3D model analysis of some Late Bronze Age and Early Iron Age swords from Cyprus

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ABSTRACT

This paper focuses on the study of ten swords from Cyprus of the Late Bronze Age (LBA) and the Early Iron Age (EIA). Using SolidWorks, a modelling computer-aided design and engineering program, we have produced 3D models of five bronze and five iron swords, based on their physical characteristics (mainly form and alloys). We ran tests on them by simulating cutting and thrusting blows at the maximum load of force, until their yielding point was identified. The iron swords were compared with their bronze predecessors and the benefits of using iron (as steel) instead of bronze were evaluated. This analysis offers new evidence on the old question of whether swords were used only as prestige objects by members of the elite or also as functional weapons. All the swords in our study were found to be capable of being used for both cutting and thrusting and we can therefore suggest that they were functional weapons, able to be used in battle.

INTRODUCTION

Our research project, entitled "*Swords in the Eastern Mediterranean from the Late Bronze Age to the Early Iron Age*", offers new evidence on an old question, namely whether swords were only prestige objects for the elite or functional weapons as well. Within the framework of this project, we explore the utilitarian aspects of swords by using the Computer Aided Engineering software SolidWorks, which examines the resistance of an object to applied force. By comparing bronze and iron swords, we investigate if iron swords were always better than bronze ones, as well as the reasons behind the predominant use of iron for this particular type of weaponry. Finally, we consider what, if any, relationships exist between socioeconomic changes and technological advances. In this paper we present some preliminary results from the mechanical simulations (tests) conducted on ten swords from Cyprus (Table 1) and discuss their implications.

METHODOLOGY

SolidWorks is a Solid Modelling Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) software, designed to evaluate the mechanical and physical properties of objects including heat transfer, motion and resistance to force. SolidWorks uses Finite Element Analyses (FEA), an approach for mathematically analysing the resistance to force of an object's form and material, based on mathematical equations. Miller was the first to use this software within the framework of his MA research on a group of Mycenaean swords, based on

Sword	Site	Context	Length	Reference
T.18 (Bronze)	Enkomi	Tomb 18	75 cm	Schaeffer 1952, pl. LXVIII
W.212a (Bronze)	Enkomi	Workshop-Well 212	60.9 cm	Matthäus 1985, taf. 140–41
W.212b (Bronze)	Enkomi	Work-shop-Well 212	59.2 cm	Matthäus 1985, taf. 140–41
Loizou Collection (Bronze)	Cyprus	Unknown	55 cm	Matthäus 1985, taf. 140–41
T.47 (Bronze)	Enkomi	Tomb 47	42.5 cm	Matthäus 1985, taf. 140–41
Idalion (Iron)	Idalion	W. Acropolis	79.7 cm	Åström 1967: 1, 89
T.76a (Iron)	Kouklia-Palaepaphos *Skales*	Tomb 76	67 cm	Karageorghis 1983, 216, 217, 230, pl. CXLIII, fig. CXLII; Vonhoff 2013, 202
T.76b (Iron)	Kouklia-Palaepaphos *Skales*	Tomb 76	54 cm	Karageorghis 1983: 216, 217, pl. CXLIII, fig. CXLII
T.210 (Iron)	Kouklia-Palaepaphos *Skales*	Tomb 210	64.5 cm	Karageorghis and Raptou 2016, pls. LXVI, XCVI
T.145 (Iron)	Kouklia-Palaepaphos *Plakes*	Tomb 145	45.5 cm	Karageorghis and Raptou 2014: 67, pls. XXXIX, XCII

Table 1. The swords chosen for our study and their contexts.

drawings from Sanders' typology.[1] We are adopting a much more detailed and diverse approach, also taking into strict consideration the methodological limitations of this software, when applied to ancient materials.

We designed 3D models of intact swords that are close to their actual and complete forms. We then ran tests by applying forces to these models, imitating sword blows, in order to determine their resistance. The applied forces simulate cutting and thrusting blows, applied to the sides of the blade and to the tip respectively. It should be noted here that SolidWorks shows the plastic deformation of an object, and not its breaking point. In our case, plastic deformation is sufficient to render a sword useless. SolidWorks gives one the opportunity to create and define new materials[2] and to evaluate the physical properties of a great variety of archaeological artefacts rapidly and without the expense of manufacturing them.

