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How accurate was Bronze Age weighing in Western Europe?

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This paper aims to bring new insights about weighing practices and instruments during Late Bronze Age in Western Europe. Northern France and Southern England share the particularity of providing tiny balance beams and weights dedicated to weigh small quantities. It is traditionally accepted that most of the Bronze Age weights found in Western Europe correspond roughly to a same practice built around one metrological system. Nevertheless, the deviations observed between several weights which should correspond to the same values in the metrological system raise questions about the accuracy of the Bronze Age balances.

This paper synthesizes the general categories of weights and beams used during the Bronze Age in Northern France and Southern England and their main characteristics. Using new mathematical and digital protocols – sensitivity analysis, 3D modelling and simulation, and finite element analysis – we highlight the main mechanical features of the Bronze Age balances, the accuracy that should be expected with them and their resistance to use.

Our results show that ancient balances were way more accurate than what is generally estimated. They show that most of them should probably allow to see differences between the loading of the two pans less than 0.5 g in most of cases. These results also raise new interpretations about the use of metrological systems during the Bronze Age considering that certain weights, generally interpreted as the same value, would appear as completely different if they were put on each pan of such a balance. The resistance simulations also show that the bone beams were very robust and could support loading much heavier than the weights identified for the same period.

1. Introduction

For many years, archaeologists paid little attention to the mastery European protohistoric populations had over the concepts of numeration and metrology. It was not until the late 1990s that a research dynamic gradually developed on this matter based on new research tools and protocols. Over the past two decades, our knowledge of these systems has been completely renewed and it is now possible to attest the use of weights, weighing devices, and relatively complex metrological systems since at least the end of the Late Bronze Age (circa 13th Century BCE) in much of western and central Europe (Cardarelli et al., 1997; Cardarelli et al., 2001; Ialongo, 2019; Pare, 1999; Peake et al., 1999; Peake and Séguier, 2000; Rahmstorf, 2019; Poigt, 2019¹; Vilaça, 2003, 2011).

While balance weights are subject to particular interest today and lie

at the heart of research into ancient metrology, the weighing devices themselves remain poorly understood. This article proposes to consider the current tools allowing us to ascertain the precision and the limits of ancient weighing practices, most specifically in the Late Bronze Age in Western Europe.

Most of the weighing devices were probably only made from perishable materials from their first invention right up until modern times. As a result, they are inaccessible to archaeologists today. As such, the Western European context of the Late Bronze Age offers a real exception. Indeed, for this period we know of several balance beams made from hard animal matter (bone or deer antler), which helped them to be preserved, in several cases completed by copper alloy suspension elements. Given their small dimensions (most of the beams being less than 12 cm in length), these instruments were clearly used for weighing small quantities, traditionally known as “precision weighing”. However,

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¹ Most of the data presented here comes from a PhD thesis defended in September 2019 (Poigt, 2019) except for the whole finite element analysis developed by F. Comte and L. Adam.

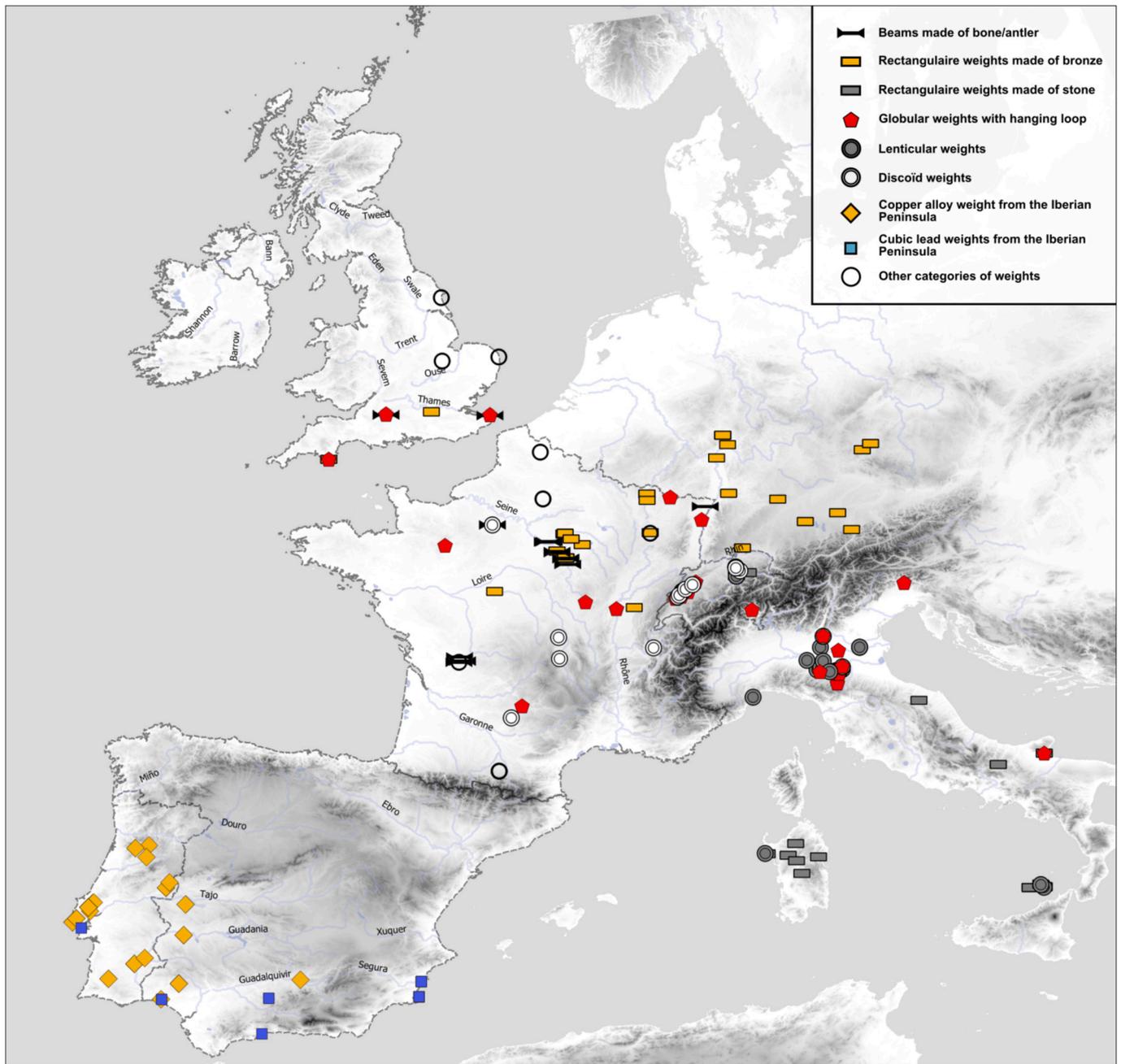


Fig. 1. Geographical distribution of Late Bronze Age beams and balance weights in Europe excluding the Mediterranean; geographical data after [Pare, 1999](#) (Central Europe); [Cardarelli et al., 1997 and Jalongo, 2019](#) (Italy and Sardinia); [Poigt, 2019](#) (Western Europe, thesis study area marked by the countries boundaries); map background: CGIAR-CS; GIS and DAO: T. Poigt.

the real sensitivity of these balances, the precision of a Late Bronze Age weighing operation, and the mechanical limits of such balance beams remain largely unknown.

We will try to shed new light on these questions here, basing our work on a paper by Sperber on this matter, from which we borrowed the title of this article ([Sperber, 1988](#)), as well as on the considerable contribution of digital tools in dealing with such problems.

2. Data

The balance beams we know of are only those made from deer antler or bone which were stored or abandoned in such a context that allowed them to be preserved. For this reason, their identification mainly reflects the use of a specific material for making the beams rather than the use of

balances. The most common examples have been found in funerary contexts in the Yonne valley, but balance beams have also been found in western France, including one dating to the Middle Bronze Age in Grotte des Perrats (Agris, France), in the south of England, and in the east of France ([Fig. 1](#)). Chronologically, apart from the above-mentioned example from Agris, the beams are almost all dated to the Late Bronze Age (circa 1300–850 BCE).

