Experimental Studies in the Field of Ballistics on Different Types of Arrow Shafts

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The invention of metallurgy improved the manufacture of arrow shafts made from split wood; however, it is likely that before this innovation this process relied mainly on stems from trees and shrubs. In Europe, the species employed in shaft manufacture included willow, hazel, dogwood, and viburnum. The goal of the study presented here was to examine how wood type influences arrow flight trajectory. Towards this aim, an experiment was carried out in 2019 using replicas of bows modeled on prehistoric finds from Europe, namely the Bolków and the Holmegaard bows. This article presents the results of this ballistic research, showing possible differences in the use of different species of trees and shrubs.

Introduction

In Europe, interest in archery emerged around the mid-nineteenth century as a result of the then popular image of the "noble savage" and the "fashion for history" in Victorian England, when the bow was a toy for the elite[1]. The development of science drove scholars to look at this tool as an object that could be studied, and at archery as an issue that could be analyzed from various perspectives[2]. Scientific research on this subject dates back to the beginning of the twentieth century and has continued to this day. Early research often focused on evaluating the effectiveness of bows and, above all, the ballistic coefficient of arrows. An example of such work can be found in studies of shooting trials published in 1918, which used bows and projectiles from different eras and cultures around the world[3]. Another common type of research was the reconstruction of ancient bows and arrows based on finds from archaeological sites. This made it possible to compare bows from different times periods and regions, therefore informing us about the way they may have been used in the past.

However, so far, experimental archaeology has mainly focused on the study of projectile point function, especially in terms of microscopic evidence of damage caused by shooting[4]. This focus naturally arose from the fact that the most frequently recovered archery pieces in archaeological contexts are arrowheads. Made of durable materials, such as stone, flint[5], bone[6], or metal[7], arrowheads tend to be the better-preserved part of an arrow. This fact has had a key impact on the study of ballistics of prehistoric arrows. Yet, the organic elements that constitute the rest of the arrow are also important when trying to achieve the perfect shot. Still, this has rarely been studied, probably due to the scarce reference-base available. Indeed, organic elements are preserved only in specific environmental contexts, and only a few of these, such as bogs or glaciers, allow them to survive for many hundreds of years. Therefore, the number of complete arrows recovered to date is limited. This lack is reflected in the literature, where studies devoted to the preservation and influence of the arrow shaft on flight trajectory are absent. Only a few prehistoric sites where preserved arrow shafts were found are known in Europe. These include Stellmoore in northern Germany[8], Similaun in the Ötztal Alps[9], and Langfonne in Norway[10]. At these sites, the use of several tree species for shaft production has been recorded. Among them were dogwood, viburnum, hazel, and pine.

In 2019, the archaeological experiment discussed here was conducted to verify and interpret data on the effectiveness of using arrows with shafts made from the above-mentioned species. To achieve the study's goals, the following steps were undertaken: the acquisition of raw material, the manufacture of arrows, and experimental shooting sessions. The aim of this experiment was to produce arrows with shafts made from various plant species while using arrowheads inspired by material known from Late Neolithic/Eneolithic sites co-researched by the author. The focus was solely on plant-firing arrows, since an accurate replication of the process of making split-wood arrows would require the production of prehistoric metal tools. The author realizes that it is possible to produce prehistoric arrows without the use of metal, but this is beyond his possibilities. This experimental project made it possible to check the ballistic properties of particular tree and shrub species, the influence of these shafts on the arrows' flight trajectory, the significance of wind pressure on shooting, as well as the effective distance between the shooter and the target. The steps of this study were documented photographically and descriptively.

