance over which it is pushed), gestures used by the shooter and the dart's flexibility. All these parameters influence each other and constitute what we call the "spine dynamics" of the missile. In practice, this flexion absorbs part of the missile's energy, and it influences the dart's flight.

The flexibility of a dart is determined by the material, length, diameter, and shape of the shaft. A rigid dart possesses a low spine, whereas greater flexibility results in a higher spine. For a cylindrical shaft, the flexibility is assumed to be the same over the entire length, but for a tapered shaft, the thinnest part of the shaft will be the most flexible. For good ballistic qualities and equilibrium (see below), the notch of tapered darts is always placed at the thinnest end of the shaft and the spine is measured from its most flexible part. The flexibility of darts has not yet been studied as precisely as for arrows. The way to measure the spine of a dart is adapted from practices developed for arrows. The spine is measured by suspending a 2 lb (908 g) mass on a dart that is placed on two supporting devices, placed 65 inches (165.1 cm) away from each other (2.5 times the spacing used for the spine measurements of an arrow) (Lepers, 2010: 119).

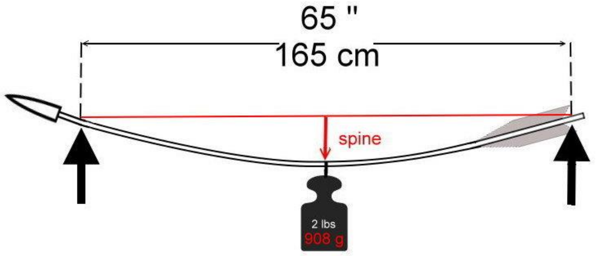

Fig. 2 Details on how to measure the spine of a dart.

3.2.1.2. FOC and balance point

To ensure a good flight, the point of equilibrium of the missile must be situated in front of its geometric centre (Frédéric, 1985: 71; Greenland, 2000: 37; Lepers, 2005: 130; 2010: 115). The precise location of the point of equilibrium can be achieved by adapting the weight of the head or by modifying the shaft. If the point of equilibrium is too far forward, it increases the inertia of the front of the missile and its flexion during flight. If the point of equilibrium is placed too far back, the projectile's flight is unstable (Cundy, 1989: 28; Hughes, 1998: 349). The ideal point of equilibrium for an arrow is situated between 35 and 40% of its length, as measured from the head of the missile. We found that these ballistic characteristics can be transposed to darts. Therefore, we use the same expressions for the balance of a dart by measuring its FOC (front of centre). The FOC is the percentage of the length of the dart (or arrow) between the balance point and the geometric centre of the dart (or arrow) (see also Lepers and Rots, 2020).

$$FOC = ((L_{proj}/2-L_{balance})\ x100/\ L_{proj})$$ (Lepers, 2010: 115).

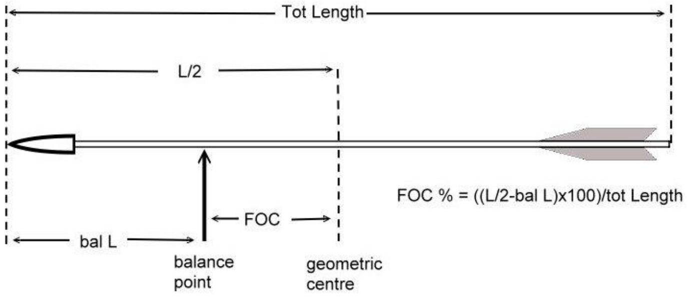

Fig. 3 Calculation of the front of centre (FOC).

As such, a point of equilibrium located at 35% and 40% of the length of a dart corresponds to a FOC of 15% and 10%, respectively. In this paper, the calculation of the FOC is made from the tip of the projectile. A different formula can be used to measure the FOC from the notch of the arrow, but the result is the same.

3.2.1.3. Fletching

Fletching is a key factor to ensure the flight quality of traditional projectiles (arrows and darts), but few studies have devoted attention to this (but see Lepers and Rots, 2020 for details on arrow fletching) even though the usefulness of fletching is commonly accepted. Fletching contributes to stabilising a projectile on its flight path by creating additional drag on the back of the projectile. The underlying physical phenomena relate to the physics of fluids. The size of the fletching area is important, but also other more subtle factors play a role (see Lepers and Rots, 2020 for a complete overview).

3.2.2. Parameters of the projectiles used in the experiments

We opted for a total of 14 darts (Table 2). Except for darts D9, D10 and D11, all darts were fletched with three half-feathers glued in the axis of the shaft and spaced at 120° (see Table 2 for details). These triangularly shaped feathers, 20 cm long and 3 cm high, offer a total fletching area of 90 cm² (and a total friction area of 180 cm²). Darts D9, D10 and D11 are those owned by the external shooters involved in experiment 4. The total fletching surfaces of the latter three darts has been estimated (values reported in Table 2). Dart D3 is a modified spear with a fletching and a notch to transform it into a dart with a very low spine (spine of 0.6 cm; see table 2).

Projectile	Material	Haft type	Total length (cm)	Weight (g)	Spine (cm)	Fletching (l, h (cm))	Total fletching area (cm²)	Balance point (from the tip) (cm)	FOC	Reference length (cm)	Experiment
S1	spruce (*Picea*)	tapered	215	660	< 0,5	unfletched	0	99	3,95	93	1
D1	hazel (*Corylus avellana*)	tapered	210	165	4,75	3 x (triangle, l 20, h 3 (30cm²))	90	89	7,62	210	ERM
D2	hazel (*Corylus avellana*)	tapered	210	170	4,4	3 x (triangle, l 20, h 3 (30cm²))	90	92,5	5,95	91	1,2
D3	spruce (*Picea*)	tapered	209	382	0,6	3 x (triangle, l 20, h 3 (30cm²))	90	92	5,98	92,5	2
D4	hazel (*Corylus avellana*)	tapered	209	157	3,7	3 x (triangle, l 20, h 3 (30cm²))	90	92,5	5,74	92	2
D5	hazel (*Corylus avellana*)	tapered	210	138	7,1	3 x (triangle, l 20, h 3 (30cm²))	90	94	5,24	94	2
D6	Pine (*Pinus)*	cylindrical	215	98,2	14,5	3 x (triangle, l 20, h 3 (30cm²))	90	102	2,56	103	2
D7	hazel (*Corylus avellana*)	tapered	216	176	4,7	3 x (triangle, l 20, h 3 (30cm²))	90	98,5	4,40	98,5	2
D8	hazel (*Corylus avellana*)	tapered	212,5	161	5,7	3 x (triangle, l 20, h 3 (30cm²))	90	89	8,12	212,5	3,4
D9	hazel (*Corylus avellana*)	tapered	212	174	5,6	3 x (triangle, l 20, h 3 (30cm²))	90	89	8,02	212	4
D10	hazel (*Corylus avellana*)	tapered	213	170	4,8	3 x (triangle, l 20, h 3 (30cm²))	90	90,2	7,65	213	4
D11	bamboo	cylindrical	202	85	12,3	3 x (triangle, l 15, h 3 (22,5 cm² estimation))	67,5	83	8,91	83	4
D12	bamboo	cylindrical	229	108	11	3 x (parallelogram, l 20, h 3 cm (22,5 cm² estimation))	180	90,5	10,48	90,5	4
D13	bamboo metake (*Pseudosassa japonica*)	cylindrical	210,5	84	no data	3 x (triangle, l 20 cm, h 3 cm (30cm² estimation)	90	93	5,82	93	4

Table 2 Characteristics of the projectiles used for the experiments.