Their dimensions are particularly small, with the length of the beams generally between 7 and 17 cm. Most of them are cylindrical in shape with a central bulge. This central body has a very small diameter, of around half a centimetre but some examples are less than 3 mm in diameter in their thinnest part. Their distal ends can take the form of discs, knobs, or a tapering in diameter ([Fig. 2](#)). At least one well identified piece (beam no. 2 from Grave 298 in Migennes) is made of a

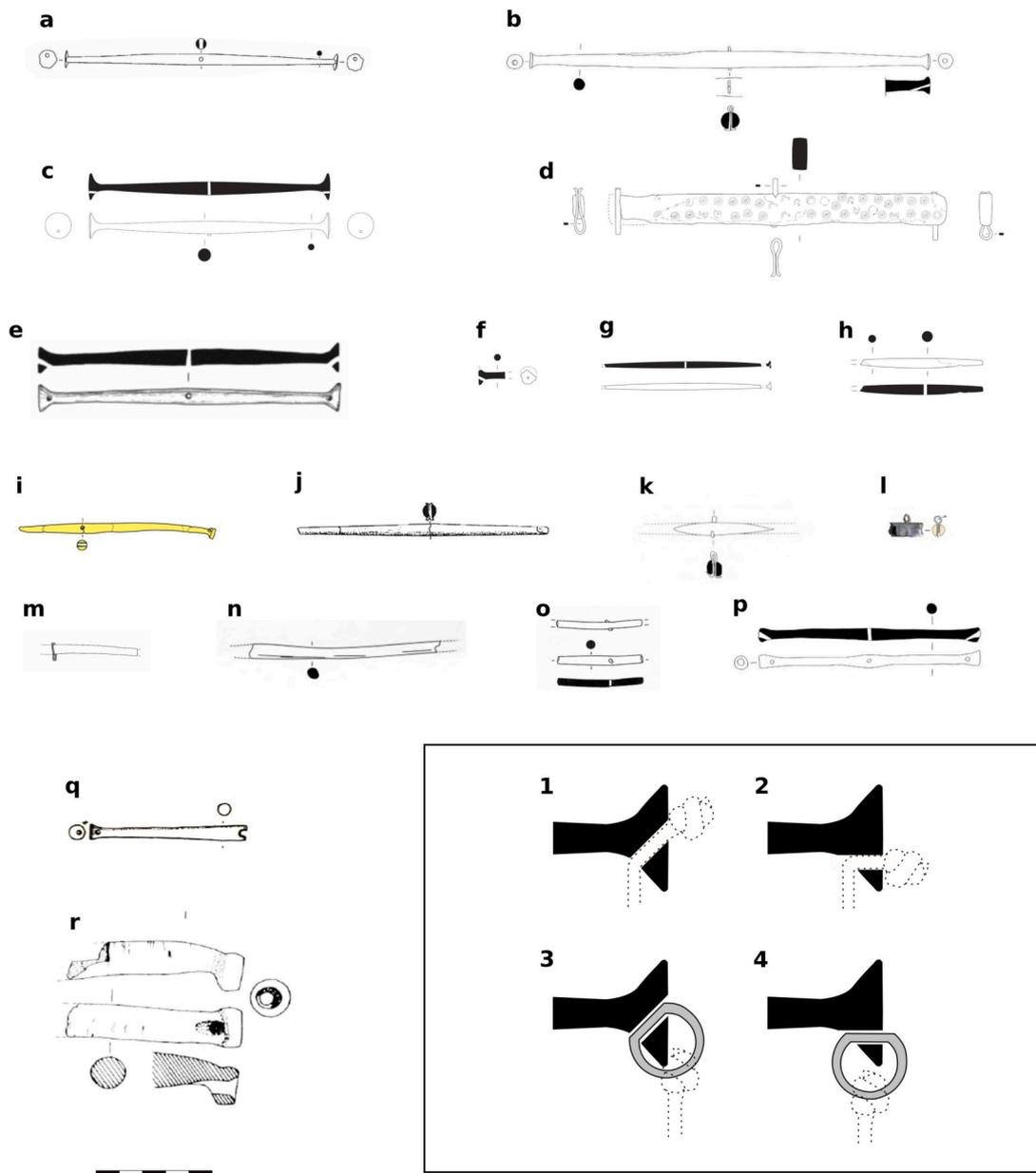


Fig. 2. Bone and deer antler beams identified in Western Europe (a-r) and suspension devices with (1–2) or without (3–4) intermediary element; a) Grave 13 from “La Croix de Mission”, Marolles-sur-Seine, after [Peake et al., 1999, Fig. 1-1](#); b) Cave Chaude “Bois du Roc”, Vilhonneur, after [Peake et al., 1999, Figs. 1-3](#); c) Beam 1 from Grave 298, “Le Petit Moulin”, Migennes, after [Roscio, 2007, fig. 32/298,35](#); d) Beam 2 from Grave 298, “Le Petit Moulin”, Migennes, after [Roscio, 2007, fig. 32/298,13](#); e) Midden of Potterne, after [Lawson, 2000, fig. 97–98](#); f) Grave 267 from “Le Petit Moulin”, Migennes, after [Roscio, 2007, fig. 32/267,5](#); pl. 68–5; g) Grave 284 from “Le Petit Moulin”, Migennes, after [Roscio, 2007, fig. 32/284,6](#); h) Grave 251 from “Le Petit Moulin”, Migennes, after [Roscio, 2007, fig. 32/251,5](#); i) Grave 90 from “Le Brassot”, Étigny, after [Muller, 2007, fig. 18–28](#); j) Grave 5 from “Les Gours aux Lions”, Marolles-sur-Seine, after [Pare, 1999, Fig. 20-14](#); k) Grave from Monéteau, after [Joly, 1965, Fig. 21-3](#); l) Cliffs End Farm, Isle of Thanet, after [McKinley et al., 2014, Fig. 5.9-1](#); m) Grave 61 from “La Croix-Saint-Jacques”, Marolles-sur-Seine, after [Prévost-Delattre and Peake, 2015, fig. 18, pl. 60](#); n) Grave 18 from “Les Prés Pendus”, Passy-Véron, after [Peake and Séguier, 2000, Fig. 3-3](#); o) Grave 57 from Weissensee/Oberfeld, Haguenau, after [Roscio, 2018, pl. 20–7](#); p) SU 1084 from “La Grotte des Perrats”, Agris, after [Peake et al., 1999, Figs. 1-2](#); q) “locus” B543 from Fort-Harrouard, Sorel-Moussel, after [Mohen and Bailloud, 1987, pl. 85.8](#); r) “Salle des Dalles”, Grotte du Quéroy, Chazelles, after [Gomez de Soto et al., 1991, fig. 16.31](#).

quadrangular bar, 14 cm in length ([Fig. 2](#)).

