# Human performance in two-handed spear thrusting

Annemieke Milks[a,*], Stephen Champion[b], Elizabeth Cowper[bc], Matt Pope[a], Debra Carr[b]

[a]Institute of Archaeology, University College London, 31-34 Gordon Square, London WC1H OPY, UK. Email: Annemieke Milks: a.milks@ucl.ac.uk Matt Pope: m.pope@ucl.ac.uk
[b]Impact and Armour Group, Centre for Defence Engineering, Cranfield Defence and Security, Cranfield University, Defence Academy of the United Kingdom, Shrivenham, Oxon SN6 8LA, UK. Email: Stephen Champion: s.m.champion@cranfield.ac.uk Debra Carr: d.j.carr@cranfield.ac.uk
[c]Centre for Advanced Materials and Performance Textiles, RMIT University, 25 Dawson Street, Brunswick, VIC 3056, Australia. Email: Libby Cowper : libby.cowper@rmit.edu.au

## Abstract

Human hunting has been a cornerstone of research in human evolutionary studies, and decades of research into early weapon systems have improved our understanding of the subsistence behaviours of our genus. Thrusting spears are potentially one of the earliest hunting weapons to be manufactured and used by humans. However, a dearth of data on the mechanics of thrusting spear use has hampered experimental research. This paper presents a human performance trial using military personnel trained in bayonet use. Participants thrusted replicas of Middle Pleistocene wooden spears into PermaGel™. For each spear thrust, impact velocity was recorded with high-speed video equipment, and force profiles were recorded using a force transducer. The results demonstrate that training improves performance when compared with previous experimental results using untrained participants, and that the mechanics and biomechanics of spear thrusting are complex. The trial confirms that previous spear thrusting experiments firing spears as projectiles are failing to replicate the entire spear thrusting event, and that crossbows are too powerful to replicate the low velocities involved in spear thrusting. In order to better understand evidence of spear thrusting in the archaeological record, experimental protocols accurately replicating and recording the mechanics of spear thrusting in the past are proposed.

Keywords: weapon delivery systems, Middle Pleistocene, projectiles, experiment, untipped wooden spears

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[*] Corresponding Author. Tel: +44 (0) 20 7679 7495 Email: a.milks@ucl.ac.uk

## 1. Introduction: replicating and recognising thrusting spears in prehistory

The use of weaponry throughout human evolution has far-reaching implications for understanding human subsistence behaviours, interpersonal violence and self-defence against both animals and other humans (Shea 2006; Churchill et al. 2009). These implications are most significant for understanding changes in cognitive or physiological capacities of earlier species of *Homo* as opposed to anatomically modern humans (e.g. Churchill 1993; McBrearty & Brooks 2000; Churchill & Rhodes 2009; Rhodes & Churchill 2009; Roach et al. 2013; Roach & Richmond 2014; but see Lombard & Parsons 2010), with the role of weapons contributing to recent discussions on hunting and scavenging strategies (e.g. Villa & Soriano 2010; Hardy et al. 2013), human dispersal events (e.g. Shea & Sisk 2010; Sisk & Shea 2011) and tool use amongst extant primates (Huffman & Kalunde 1993; Pruetz & Bertolani 2007). While a significant trend in research has involved better understanding 'complex' projectile technologies, i.e. those mechanically aided such as spearthrower and bow-and-arrow technologies, much of the focus has recently shifted to an interest in hand-delivered thrusting and throwing spears, including those with hafted lithic points as well as untipped wooden spears (Rieder 2001; Shea et al. 2001; Shea et al. 2002; Schmitt et al. 2003; Hutchings 2011; Wilkins et al. 2014; Iovita et al. *in press*).

A better understanding of the timing of the development of weapon systems is not just a matter of interest in and of itself, as the development of weaponry has long been seen as key to understanding the abilities of our hominin ancestors to hunt ever more successfully with progressively complex technologies (e.g. Darwin 1871;  Dart 1949; Washburn et al. 1968; McBrearty & Brooks 2000; Shea & Sisk 2010). A simplified unilinear model of the evolution of weaponry suggests that thrusting spears were an early weapon, although the timing of their appearance remains poorly understood (Rieder 2003; Shea 2006; Shea & Sisk 2010; Wilkins et al. 2012; Wilkins et al. 2014; Iovita et al. *in press*). The hand-delivered throwing spear, presumably coincident with or subsequent to the human capacity for throwing, is generally thought to have emerged after the first use of thrusting spears, though the timing of this is debated as well (Rhodes & Churchill 2009; Roach & Richmond 2014; Iovita et al. *in press*).

The ability to distinguish between different weapon systems, for example by identifying delivery-dependent ballistic properties and usewear on lithic points would, according to the linear model, help to understand the timing of the appearance of weapon systems (Shea 2006; Hutchings 2011; Iovita et al. 2014). Leaving aside issues thrown up by the persistence of both untipped and composite hand-delivered spears amongst modern hunter-gatherer groups either alongside or in the absence of 'complex' projectile technologies (e.g. Moseley 1877; Spencer 1914; Driver 1939; Swanton 1946; Hiatt 1968; Hitchcock & Bleed 1997; Goodale 1994), the search for these data is hampered by a poor understanding of the mechanics and biomechanics of hand-delivered weapons, with experimental work relying upon estimates of impact velocities and forces involved (e.g. Shea et al. 2001; Shea et al. 2002; Wilkins et al. 2014; Iovita et al. *in press*).

The earliest complete weapons in the archaeological record are a collection of as many as 11 untipped wooden weapons from Schöningen, Germany dating to MIS 9 (Thieme 1997; Urban et al. 2011; Balter 2014). A broken tip of a wooden implement, with a tip morphology similar to the collection of spears from Schöningen, comes from Clacton-on-Sea and probably dates to MIS 11 (Oakley et al. 1977; Bridgland et al. 1999). Interpretation of the function of these Middle Pleistocene wooden spears has varied and has included thrusting spears, hand-thrown spears and snow probes for locating carcasses (e.g. Oakley et al. 1977; Gamble 1987; Thieme 1997; Schmitt et al. 2003). Particularly in light of recent *Homotherium latidens* finds from the 'spear horizon' at Schöningen, and possible evidence of interpersonal violence at Sima de los Huesos dating to MIS 11, other possibilities include weapons for self-defence and violence amongst conspecifics (Serangeli et al. 2014; Sala et al. 2015). However, given the abundance of butchered zooarchaeological remains, in particular at least 46 *Equus mosbachensis* thus far described from

Schöningen 13 II-4 (van Kolfschoten 2014), an interpretation of these finds as hunting weapons remains a reasonable functional assignment.

With the 'spear horizon' at Schöningen probably corresponding to MIS 9 (Urban et al. 2011), candidates for the species that made these weapons include *H. heidelbergensis* or possibly early *H. neanderthalensis* (Street et al. 2006; Stringer 2012). Male *H. heidelbergensis* had an estimated mean body mass of 79.3 kg, compared with estimates of between 66.5 kg – 69.2 kg for Palaeolithic male *H. sapiens* (Froehle et al. 2013). The stature and body mass estimates for *H. heidelbergenis* imply a powerfully built, robust species of human.

In a landmark paper on prehistoric weapon technology, Susan Hughes (Hughes 1998) identified a lack of reported data on thrusting spears, not only restricted to design of lithic tips of composite thrusting spears, but also on the forces and velocities that might occur during spear thrusting. Shea et al. (2001, p.809) reiterated this absence of data, thus relying on data from one-handed stabbing experiments to design their controlled experiment investigating Levallois point-tipped thrusting spears. The one-handed stabbing experiments to which Shea et al. (2001) referred were conducted to understand the effects of knife stabbing (see Table 1), in order to design appropriate clothing for law enforcement officers (Horsfall et al. 1999; Miller & Jones 1996). However, the mechanics and biomechanics of one-handed stabbing are different from two-handed spear thrusting, and the weapon considered in this previous work (a knife) is different from a thrusting spear in mass, morphology and material, rendering use of these data not appropriate. Controlled experiments aiming to replicate two-handed spear thrusting continue to rely on estimates of velocity and force, with a wide range of velocities being tested, spanning from 1.0 m/s to 10.3 m/s (Table 2) (e.g. Shea et al. 2001; Wilkins et al. 2014a; Wilkins et al. 2014b; Iovita et al. *in press*). The use of such a wide range of impact velocities calls into question results relating to the effectiveness of the weapons tested and damage caused to lithic points, and makes comparison of results between experiments problematic. In comparison, Schmitt et al. (2003) provided experimental data on thrusting spears, using aluminium poles on a 'padded' target, but the experiment was designed to understand the forces acting on the human body during spear thrusting in order to aid the identification of spear use on human fossil material. This difference in objective led to an under-reporting of data on impact velocities, an absence of data on forces imparted on the spear itself, and the use of untrained participants.