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3.3. Hand-cast spears

Hand-cast spears are only integrated to a minimal extent as a means of comparison with the spear-thrower and dart system. General technical parameters of hand-cast spears are described by Cotterell and Kamminga (1990: 163) and recent studies have begun to document its external and terminal ballistic behaviour (Coppe et al 2019; Milks et al. 2019). Spears consist of a wooden shaft with a point at their distal end. To ensure a good flight, the point of equilibrium of the missile must be situated in front of its geometrical centre. Therefore, spears are tapered towards their distal tip. The spear used is made of spruce and tapered toward the tip. It has a wooden point and no fletching. A coloured sticker marks its point of equilibrium (see Table 2). Its spine is less than 0.5 cm, but this value is irrelevant as a spear is not propelled by its back end (like a dart), but by placing the hand near its balance point. As for the dart, the distance between the tip of the projectile and the coloured sticker is used as a reference length when analysing the videos.

3.4. Gestures used in propulsion

3.4.1. Spear-thrower and dart

One propulsion gesture is used throughout experiment 1, 2 and 3. The gesture used tends to maximise the energy transmitted to the projectile, but it is made without a run-up. The gesture requires a stable position on widely spaced legs; the whole body is put in motion and a maximum of different muscles is used. For a right-handed person, the body weight is first supported by the right leg (placed at the back) and the body is tilted backwards with the shoulders perpendicular to the target. The movement begins with the body weight shifting from the right to the left leg. At the same time, the torso tilts forward and the shoulders rotate while the arm is projected forward, pulling the hand holding the spear-thrower. The hand and spear-thrower move toward the front of the shoulder and body. During this movement, the wrist flexes and the hand (which will end lower than its initial position) begins a rotational movement that drives the spear-thrower. Through its rotation, the spear-thrower acts as a speed amplifier lever (see section A1.2.2) and thus contributes to increasing the hook’s speed. To ensure a stable flight trajectory, the acceleration generated throughout the entire movement must remain as regular as possible. Such a propulsion gesture ensures that the dart receives the maximal energy generated by the muscles, thereby maximising the distance over which the dart is propelled (see also Coppe et al., 2019: 11; Lepers, 2010: 121).

For experiment 4, a shorter propulsion movement was used in order to be able to compare the result. This shorter movement is made as follows: before propulsion, the chest is vertical, and the shoulders are parallel to the direction of the throw. The movement begins with the horizontal rotation of the chest followed by the arm being launched forward, thereby pulling the hand holding the spear-thrower. Videos of other shooters using their usual gestures and their personal equipment were also examined to verify if our method of motion analysis could be generalised.

3.4.2. Hand-cast spears

The propulsion movement is made without a run-up. The grip of the spear is located at the equilibrium point of the shaft (Coppe et al., 2019: 11). The propulsion movement requires good support on widely spaced legs and puts the whole body in motion, using a maximum of different muscles. For a right-handed person, the body weight is first supported by the right leg (placed at the back) with the body tilted backwards. The movement begins with the shift of the body weight from the right to the left leg. At the same time, the torso tilts forward and the shoulders rotate (see also Coppe et al., 2019: 11) while the arm is projected forward, thereby pulling the hand holding the spear. The hand passes in front of the shoulder and the body of the shooter.

During its movement, the wrist flexes and the hand begins a rotational movement. The spear leaves the hand at the higher point of this rotation.

3.5. Experimental protocol

The first three experiments involved two shooters of similar posture but differing levels of experience: Christian Lepers (CL) with a height of 1.82 m and 25 years of experience in using a spear-thrower, and Justin Coppe (JC) with a height of 1.84 m and 5 years of experience in throwing spears by hand and darts with a spear-thrower. The fourth experiment was performed by CL and three external experienced shooters (A, B, C) who regularly participate in the European Prehistoric Shooting Championship. In order to guarantee representative measurements, several propulsion sequences were performed for experiments 1 and 2. The spear was fired at two distances (10 m and 5 m) for JC and at 5 m for CL (experiment 1). All darts were fired at a distance of 10 m from the target. The centre of the target was placed 1.25 m from the ground to maintain the same elevation between all shots (i.e. angle between the horizontal plane and the axial direction of the projectile) (experiment 1, 2, 3 and 4). All measurements performed in the different videos are detailed in the online supplementary files.

Each dart (and spear-thrower when relevant) was marked with a coloured sticker indicating the point of equilibrium of the projectile. The distance between the tip of the projectile and this coloured sticker was used as a reference length allowing the calibration of the measurements and permitting the analysis of the footage and comparisons between the throws (for certain videos the complete length of the dart was used).

- The first experiment focused on comparing the propulsion phase between hand-cast spear S1 (21 videos) and dart D2 propelled with spear-thrower ST1 (28 videos) used by both shooters (CL and JC). Dart D2 presents similar characteristics to our usual standards, such as the dart used in the experiments performed in the ballistics lab in Brussels previously (see also Coppe et al., 2019). This first experiment served as a basis to study propulsion movements and their effects on the projectile's trajectories.
- The second experiment was focused on the influence of the dart's spine. A total of 53 videos were recorded with five darts of varying flexibility (D3, D4, D5, D6, D7). They were fired with spear-thrower ST1 used by both shooters (CL and JC). Two of the darts were more flexible than reference D2 (D6: spine 14.5 cm, D5: spine 7.1 cm) and two more rigid (D4: spine 3.7 cm, D3: spine 0.6 cm, i.e., the spear turned into a "rigid" dart). Another dart (D7: spine 4.7 cm), very close in characteristics to D2, was also tested. All results were compared with data obtained for reference dart D2 (experiment 1).
- In the third experiment, the influence of the spear-thrower length was studied. One shooter (CL) used three spear-throwers of different lengths (ST1: effective length of 51 cm, ST2: 30 cm, ST3: 75 cm) for throwing a single dart (D8) with a gesture identical to experiment 1 and 2 (three videos).
- In the fourth experiment, the influence of the length of the propulsion phase was studied and it was evaluated whether our analytical method could also be applied to other shooters, materials, and practices. First, a single spear-thrower (ST1) was used in combination with three darts (D8, D9, D10) and one shooter (CL) used both his usual long gesture and a short gesture (seven videos). Secondly, the propulsion movements of three external experienced shooters (A, B and C) were filmed (five videos). Selected shooters used their own equipment and personal technique (darts D11, D12 and D13, spear-throwers ST4, ST5 and ST6).