Two main factors affect the accuracy of our study. First, the models are more symmetrical than the originals because they are created by design software, and imperfections in the manufacture of the actual swords, both in materials and design, should also be considered. Second, although SolidWorks has a material library of bronze and steel alloys, none of them is an exact match to the ancient ones. It is possible to add new materials to the library of SolidWorks, but four basic mechanical properties need to be known: a) tensile strength, b) yield strength, c) ductility and d) Brinell Hardness. Unfortunately, these are not available for ancient alloys. In the future, we intend to conduct tests on metallic tubes made of recreated ancient alloys to define their mechanical properties more accurately. To overcome this present obstacle, we identified industrial alloys very similar to the ancient ones. Although this was a very tedious and time-consuming task, it enabled us to ensure a greater degree of accuracy in our study.

1 Miller 2017, 16–21.
2 Miller 2017, 16–7.

For the bronze alloy, we focused on two main factors in order to close the gap between the modern and the ancient alloys: first, the percentages of lead, tin and copper, and second the percentage of impurities and their influence on mechanical properties. It is worth mentioning here that one factor that affects mechanical properties, but cannot be measured exactly, is the very process of shaping the bronze object. The physical properties of the alloys dictate how the material should be worked by a metalsmith, but the exact process remains unknown in any detail, even though it seems that craftsmen followed a standard workflow, depending on the objects they wanted to create.[3] Experimental work regarding the techniques of manufacturing[4] and the metallography of some swords[5] helped us understand not only the process of hardening but also the most probable process of manufacturing.[6] Even so, overall, knowledge of the manufacturing process offers only limited assistance in understanding the variations in the values of the mechanical properties.

For our study we selected a bronze alloy after careful examination of 54 archaeometric analyses of swords from the Eastern Mediterranean.[7] The alloys range from 85–90% Cu and 9–11% Sn with <0.5 Pb. For bronze swords a high percentage of tin was used to increase their strength and elasticity,[8] while impurities were kept to a minimum to enhance performance.[9] Impurities such as Fe, Sb, P, Zn, As and Ni, below specific values, are considered either naturally present in the ore or an unintentional result of the smelting process. Their natural incidence may generally be set at Pb <0.3%,[10] Ni is an inadvertent impurity at <1%,[11] Fe <0.5%,[12] Zn <1.5%,[13] and Sb.[14] Some of these elements, as tests in modern alloys have indicated, can influence the mechanical properties of the artefact even in small quantities – thus P at >0.1%,[15] Zn >0.8%,[16] Sb >0.2%,[17] Ni >0.2%[18] and Fe >0.15%.[19]

Given the fact that swords were constructed from bronze with an insignificant quantity of impurities and with tin percentages ranging from 8–11%,[20] we decided to use an industrial bronze alloy with no impurities (UNS C90700). Every archaeometric analysis was matched with an industrial alloy from the Unified Number System (UNS) of the Copper Development Association. From these matches emerged two dominant groups of alloys, the first being Cu 87–90%, Pb <0.9% and Sn 9–11%, and the second Cu 82–85%, Pb <0.25% and Sn 15–17%. Each group corresponds to a UNS code of the American Copper Association. The applied type of alloy (UNS C90700)[21] has an average value of elements (Cu 89%, Sn 11%). It was chosen because in the majority of the archaeometric analyses tin does not surpass 10%. Every bronze 3D model sword in our study was "created" with this alloy.

3 Nerantzis 2012, 238.

4 Nerantzis 2012; Sapiro and Bryan 2016.

5 Tselios 2013, 91–2, 109.

6 As Nerantzis (2012, 238) notes "three hammerings, intervened by two annealing stages appear suitable for working a range of compositions in tin bronzes at 600°C for a short period of time".

7 A detailed discussion will follow in the final publication of the results of our research project.

8 Tselios 2013, 91–2.

9 Tselios 2013, 93, 104.

10 Papadimitriou 1995, 151.

11 Cheng and Schwitter 1957, 351.

12 Papadimitriou 1995, 155; Garbacz-Klempka et al. 2016, 227; Gouda et al. 2019, 1.

13 Craddock 1978, 2.

14 Eggenschwiler 1932, 626, 633–34; Dardeniz 2020, 2–3.

15 Durowoju and Babatunde 2013, 1801–3.

16 Osakwe et al. 2017, 34; French and Staples (1929, 1037) mention changes from Zn >4%.

17 Eggenschwiler 1932, 634.

18 Nnakwo et al. 2017, fig. 14-7.

19 Papadimitriou 2001, 719; Garbacz-Klempka et al. (2016, 234), however, suggest the largest changes at Fe >0.8%.

20 Tselios 2013, 93,104.

21 "Tin Bronze Sand Casting Alloy" by Azo Materials.