**Table 1. Impact velocities from previous human performance trials.**

| Type experiment | Velocity (range) | Velocity (mean) | Estimated or Filmed | Firing mechanism | Source |
|---|---|---|---|---|---|
| Human Performance One handed stabbing: overarm and underarm | 6 - 10 m/s | 5.8 m/s (underhand)<br>8.9 m/s (overhand)<br>(*n*=203) | Calculated via acceleration data, verified with high speed video for some trials | Humans (*n*=not reported), mixed male/female | Horsfall et al. 1999 |
| Human Performance One handed stabbing: overhand, short forward thrust, side sweep | 2.6 - 9.2 m/s | 5.8 m/s (*n*=600) | Six-camera VICON motion analysis system | Humans (*n*=20), mixed male/female, mixed students and trained police | Chadwick et al. 1999 |
| Human Performance One handed stabbing: short underhand, short overhand, long underhand, long overhand | 5.8 - 12.0 m/s | 6.6 m/s short underhand; 7.0 long underhand; 9.1 short overhand; 12 m/s long overhand (*n*=10 stabs each type) | Filmed, standard video recorder (Panasonic M10 video recorder) | Humans (*n*=10), mixed male/female | Miller & Jones 1996 |
| Human Performance Two-handed spear thrusting | 1.7 - 4.5 m/s | Not reported | Filmed, standard video recorder, 60 frames per second | Humans (*n*=7), mixed male/female (untrained) | Schmitt et al. 2003 |

**Table 2. Summary of estimated and filmed velocities from archaeological experimental studies on spear thrusting.**

| Type experiment | Velocity (range) | Velocity (mean) | Estimated or Filmed | Firing mechanism | Source |
|---|---|---|---|---|---|
| Controlled Archaeological Experiment | 1.0 - 1.5 m/s | N/A | Estimated | Crossbow<br>28 kg draw weight | Shea et al. 2001; Shea et al. 2002 |
| Controlled Archaeological Experiment | 1.1 - 2.7 m/s | Not reported | Transient recorder, light curtains | Pendulum, swinging metal arm with added mass | Iovita et al. *in press* |
| Controlled Archaeological Experiment | 7.8 - 10.3 m/s | 8.9 (untipped)<br>9.4 (tipped)<br>(n=23) | Filmed Bushnell Speedster III radar gun | Crossbow<br>20 kg draw weight | Wilkins et al. 2014a; Wilkins et al. 2014b |

In response to these problems and the resulting need to develop a new experimental framework, the current paper describes the results from a human performance trial of 11 males trained in military bayoneting that was designed to record impact velocities and force profiles for two-handed spear thrusting. Trained males were chosen with the aim of evaluating the upper limits of performance because males produce significantly higher energies when stabbing than females (Horsfall et al. 1999), and with the further aim of evaluating the hypothesis that training improves performance in spear thrusting. The study was not designed to capture data on 'effectiveness' of these spears with respect to killing animals, though depth of penetration (DoP) in PermaGel™ (which is a muscle simulant) was recorded. Untipped wooden spears were chosen as they are the earliest implements identified as weapons in the archaeological record, are known to have been in use throughout the Pleistocene and Holocene (Moseley 1877; Noetling 1911; Davidson 1934; Davidson 1936; Driver 1939; Swanton 1946; Stewart 1947; Adam 1951; Clastres 1972; Luebbers 1975; Oakley et al. 1977; Goodale 1994; Thieme 1997), and provide a homogenous tip material and shape.

## 2. Materials and Methods

### *2.1 Materials*

### *2.1.1 Spear Replicas*

Spear replicas were designed to match published measurements for Spear II from the collection of wooden implements from Schöningen (Thieme 1999a p.470; Thieme 1999b p.389). Two spear shafts and three removable spear tips were used in this study; the shaft and tips were joined by a device consisting of aluminium caps containing a load cell, which is described in detail below. Measurements were made of all spear replicas including diameters at a number of points measured from the distal end of the spear, point of balance, mass of spear, and shape characteristics of the front 100 mm of the tips (Table 3). All measurements were within a millimeter of the measurements available for Schöningen Spear II (Table 3). Schöningen Spear II was chosen as it is a complete example with published measurement data available, and with measurements closest to mean values of the sample of published complete spears from Schöningen (Thieme 1999a). Although specific measurement data on the distal tips of the Schöningen spears were unavailable at the time the current study was conducted, the replica tips were designed according to the taper and size as observable in photographs of Spear II (Thieme 1999a, p.391). The slight difference in mass between the two replicas is due to slight variations internal to the wood. Combined with the added mass of the load cell, the mass difference between the two spear replicas used only accounts for 4% additional mass of spear replica 2 and is thus unlikely to have affected results.

**Table 3. Measurement data for spear replicas (SR) compared with published measurement data on Schöningen Spear II at the time of replica manufacture. All measurements are in mm except mass, in grams. * Measurements are distances measured from distal end. † Measurement data from Thieme 1999b: 389. ‡ Data not available at time of experiment.**

| Spear | Length | Dia. at 10 mm | Dia. at 50 mm | Dia. at 800 mm | Dia. at 1150 mm (midpoint) | Dia. at 1530 mm | mass | point of balance* |
|---|---|---|---|---|---|---|---|---|
| Schöningen Spear II† | 2300 | ‡ | ‡ | 37 | 35 | 34 | ‡ | ‡ |
| SR1 | 2300 | 5 | 16 | 37 | 35 | 34 | 752 | 1080 |
| SR2 | 2300 | 5 | 15 | 36 | 35 | 33 | 806 | 1095 |

Wood for the spear replicas was obtained from a stand of Norwegian spruce (*Picea abies*) that had been planted on limestone/clay soil in the mid 1980s at Bedgebury Pinetum in Kent, England. The trees grew in natural forested conditions. The replicas were manufactured from spruce grown in warm conditions; therefore, trees with a circumference larger than necessary for the finished product were chosen. The use of the heartwood provided the use of higher density wood by avoiding the soft sapwood, as the Schöningen weapons were manufactured from dense slow-growing spruce (Thieme 1997). Like the Schöningen spears, the distal ends of the spears were created from the hardest base of the trees (Thieme 1999b, p.391). Spear replicas were made within 3 months of cutting the trees, and as the current study was not designed to examine usewear and spear thrusting is not affected by aerodynamics, were made manually using metal tools.

**Figure 1. Replica of Schöningen Spear II. Scale (length = 100 mm) is by distal end.**

A load cell (Kistler; 1-Component Force Sensor 9031A, serial number 490937; maximum range = 60 KN) was mounted in a custom-made device fitted between the spear shaft and point; two aluminium caps fitted to the spear shaft and point, enclosing the load cell (Figure 2 and Figure 3) (Horsfall et al. 1999). The device measured 224 mm in length and weighed 452 g. It is recognised that adding the mass of the load cell to the spears increased the total mass of the spears by a significant percentage (Table 3). This mass increase might slow down impact velocity, but it is unlikely to have affected kinetic energy (Horsfall et al. 1999). Along with the measurements replicated based upon archaeological data, the replicas' total masses fit very comfortably within the range of masses of ethnographic untipped wooden spears studied by one of the authors (AM) (range 150 g – 2246 g; mean = 775.6 g; *n*=55).