3.6. Video recordings and analysis

A total of 117 videos were recorded and analysed for all four experiments. The slow-motion playback of the different videos was studied and analysed with Kinovea software (0.8-15 www.kinovea.org). For each video, we traced the trajectories followed by the spear-thrower hook, and by the hand holding the spear-thrower. Distances, angles, and times were measured (see online supplementary files). In order to smooth out irregularities between different shots of the same series, comparisons between the different series of shots were made when possible using the arithmetic average of the series considered (rounded off to: 1 cm; 1°; 0.01 s) with their standard deviation in order to assess their dispersion and accuracy (or single measurements if only one video was made). To permit a correct appreciation of the times measured from the start of the propulsion motion, we conventionally fixed the initial moment (t_0) after a displacement of 5 cm of the spear-thrower hook or the hand.

With the exception of shots fired with dart D2, the speed measurements of the dart after separation from the spear-thrower were not taken into account because of possible parallax issues. Indeed, the point where the dart left the spear-thrower was at the edge of the field of the camera and parallax issues may thus have hindered the accuracy of the measurements.

4 Results

4.1. Comparison of the propulsion phase between hand-cast spears and darts (experiment 1)

The videos from experiment 1 show that the trajectories of the hand throwing the spear and of the contact point between the dart and the spear-thrower differ and that both weapon systems are thus ballistically distinct. For both propulsion modes, the movement gradually accelerates due to the cumulative effect of the investment of different body parts, while the arm and wrist only start to intervene during the final propulsion phase. For the hand-cast spear, the propulsion also proves to follow an ascending trajectory. Whatever the shooting distance, the spear starts at a greater angle than the dart; its larger mass (540 g) largely explains this increase.

4.1.1. Differences

A hand-cast spear is projected along a trajectory that is generally rectilinear and ascending (Fig. 4), whereby the hand travels parallel to the projectile throughout the propulsion motion. The application of force is located where the hand holds the spear (close to its point of equilibrium). For a spear-thrower, the force is exerted further back on the notch of the dart. The hand begins the movement with a trajectory parallel to the dart, but both paths separate once the spear-thrower rotates (Fig. 5). The spear-thrower propulsion movement can be divided into two main phases: a linear phase followed by an elliptical phase. the push starts further back, and the elliptical phase (thanks to the spear-thrower) ends further forward than for the manual propulsion.

When both systems are compared, it is clear that the altitude at which the projectile becomes autonomous (for both weapons fired at 10 m) is the same, but that the dart's propulsion distance is more important than the one of the spear (see Table 3).

The videos show that the overall trajectory of the spear-thrower hook is not linear, contrary to what some authors have argued (i.e., Denny, 2019: 69; Howard, 1974: 102; Lepers, 2010: 124; Palter, 1971: 164; Raymond, 1986: 158; Stodiek, 1988: 317), However, it is also not comparable to the circular trajectory followed by the tip of a lever, where both ends move along a circular path.

Propulsion distances were calculated for both hand-cast spears and darts for each shooter (Table 3). For both shooters, the use of the spear-thrower allowed an increase of 30 to 40% of throwing distance compared to a hand-cast spear but note that this distance is partly conditioned by the length of the spear-thrower (see below), though the increase is greater than the effective length of the spear-thrower and thus also relates to its movement (for more detail see supplementary online file 1). The measured data cannot be generalised, as they are influenced by numerous factors related to the shooter and the equipment used. However, the significant increase in propulsion distance achieved with the spear-thrower clearly demonstrates the difference between the two weapon systems. A more precise comparison between both remains challenging at this stage, as the ballistic exploration of hand throwing is only in its early stages (see Milks et al., 2019).

Hand-cast spear		Spear-thrower ST1				
Shooter	Average propulsion distance spear (cm)		Average propulsion distance spear-thrower hook (cm)	Average total rectilinear spear-thrower hook displacement (cm)	Difference (cm)	Difference (%)
JC 10m	167 +/11	JC 10m	238 +/-18	235 +/-20	71	29.80
JC 5m	146 +/-7				92	38.70
CL 5m	151 +/-10	CL 10m	232 +/-11	224 +/-13	81	34.90

Table 3 Comparative analysis of the propulsion of the hand-cast spears and the spear-throwers and darts.

4.1.2. Specificity of the propulsion of spear-throwers and darts

While the rotational movement of a spear-thrower centred on a user’s hand is comparable to a lever movement, the videos show that the overall movement of the hook follows an elliptical path, because the hand continues its own movement at the same time. The propulsion movement cannot be considered as a simple lever because this would ignore the movement made by the hand before and during the rotation of the spear-thrower. The spear-thrower is also not a simple extension of the arm because even though it increases the distance of propulsion, this is due to the rotation of the spear-thrower as it modifies the initial linear trajectory of the hook.

A correct analysis of the propulsion phase must focus on the overall hook displacement. The linear phase initiates the shift of the hook, while the elliptical phase allows a significant increase in speed along a different orientation compared to the initial trajectory. This is caused by a longer hook displacement during the elliptical phase. However, the dart does not fully benefit from the speed and energy developed by the hook, due to which it bends.

None of the existing hypotheses regarding spear-throwers, be it that it functions as a lever (Cattelain, 1994: 6; Cotterell and Kamminga, 1990: 166; Cundy, 1989: 45; Lansac, 2004: 30; Whittaker, 2016a: 65; Whittaker et al., 2014; Whittaker and Maginniss, 2006) or an arm-extender (Howard, 1974: 102; Palter, 1977: 164; Raymond, 1986: 158; Stodiek, 1988: 317) fully explain the movements of the hand and the hook or the composition of the different forces that work on the dart. The overall motion must therefore be considered as a mix of both hypotheses: the spear-thrower increases the length of the projectile’s propulsion phase and the speed by its rotation at the end of the movement. The assumption that energy would accumulate in the dart through bending (Baugh, 1998: 38, 40; 2003: 349; Cundy, 1989; Perkins, 1993) is incorrect and was invalidated previously (Whittaker and Maginniss, 2006; Denny, 2019). The detailed analysis of the elliptical propulsion phase (supplementary online file 1) shows that the flexions of the dart are easily explained when the movements of the hook are deconstructed.

Fig. 4 Throwing motion of a spear and trajectory of the hand. The trajectories of the hand (in yellow) and of the point where the spear is held (in red), from the initiation of the movement to the moment when the hand releases the projectile (shooter JC).

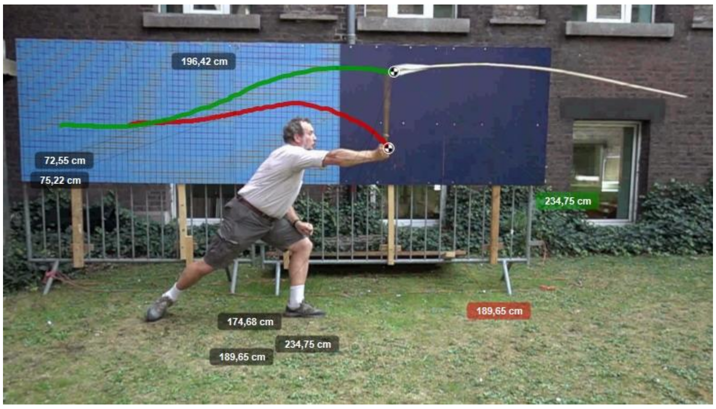

Fig. 5 Trajectory of the hand (in red) and the spear-thrower hook (in green) during the dart's propulsion phase from the initiation of the movement up to the release of the dart (shooter CL). Also note the third flexion (n-shaped) (see below).