Materials and Methods

The experiment was divided into two phases: (1) manufacturing and (2) shooting, for which the reconstructive, experimental, and comparative methods were adopted as the methodological basis. During the first phase, shoots of different types of plants were subjected to treatment aimed at eliminating defective material. The use of various types of shafts made it possible to analyze their properties in terms of quality of the raw material and labor intensity of the workmanship. The weight of each arrow was compared, and a record was kept of the individual components (arrowhead, fletchings, and shaft) that could affect the arrow's flight trajectory. A DIGILAB TRADING JKH-4000 electronic scale was used for this purpose. The arrows were grouped according to weight and plant species, and given serial numbers. The dogwood (*Cornus mas* L.) arrows weighed from 31 to 39 g. and were divided into three weight groups each with five arrows. The viburnum (*Viburnum opulus* L.) arrows weighed from 27 to 31 g. and, like the dogwood arrows, were divided into three groups, each with five pieces. There were also 10 arrows of hazel (*Corylus* L.). They weighed from 25 to 32 g. They were divided into two groups of five pieces each. Due to the small representation of willow arrows, it was decided to leave them in one group. They weighed from 23 to 28 g, and their number was six. Also the tension of the bows was measured, after which test shooting sessions were conducted to check their efficiency. In addition to combining different arrows and bows during the shooting phase, distance variation was introduced to test the effectiveness of each arrow under specific conditions.

Two straight bows made by an external qualified person and modeled after finds from sites in Bolków and Holmegaard were used during the experiment. They both represented different types from various periods, which, in the author's opinion, helped to indicate potential differences between shafts. While the structures of the bows were reconstructed in reference to the finds, it was impossible to reproduce bowstrings as the originals were not even fragmentarily preserved in archaeological contexts. Therefore, the bowstrings used were made after the English longbow model[11], and linen chords were applied. Arrowhead shapes were modeled after the Late Neolithic materials from Poland coming from sites in Suchacz (Rzucewo type)[12] and Supraśl (Bell Beaker type)[13], which appear to the author as very unique and flexible for such an experiment. The shafts were made from the following plant species whose presence was confirmed in the archaeological record: dogwood[14], viburnum[15], hazel[16], and willow[17]. For reference analyses, the day before and on the day of the main research, a comparison shooting session with replicas of medieval

Figure 1: Replica bows from Holmegaard and Bolków.

Figure 2: Examination of the maximum range (moment of the shot from the replica bow from Bolków).

bows with split arrows was conducted. As a result, it was possible to measure the maximum range for both bows (around 150 m) and the dispersion zone of arrows at the target (between 1.5 m. wide by 3 m. deep). This experiment showed a high degree of repeatability of the archer (shooting repeatability), which seemed to prevent the potential risk of data manipulation related to shooter fatigue. The experiment was carried out respecting all research principles, as well as the methodological limitations arising from the problem of reproducing prehistoric phenomena.

Figure 3: Skin of a calf spread on a target.

Experiment

The experiment consisted of two phases: manufacturing and shooting. The first lasted from late February 2019 to mid-October 2019, while the second was conducted over two days in early November 2019. While the arrows were prepared in-house and following the model of Ötzi's arrows[19] (with minor change applied to the individual components)–in some pieces a horizontal fletching system was introduced instead of a radial one–the bows were commissioned from a professional bow-maker, who made them according to the models coming from sites in Bolków and Holmegaard[20]. The manufacture of the stems began with a search for suitable plants (shrubs and trees), and the gathering of stems. These included: dogwood, viburnum, hazel, and willow. Due to seasonal variations affecting the structure and physical properties of each species differently, the material was obtained both at the end of February and the beginning of March, and also several months later–in June and September. The periods of material acquisition were related to the cycle of plant growth, which affects the parameters of the collected raw material due to the plants growth on the diameter–during these periods they display ideal qualities due to nutrient storage. Stems that were approximately two years old were obtained due to the need for a slight stiffening which occurs through the wooding process. The material was obtained from forests near Stężyca, Rycki County, Lubelskie Voivodeship, Poland. All analyses were carried out by the author of the article, an archer with several years of experience. In the case of the shooting phase, the assistance of an archer with additional experience was also sought to measure shot repeatability and shot range.