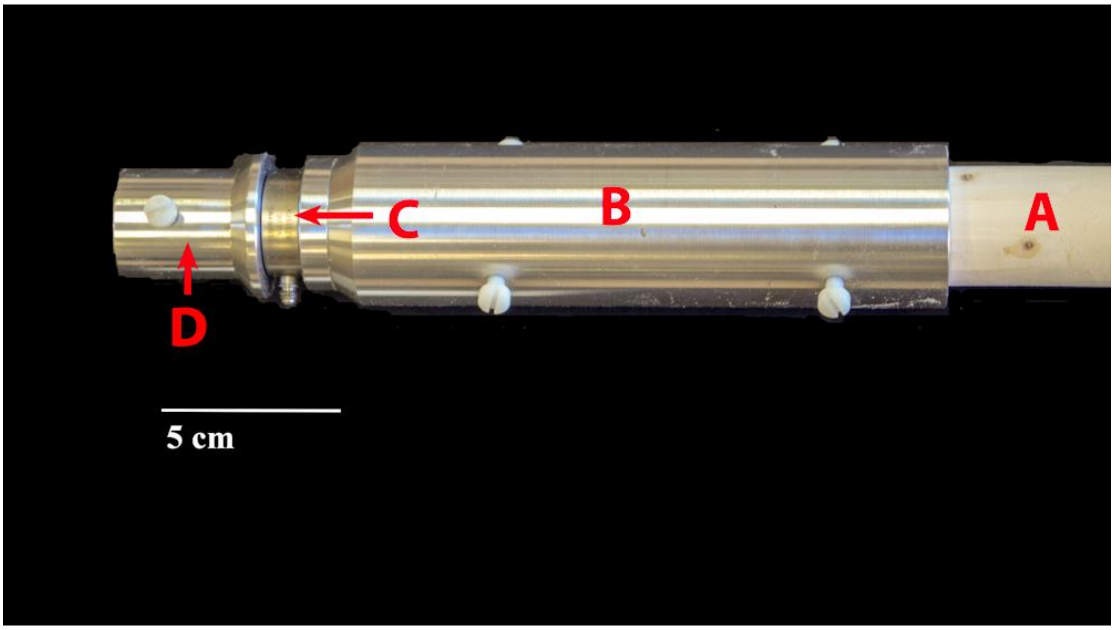

**Figure 2. Load cell mounted on a spear shaft. (A = spear shaft, B = custom made mount, C = load cell, D = spear point mount).**

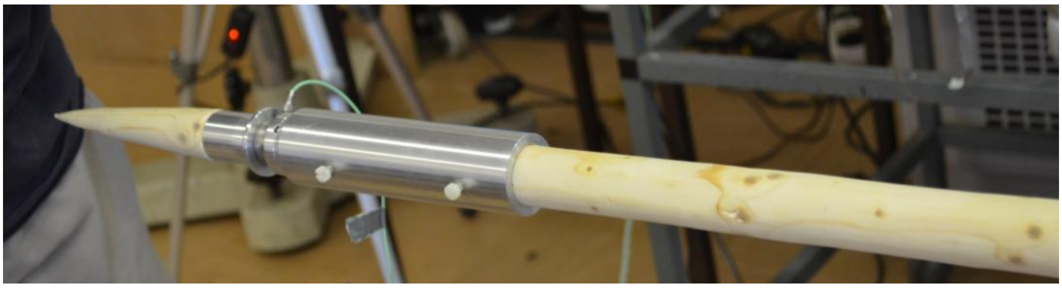

**Figure 3. Spear replica with custom-fitted load cell.**

Casts were made of all the spear tips from 100 mm the from distal tip of each spear replica. Moulds of the spear tips were made using a high quality silicone moulding agent (Prevest DenPro® Hiflex Putty) and casts were made using a liquid polyurethane resin (Prevest DenPro® EasyFlo 60) (Figure 4). To compare the relative pointedness of the spear tips, a guided free-fall impact test was designed and performed for the casts made from the 3 tips used in the spear thrusting trial. A two-metre long plastic pipe with a 30 mm diameter opening was used for the impact drop test. Holes were drilled along the pipe to reduce air resistance during impact testing and a level was used to ensure the pipe was vertical. A metal bar (150 g) was attached to the rear of each cast in order to ensure adequate kinetic energy upon impact, and a small amount of plastiline was added if necessary to ensure that each cast and bar combined weighed exactly 175 grams. The points were then dropped from 2.21 m down the tube into a block of plastiline sculpting compound (softness 50) at an air temperature of 16° C. Each cast was dropped 10 times, measuring the depth of penetration (DoP) to the nearest mm for each drop into the plastiline. The purpose of this test was to confirm that slight variations in each spear tip's morphology did not greatly affect results of the human performance spear thrusting experiment.

**Figure 4. One of the resin casts of a spear point for use in impact tests.**

### *2.1.2 Target*

As this was a study designed to understand the interaction between human performance in spear thrusting and wooden spears, a homogenous target was preferable for experimental control. Targets consisted of 3 blocks of PermaGel™ measuring 440 mm x 290 mm x 130 mm, weighing ~13 kg each. PermaGel™ is a muscle simulant used in ballistic testing and approximates the performance of 10% (by mass) gelatine (Mabbott et al. 2013). PermaGel™ is a translucent, reusable, synthetic material that does not require temperature conditioning (as gelatine does) (Figure 5).

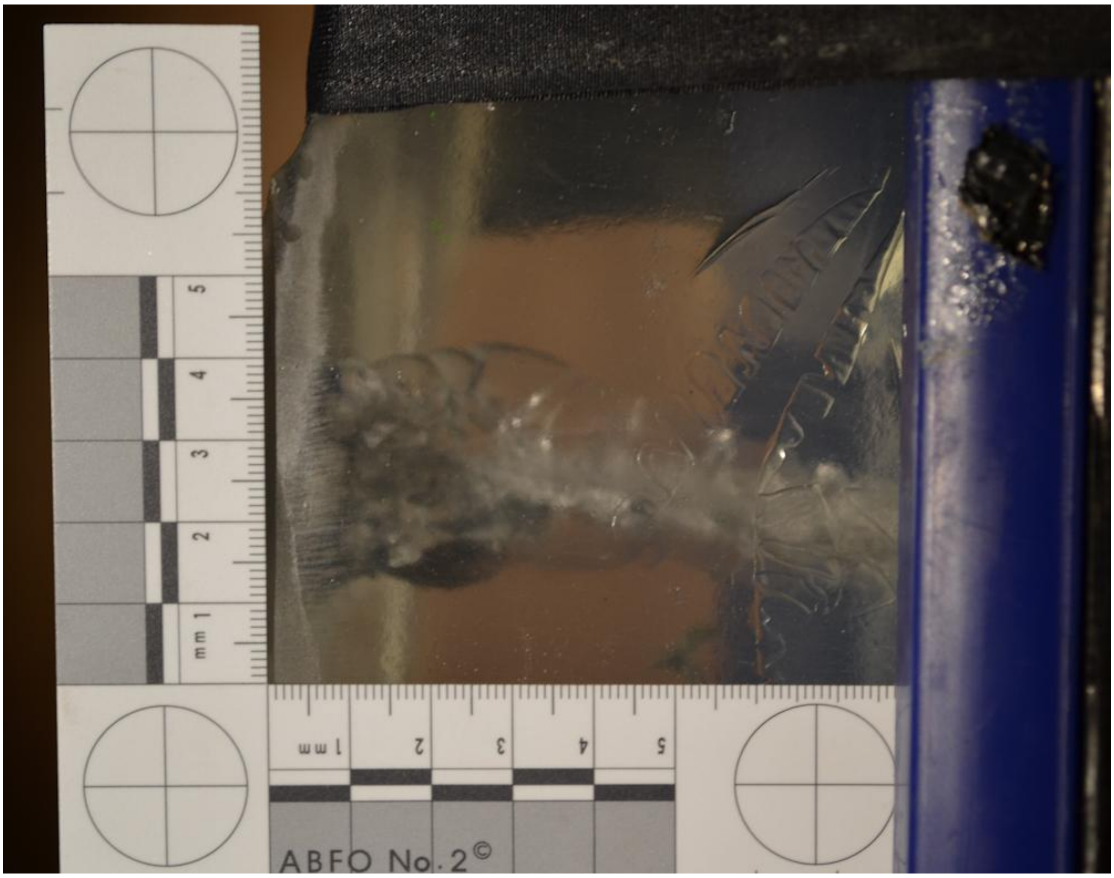

**Figure 5. Block of used PermaGel™ displaying spear thrust 'wound' track.**

### *2.1.3 Human Participants*

Eleven male participants, recruited from the military staff at the Defence Academy of the United Kingdom (Shrivenham, Oxon, UK) volunteered to take part in the human performance trial (July 22, 2014). Ethical approval was obtained from the Science and Engineering Research Ethics Committee of Cranfield University, Shrivenham, UK (approval number 004_2013). Participants were orally briefed, provided signed informed consent and were aware they could withdraw at any stage of the work without penalty. Participants were not allowed a practice thrust and were not paid. All participants had received training in bayonet use (two-handed thrusting with a sharp weapon), as part of their military training. Each participant performed at least 3 thrust impacts taking approximately 10 minutes total. Self-reported masses of participants ranged from 61 kg - 100 kg (mean=81.2 kg; SD=10.3 kg), and self-reported heights were 1.68 m - 1.95 m (mean=176.8 m; SD=7.7

kg). The mean body mass and height of the participants correspond well with estimates for *H. heidelbergensis* (Trinkaus et al. 1999; Froehle et al. 2013).