The term “iron”, when used in archaeology, covers many different forms in which the metal was used (iron bloom, wrought iron, steel etc.). Iron becomes superior to bronze when in the form of steel. To reach this state, it has to go through a complicated and difficult process (carburisation, quenching, tempering) in order to achieve its full potential. For the first phase of this experiment, and specifically for the Cypriot swords, we chose to use a medium-carbon steel alloy. There is evidence to suggest that the technological expertise to produce steel existed in Cyprus by the 11th–10th centuries BC at the latest.[22] More specifically, the alloy chosen from the existing material library is the AISI 1025 Carbon Steel (UNS G102500),[23] the chemical composition of which is most similar to the results of the archaeometric analyses, containing only carbon as its key alloying element. The percentage of Fe is very high, as it is in almost all the iron objects.[24] Other impurities do not affect the alloy properties. For example, manganese acts only as a deoxidiser, since it is considered an alloying element only when it exceeds 0.80%.[25] Therefore, the sole criterion for our choice was the percentage of carbon. There are specific examples from the metallographic analyses which give a percentage between 0.2 and 0.3% C.[26] When an iron object has been carburised and yields this percentage of carbon, it is considered a medium-carbon steel, which is a relatively hard metal, at least by ancient standards. Even with only the first step of the steeling process completed, the metal produced is still stronger than bronze.[27]

It is impossible to simulate a real-life battle environment and calculate all the applied forces on the swords. There are too many unknown variables which would influence the outcome: both regarding the environment of the battle and the user himself, namely his strength and training. Furthermore, the force applied to a sword depends on the velocity of the blow and the angle of impact, the warrior’s mass, the kinetic energy and acceleration of the object as well as the distance from the target.[28] Fortunately, it is not necessary to try to guess all these variables, which would in any case be an impossible task. For our experiment it was sufficient to calculate the yield point of the swords. The yield point is defined as a point on the stress–strain curve beyond which the material enters the phase of nonlinear pattern and suffers irrecoverable strain or permanent deformation. If a greater force is applied, the sword will deform and finally fracture. If the same force is repeatedly applied, there is a very real danger of fatigue. This is a very significant aspect, since plastic deformation renders a sword useless.[29] We therefore decided to apply to our sword models the maximum force until their “yield point” was reached.

Swords were usually equally capable of being used in both cutting and thrusting motions. However, scholars in the 19th and early 20th centuries favoured the idea that swords were either used only for thrusting or for cutting, mainly based on their own experience of their “gentlemanly” use.[30] Nevertheless, this is far from proven. Thus, one of the aims of our research project was to explore whether swords were used for cutting, thrusting or both. In order to investigate this question, we applied the loading force to the tip of the sword (simulating a thrusting blow) and also laterally to the centre of percussion (simulating a cutting blow), where the harmonics are such that maximum force is transferred at the target.[31]

In Von Mises plots the region that sustains the maximum pressure –and therefore is a potential weak point in the effectiveness of the weapon– is depicted. The URES scales, both in the case of cutting and thrusting, indi-

22 Tholander 1971, 22; Karageorghis 1982, 299; Maddin 1982, 310–11; Stech et al. 1985, 200; Kassianidou 2012, 237–40.

23 By Azo Materials. Chemical composition: Fe 99.03–99.48%, C 0.22–0.28%, Mn 0.3–0.6%, S ≤0.05, P ≤0.04%.

24 When observing low percentages in element tables from analyses, one must remember that this is due to the extensive corrosion sustained by the artefact; under normal circumstances Fe is about 97–99%.

25 Singh 2016, 7–11.

26 For analyses of Cypriot iron objects with similar results see Åström et al. 1986; Tholander 1971. Also, there are analyses in progress of EIA objects in NCSR Demokritos by M. Roggenbucke (personal communication, December 2020), which yield an average of 0.2–0.3% C.