Figure 4: Removal of bark from a fresh shoot (note the long, easily descending strands of bark).

Manufacturing Phase

The preparation of the arrow shaft was divided into five phases: (1) pre-treatment of the shafts, (2) drying, (3) straightening, (4) grinding, removal of protrusions, and trimming to the appropriate length, and (5) preparation of the nock and pocket for the arrowhead. In the first phase, the stems were cut in such a way that the drying process would not prevent further length correction. In the second phase, the prepared stems were debarked and dried (for ten days in total) in conditions with continuous air flow. In the third phase, the main straightening (using the most effective high temperature treatment) took place after the material had been seasoned. It helped to prevent all rapid returns of shafts to their original curved form or even their splitting. The arrows were straightened by heating them directly over a fire (leaving characteristic tanning marks), as well as indirectly, by placing the shafts by the fire on a structure built for this purpose[21]. In the fourth phase, grinding was carried out using pieces of red and white sandstone specially prepared for this experiment. Removal of protrusions was carried out by cutting off the excess material with the edge of a flint chip, followed by grinding on abrasive stone slabs. In the fifth phase, the natural thickening on harvested stems was used for the nock and the arrowhead's pocket. The tip of the arrow shaft was flattened to about 1 cm by cutting excess material using a flint chip and grinding on sandstone. This was accomplished to reduce the contact area between the bowstring and the arrow, while at the same time properly shaping the nock. Flint arrowheads were mounted onto the prepared shafts using a binder made of pine resin mixed with charcoal to make them more flexible. Feathers of wild ducks and geese were used as fletching by attaching them to the shaft with linen fiber wrapping. Fletchings were set up in the manner of those discovered on Ötzi, changing only the radial to horizontal arrangement due to resource constraints[22]. The fletchings of wild duck and wild goose feathers were selected for their good flight properties[23]. Linen wrap was used to strengthen critical parts of the arrow such as the nock and the arrowhead's pocket[24]. During the manufacture of the shafts, longitudinal cracking of their structure was often observed, especially when shaping the arrowhead's pocket[24]. Thus, it was decided to reinforce both ends of the shaft with linen wraps secured with bone glue.

Shooting phase

The shooting phase of the experiment took place in November 2019 in Żmijowiska, Wilków commune, Lubelskie voivodeship, within meadows near the reconstruction of an early medieval stronghold. This location now functions as an archeological field base belonging for the Nadwiślańskie Museum in Kazimierz Dolny, Grodzisko-Żmijowiska Department. The site was chosen for two reasons: on the one hand, because of the cooperation the author of the experiment had with the museum, and on the other, because of its good terrain properties - its location being far from human settlements and the lack of vegetation allowing good visibility.

The period of the shooting was chosen at a time when the experimental site is no longer visited by tourists, and days with favorable weather conditions were selected. There was light cloud cover (about 40% on November 13, and 60% on November 14). Occasional east and north-east winds of 8 to 12 km/h were recorded. The pressure was 1020 hPa and the temperature fluctuated between 7 and 9 ^{o}C. Accurate weather data was obtained from the meteorological station at the military airport in Dęblin for both days.

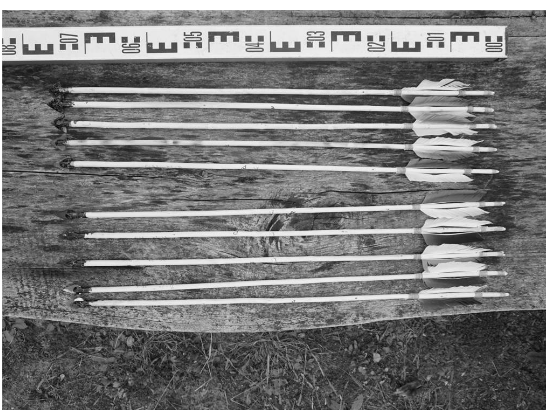

Figure 5: Dogwood arrows.