## *2.2 Methods*

### *2.2.1 Experimental data collection*

Participants were not coached on spear hold or stance, and were asked to thrust the spear into a PermaGel™ target with maximum force. Participants stood behind a foot plate, and thrusts were from a standing position without approaching the target (Figure 6). Participants were asked to avoid previous thrust areas into the PermaGel™. They were requested to perform a ‘strike hold’, in other words, thrusting the spear into the target with maximum force and then holding the spear in the target until DoP of the spear point into the PermaGel™ was measured (in mm) using a calibrated ruler.

**Figure 6: Participant performing spear thrusting in a block of PermaGel™. Hand position was the most typical used by participants.**

The load cell was connected to a data acquisition system (Figure 7) and the force (N) and time (ms) profile of the impact event was captured using Imatek Impact Analysis (version 3.3.7) (maximum recording time = 100 ms; 8000 data points were collected). Every impact event was recorded using a Phantom V7 high-speed video camera (1000 fps) allowing velocity to be calculated using Phantom 675.2, software. A sample video is included as a supplementary file.

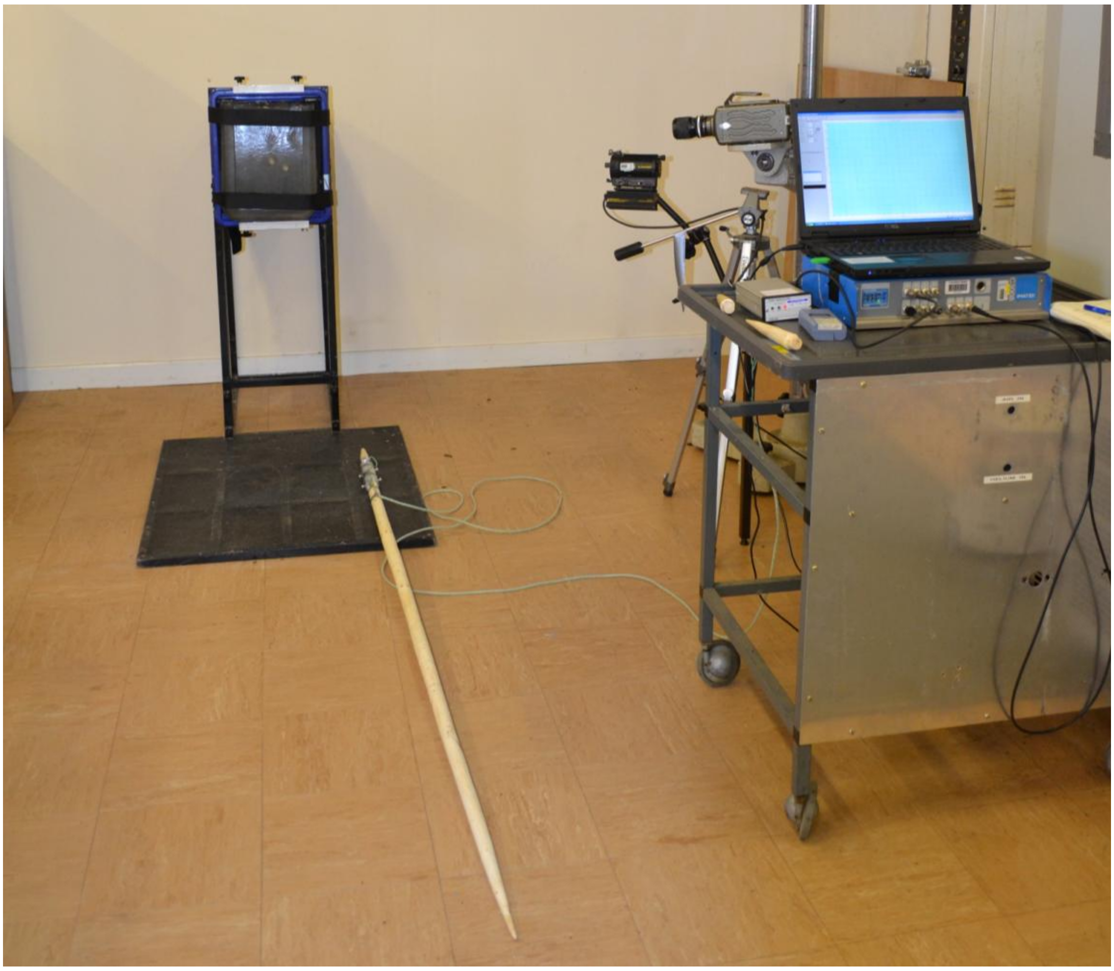

**Figure 7. Experiment setup showing spear, PermaGel™ block, data acquisition and high speed video camera.**

### *2.2.2 Data analysis*

High speed video analysis was conducted using the software package Phantom Cine Viewer v2.5.744.0. All the videos were analysed by the same individual (AM) to minimise variation in technique. Impact was defined as the high speed video frame in which the spear first interacted with the PermaGel™ block and was considered to be frame = 0. Impact velocity was defined as the mean velocity calculated from frames -2 to -22 before impact (Figure 8). All statistics were calculated using the software package SPSS version 22. Force/time profiles were produced in Excel version 12.3.6.

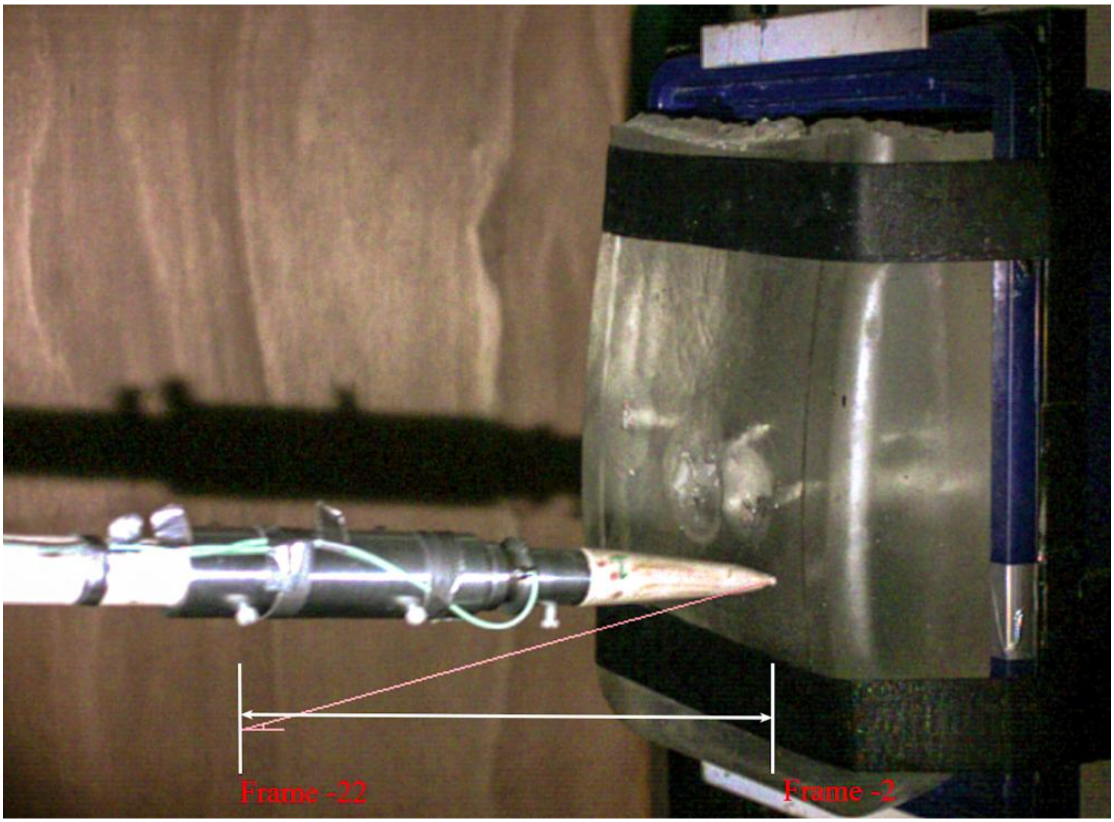

**Figure 8. Still frame demonstrating high speed video analysis. The pink line shows the distance traveled from the beginning of the analysis (Frame -22) to impact with the target.**

# 3. Results

Thirty-nine stab events were recorded, capturing force (Newtons) and impact velocity (meters per second, m/s). One video was unsuitable for analysis, due to the video containing fewer than 22 frames before impact, leaving a sample of thirty-eight videos for velocity results.