The identified beams all have a central vertical perforation with the exception of the beam from Grave 90 in Étigny, where it is horizontal. In many cases (8 of the 18 identified beams), the remains attest to the use of a copper alloy loop to ensure the central suspension and balance of the instrument ([Fig. 2](#)), while this is the case with the distal suspension only for beam 2 from Grave 298 in Migennes. The recurrence and homogeneity of these metallic elements suggests that they must have been a common solution, perhaps also in the case of wooden beams, although

no such suspension loop has yet been found isolated. From a mechanical point of view, it ensues that the point of support of these beams is higher than the axis of the beam itself which, according to Sperber’s observations and calculations, tends to move the centre of gravity away from the geometrical centre of the beam and thus to reduce its sensitivity ([Sperber, 1988, 160](#)). The indications of distal suspension systems, intended to hold the pans, are more varied. In the case of beams with discoid ends, the lower part of the disc has sometimes been horizontally perforated. In the case of beams with simple ends or with distal knobs,

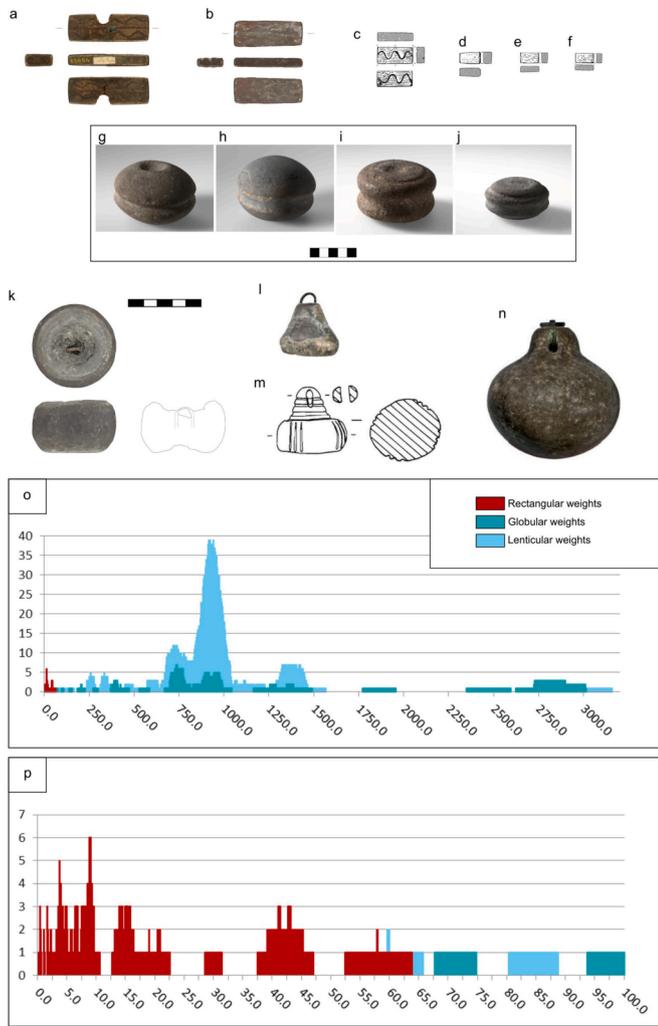


Fig. 3. Examples of rectangular weights (a-f), lenticular weights (g-j) and globular weights with hanging loop (k-n); mass distribution of the weights analysed by category between 0 and 3000 g (o) and 0–100 g (p) accepting a 5% error; a) Noyers-sur-Cher “Saint-Lazare”, b) Salcombe shipwreck, (c-f) Barbuise-Courtavant “Les Grèves”, grave 7 (Pare, 1999, fig. 16); (g-h) Zürich-Alpenquai (Landesmuseum Zürich, n# A-26108 and A-26091), i) Berg am Irchel (Landesmuseum Zürich, n# A-2303.8); j) Zürich-Wollishofen (Landesmuseum Zürich, n# A-1152); k) Auvernier, l) Estavayer (Feth, 2014, Figs. 3-5), m) Mörigen (Mohe and Bailloud, 1987, pl. 173–12) n) Grandson-Corcelettes (Feth, 2014, Figs. 2-10).

the perforations are generally vertical. At the same time, oblique perforations have been observed regardless of the type of extremity concerned. They always have an opening towards the extremity in the axis of the beam, which continues diagonally towards its inner part and then opens out in the lower part of the beam in its central body (Fig. 2). For optimal use, to limit friction on the edge of the beam, it is likely that the suspension wires were passed up through the lower part of the beam. They could then have been retained quite simply by a knot in the upper, distal part of the oblique perforation (Fig. 2).

The use of an intermediate metal piece between the beam and the suspension wires has been proposed on the basis that the perforations are too narrow (1.5 mm in diameter) to allow a sufficiently solid fibre to be passed through them to allow for suspension (Peake and Séguier, 2000, 23). However, there is currently no material evidence to support this, with the exception of the quadrangular beam from Migennes (Fig. 2) which had three equal sized suspension loops: one central loop and two distal loops.

While the beams have relatively homogeneous characteristics,

several categories of balance weights can be identified for the Late Bronze Age in Europe: rectangular weights made from stone and copper alloy, lenticular weights made from stone, and globular or pear-shaped weights made from either stone, a stone body with a metal hanging loop, or entirely of metal. These categories of weights appear to correspond to different traditions and customs. Except in the Terramare and the Alps, where lenticular and globular weights have been identified in the same contexts, the different categories do not appear together in the same stratigraphic contexts. The rectangular metallic weights, whose identification we owe to Pare (Pare, 1999), are most closely related to the balance beams made from deer antler or bone. To begin with, they are found in spatially overlapping geographical areas and they have been found in clear association in two graves: Grave 298 in Migennes and Grave 90 in Étigny in the Yonne (France). They are also the only category of weights whose mass, like the dimensions of the beams, indicates the weighing of relatively small quantities (Fig. 3-a).

The weights in question, most of which were found in funerary contexts, have been the subject of several studies (Pare, 1999; Rahmstorf et al., 2010; Roscio et al., 2011; Poigt, 2019; Rahmstorf, 2019; Ialongo and Rahmstorf, 2019). The weights show a high technical investment – including inlay or tinning – and they tend to be associated with high social status markers as weapons, jewellery or precious materials as gold or amber, especially in tombs. For this reason, it is likely that they have been elite possessions rather than everyday object. In the funerary context, even if only a small part of the skeletons allows efficient anthropological studies, the best preserved ones are mostly grown up males (Roscio et al., 2011; Roscio, 2018; for a recent discussion on weights identity, see Poigt, 2021).

Despite a strong homogeneity in their form, in particular in the case of certain quadrangular ones with inlaid sinusoidal decoration (Fig. 3), the weights show a certain metrological heterogeneity in the geographical area studied (Poigt, 2019). The sets are made up of different numbers of balance weights which correspond to different measurement intervals and which do not appear to be based on a single specific unit (Fig. 3-b). In this regard, Ialongo and Rahmstorf recently concluded that there may have been a homogeneous metrological system at a European scale but based on different units (Ialongo and Rahmstorf, 2019).

Pare has put forward the hypothesis of the use of a European unit of approximately 6.1 or 12.2 g (Pare 1999, 505-506), derived from a unit of Aegean origin (Petrușo, 1978, 1992). While the results of his analysis appear valid for a large part of central Europe, with a few exceptions (see Rahmstorf et al., 2010, 99), the situation seems significantly different to the west of Europe (Poigt, 2019). Indeed, the only consensus that seems present here is that of a structuring unit which was frequently, but not exclusively, comprised between about 3.9 and 4.7 g, but the composition of the known sets shows a high variability in this regard. This interval is relatively small and one could envisage the existence of a single unit with a certain accepted margin of error (*Normzone* concept, see Viedebantt, 1917, 1923; Petrușo, 1992, 6-7, 13; Ascalone and Peyronel, 2006, 18). However, in some graves, sets of weighing equipment have been found intended to weigh reduced fractions of such a unit—in particular in Graves 90 in Étigny “Le Brassot” and 298 in Migennes “Le Petit Moulin”, in the Yonne, France—suggesting a system based on a sub-multiple of about 0.3 g. Such observations raise questions about the technical limits of Late Bronze Age balances and their capacity to estimate such low values. Through this, we can also question the reality of a 3.9–4.7 g structuring unit. Indeed, depending on the precision of the balances, we can either consider that the interval is the result of technical imprecision or postulate that metrological precision was not a fundamental objective for the populations that used these instruments.