4.1.3. Dart flexion during the propulsion phase

At the end of the linear propulsion phase, the dart begins to bend. This flexion occurs when the torso bends forward, the shoulders are rotated and the hand begins its forward upward movement, but before the spear-thrower starts to rotate. This convex flexion[1] is visible on the central part of the dart and results from the upward component of the hand movement while the dart is held by the hook and the fingers (Fig. 6).

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[1] Concave or u-shaped flexion: flexion in which the centre of the dart is lower than its extremities. Convex or n-shaped flexion: flexion during which the centre of the dart is higher than its extremities.

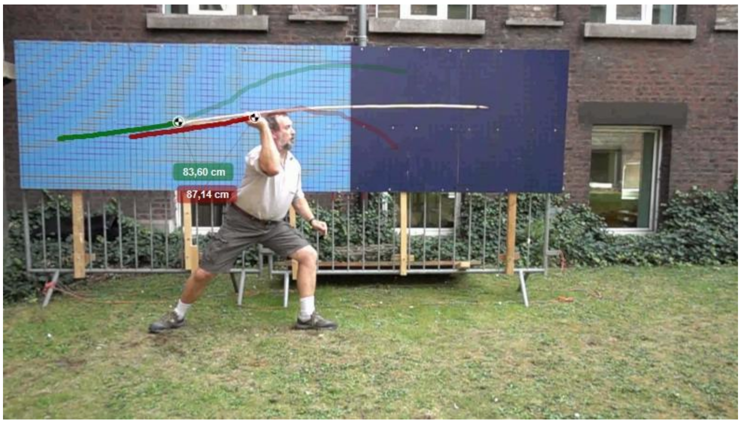


Fig. 6 End of the linear phase and first convex bending of the dart.

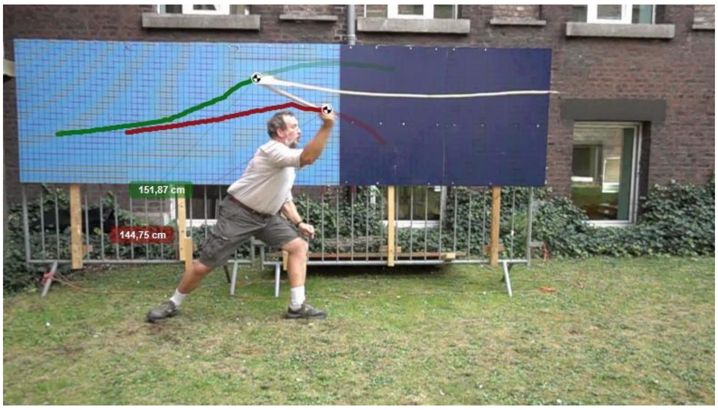


Fig. 7 Photo and plot of hook and hand trajectories from the beginning of the elliptical phase to the end. The concave flexion of the dart can be seen when the spear-thrower is in its ascending phase.

During the first part of the spear-thrower rotation, the dart undergoes a concave (u-shaped) flexion (second flexion) which originates near the butt (Fig. 7) and thus differs from the previous one. Shortly before the hook of the spear-thrower reaches a vertical position, the flexion disappears and is followed by a convex (n-shaped) flexion (third flexion), again initiated at the butt (Fig. 5). Subsequently, the dart becomes autonomous and moves towards the target. These deflections of the dart during the rotation of the spear-thrower are not unique to our equipment or projection technique and have been observed by others as well (e.g., Baugh, 1998: 40; Cattelain, 1994: 6; Cotterel and Kamminga, 1990: 169; Denny, 2019: 71; Perkins, 1993; Pettigrew, 2013, 2014: 10, 2015a: 10; Whittaker, 2014: 1, 2016a: 67; Whittaker et al. 2017: 163; Whittaker and Maginniss, 2006: 1).

Analysis of the videos shows that these bends are concave (in a u-shape) when the spear-thrower hook is up, and convex (in an n-shape) when the hook is down. These dart flexions (made possible by the shaft's flexibility) are created by the vertical movement of the hook. This vertical hook movement is inherent to the elliptical phase and essential to its normal unfolding.

Contrary to many authors (Baugh, 2003; Cundy, 1989; Lyons, 2011; Perkins, 1993, 2000; Perkins and Leininger, 1989a, b, 1990), we believe that these flexions do not constitute a storage but a loss of energy for the projectile because the vertical movements of the hook and dart butt are not made in the direction of the target. The mathematical simulations made by Denny (2019: 71) show that these vibrations of the dart reduce its speed and range.

4.1.4. Projection angle of the dart

The dart and hand move in different directions. A straight line can be drawn from the initial point of the hook to its position when the dart leaves the spear-thrower. If we draw a second line from this same initial point to the position occupied by the hand when the dart becomes autonomous, we can measure this difference in trajectory by an angle (α) that we call the projection angle (Fig. 8) (projection angle of CL: 12 +/-1°, of JC: 10 +/-1°). This angle appears to be specific to the propulsion movement and differs from the angle of elevation that the shooter will communicate to the projectile in order to hit a more or less distant target.

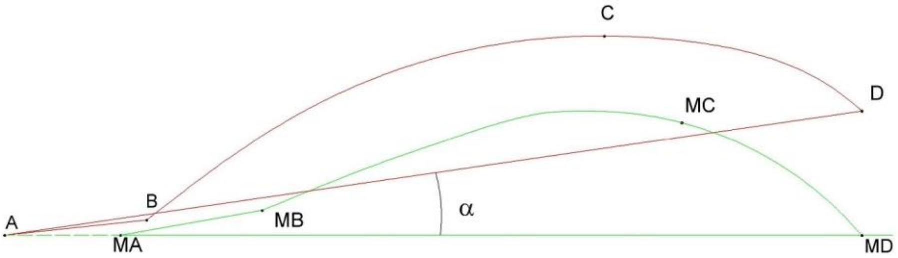


Fig. 8 Existing projection angle (α) between the trajectory of the hand and that of the spear-thrower hook when two rectilinear segments are traced between the point of origin of the movement of the spear-thrower hook and their respective positions when the dart becomes autonomous. A: Initial point of the hook; B: start of the elliptical phase of the hook; C: maximum elevation reached by the hook and the dart's butt; D: release of the dart. MA, MB, MC and MD, position of the hand at these different propulsion moments.

The projection angle varies according to the individual technique and the length of the spear-thrower. For an experienced shooter, this angle remains constant, as it is a fundamental condition for the repeatability between throws and, consequently, for accuracy. This measurement is therefore a valuable tool for evaluating technical variations between shooters and assessing the consistency of their movements.