## *3.1 Spear replicas*

The first shaft, spear replica 1 (SR1), broke after 22 stab events, and was thereafter replaced with SR2. SR1 broke in the front half of the spear at a point where several knots conjoined in the wood (ca. 1000 mm from distal end), forming a point of weakness in the wood. Possibly this weakness led to the spear breaking.

Table 4 presents the results of the impact drop tests of the spear tip casts. The mean DoP into the plastiline block, measured to the nearest millimetre, had little variation from point to point. A Shapiro-Wilk's test ($p > .05$), a visual inspection of the skewness and kurtosis measures and standard errors, as well as a visual inspection of the histograms, normal Q-Q plots and box plots showed that the data were not normally distributed. A nonparametric Levene's test was used to verify the equality of variances in the samples (homogeneity of variance, $p$=1.000). Therefore there is an equality of variance in DoP into the plastiline by each spear tip. Thus interchanging the spear tips in the human thrusting experiment had a negligible impact on DoP into the PermaGel™ (measured to the nearest millimetre).

**Table 4. Results of the impact drop tests. *DoP = Depth of Penetration, measured as how many millimetres the point impacted into the plasticine.**

| Spear tip cast ID number | mean DoP* (mm) | minimum DoP (mm) | maximum DoP (mm) | Standard Deviation | *n* |
|---|---|---|---|---|---|
| 1 | 22.9 | 22 | 24 | 0.74 | 10 |
| 2 | 23.9 | 23 | 25 | 0.74 | 10 |
| 3 | 22.8 | 22 | 24 | 0.79 | 10 |

### *3.2 Depth of Penetration into PermaGel™*

Depth of penetration was measured as a means of further understanding the interaction of impact velocities and forces. The spear thrusts frequently impacted into the foam backing behind the PermaGel™. This study did not include bone or hide simulants as a homogenous target was desirable for experimental control to capture human performance, and the study was not designed to understand the 'effectiveness' of these spears on targets.

**Table 5. Descriptive Statistics for Depth of Penetration (mm).**

| Mean | SD | Minimum | Maximum | n |
|---|---|---|---|---|
| 119.4 | 13.0 | 93 | 145 | 39 |

### *3.3 Participants*

Participants were a mix of right-handed (n=8), and left-handed (n=3). All but one chose their dominant hand as the trailing limb; Participant 6 used the right hand as the trailing limb. Upon questioning, the participant responded that this choice was due to training to use a bayonet right-handed regardless of handedness. Handholds, recorded as overhand or underhand for each participant varied more widely but never changed within a participant's series of stabs. Variations included overhand for trailing limb and underhand for leading limb (n=9) (Figure 6), underhand for trailing limb and overhand for leading limb (n=1), and overhand for both trailing and leading limbs (n=1). The impact event associated with the highest peak force involved one of the unusual handholds (underhand for trailing limb, overhand for leading limb).

### *3.4 Impact Velocity*

Impact velocities ranged from 2.80-6.26 m/s, (mean=4.650 m/s, SD=0.748 m/s). A histogram of the dataset (Figure 9) shows a bimodal distribution, and so normality tests were conducted, using the Shapiro-Wilk test as it is suitable for small sample sizes. The velocity dataset had a *p*-value of 0.627 confirming a normal distribution. The boxplot in Figure 10 shows impact velocities achieved by each participant.

**Table 6. Descriptive Statistics for Impact Velocities (m/s).**

| Mean | StDev | Minimum | Maximum | n |
|---|---|---|---|---|
| 4.650 | .748 | 2.80 | 6.26 | 38 |

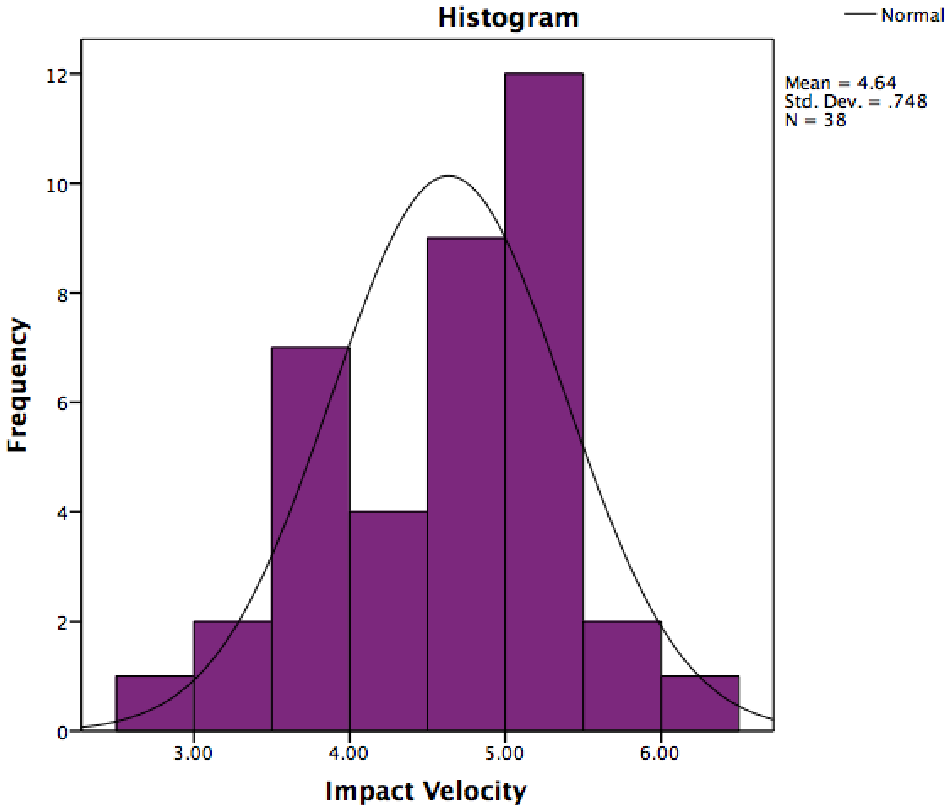

**Figure 9. Histogram of the frequency distribution of impact velocities (m/s).**

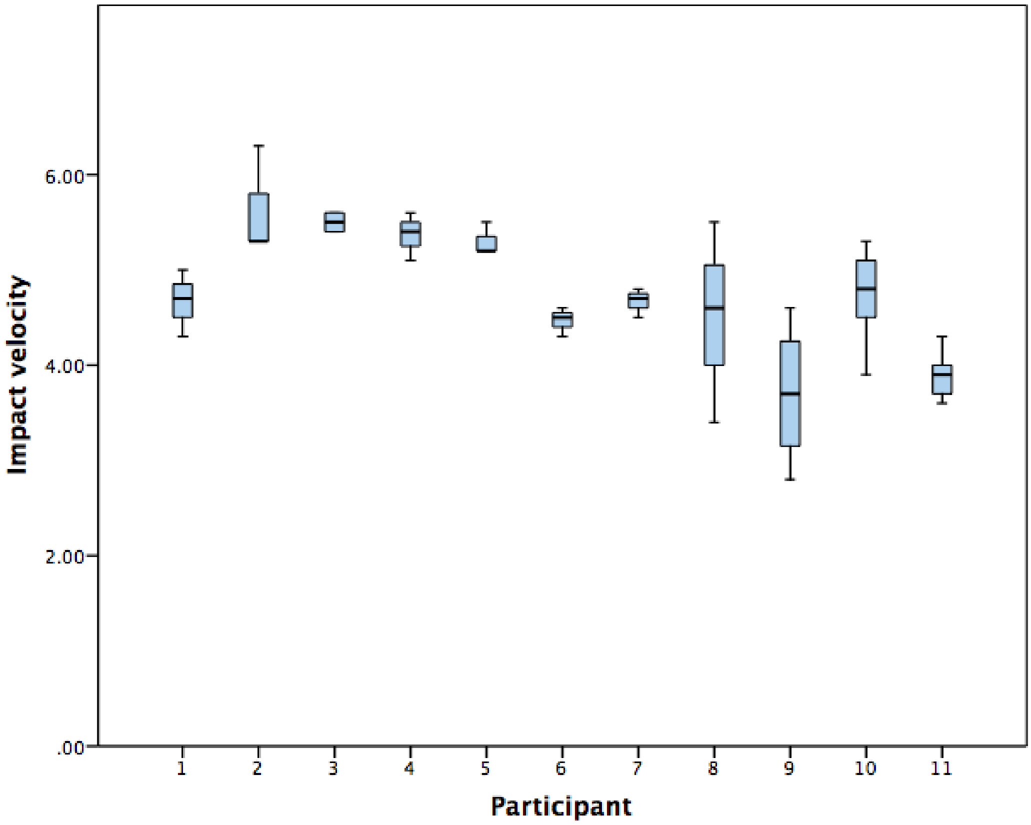

**Figure 10. Boxplot of the impact velocities by participant.**

### *3.5 Force*

Peak forces ranged from 362-1120 N, (mean=661.0 N; SD=186.2 N). A histogram of the data obtained showed a bimodal distribution (Figure 11). The Shapiro-Wilk test had a *p*-value of 0.056 confirming a normal distribution. The boxplot in Figure 12 shows peak forces achieved by participant.