3. Method

It is impossible to estimate the exact precision of an ancient balance because we would need to know the complete context of its use, the

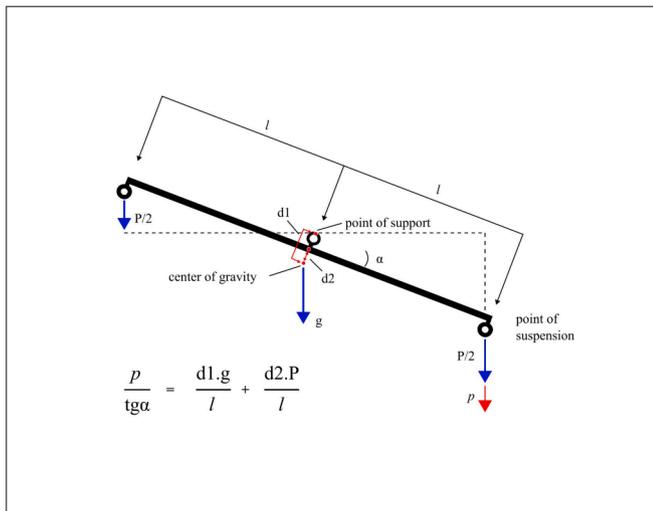


Fig. 4. Scheme of the balance beam deflexion and Sperber's equation (Sperber, 1988, 160).

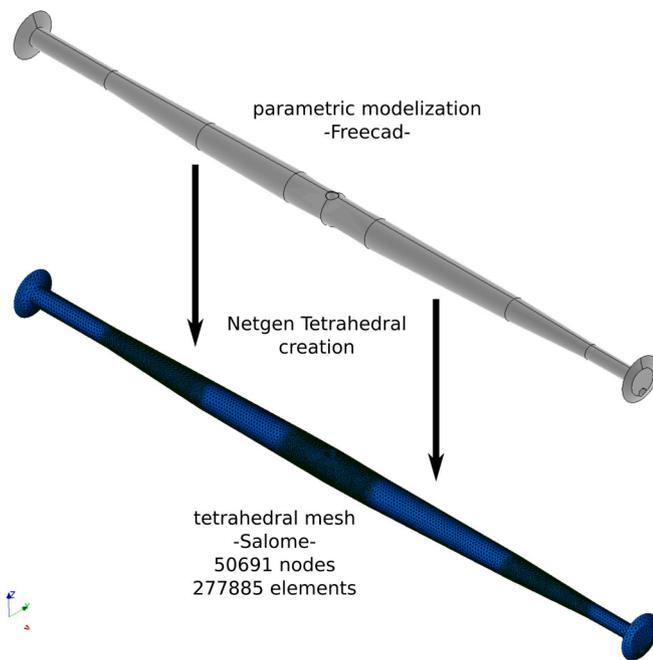


Fig. 5. Steps for creating a 3D model usable for mechanical study of the beam from "La Croix de Mission" (Marolles-sur-Seine): a parametric CAD type model at scale (top) allows the creation of a tetrahedral mesh with the NetGen tool (bottom).

degree of tolerance accepted by each weigher, whether or not any back-checks were carried out, and whether there existed any institutional standardization. It is, however, possible to gain an understanding of their sensitivity, in other words, the capacity of a balance beam to tip according to the difference in load between the two pans.

One of the most comprehensive experiments on the subject is that carried out by Sperber on several Viking balances by comparing the results of different weight combinations and the results obtained using mathematical models. In particular, he proposed to reduce the deflection of a balance beam to an equation whose variables correspond to the morphometric data of the balance (Fig. 4). Such an equation can easily be applied to the best-preserved balance beams from the Late Bronze Age. One of the main difficulties posed by his equation, however, was establishing the centre of gravity of the beam, which was necessary in

order to carry out the measurements. Nonetheless, the technological advances made since the publication of his article and their increasing accessibility now make it possible for us to circumvent this problem with the use of 3D digital modelling.

The first stage of the procedure therefore consists in creating 3D models of these beams from their 2D drawings. A certain degree of imprecision is of course inevitable with such an approach. However, our objective here was not to establish the precise sensitivity of each beam identified in the archaeological record but to estimate the sensitivity that can be achieved by the main known categories of beam in relation to their overall measurements². The different elements of the beams (main body made from deer antler or bone and copper alloy suspension loop) were the subject of different 3D models, based on which it was then possible to establish their volume and relative centre of gravity. By associating them with theoretical densities (8.7 for copper alloy and 0.5–2.3 for a wooden or bone element), it was possible to calculate the position of the centre of gravity of the complete beam and the mass of the beam. This data was then entered into the equation as values **d1** (distance between the centre of gravity and the central point of support), **d2** (distance between the centre of gravity and the virtual horizontal line connecting the two distal suspension points) and **g** (total mass of the beam) (Fig. 4). While the length, **L**, of the beam was an easily accessible figure, the value **P** was more problematic because it corresponds to the total mass of the elements suspended at the ends of the beam (pans and suspension elements) which have never been found in excavations in the chrono-geographical framework that interests us. We can deduce that they must therefore have been made of perishable materials, either in the form of wooden pans or simple nets, and that they must therefore have been relatively light. In our tests, we opted for a total arbitrary value of 20 g (i.e. 10 g at each end), as some of the copper alloy pans identified for other periods, such as the Late Iron Age in the Iberian Peninsula, weigh around 10 g. This is a high value intended not to overestimate the sensitivity of the balances. We can however consider that hanging elements made from perishable materials could have been lighter (about 7 g in the case of a material reconstruction based on a wooden pan and linen threads).

Using a simple computer tool, we digitalized Sperber's equation to allow a more dynamic display of the results of the experiments. It was thus possible to calculate the deflection of the beam (angle α) in relation to the overloading of one of its pans (p). This tool, which is more flexible than Sperber's calculations for different values, made it possible to visualize the evolution of this deflection in relation to the overload (see appendix). We were also able to determine the loss of sensitivity caused by the increase in loads specific to each pan. The more the pans are loaded, the more the balance will tend to lose its sensitivity for the same overload. In other words, an overload of 1 g will always have more of an impact on the deflection of a balance beam if the pans are empty than if they are already loaded with 100 g each, for example.

Studying the use of balance beams made from bone material also raises the question of the resistance to stress that this type of artefact would have had. Using tools for analysing mechanical phenomena, it is possible to estimate the maximum force that these beams could be subjected to before fracturing. For this we used the Salome-Meca software, which is specialized in finite element analysis. This numerical method makes it possible to discretize a continuous domain (such as a

² In order to evaluate precisely the mechanical characteristics of each discovered beam, one could argue that models from drawing can differ from the original object because of the conservation state of the artefact, the quality of the illustration or the modelling process itself. In that respect, a direct 3D scan of the beams should be preferred. Nevertheless, such a procedure was impossible in the context of this study – access to a 3D scanner, access to the artefacts and funding of the mission. Therefore, the method presented here shall be understood as an approach of the characteristics of Late Bronze Age balance in the broadest sense, and not a specific mechanical study of each beam.