4.1.5. Conclusive observations for experiment 1

Four distinctive features could be identified that are essential to understand how a spear-thrower operates:

- a longer displacement of the spear-thrower hook in comparison to the hand;
- the movement of the hook begins with a linear phase and continues with an elliptical displacement;
- the dart undergoes several successive flexions;
- the overall trajectories of the hand and the hook of the spear-thrower create a specific projection angle.

4.2. Evaluating the impact of different variables on dart propulsion

A set of experiments was conducted to evaluate the impact of the flexibility of the dart (spine), the length of the spear-thrower and the length of the propulsion phase.

4.2.1. Impact of the dart's spine (experiment 2)

In addition to the reference dart (D2) used in the first experiment, we tested five more darts (D3–D7). Independent of the rigidity of the dart, all confirm the same four characteristics of the propulsion phase identified earlier: the hook moves more than the hand, the propulsion shows two linear and elliptical phases, the dart flexes, an angle of propulsion results from the differing trajectory of the hand and the hook. No significant differences can be noted for the altitude reached by the hook and the hand (supplementary online file 2, Table 1) or for the propulsion times. Nevertheless, the most flexible darts (D5 and D6) have a greater propulsion distance than the other darts (supplementary online file 2, Table 2). The increased flexion of the dart and perhaps also the slightly later separation may explain this. The increased flexibility does not, however, seem to offer any gain in terms of the energy transferred to the dart, judged by their more limited penetration into the target (impact energy was not measured in this experiment). We found that D6, because of its important flexibility, shows a delay in its flexion when it separates (see Fig. 9). The comparison of Fig. 5 and 9 clearly shows the influence of the spine on the behaviour of the dart. The second flexion of the dart (concave, u flexion) is so intense that the descending movement of the hand and the spear-thrower attenuate it, but this is not sufficient to fully straighten the dart or to create the third convex flexion (n flexion), as observed for more rigid projectiles. The third flexion appears once the dart has become autonomous, probably caused by the downward movement of the hook and the inherent elasticity of the projectile. The more rigid darts (D3 and D4) also show these successions of flexions, but to a lesser extent, and a certain tendency for the projectile's butt to tilt during separation. This experiment shows that the dart's spine significantly influences the flight of the projectile and the angle of incidence, i.e., the angle between the ballistic trajectory and the actual trajectory of the projectile's tip at impact (see Coppe et al., 2022). For more details, see supplementary online file 2.

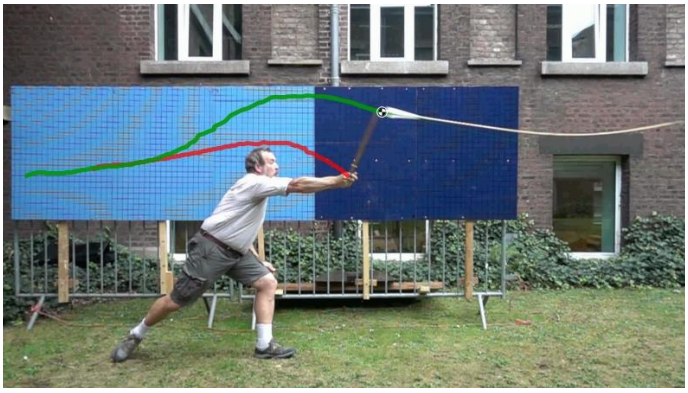


Fig. 9 Dart D6: because of its great flexibility, it shows a bending "delay" at the moment of its separation.

4.2.2. Impact of spear-thrower length (experiment 3)

Three spear-throwers with different lengths were used to shoot a single dart by one shooter to evaluate the impact of spear-thrower length. For the three spear-throwers, the same four characteristics of the propulsion phase mentioned earlier could again be observed. We observe that the length of the spear-thrower influences the linear and the elliptical sub-phase of the hook as well as the total propulsion distance (supplementary online file 3, Table 3). While the displacement and altitudes reached by the propelling hand remain the same regardless of the spear-thrower used, those reached by the hooks vary according to their length during the elliptical phase (supplementary online file 3, Table A.3.2 and A.3.3). This gives the dart launched by the 75 cm spear-thrower a greater angle of projection (16°) than the other two spear-throwers (angle of projection of 8° with the 30 cm spear-thrower, 12 +/-2° with the 51 cm spear-thrower) (supplementary online file 3, Table A.3.4). The three curves for the hook show that the starting altitude of the movement is identical. Evidently, when the length of the spear-thrower increases, the starting point moves backward and the release moves further forward and upward. Whatever spear-thrower is used, the sequence of dart flexions detailed above remains the same. The total duration of the propulsion phase varies little amongst the three spear-throwers (max 0.04 s) (supplementary online file 3, Table A.3.4). A longer spear-thrower increases the distance covered in nearly the same time, thereby granting the hook and dart a higher release velocity, though this demands additional effort from the shooter. This increase in speed stems from the greater total distance travelled by the hook, both during the linear phase and, more notably, during the elliptical phase. Indeed, the longer the spear-thrower, the greater the circular velocity of the hook during the wrist's rotation but a longer spear-thrower requires more effort from the shooter's wrist (see section A 1.2.2). If the spear-thrower is too long (compared to the dart’s weight) and the wrist lacks sufficient strength, the spear-thrower's rotation will be slower, thus prolonging the duration of the elliptical phase. The optimal length of a spear-thrower is likely to be found in balancing the increase in distance covered by the hook and the shooter’s ability to ensure its rotation as swiftly as possible. Additional experiments will help to clarify the extent of the phenomenon and its limitations. For more details, see the supplementary files.

Fig 10. Curves of hook and hand displacement for different spear-thrower lengths (experiment 3). To improve readability, travel curves of the hook have been artificially separated from those of the hand. The trajectories of the hand are highly similar regardless the spear-thrower, but the trajectory of the hook proves to be strongly influenced by spear-thrower length.

4.2.3. Influence of the length of the propulsion phase and the shooter (experiment 4)

This experiment has two components: first, the influence of the length of the propulsion phase is evaluated and subsequently the influence of the shooter. Again, the same four characteristics were observed and details can be found in supplementary file 4.

4.2.3.1. Shorter propulsion phase

In the case of a shorter propulsion phase, the movement is essentially centred on the arm and shoulders, the body is in a more vertical position and the starting point moves upward. This gain in altitude is maintained throughout the two phases of propulsion. The curves made by hand and hook have the same general shapes but with a variation in altitude due to the shooter's body position. We see that the total propulsion distance is shorter than for the reference series: the linear displacement phase is about 30 cm shorter, while the elliptical phase remains largely the same. The linear displacement now represents only 25% of the motion whereas it was 34% of the total propulsion previously (Fig. 11). By contrast, the propulsion time is longer for the short movement. Several hypotheses can explain this: a lack of experience on our part with the difficulty of setting the projectile in motion over a short distance, or the difficulty to rotate the spear-thrower during the elliptical phase when the mass of the projectile is high (the dart used weighs 161 g). The angle between the hand and hook trajectory increases by 3 to 4° in comparison with a long movement. As a result, the dart flies along an accentuated parabola (cf. Fig. 11).