**Table 7. Descriptive statistics for peak forces (N).**

| Mean | SD | Minimum | Maximum | n |
|---|---|---|---|---|
| 661.4 | 186.2 | 362 | 1120 | 39 |

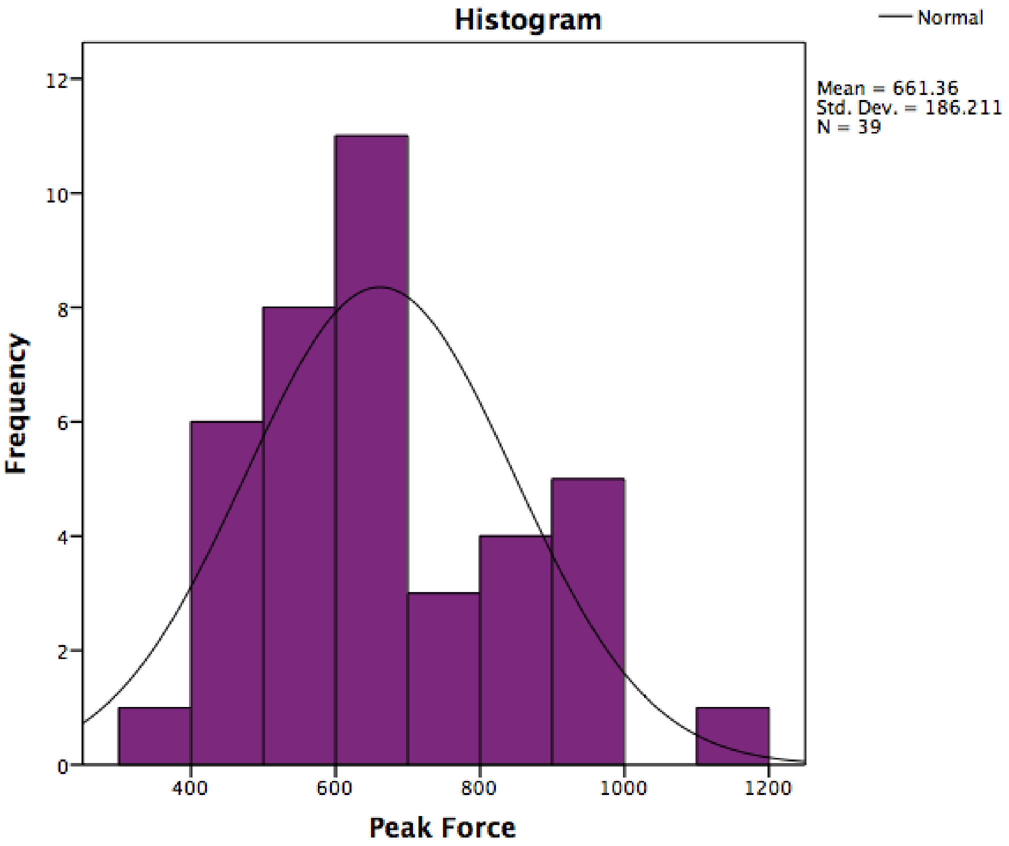

**Figure 11. Histogram of the frequency distribution of peak force achieved per thrust.**

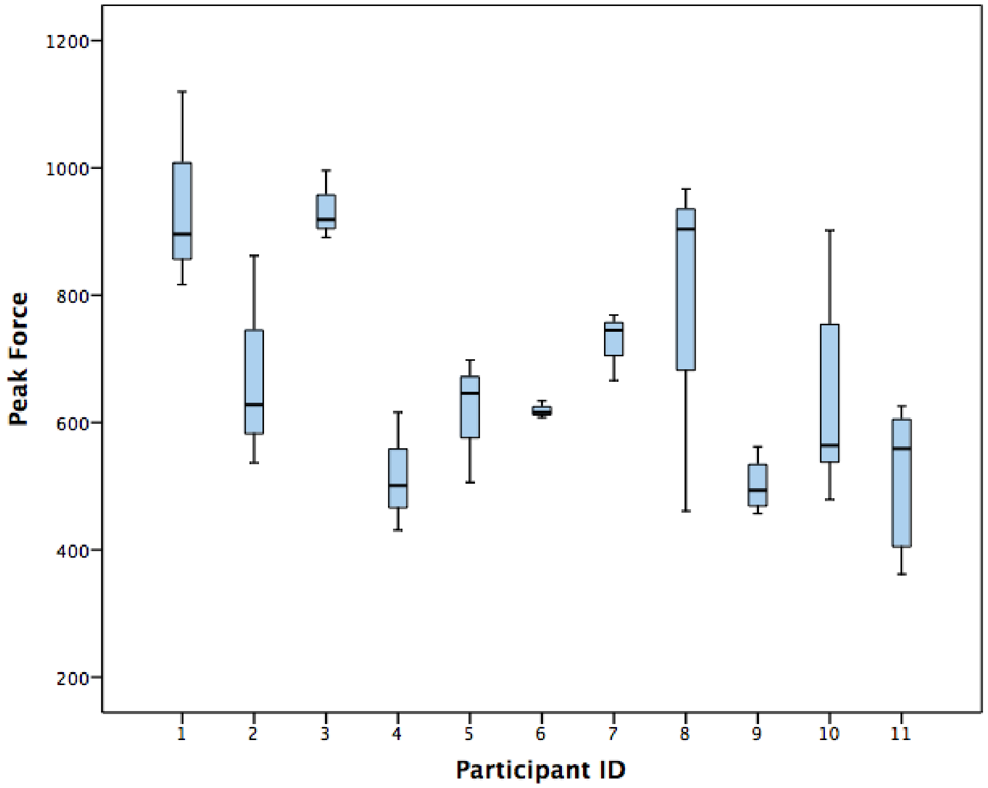

**Figure 12. Boxplot of the peak force achieved per thrust, sorted by participant.**

Each spear thrust recorded force over time; selected force-time profiles are presented and discussed. Typical force profiles (n=29) show a single peak force followed by a tail as the spear was held in the target for the purpose of measuring DoP (e.g. Figure 13). A more unusual profile (n=3) involved a double peak, where there are two peaks roughly similar in force (e.g. Figure 14). There were a number of 'push' force profiles in the dataset (n=7), where a participant pushed their body mass into the target, achieving peak force at the end of the thrust (e.g. Figure 15). Overall these profiles clustered by individual, and with coaching, individuals (e.g. P10 and P11) were able to change their technique to produce a different profile. For example, P11 first produced 3 'push' profiles, and with coaching was able to produce 2 single peak profiles and one further 'push'. All three double peak profiles were produced by P1.