The first stage involved testing the ability of two archers of varying experience who each shot 10 arrows in two bursts. These activities were aimed at warming up the muscles, determining the maximum range, and establishing the influence of the weather on arrow flight.

These activities were followed by shooting at a straw target set up on a wooden frame. The aim of the activity was to check the effectiveness, i.e. accuracy and perforation properties, in relation to the distance and type of stem from which the shafts were made. Due to increasing gusts of wind, the shooting was carried out in the area of the nearby field-base belonging to the Museum, where trees and neighboring buildings created a forest-like shelter for the experiment. The shots at the base were fired solely by the research author.

Shots were fired in series from Holmegaard and Bolków bow replicas. A straw disk with a diameter of 1 m was used as a target, first with a paper shooting matrix glued on, and in later tests covered with calf skin with retained hair. At a distance of about 3 m behind the target, an arrow holder made of plastic was placed in order to stop the shots. Shooting was done from to 40 m and 25 m trials; the focus was also put on shooting from a distance of 20 m. Forty meters is considered the maximum at which–according to the Polish Hunting Association[25]—a shooter can, in favorable conditions, approach an animal without scaring it away.

Results

Effects and Results of the Manufacturing Phase:

The first stage of the experiment produced 46 arrows from tree stems. They were categorized according to their total weight, the species from which the shaft was made, and the type of arrowhead mounted. During the manufacture of the arrows, differences in the structure and physical properties

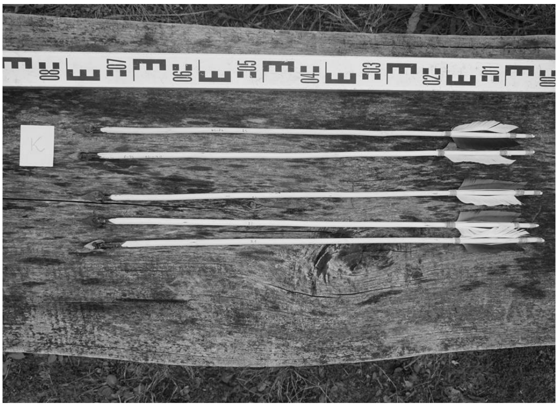

Figure 6: Viburnum arrows.

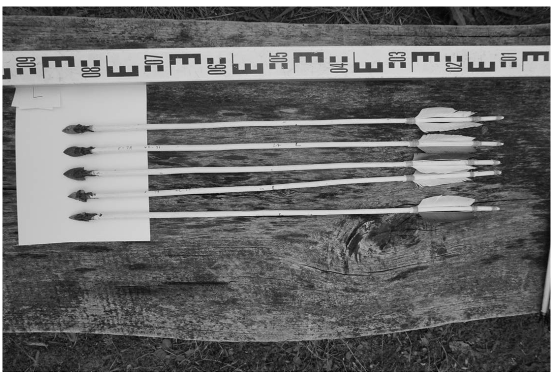

Figure 7: Hazel arrows.

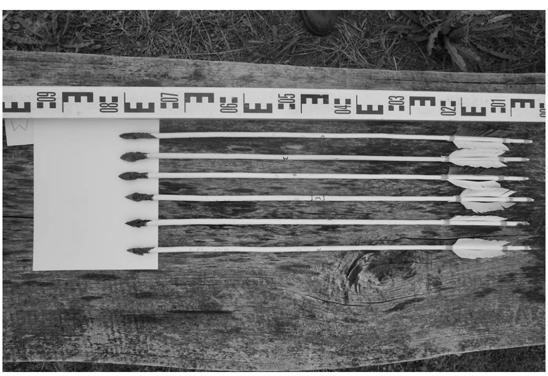

Figure 8: Willow arrows.