Fig. 11 Curves of the hook and hand displacement for the spear-thrower (ST1) used with different propulsion gestures (experiment 4). For clarity, the curves over which the hook travels have been separated from those of the hand. In reality, different body positions and gestures can cause variations in initial hand and hook altitude.

4.2.3.2. Influence of the shooter

Exploratory videos were made with three external shooters who regularly participate in the European Prehistoric Weapons Championship. The general propulsion trajectories prove to correspond to our model with some variation due to the individual gestures (Fig. 12). Shooter A uses a very short propulsion movement centred on the arm and forearm, with very little rotation of the chest. His propulsion movement takes place in a vertical plane. Shooter B uses a propulsion movement similar to ours with a displacement of the body weight from one leg to the other and a rotation of the chest. The propulsion movement also takes place in a vertical plane. Shooter C uses an intermediate propulsion movement centred on the arm and forearm, with a rotation of the chest, but with a movement in an oblique plane. Ideally, the latter gestures require another observation angle to be able to adequately take into account the displacement in three dimensions. The very short linear phase of shooter A (29 cm!) is particularly noteworthy with the elliptical phase representing the main part of the propulsion movement. The lateral movement of shooter C is difficult to analyse but his linear phase appears to be intermediate between shooter A and B.

With the starting altitude as reference, the dart launched by shooter B has a “flat” trajectory (angle of 11° +/-2°) that is quite similar to the ones of JC, CL and shooter C. Shooter A reaches very high altitudes during projection because of his size, position and short movement (the hook is 206 cm from the ground during dart separation, in comparison to between 125 and 170 cm for other users. Given his particular gesture, shooter A also has the highest projection angle (22°). Shooter C keeps a rather constant altitude, but his elliptical propulsion phase ends higher, probably to provide his projectile with sufficient elevation to fly to the target. The angle between the trajectory of the hook and the hand is difficult to specify for Shooter C.
Shooter A shoots with the shortest propulsion phase (0.112 s) (but not necessarily the fastest given the short distance travelled by the spear-thrower); shooter B shows propulsion times similar to JC and CL, while shooter C is again difficult to classify given the difficulty of analysing his propulsion sequence (see Fig. 12).

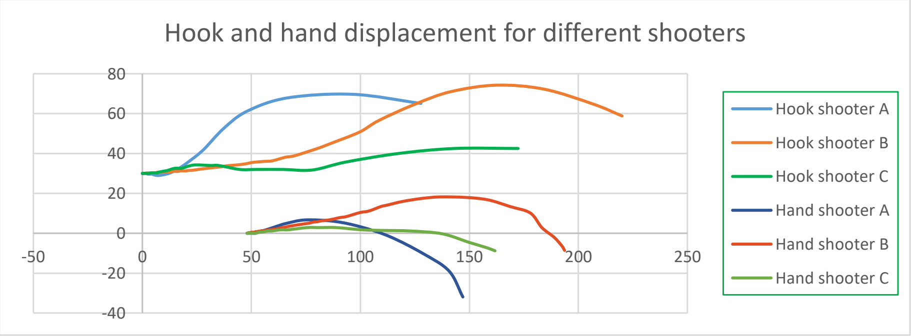


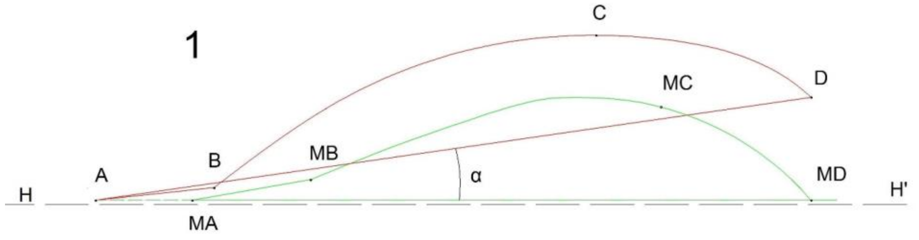
Fig. 12 Hook and hand curves obtained from external users (experiment 4). Each shooter’s hand movement curves were drawn from a single initial point. In reality, body positions and gestures can cause variations in initial hand and hook altitude. For clarity, curves travelled by the hook have been separated from those of the hand.

4.3. Theoretical model for dart propulsion

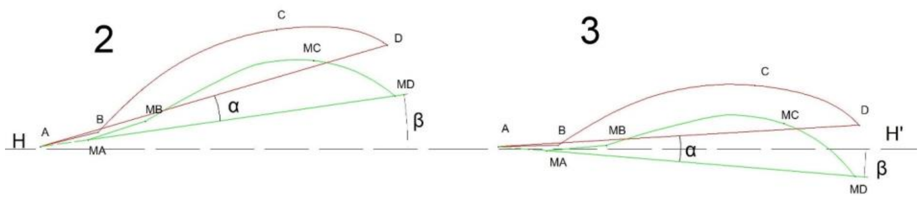
The experiments and analyses of propulsion sequences (also see supplementary online file 1) show that the four characteristics of the propulsion phase observed during the first experiment occur whatever the material (dart and spear-thrower) and gesture used. They can thus help to explain how a spear-thrower operates. A theoretical model can thus be proposed that reflects the greater displacement of the spear-thrower hook than the hand, two successive phases (linear and elliptical) for the hand and hook movement, a specific propulsion angle due to how the hook and hand move and the flexions of the dart created by the elliptical movement of the hook (see Fig. 13). During the linear phase (between points A and B), hook and dart trajectories are parallel and almost straight. The angle between the trajectory and the horizontal reference varies depending on the elevation provided by the shooter and his gesture. During this phase, a first convex flexion of the dart may appear due to the lifting of the propelling hand. Between point B and D, the hook follows a more or less accentuated elliptical trajectory. The path of the hook results from the movement of the wrist combined with the rotation of the spear-thrower. Between B and C, the hook goes up and pushes the dart's butt upwards (which causes the concave (u-shaped) dart flexion). Between C and D, the hook goes downwards together with the dart's butt (which causes the convex (n-shaped) dart flexion). Between MA and MB, the movement of the hand is linear. Between MB and MD, the hand follows an elliptical trajectory where MC corresponds to the position of the hand when the hook is higher. MD is the point reached by the hand when the projectile takes off.

The particular characteristics of the trajectories and their different segments are influenced by the shooter, his gestures and the effective length of the spear-thrower. The degree to which the dart flexes depends on its spine and the energy transferred by the spear-thrower hook. This theoretical model can be used as a reference to study the positions and gestures of other shooters, but also to simulate propulsion curves for when a shooter changes his movement or his spear-thrower.

While the theoretical model is based on an ideal shooting distance, two variations are also presented (Fig. 13). When propulsion conditions remain the same, a heavier dart or a differing launching distance will necessitate another angle under which the dart will be launched. The movement of the hand will remain the same, but the angle of elevation will have to be modified. This practice (common to all types of projectiles, balls, bows and firearms) will be marked by the appearance of a more or less important angle (β) between the MA–MD line (movement of the hand) and a horizontal reference line (the maximum range is reached at an angle close to 45°, Courtly and Kierlik, 2012).