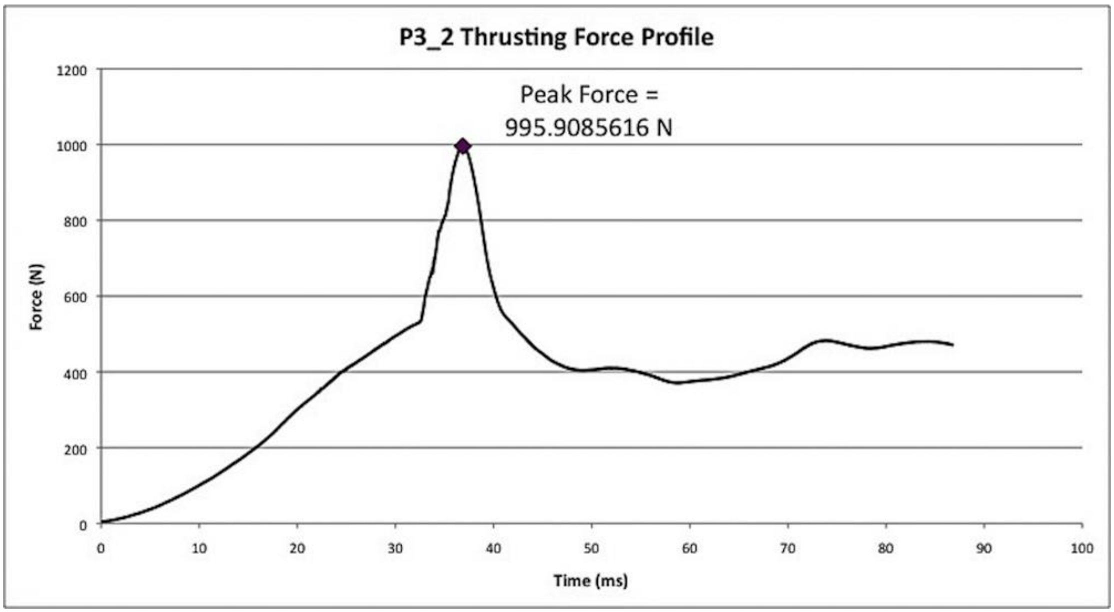

**Figure 13. Force-time profile (for participant 3, replicate 2). Example of 'single peak' profile**

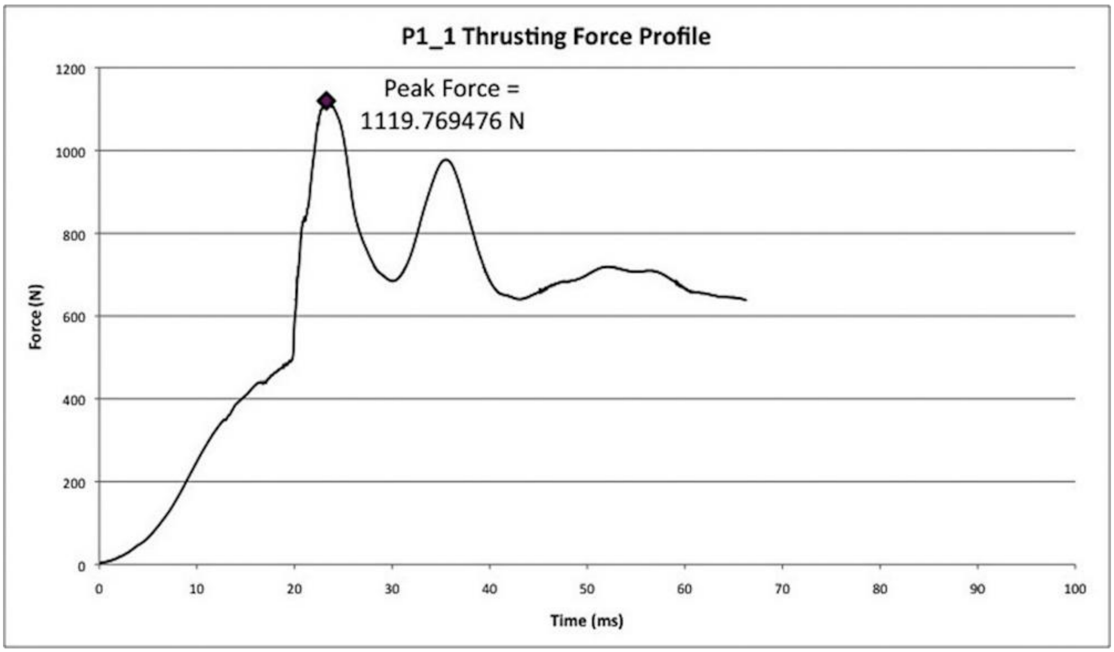

**Figure 14.Force-time profile for participant 1, replicate 1. Example of 'double peak' profile.**

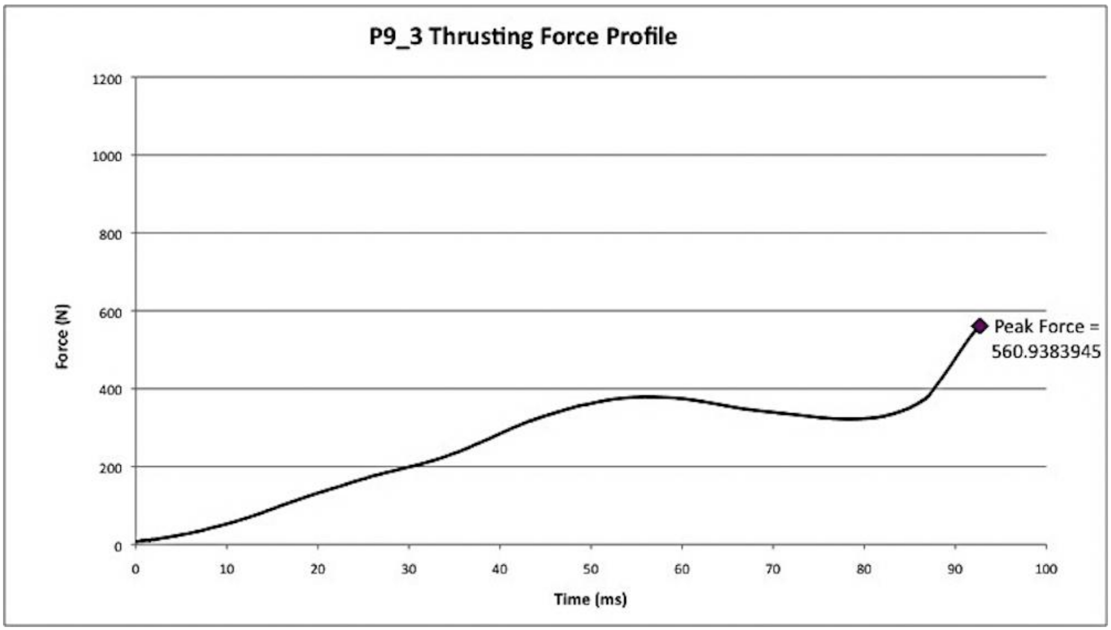

**Figure 15. Force-time profile for participant 9, replicate 3. Example of 'push' profile.**

### *3.6 Relative factors in human spear thrusting performance*

A regression analysis of peak force and impact velocity per thrusting event resulted in a low $R^2$ value of 0.139 (Figure 16), suggesting that impact velocities do not reliably predict peak force in a human spear thrusting event. Peak force also correlated poorly with other variables such as participant's body mass ($R^2 = .012$) and DoP ($R^2 = .034$) into the target. This is not surprising given the complexity in the biomechanics of the two-handed thrust.