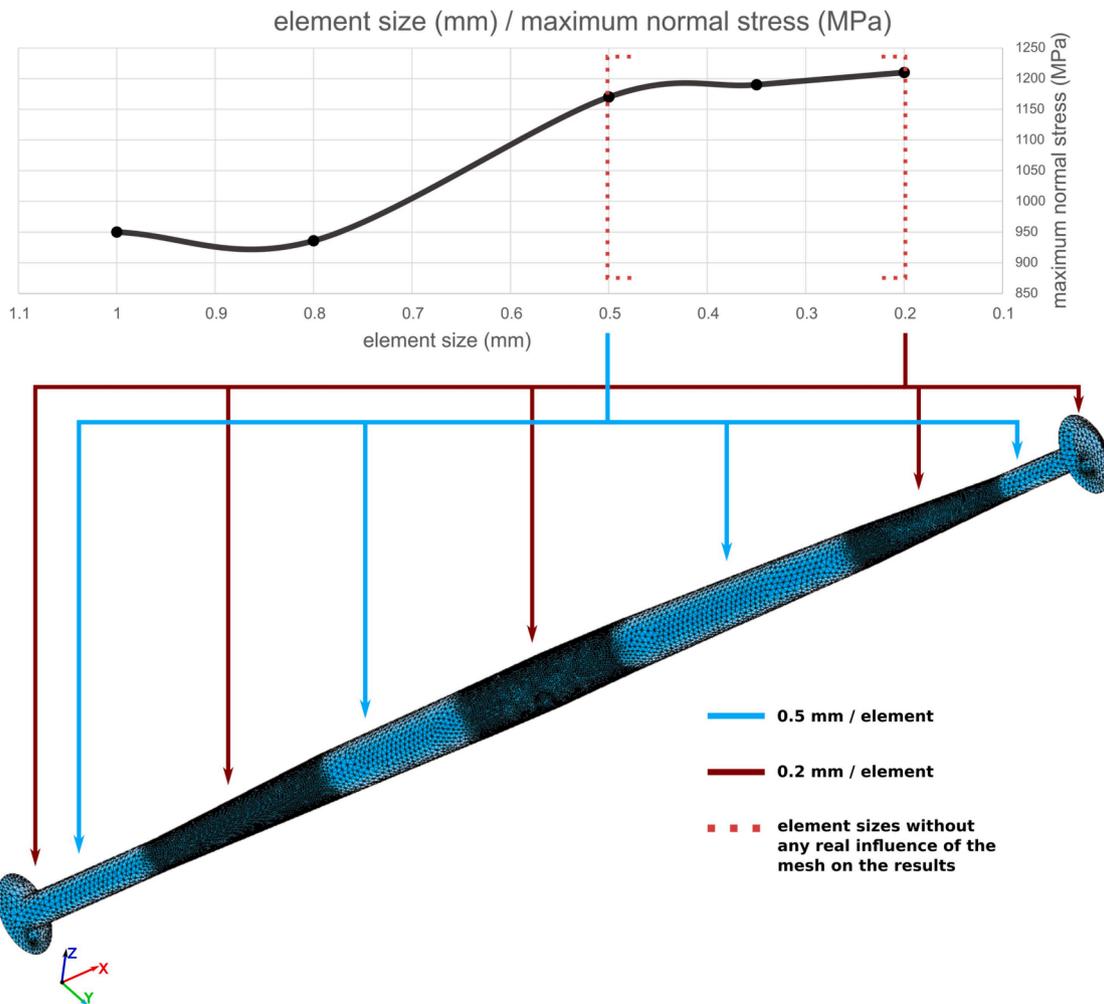


Fig. 6. The convergence study of the beam from “La Croix de Mission” (Marolles-sur-Seine) aiming to identify when the elements are no longer a significant factor in the measured results (the size, shape and complexity of the elements can change the results). It shows the importance of creating elements smaller than 0.5 mm with the more realistic results with elements about 0.2 mm.

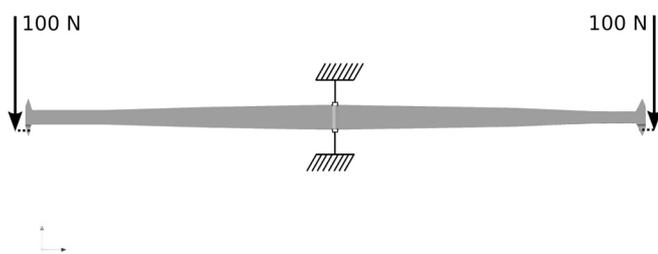


Fig. 7. Diagram of the forces applied on each beam with the central part “blocked” (either above or below to avoid divergences in the study) and a force of 100 N applied to the underside of each perforation of the disc.

surface or a volume) into a set of linked elements (via nodes) which makes it simpler to solve equations governing different physical domains, in this case, mechanics.

The objective of the analysis is simple: identifying the points of fragility in this type of beam and establishing the maximum load they can bear before breaking. Several factors limit the accuracy of the results, however.

Firstly, the analysis is linear, in other words, the relationship between the force applied and its consequences (internal strain and displacement) is linear, which is an approximation of reality. It is also static because the forces do not vary over time. These hypotheses make

the analysis simpler, while remaining close to reality for the purposes envisaged here.

At the same time, several parameters concern the material used. Each material has different characteristics, such as stiffness, strength, and ductility. Here, the material modelled in the analysis was a bovine cortical bone (used to make the beam from Marolles). Cortical bone is by nature a fragile material, that is to say, a material with low ductility: it fractures suddenly, without any real plastic deformation. Thus, the fundamental characteristic in studying its strength is its “normal stress upon rupture”, also called ultimate tensile stress. We know this from tensile tests, although it differs according to the specimens used. Here, we used an ultimate tensile stress of 220 MPa (Charron, 2008, 25), which represents a mass of approximately 22 kg per mm². Other approximations exist in defining the parameters of the material used, in particular its anisotropy, that is to say its mechanical behaviour, which differs according to the directions put under pressure. Because most of the pressure is towards bending, the stress mainly occurs along the axis of the beam. The characteristics of the material were therefore taken in this direction in order to minimize the consequences of the hypothesis of isotropy.

The first part of the work involved modelling the different beams as precisely as possible using the CAD software FreeCad, based on the published reports (including differences between the two sides and without restoring perfect symmetry, as with the sensitivity analyses of this study). This model was then imported into Salome-Meca, in order to

| No-load measurement (2x10g of suspension equipment) | | | Angle of deflexion | Ends movement | Angle of deflexion | Ends movement | Angle of deflexion | Ends movement |
|---|--------------|---------------------|--------------------|---------------|--------------------|---------------|--------------------|---------------|
| Beam material | Beam density | Beam total mass (g) | 0.1g | | 0.5g | | 1g | |
| Cedar | 0.5 | 0.8 | 1.9° | 1.9mm | 9.5° | 9.4mm | 18.5° | 18.1mm |
| Boxwood | 0.9 | 1.27 | 1.9° | 1.9mm | 9.4° | 9.3mm | 18.3° | 17.9mm |
| Deer antler | 1.7 | 2.25 | 1.8° | 1.8mm | 9.1° | 9.0mm | 17.8° | 17.4mm |
| Actual material | 2.28 | 2.96 | 1.8° | 1.8mm | 8.9° | 8.8mm | 17.4° | 17.0mm |

| Loaded with 60g (2x10g of suspension equipment) | | | Angle of deflexion | Ends movement | Angle of deflexion | Ends movement | Angle of deflexion | Ends movement |
|---|--------------|---------------------|--------------------|---------------|--------------------|---------------|--------------------|---------------|
| Beam material | Beam density | Beam total mass (g) | 0.1g | | 0.5g | | 1g | |
| Cedar | 0.5 | 0.8 | 0.5° | 0.5mm | 2.4° | 2.4mm | 4.9° | 4.8mm |
| Boxwood | 0.9 | 1.27 | 0.5° | 0.5mm | 2.4° | 2.4mm | 4.9° | 4.8mm |
| Deer antler | 1.7 | 2.25 | 0.5° | 0.5mm | 2.4° | 2.4mm | 4.9° | 4.8mm |
| Actual material | 2.28 | 2.96 | 0.5° | 0.5mm | 2.4° | 2.4mm | 4.8° | 4.8mm |

Fig. 8. Synthetic table of the sensitivity of the beam from Grave 13 "La Croix de Mission", Marolles-sur-Seine according to different materials.

| No-load measurement (2x10g of suspension equipment) | | | Angle of deflexion | Ends movement | Angle of deflexion | Ends movement | Angle of deflexion | Ends movement |
|---|-------------|---------------------|--------------------|---------------|--------------------|---------------|--------------------|---------------|
| Beam | Length (mm) | Beam total mass (g) | 0.1g | | 0.5g | | 1g | |
| Grave 13 "La Croix de la Mission" | 114 | 2.96 | 1.8° | 1.8mm | 8.9° | 8.8mm | 17.4° | 17.0mm |
| "La Cave Chaude" | 173 | 11 | 2.4° | 3.6mm | 11.7° | 17.6mm | 22.6° | 33.2mm |
| Beam 1 from Grave 298 "Migennes" | 101 | 2.64 | 1.6° | 1.4mm | 8.1° | 7.1mm | 15.9° | 13.8mm |
| Beam 2 from Grave 298 "Migennes" | 141 | 24 | 0.9° | 1.1mm | 4.3° | 5.3mm | 8.6° | 10.5mm |

| Loaded with 60g (2x10g of suspension equipment) | | | Angle of deflexion | Ends movement | Angle of deflexion | Ends movement | Angle of deflexion | Ends movement |
|---|--------|---------------------|--------------------|---------------|--------------------|---------------|--------------------|---------------|
| Beam | Length | Beam total mass (g) | 0.1g | | 0.5g | | 1g | |
| Grave 13 "La Croix de la Mission" | 114 | 2.96 | 0.5° | 0.5mm | 2.4° | 2.4mm | 4.8° | 4.8mm |
| "La Cave Chaude" | 173 | 11 | 0.8° | 1.1mm | 3.8° | 5.7mm | 7.5° | 11.3mm |
| Beam 1 from Grave 298 "Migennes" | 101 | 2.64 | 0.4° | 0.4mm | 2.2° | 1.9mm | 4.3° | 3.8mm |
| Beam 2 from Grave 298 "Migennes" | 141 | 24 | 0.3° | 0.4mm | 1.5° | 1.9mm | 3.0° | 3.7mm |