Hand and hook trajectories without elevation



Hand and hook trajectories with positive elevation

Hand and hook trajectories with negative elevation

Fig. 13 Theoretical model of propulsion. (1) Propulsion trajectory of the dart's butt and the spear-thrower hook without initial elevation (10 m shots). (2) Modelled trajectory for when the shooter wants to reach a greater distance (positive elevation angle β). (3) Modelled trajectory for when the target is nearby (negative elevation angle β). A: Initial point of the hook; B: start of the elliptical phase of the hook; C: maximum elevation reached by the hook and the dart's butt; D: release of the dart. MA, MB, MC and MD, position of the hand at different propulsion moments.

4.4. The flight of the dart

In theory, and without considering the elevation angle at which it was propelled, a dart flies along a more or less accentuated parabolic trajectory (Benson, 2004: 95; Cotterell and Kamminga, 1990: 160; Lepers, 2010: 111) determined by its own characteristics (mass, spine, fletching area, etc.) and the energy received during the propulsion phase. In reality, the displacement of the dart is not parallel to the theoretical trajectory but shows an undulating movement in a conical volume of which the characteristics have been mentioned earlier (see Coppe and Rots, 2017: 114; Coppe et al., 2022; Lepers, 2010: 114). Many authors mention these oscillations without considering their orientation (Baugh, 1998: 40, 2003: 349; Cotterel and Kamminga, 1990: 169; Denny, 2019: 71; Pettigrew, 2014: 10, 2015: 7; Whittaker, 2014: 1, 2016a: 67, 2017: 163; Whittaker and Maginnis, 2006: 1), though Pettigrew (2015: 9) specifies that "spinning is not correlated with the plane of oscillation". The oscillating movement results from the combination of several factors (Coppe and Rots, 2017: 114; Lepers, 2010: 111, 114): the amount of energy transferred to the dart's butt by the spear-thrower, the flexion resulting from the various vertical impulses received during propulsion, and the dart's characteristics (spine, tip mass, fletching surface). These oscillations can have a significant effect on the accuracy and angle of incidence of the projectile (Coppe et al. 2022). If the flight distance before impact is sufficiently long, these flexions disappear and the dart adopts a flight parallel to its theoretical ballistic trajectory (Lepers, 2010: 114, Coppe and Rots, 2017: 114). In the case of our experiments with firing distances of 10 m and a dart with a spine of less than 5 cm, the dart's shaft is not yet completely "straightened" at the time of impact and its actual trajectory does not (yet) correspond to the theoretical ballistic trajectory (Coppe et al., 2022).

5. Discussion

The experiments presented here document the interactions between the shooter and the spear-thrower. This allows for a more detailed explanation of the complex phenomenon in which energy is transferred from the shooter to the dart. Compared to a manual launch, the spear-thrower offers several advantages: it extends the projectile's propulsion distance without significantly increasing the duration of the initial movement (first acceleration) and it enhances the projectile's velocity by considerably increasing the speed of the spear-thrower's hook during the elliptical phase (second phase of acceleration). The spear-thrower also facilitates a more efficient transfer of muscular effort from the shooter to the projectile. Up to now, three hypotheses had prevailed in the literature to explain the functioning of the spear-thrower. Most authors consider that the spear-thrower is a lever (Cattelain, 1994, 1997; Cotterell and Kamminga, 1990; Cundy, 1989; Lansac, 2004; Whittaker, 2016a; Whittaker et al., 2014; Whittaker and Maginnis, 2006) that operates like a speed amplifier (Cundy, 1989; Cotterell and Kamminga, 1990; Whittaker, 2016a: 66), though Cundy admits that this does not represent the complete picture (1989: 53). Other authors argue that the spear-thrower provides a thrust extender (Howard, 1974; Palter, 1977; Raymond, 1998). Stodiek (1988) considers the spear-thrower as an arm extender, but he relies on Cundy's technical explanations (Stodiek 1993). A third group of authors considers that the spear-thrower and dart function as a spring (Perkins and Leininger, 1989a, b, 1990; Perkins, 1993, 2000a). By contrast, we have shown that two phenomena interact, the lever and the arm extender and that an important part of the flexions of the dart is created by the vertical movement of the spear-thrower.

Even though many authors consider that spear-throwers operate through a “complex lever system” or a multiple lever system (Cattelain, 1994: 6; Cundy, 1989; Cotterel and Kamminga, 1990: 166; Lansac, 2004: 30; Whittaker, 2016a; Whittaker et al., 2014; Whittaker and Maginniss, 2006), consisting of a series of successive body levers, we are not aware of a detailed study that would support this hypothesis. Some authors offer partial explanations of how the wrist and forearm operate (Cundy, 1989; Cotterel and Kamminga, 1990) but they do not extend their study to the other joints of the body, aside from mentioning that the spear-thrower’s energy can be increased by mobilising the entire body (Cotterel and Kamminga, 1990: 164). As an example, our films showed very clearly that the spear-thrower provide a greater extension of the forearm at the end of the propulsion movement compared to a hand-cast spear (Fig. 4 and 5). This extension allows for an increase in the horizontal movement of the spear-thrower and increases the energy transmitted to the projectile by the work of the forearm. It seems that since the rediscovery of the spear-thrower and its practice, the attention has mainly been focused on the rotational movement of the spear-thrower, wrist and forearm to the detriment of the entire propulsion phase. By contrast, the displacement of the spear-thrower through the movement of the hand before and during rotation is not taken into account. In fact, we have observed that the key point of the propulsion phase is not the rotation of the spear-thrower, but the displacement of the spear-thrower hook during the entire propulsion phase. The hook transmits the energy of the shooter and the spear-thrower to the dart. A spear-thrower cannot be reduced to a lever or an arm extender, but its operation combines both. The spear-thrower increases the propulsion distance, the acceleration given to the projectile, and it changes the propulsion angle (the difference between the movement of the hook and the hand).

The essential point to understand the total movement of the spear-thrower hook requires a fixed reference point, outside the movement. Indeed, the propulsive hand or the spear-thrower fulcrum are not acceptable reference points because they move and participate in the propulsion movement.

Whittaker has argued that the spear-thrower functions as a lever based on a comparative experiment using two atlatls of different length in which he consistently achieved a greater distance with a longer atlatl (Whittaker and Kamp, 2011: 21, Whittaker, 2016a: 66). The extended lever of a longer spear-thrower indeed ensures that the hook achieves a greater velocity at the end of its rotation. However, our theoretical model introduces two additional factors that contribute to the increased range of the dart when a longer spear-thrower is used: the hook's starting position lies further back and the angle of projection of the overall propulsion motion is higher. These three factors (extended thrust distance, higher hook speed, greater angle of projection) collectively explain the superior range achieved with the longer spear-thrower. This explanation is consistent with the principles of ballistics: it is possible to increase the range of the projectile by increasing the energy of the projectile (in our case a longer and faster movement) and/or by throwing the projectile with a higher elevation angle (Courty and Kierlick, 2012: 96; Pirlot, 2014: 81).