of the various stems were noticed, and these differences affected the process of production and the flight properties of the arrows. Stems of the same species (in this case, both viburnum and dogwood) collected at different times of the year behaved the same, both during arrow production and during arrow use. During shoot debarking, it was observed that fresh stems, which were also processed, behaved much better when using the flint tool than stems naturally dried with the bark. Nevertheless, only dried stems were used for the following manufacture and shooting. The time taken to debark such a stem ranged from 10 to 15 min, irrespective of the plant species. The bark came off in the form of long moist "strands", even after pulling once with the edge of the tool. In the case of dried stems (after a minimum of 14 days of drying), the working time increased considerably and significant differences between individual plant species could be observed. The hazel specimens took the longest to debark, and they were ready only after 40–45 minutes. Less time was needed to work with the raw material obtained from willow and dogwood; in their case it was about 25 minutes. The fastest, about 20 minutes, was the debarking of the viburnum. The way the bark came off also varied: dry pieces resembling elongated sawdust fell off, and one place had to be processed many times due to pulling off successive layers of bark. Therefore, it is likely that in the past shoots were debarked fresh, using a flint tool, regardless of wood species, to minimize processing time. Individual stems differed in their physical properties: the stiffest were the dogwood shafts, followed by the viburnum and hazel ones, while the willow stems were the most flexible. A correlation between shaft stiffness and mass existed: thicker shafts were stiffer. Moreover, stiffer shafts were less susceptible to straightening and mechanical processing, such as trimming or cutting. However, during shooting, they had better ballistic properties, such as: keeping the given flight trajectory, better accuracy, and resistance to wind gusts.

Plant Species and Shafts Parameters:

Dogwood (*Cornus mas* L.):

The material is hard and compact, difficult to break, and ideal for arrows despite two defects, one of which disappears during processing: it is heavy and returns to its original shape. Drying eliminated the curving shape of the spar but it had no effect on the weight of the shoot.

Viburnum (*Viburnum opulus* L.):

After initial straightening, the stems held their shape without wiggling. There was a concern during production that they may be too fragile, but the ballistic experiment showed that these arrows worked perfectly with the Bolków bow. Still, they appeared to be lightweight and more brittle than dogwood arrows. With a distinct spongious inside, this wood can be classified as very good shaft material. because pinned tips could be inserted easily. Lastly, it dries much faster than dogwood.

Hazel (*Corylus* L.):

After exchanging experiences with archer fellows from the Polish archery community, the author worried whether hazel shafts would perform well during ballistic research. The concern was about elasticity as one of the fellows claimed that hazel rods were not elastic but rather plastic (they deform, but do not return to their shape). Therefore, the danger was that they may not remain straight. However, not only did the experimental work show that hazel shafts could be shaped well, but instead of revealing "plastic" behavior, shooting results showed that hazel is too elastic by nature. This disturbed the flight trajectory of the arrows even more than potential plasticity. The relationship between hazel wood's mass and elasticity was found to be unbalanced in favor of the latter, which prevented accuracy.

Willow (*Salix* L.):

During the shooting sessions, it became apparent that willow was too light, brittle, and prone to deformation. Its flying behavior was clearly related to the force imparted during firing, which manipulated it in the process. Nevertheless, six such arrows were made for comparison. Due to the fact that this wood produces light arrows, it was perhaps not used for classic hunting but for long distance shots.

Effects and Results of the Shooting Phase:

Even though the willow arrows had the most hits in relation to the number of shots, the shooter found releasing them to require the most effort and the longest aiming. They were shot at the end of the trials, which could bias the results due to the archer gaining "practice" in that particular position and for a particular target[26]. The dogwood and viburnum shaft arrows showed good ballistic properties, achieving 37.5% and 33.3% hits of the target respectively. Hazel arrows performed the worst, which may be due to their excessive flexibility. The replica bow from Bolków was clearly dominant when it came to accuracy, with the dogwood and viburnum arrows achieving very good results (>50% hits). The Holmeggard bow, even when shooting large numbers (>5) of arrows, achieved very poor results or no hits at all, which may be related to a mechanical defect in the bow (weaker lower arm). A similar number of arrows were shot from both bows (28 to 25 in favor of the replica of the bow from Bolków), but accuracy was almost twice as high in the Bolków case. Preparatory shooting with replicas of medieval bows with split wood arrows, conducted the day before and on the day of the tests, showed more precision at the best distance (20m) which was 85 percent (17 hits out of 20). Even at a distance of 40 m, medieval arrows hit the target more often than arrows made from tree stems (12 hits out of 20).