Fig. 9. Synthetic table of the sensitivity of beams with different morphometric features.

| beam origin | | fig2-a - Marolles | fig2-b - Vilhonneur | fig2-c - Migennes |
|--|---------------------------------------|-------------------|---------------------|-------------------|
| bovine cortical bone ultimate tensile stress (Mpa) | | 220 | 220 | 220 |
| area A (the central pin) | measured stress for 100 N / pan (MPa) | 1900 | 702 | 1200 |
| | force for fracture (Newton) | 11.6 | 31.3 | 18.3 |
| area B (the distal tapering on the left arm) | measured stress for 100 N / pan (Mpa) | 686 | 206 | 540 |
| | force for fracture (Newton) | 32.1 | 106.8 | 40.7 |
| area C (the distal tapering on the right arm) | measured stress for 100 N / pan (Mpa) | 863 | 82.8 | 520 |
| | force for fracture (Newton) | 25.5 | 265.7 | 42.3 |
| area D (the left perforation) | measured stress for 100 N / pan (Mpa) | 265 | 264 | 91.2 |
| | force for fracture (Newton) | 83.0 | 83.3 | 241.2 |
| area E (the right perforation) | measured stress for 100 N / pan (Mpa) | 160 | 138 | 70 |
| | force for fracture (Newton) | 137.5 | 159.4 | 314.3 |

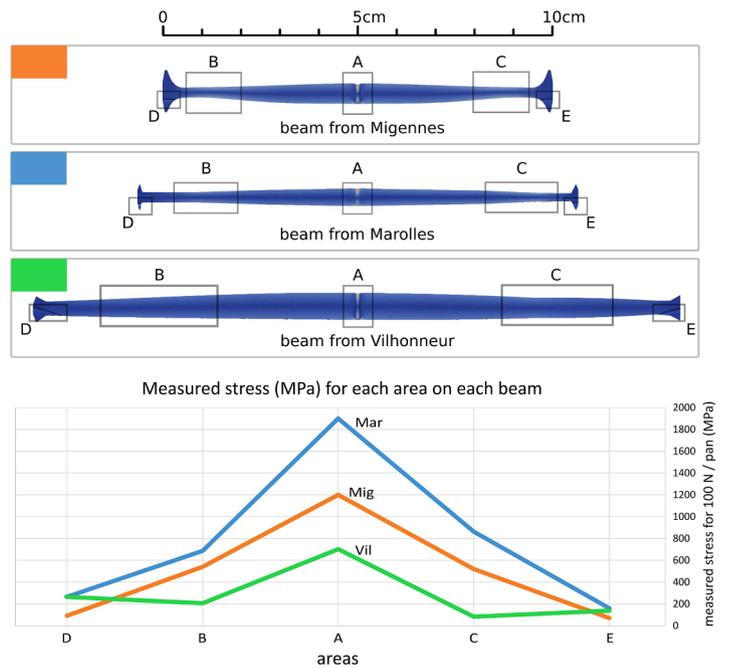


Fig. 10. Table, schemes and chart synthesizing the measured stress for the beams 1 from Grave 298, "Le Petit Moulin" Migennes, the beam from Grave 13 "La Croix de Mission", Marolles-sur-Seine and the beam from "La Cave Chaude", Vilhonneur with results showing that the central part is much more solicited than the rest of the beam.

mesh this parametric geometry with elements supporting the analysis. Those used for the study were tetrahedra because they are suitable for meshing complex shapes (Fig. 5). Furthermore, we used first order elements, which are faster to calculate but more approximate: the displacements are linearly approximated within the elements, which

implies that the stress on each element is constant. A large number of elements were therefore needed to take into account the spatial variations in stress. A convergence study was thus carried out on one of the beams in order to define the size of elements that made it possible to minimize the influence of the mesh on the results obtained (Fig. 6).

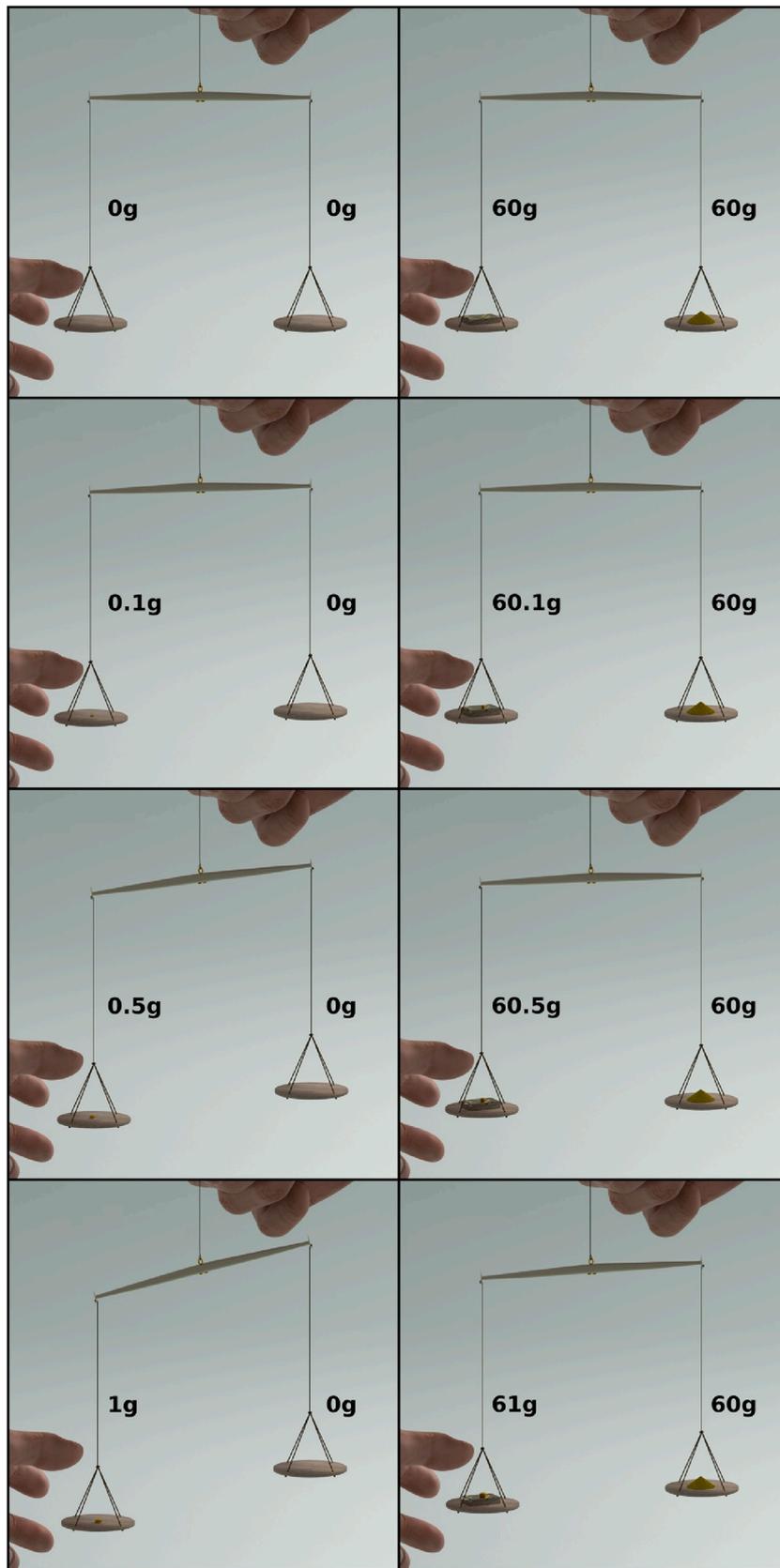


Fig. 11. Deflexions simulation of the beam from the Grave 13 "La Croix de Mission", Marolles-sur-Seine according to different overloading of one pan.