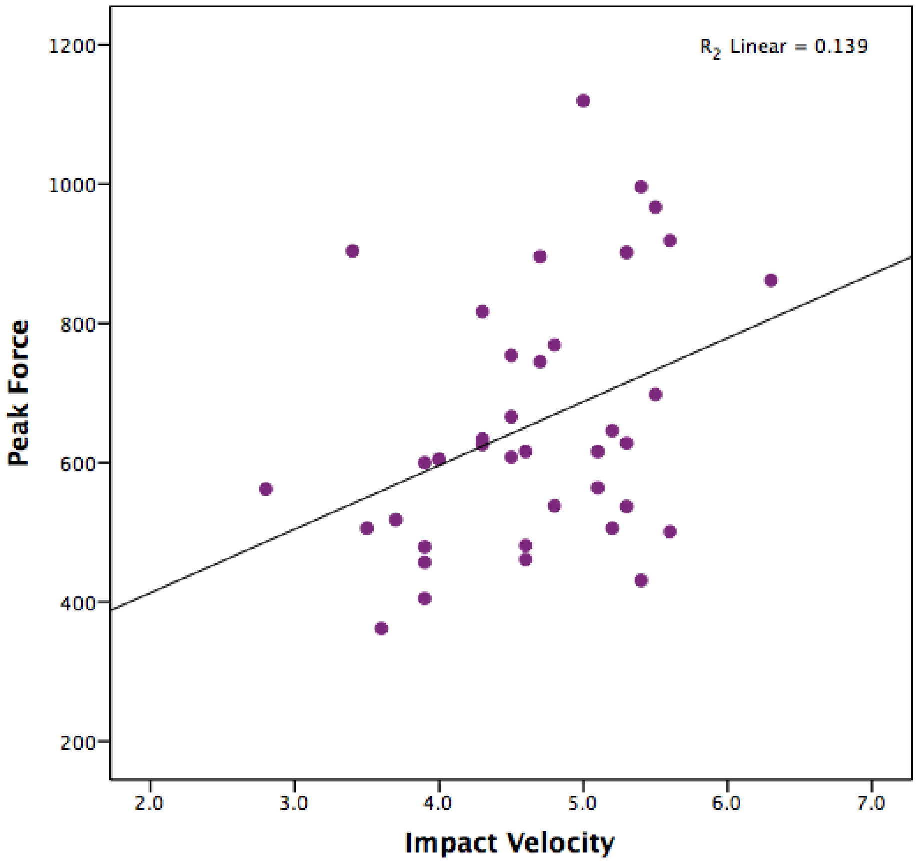

**Figure 16. Regression analysis of impact velocity (x axis) and peak force (y axis).**

# 4. Discussion

## *4.1 Impact Velocity*

Impact velocities were within the range reported for one-handed stabbing, though the mean was lower than those of all knife stabbing trials (Table 1). Although some have theorised that two-handed spear thrusting should result in faster impact velocities than one-handed stabbing (Wilkins et al. 2014), the heavier mass of the spears probably contributed to slower velocities, something that has also been seen in one-handed knife stabbing (Horsfall et al. 1999). As seen in Table 1, mean velocities from one handed stabbing studies range from 5.8 m/s to 12 m/s depending upon stab type (e.g. underhand vs. overhand), and vary partly due to mass of the knife, with heavier knives suggested to produce slower velocities (Miller & Jones 1996; Chadwick et al. 1999; Horsfall et al. 1999). Schmitt et al. (2003) studied forces imparted on humans in two-handed spear thrusting with the reported range of velocities by untrained males (*n*=3) and females (*n*=5) as being 1.7 m/s to 4.5 m/s (no mean reported) (see Table 2). Trained male participants performing two-handed spear thrusts in the current study produced a mean impact velocity of 4.65 m/s, with a maximum of 6.26 m/s, thus clearly indicating that the use of trained males results in faster impact velocities.

Researchers have been setting controlled spear thrusting experiments at velocities of either between 1.0 m/s and 2.7 m/s, or between 7.8 m/s and 10.3 m/s (Table 2). Wilkins et al. (2014a; 2014b) filmed the velocity of spears fired from a crossbow at a 20 kg draw weight resulting in a mean impact velocity of 8.9 m/s. These results indicate that Shea et al.'s (2001; 2002) estimated impact velocities of 1.0 m/s to 1.5 m/s when fired with 28 kg draw weight were in all probability underestimated. The wide range of velocities being tested brings into question the results of some experiments aimed at understanding lithic wear patterns and thrusting spear 'effectiveness'. It also brings into question the suitability of calibrated cross-bows in replicating thrusting spear use.

### *4.2 Force*

The maximum peak force measured in this study was ~10% higher than that reported for one-handed knife stabbing (1120 N; 1000 N) (Horsfall et al. 1999). This is probably due to factors including the use of both arms as well as shifting of body mass against the target. Most significantly this outcome, particularly when compared with impact velocities, demonstrates that force loads in spear thrusting need to be accounted for in experimental work.

### *4.3 Thrusting spears vs. projectiles*

Thrusting spears remain in the hand in use, and therefore are not projectile weapons (Hughes 1998; Hutchings 2011). Their mechanics differ from those of projectiles and this should be reflected in how they are replicated in experimental work. A person using a thrusting spear literally puts their body mass behind the weapon. This is true whether an 'on guard' standing position is used, such as that used in the current experiment, or an overhead stabbing such as those observed by Kortlandt (2002) by native hunters in the former

Belgian Congo. Modern day troops undergoing bayonet training practice stabbing dummies on the ground as well, using either a pushing with the body in a downward motion, or by bending the knees and leaning over the target (Ripley 1999, p.15). In either position, a pushing movement carries on after initial impact, and while deceleration happens after contact in stabbing (Horsfall et al. 1999), this motion differs from that of a projectile, which loses momentum upon impact and thus relies entirely upon kinetic energy at impact and the object's tip design to penetrate the target. In stabbing and thrusting motions, the person using the weapon carries on producing momentum on the weapon after impact, until finished with the thrust or upon hitting something impenetrable with the weapon (Hutchings 2011).

This study has demonstrated that impact velocity and peak force have a poor correlation (Figure 16) in spear thrusting. Previous work in one-handed stabbing has shown that different techniques in stabbing affect performance (Miller & Jones 1996). Factors such as body mass of the person and how much of that body mass they co-opt into the thrusting, fitness of the individual, and spear holds will all have contributed to variations in performance achieved in this study, including both impact velocity and peak force. Adrenaline may also have played a role in spear use in the past, as challenging situations increase the adrenaline response, which can improve athletic performance (Blascovich et al. 2004). An additional complexity is that spear thrusting whether in human-human or human-animal conflict is unlikely to have been a static process, with either or both parties potentially running and moving in complex ways. In a realistic hunting or violent encounter these multiple factors would have come together to produce an action with high variability, with some factors mitigating and others enhancing performance.

By analysing knife impacts used in a drop tower, Chadwick et al. (1999) demonstrated that only two measures out of the three involved in stabbing - velocity, momentum and energy - are matched at any time to actual knife stabbing by human participants. Because of mechanical differences between thrusting spears and projectile weapons, it is clear that impact velocity alone cannot accurately replicate thrusting spear mechanics. Firing a spear as a projectile, for example by crossbow or air-cannon, can mimic impact velocity, but not the momentum in the thrusting action after initial impact. Therefore using such equipment even if set to replicate correct impact velocities, will fail to fully replicate spear thrusting. Adding mass to the mechanism like Iovita et al. (*in press*) do, may go some way to modeling spear thrusting mechanics but using drop towers and air-cannons, which may simulate the correct impact velocities (unlike calibrated cross-bows) is still less than ideal (Chadwick et al. 1999). Sacrificing experimental control and manually thrusting, such as Hutchings (2011) and Parsons & Badenhorst (2004) do, probably still best replicates spear thrusting and is a frequently utilised method in impact and armour research (e.g. Horsfall et al. 1999; Bleetman et al. 2003; Cowper et al. 2015). The use of trained participants and recording equipment to verify impact velocities and/or forces provides significant improvements to experimental work of this kind. If a controlled firing mechanism is preferred for purposes of experimental control, the current paper provides data on impact velocities and forces on thrusting spear use. Future experimentation on the mechanics and biomechanics of thrusting spears should focus upon the effects on force values by using an animal carcass, and the use of lithic and bone points.

## 5. Conclusions

It is a fair assumption that human groups who were reliant, even in part, on large meat packages for their survival, would have had members of the group who were fit, aggressive and highly experienced in the technologies and strategies that enabled both confrontational scavenging and hunting. Spear technologies such as those found at Schöningen would have provided not only the means to potentially hunt swift flight animals such as horses, but also to compete with and defend themselves against dangerous animals in their environment such as sabre-toothed cats, wild boar and wolves (Serangeli et al. 2014; van Kolfschoten 2014). Better understanding the one of the technologies enabling both subsistence and self-defence in the Middle Pleistocene provides important insight into human-animal interactions during this period.

This human performance trial has provided a body of data to better understand the mechanics and biomechanics of two-handed spear thrusting and provides the first study linking impact velocities and forces of two-handed spear thrusting, demonstrating a complexity even when using trained participants, due to human variability in technique and physiological capabilities. These data are key for evaluating existing results from spear thrusting experimental research, and provide a framework for developing new methodologies in understanding this hunting strategy. Future experimental work on hunting lesions, 'effectiveness' of untipped, lithic- and organic-tipped thrusting weapons, and damage signatures on weapons will need to re-evaluate existing methodologies for replicating thrusting spear use in light of these results.

Identifying the development of the use of thrusting spears in the archaeological record, can enhance discussions on human-animal interactions, social group hunting and/or scavenging strategies, and even possibly early indications of interpersonal violence. Thrusting spears have continued to be a part of modern human hunters' toolkits, and thus the study provides a better understanding of the use of this delivery method from the earliest signals of hunting in the archaeological record through to recent hunter-gatherer groups.

## Acknowledgments

The authors gratefully acknowledge and thank UCL's Centre for Humanities Interdisciplinary Research Projects (CHIRP) for a grant covering the expenses of this experiment and Arts and Humanities Research Council (AHRC) for funding the PhD research of Annemieke Milks. We would like to thank Prof. Ian Horsfall for enabling a subsidised use of the facilities at Cranfield Defence and Security for our research purposes, and all of our participants in the study for their contributions and interesting conversations. We thank Radu Iovita and colleagues for allowing us to cite their 'in press' work. We would also like to thank Dan Luscombe and Bedgebury Pinetum for donating the spruce trees for the spear replicas.

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