<u>Discussion</u>

The experiment was conducted as designed,

Arrow shaft	Number of shots	Bow type	Number of hits	Number of hits (percent)
Dogwood	16	Bolków (B) (10) Holmegaard (H) (5)	5 (B) 1 (H)	37.5
Viburnum	18	H(11) B(7)	2 (H) 4 (B)	33.(3)
Hazel	13	B(8) H(5)	3(B)	23
Willow	6	B(2) H(4)	3 (H)	50
All	53	B(28) H(25)	18: B(12) H(6)	33,9: B(42.8) H(24)

Table 1: Shooting results according to shaft and bow type.

and the results provided data on the characteristics and performance of arrows made from shoots of selected species of trees and shrubs. Although this was not the immediate aim of the study, during the shooting phase it was found that the arrowheads that collided with the tripod of the target made of pine wood repeatedly cut through the wrapping as well as the shafts. It may suggest that despite the stems being reinforced with bone glue, they could also split when hitting the target, especially the hard parts of the animal, such as thicker skin, bones and antlers. This may also serve as indirect evidence that arrows were usually used as a one-shot projectile, since most of the important vital organs of an animal are in the chest chamber, well-protected by the rib cage (as in case of a wild pig or a deer). Hunters usually aim for the chest in order to kill the animals instantly. Nowadays, this is due to hunting ethics and tradition, but in the past this was a necessity. Indeed, a badly hit animal could get away, which forced a long search and sometimes even the loss of the prey[27]. In some communities, however, it was sometimes advisable to injure a large animal first and, while tracking it (persistance hunting strategy), wait for it to die of exhaustion. This is risky, because of the possibility of the animal escaping and the increased probability of attracting predators, also dangerous to the hunters.

It follows that arrows (and especially arrowheads) may not have been reusable especially when used on large preys. The easy availability of the stem material, and its simple and effective processing, seem to support this as well. It should be stated that the stems of the dogwood and viburnum arrows proved to be the best samples in terms of ballistic research. During the shooting sessions, willow and hazel arrows were found to be inadequate, especially their susceptibility to the negative influence of atmospheric conditions. Gusts of wind changed the flight path of the arrows slightly. They were also too elastic in relation to their low mass, which resulted in flight disturbances

The 33.9% overall hit rate with the arrows made from stems may seem quite low. Preparatory shooting with replicas of medieval bows with split wood arrows, conducted the day before and on the day of the tests, showed, at the best distance (20m) about 90% accuracy. Even at a distance of 40 m, about 40% of the arrows hit the target. On this basis, the following reasons for the poorer accuracy of prehistoric bows and arrows can be deduced:

(1) Stem versus split arrows: the stem structure is a smaller scale reflection of the tree structure with all of its weak points (i.e., irregularities in the grain, curvature, knots). The small scale of such weak points in the stem structure makes the arrow much more difficult to shape by the archer. Even when it can be shaped properly, there still remain some natural defects at the microscopic level that are impossible to correct. Split wood arrows extracted from tree may be much more often reused. As the author observed and discussed with other researchers from the experimental environment, the technique for making them is more advanced, and all potential weak points are much more visible, making it easier to shape the radius properly. The comparison shooting using medieval arrows proved that split arrows made from selected solid wood strips have better ballistic properties than stem arrows.

(2) Difference between bow replicas: the prehistoric bows used in the experiment had low tension and minor design flaws (e.g., weaker lower arm in the case of the Holmegaard bow replica–the lower arm of the bow worked less when shooting).