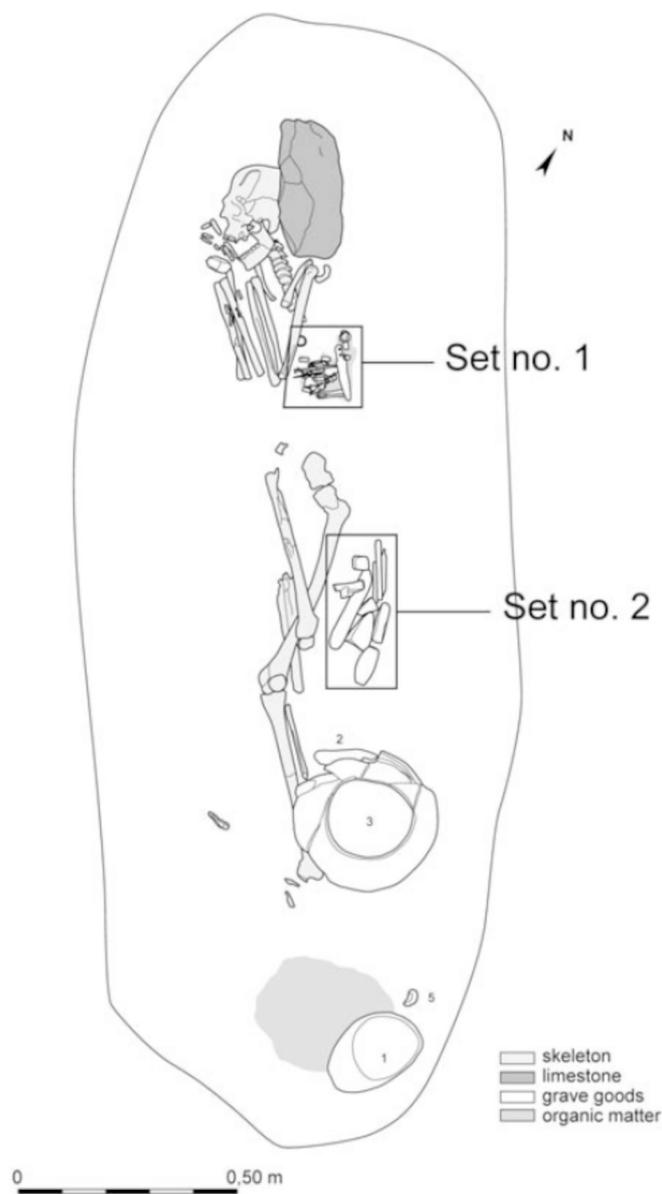


Fig. 12. Plan of Grave 298 from “Le Petit Moulin”, Migennes, after Roscio et al. 2011, Fig. 2-a.

Once the analysis model had been created, it was possible to define the parameters of study, in terms of the material, limits, and loads using Code_Aster. The area used for holding the model had to be located above and below the central hole, to prevent singularities. This choice avoids any inconsistent behaviour beyond the scope of the study. The force was applied on the undersides of the perforations onto which the pans were hooked (Fig. 7).

Each model was analysed with an applied force of 100 N (approximately 10 kg) per pan. Because the relationship between the forces applied and the stress borne was linear, a simple cross product allowed us to estimate the applied force that resulted in the observed stress upon rupture, namely 220Mpa.

4. Results

As mentioned earlier, the objective here was not to carry out a sensitivity analysis specific to each beam documented in the archaeological record. Thus, while certain elements, such as the systematic presence of a central copper alloy loop, the existence of an intermediate

metallic piece at the distal extremities (Peake and Séguier, 2000, 23), or the mass of the distal suspension elements could not be guaranteed, this did not prevent general scenarios from being proposed regarding the behaviour of these beams.

One of the first aspects that needs to be questioned regarding the sensitivity of the balances is the impact of differences in density of the central body. For, while we know of several examples made from deer antler or bone, it is likely that the majority of balances were made from wood. This factor is fundamental, because densities can vary greatly between different species of wood which have a density of less than 1, deer antler which has a density of 1.6 to 1.7, and very dense bones such as certain horse temporal bones which can reach a value of 2.3 (Crigel et al., 2001, Fig. 3). Characterizing the balance beam from Grave 13 in Croix de Mission allowed us to establish that it had been made from a bovine metapodial. By comparing the current mass of the object with the volume of the 3D model produced, its density could be estimated at around 2.28, which served us as a reference value.

In order to determine the impact of differences in density on the sensitivity of a balance, we created four scenarios involving a beam with the morphometric characteristics of the balance beam from La Croix de Mission, but made from different materials: i) not very dense wood (cedar: 0.5); ii) dense wood (boxwood: 0.9); iii) deer antler (1.7); and iv) the actual material with a density of 2.28 (here we have restored the height of the central copper alloy loop, which was found in a fragmentary state). The analyses were systematically carried out according to two hypotheses: that of empty pans and that of pans already containing 60 g each (the order of magnitude of the heaviest metallic rectangular weights). The results showed that if the overload of one of the pans increased (between 0.1 g and 1 g), the deflection also increased, but that this deflection was more marked in the case of empty pans than full pans (Fig. 8). On the other hand, we noted that the material from which the beams were made only had a small impact on the degree of deflection. Thus, even in the case of empty pans, with an overload of 1 g, the difference in deflection between a beam made from cedar wood and a beam made from a bovine metapodial, was barely 1 mm (or approx. 1°). This therefore implies that, for beams of such dimensions, the use of wood, deer antler, or bone should not visibly affect the functionality of the balance.

In contrast, the shape of the balance beams had a greater impact on their sensitivity. In this respect, we compared four beams with globally different shapes: the beam with distal knobs from the Cave Chaude in the Bois du Roc in Vilhonneur (Charente, France), the specimen with discoid ends and the rectangular beam from Grave 298 in Migennes “Le Petit Moulin” (Yonne, France) and the rectangular beam from Marolles-sur-Seine (Seine-et-Marne, France) was kept here as a reference but it should be remembered that unlike the previous three specimens, no central loop has been preserved for this balance and its height has been reconstructed here.

Comparing deflection at an equal overload clearly showed the significant difference caused by the shape and length of the beam (Fig. 9-1). Thus, the most sensitive beam was that from the Cave Chaude, which was also the longest for a mass of 11 g, i.e. a ratio of 0.64 g/cm. On the other hand, the rectangular beam was the least sensitive and had a mass/length ratio of 1.7 g/cm. However, with a globally equivalent mass/length ratio (approximately 0.26 g/cm), the two balance beams with discoid ends from Marolles-sur-Seine and Migennes showed significantly different results, the former being slightly more sensitive than the latter. The elements coming into play here were the length between the centre of gravity and the central fulcrum (reconstructed in the case of the balance beam from Marolles-sur-Seine) and the length between the central fulcrum and the horizontal line connecting the distal suspension points.

Overall, it is interesting to note that the empty balances all showed a deflection of the end of the balance beam of more than 1 mm for an overload of just 0.1 g and between 5 and 18 mm for an overload of 0.5 g. These values were obviously much lower in the scenario where the pans



Fig. 13. Deflexion simulation of the beam 1 from Grave 298 “Le Petit Moulin”, Migennes with an overloading of 0.18 g and 0.36 g of one pan.

were balanced by 60 g suspended at each end (Fig. 9-2), where deflection was around 2–6 mm for an overload of 0.5 g and around 4–11 mm for an overload of 1 g.