As documented, the trajectory of the hook differs with the direction of movement of the dart during the elliptical phase. It is thus the vertical component of the spear-thrower hook displacement that causes the flexion of the projectile’s butt during the elliptic propulsion phase. This also explains the origin of the rear flexions of the dart (which continue after the projectile separates from the spear-thrower). Cundy (1989: 66) observes the same, but considers that the deflections of the projectile store energy. The recognition of these flexions initiated the theory that a spear-thrower functioned as a spring, which was popular for several years (Baugh, 2003; Lyons, 2011; Perkins, 1993; 2000; Perkins and Leininger, 1989a, b; 1990), but was convincingly refuted by the experiments of Whittaker and Maginniss (2006). Also, mathematical simulations have shown that the dart’s vibrations reduce speed and range instead of amplifying it (Denny, 2019: 71). We have shown that the dart undergoes varying forces in different directions during the elliptical phase. The deflections of the dart result from the vertical movements of the hook during the elliptical phase and constitute a loss of energy for the projectile. This loss is unavoidable, but it is less important than the energy input provided by the elliptical movement of the spear-thrower, which increases the thrust distance and the acceleration of the dart. The amount of energy that is lost depends on how much the dart flexes.

Cundy (1989: 69) and Cotterel and Kamminga (1990: 170) insist on the necessary adjustment between the spear-thrower and the dart’s spine. We think that this statement can gain in precision. We consider that to improve the shooting of a dart, its spine must be adapted to the amount of energy received during the entire phase of propulsion. The energy accumulation depends not only on the spear-thrower but also on the power and the propelling gesture of the shooter (the influence of which was already acknowledged by Cotterel and Kamminga, 1990: 164). We can compare this with archery where practitioners know that the arrow’s spine must be adapted to the force and draw length of the bow to limit the arrow’s flexion in flight (called the archer's paradox, Klopsteg, 1943: 186; Lepers, 2010: 112; Lepers and Rots, 2020). We think that the dart’s flexion is comparable to that of an arrow and cannot be completely eliminated. The best way to limit the dart's flexions in flight is probably the use of a dart with a spine adapted to the amount of energy developed by a given shooter during the propulsion phase (the dart's paradox). The measurement system for the spine that we have proposed above allows researchers and users to obtain more precise and reproducible data in comparison to the visual observation proposed by Baugh (2013).

Our theoretical model integrates the entire propulsion movement performed by the shooter and is consistent with physical laws (i.e., $W = F.s$ or the work equals the product of the force strength and the distance traveled; expressed in joules, as for energy) (Benson, 2004: 188). In our case, the energy that is applied to the butt of the dart is equal to the force transmitted by the hook multiplied by the distance travelled by it. This formula shows that force and displacement are interactive variables and that a shooter with a spear-thrower of a given length can increase the energy transmitted to the dart by increasing the force applied to the hook, the pushing distance or both at the same time.

We have shown that the spear-thrower significantly increases the pushing distance compared to a manual launch. The spear-thrower does not multiply energy or force (no mechanical device provides more energy than it receives), but if adequately used, it allows a better exploitation of the muscular potential of the wrist, forearm, arm and also other muscles mobilised to increase the amount of energy transmitted to the dart (Cotterel and Kamminga, 1990: 164). Using a spear-thrower with a motion that would stop before the rotation phase or during rotation as proposed by Steckel is not realistic (Steckel and Vincent, 2006) because it would not lengthen the propulsion phase and even requires an interruption of the movement when it becomes most efficient. This sudden interruption (probably during the concave bending phase (u-shape)), together with the orientation of the dart at that moment, would propel the dart at a larger projection angle, which could in itself explain the increase in range that some authors observed from which they deduced a possible spring effect. Caution is also warranted for Baugh’s interpretations that only consider the horizontal displacement and the torque of the wrist (Baugh, 2003: 345). This simplification leads to erroneous mathematical simulations (see also Denny, 2019: 70). By comparison, Howard's (1974: 102) and Raymond's (1986) models, which match with Stodiek's (1988: 317) explanation, simplify the second part of the propulsion phase and do not consider the complexity of the propulsion trajectories highlighted in our experiments.

In spite of the great variability that may exist in how to launch a dart with a spear-thrower, due to spear-throwers of differing length or varying propulsion gestures, a close examination of descriptions (e.g., Baugh, 2003; Cundy, 1989; Whittaker, 2016a) and video footage permits us to confirm that all share common points that are in agreement with our theoretical model. The main differences concern a varying initial altitude of the dart when the propulsion movement starts, the length of each propulsion phase, the ratio between the amplitudes of the linear and elliptical phases and the resulting propulsion angle. The use of our theoretical model in combination with detailed motion analysis (e.g., by using appropriate software, for instance, Kinovea) would significantly improve our understanding of how the spear-thrower and dart interact. It would allow us to identify the ideal spine of a dart in correspondence with the quantity of energy that needs to be transmitted, as has been done for bows and arrows (Lepers, 2010: 109). It would also allow a better comprehension of a dart's flight. These issues are also crucial when one aims to understand fracture patterns on projectile points.

Conclusion

Several ballistic experiments published over the last decades have provided answers to fundamental questions and have improved our understanding of the hunting techniques used by past societies, but even though spear-throwers have been used and studied for a generation, they remain poorly understood. On the basis of an experimental program combined with high-speed camera recordings and detailed motion analysis, we have demonstrated that a lever effect or a prolongation of the arm do not fully explain the operation of spear-throwers. We have shown that the essential element to consider is the displacement of the spear-thrower hook during the entire propulsion movement. The flexion of the dart does not store energy but is the result of the hook being displaced perpendicularly to the shooting direction of the dart. We have proposed a theoretical model on the basis of ballistics that should be widely applicable in future examinations of spear-thrower use, for instance for spear-throwers and darts of ethnographic collections and for the few prehistoric darts found recently (Groshmeyer, 2017a, b; Hare et al., 2004, 2012; Pettigrew, 2015a). We think that a ballistic approach is an essential complement to archaeological and ethnographic studies. Some recent examples have shown that experimental and fundamental studies permit precise knowledge about how ancient weapons were used (Coppe et al., 2019, 2022; Lepers and Rots, 2020, Coppe et al. 2023). In comparison, a similar approach was successfully carried out for the study of medieval bows and arrows found on the Mary Rose (Strickland, 2005).

Many questions still remain unanswered with regard to the use of spear-throwers and additional precise and controlled experiments will be required to answer them in the future. Future progress in our knowledge of prehistoric weapons requires the acquisition of accurate physical and ballistic models. Such studies are fundamental and while they may at first seem to distract from the archaeological reality, they are a precondition for improving our understanding of the evolution of prehistoric weaponry.

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Declaration of interests

The authors declare no competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary File

Supplementary File

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