(3) Prehistoric versus modern shooters: the shooters who carried out the experiment had many years of experience with non-prehistoric bows, but even a few previous practice sessions with replicas of prehistoric bows and arrows could not eliminate some of the archer's reflexes associated with muscle memory (slight forward lean, different hand position, changed bow tension) These were advantageous in the case of modern bows and could prove to be useless or even disadvantageous for replicas of natural bows. By contrast, prehistoric archers only learned to shoot arrows from wooden straight bows, which after many years of training made them professionals in the use of this weapon.

It should also be noted that arrowhead type appeared to have no effect on shooting accuracy. If there was one, it must have been minimal and drowned out by the more influential arrow quality factors mentioned above. Instead, arrowheads appear to have a decidedly decisive effect on arrow penetration.

Conclusions

The study of arrow ballistics has a long tradition. However, experimental archaeologists have focused mainly on the mechanical damage done by arrowheads. Instead, the author of this paper, using evidence from the archaeological records, conducted an experiment testing the properties of arrow shafts made with dogwood, viburnum, hazel, and willow stems. The experiment not only demonstrated the different attributes of the various species of trees and shrubs, but also highlighted a number of difficulties associated with the proper handling of the research process. Hazel, which seemed attractive during the initial planning of the experiment, turned out to be disappointing in terms of effectiveness. Dogwood and viburnum arrows performed much better than the other types despite the relatively high spar weight. Research revealed that willow shafts are not suitable for short range shooting. The course of the experiment has shown how important the role of experimental archaeology is for the whole discipline: in the course of conducting experiments it verified that all tested species recorded in archaeological records are suitable for shooting, however each of them has particular properties. Yet, the experiment is also fraught with a certain degree of error due to the lack of a 100% reproduction of the original conditions that should have been recreated.

Acknowledgments:

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Endnotes:

1 Jankowski 2002, 6.
2 Coles 1977, 166–177.
3 Coles 1977, 7.
4 For instance: Barton and Bergman 1982, 237–248; Chesnaux 2008, 134–146; Crombe et al. 200, 253–269; Dmochowski and Pyżewicz 2012, 497–528; Fischer et al. 1984, 19–46; Grimaldi 2008a, 147–160, 2008b, 405–407; Grøn 1992, 9–12; Osipowicz and Nowak 2017.
5 For instance: Oddel i Cowan 1986, 195–212; Rots and Plisson 2014; Osipowicz and Nowak 2017.
6 For instance: Ikäheimo et al. 2004, pp. 3–20; Luik 2006; Zhilin et al. 2014; Zhilin 2016.
7 For instance: Montanari 2015, 74; Riesch 2002.
8 Meadows et al. 2018, 105–114.
9 Brizzi 2005.
10 Pilø et al. 2020.
11 Loades 2013.
12 Januszek 2016, 145–150.
13 Januszek et al. 2019; Manasterski et al 2020.
14 Oeggl 2009, 3; Sunyol 2013, 6.
15 Junkmans et al. 2019, 283–311; Oeggl 2009, 3.
16 Junkmans et al. 2019, 283–311 ; Sunyol 2013, 6.
17 Sunyol 2013, 6.
18 Foulds 2013.
19 Oeggl 2009, 3.
20 Bálint 2013.
21 Ennos 2016, 1–4.
22 Sunyol 2013.
23 Kear 1990, 49; Von Meissen 2001, 5.
24 Leuzinger and Rast-Eicher 2011, 535–542.
25 [http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU19970350215] accessed 13.04.2021.
26 Açıkada Cet al. 2004, 15–36 .
27 The performer, who is a hunter, had several cases of long searches for the so-called "shot", when, despite an exemplary hit in the heart area, the boar escaped and ran for about a kilometer. It should be noted that in spite of the use of modern weapons and ammunition, the boar was vigorous enough to escape.
28 For instance: Silberbauer 1981.

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