Regarding the resistance of these beams, finite element analysis offers particularly interesting results. The most critical points on the beams are the areas where the stress is highest in the model. They are however dependent on the quality of the graphic documentation used to model the artefacts, in particular concerning their asymmetry.

For the Marolles, Vilhonneur and Migennes n°1 type beams (Fig. 2-a, b, c), the points under the most stress were located in the area of the central perforation, as well as in the area of the distal tapering preceding the discs to a lesser extent. The perforations used to attach the pans did not appear to experience particular stress, which can be explained by their position, crossing the beam in its thicker parts.

In terms of the maximum load before rupture, the central area remains the most fragile³: for beam from Migennes (Fig. 2-c), it was at 18

N (1.83 kg) per pan. For the beam from Marolles (Fig. 2 -a), the rupture comes at 11 N (1.12 kg) per pan. For the beam from Vilhonneur (Fig. 2-b), the right arm breaks at 31 N (3.16 kg) (Fig. 10).

The maximum loads that can be borne by beams of this type are therefore high and far higher than the maximum masses of the sets of balance weights documented for the same chrono-geographical context. While it is thus theoretically possible that these balances were used to weigh loads of several hundred grams or even kilograms, their very small dimensions cast doubt on such use.

5. Discussion

There is an important step between determining the sensitivity of a balance and estimating its accuracy. While precision balances generally have a pointer or a plumb line that makes it possible to establish the deviation of the beam from a horizontal position, none of the examples identified suggest that such a device existed in the Late Bronze Age. Furthermore, it is difficult to assess the behaviour of such small instruments from drawings or figures alone. In this context, 3D rendering allows us to recreate scenarios by simulating the different weight combinations summarized in our tables. These simulations were carried out

³ The following being given for one arm, the results for a normal symmetrical use of the beam are 36N (3.67kg) for Migennes, 22N, (2.24kg) for Marolles and 62N (6.3kg) for Vilhonneur.



Fig. 14. Simulation of the comparison weighing of the weights of Barbuise (4.74 g on the left pan) and Grave 298 “Le Petit Moulin”, Migennes (4.32 g on the right pan) corresponding to a similar unit.

using our reference specimen: the balance beam from Marolles-sur-Seine. The results show that when such a balance is empty, deflection becomes perceptible at between 0.1 and 0.5 g, whereas it only becomes perceptible at between 0.5 and 1 g when it is loaded with 60 g in each of its pans (Fig. 11). All these results suggest that these balances were sensitive, or even highly sensitive.

The metrological study of certain sets of balance weights suggests the use of metrological systems based on very light units, however. This is notably the case for the set from Inhumation Grave 298 in Migennes, which appears to have been based on a unit of 0.36 g, for which the lowest theoretical value represented was 0.18 g (Rosco et al., 2011; Poigt, 2019, 221-226). One of the unique characteristics of this grave is that it included a set of at least 5 balance weights and 2 balance beams made from hard animal matter. The above results imply that the rectangular beam is unlikely to have been used in a weighing process involving such small quantities however, as it was the least sensitive in

our sample (Fig. 9).

The distribution of the accompanying items in the grave clearly highlights two groups of elements that were physically separate from each other. The beam with discoid ends and the weights are associated with a wide variety of other funerary goods including weapons, clothing elements, razor, tweezers or gold fragments (set 1, next to the elbow) while the rectangular beam appears with likely metallurgist or goldsmith tools (set 2 next to the legs) (see Roscio et al., 2011; Roscio, 2018). The rectangular balance beam was not therefore directly associated with the balance weights, unlike the beam with the discoid ends (Fig. 12), which is more sensitive. Simulating a weighing scenario for the two lowest values (0.18 g and 0.36 g) clearly shows that the deflection is perfectly perceptible for the higher value (deflection of around 5 mm) and must also have been so for an informed observer in the case of the lighter value (deflection of about 3 mm) (Fig. 13). It should also be remembered that our sensitivity calculations were carried out on the

basis of suspension materials weighing 10 g each. However, this mass could easily be reduced, in particular in the case of nets or other textile materials, which would cause an increase in the general sensitivity of the balance (deflections of approximately 10 and 6 mm for suspension material weighing 2×5 g).

These results do not allow us to guarantee the real precision of each individual Late Bronze Age balance, which depends on a large number of criteria, including the degree of tolerance accepted by the weigher. On the other hand, these different tests make it possible to reject the hypothesis of the poor sensitivity of the balances affecting the metrological systems. They also allow us to confirm that these balances did not present any technical limits to the creation and use of metrological systems based on very light units, of the order of a decigram, as the hypothesis was suggested for the set from Grave 298 from Migennes (Roscio et al., 2011; Poigt, 2019, 221-226).

Furthermore, it is clear that the mechanical limits of the beams were unlikely to be reached during “normal” use—the maximum load they could bear (between 1.2 and 3.1 kg) being at least 20 times greater than the heaviest known weights (approx. 60–65 g) and 7 times greater than the heaviest complete set identified (Richemont-Pépinville grave, approx. 182 g; Poigt, 2019).

The identification of the goods weighed by Late Bronze Age people is difficult. Associations between weighing instruments and metallurgy or goldsmithing practices markers have been pointed out in some contexts, but they are never systematic (Peake and Séguier, 2000; Poigt, 2019; Poigt, 2021; Roscio, 2018). We can roughly distinguish two different hypothetical weighing practices: a value quantification and a technical measurement. The weighing of small quantities can concern high value items or materials – as maybe amber, gold, or drugs – in a value assessment process, but also many other materials in a technical quantity calculation – as metals for alloys, plants or other natural resources for recipes or medicines. The absence of a strict association of the weighing with another activity on the base of archaeological proxies could suggest that the practice concern several kinds of materials, both in a logic of value quantification and technical measurement. However, the results presented here highlight the fact that the Late Bronze Age people was able to seek a high accuracy in the precision weighing of very light goods or materials as proven by the Grave 298 (Migennes) set of instruments.

6. Conclusion

Metrological research has clearly demonstrated the existence of tolerance margins in the weight units used during ancient periods, notably in the context of the Mediterranean societies of the Bronze Age (Viedebantt, 1917, 1923; Petruso, 1992, 6-7, 13; Ascalone and Peyronel, 2006, 18). This does not appear to explain the variation intervals observed between the structuring units of certain sets of balance weights however, and this variation cannot be explained by a technical deficiency either. Although some authors highlight a certain pan-European metrological uniformity (Pare, 1999; Ialongo and Rahmstorf, 2019), this could only have been the case, in the contexts which interest us here, if there were a tolerance in local metrological variabilities, which must have directly materialized in the use of the precision balances presented here. In other words, such a balance could not have been in equilibrium if it were used to compare two weights theoretically corresponding to the same unit but whose mass varied by a few decigrams (Fig. 14).

The homogenization of weighing practices seems to have applied more to the forms of the instruments than the metrological characteristics themselves (main unit, system of fractions and multiples, number of weights per set, etc.) even though the weighers probably had the technical skills to achieve true metrological uniformity. We cannot exclude possible chronological and geographical adaptations. But we can hypothesize that the absence of metrological uniformity in the material involved results in the fact that it was not the intended goal. These results therefore lead us to question the place of metrology in

these societies, which handled very small quantities of materials or products that appear to have been precisely quantifiable. In view of the currently available data, the practice of weighing appears to have been a relatively marginal phenomenon, which was the prerogative of an elite that shared certain codes (shapes of the instruments and general orders of magnitude) but that did not form part of any sufficiently interconnected processes to incite true metrological standardization (Poigt, 2019).

CRedit authorship contribution statement

Thibaud Poigt: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Florent Comte:** Methodology, Software, Writing – original draft, Writing – review & editing. **Louis Adam:** Methodology, Software, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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