27 Maddin 1982, 303.

28 Molloy 2008, 118; Hermann et al. 2020.

29 Molloy 2011, 74.

30 Molloy 2008, 124; 2010, 421.

31 Molloy 2011, 75.

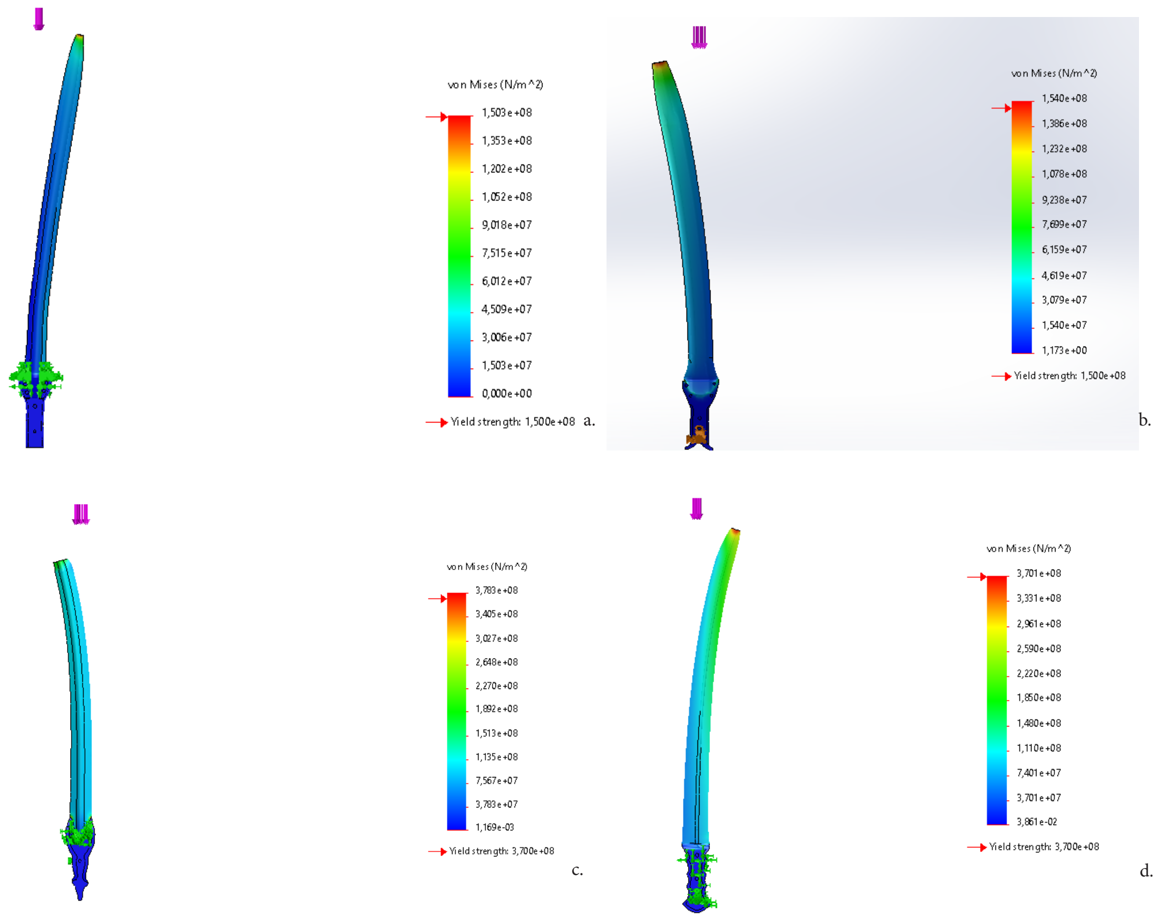

Fig. 1. Thrusting attacks: 1a: W.212a (upper left), 1b: W.212b (upper right), 1c: T.210 (down left), 1d: Idalion (down right)

cate the strain exerted on the sword due to the induced stress. The greatest deformation will occur on the tip and less towards the percussion point. It should be noted that the displacement results, as calculated by SolidWorks, are not one hundred percent accurate. Most of the millimetres of deflection will spring back to their original form (due to oscillation) and a low percentage may be residual. This applies to all swords; therefore, we will not present the URES scales for each individual case.

TEST RESULTS: BRONZE SWORDS

All the bronze swords in the study display a great resistance when employed in thrusting attacks, when forces of thousands of newtons result. Sword W.212b (Fig. 1b) and the example from the Loizou Collection present almost the same resistance in thrusting attacks, perhaps due to morphological similarities such as their length (ca 55–60 cm), width and the absence of a prominent midrib. It is surprising that in a thrusting attack sword T.18 can withstand double the force of sword T.47. A short blade like that of sword T.47 is very efficient for stabbing in a close-quarter thrusting attack.[32] Moreover, the significant discrepancy between the resistance of sword T.18 and sword W.212a (Fig. 1a) is very hard to interpret. Maybe these ambiguous observations are due to the fact that sword T.18 was reconstructed by Schaeffer from three fragments[33] or to the fact that it is heavier

32 Jung and Mehofer 2008, 121.

33 Schaeffer 1952, fig. 107; Jung and Mehofer 2008, 123.

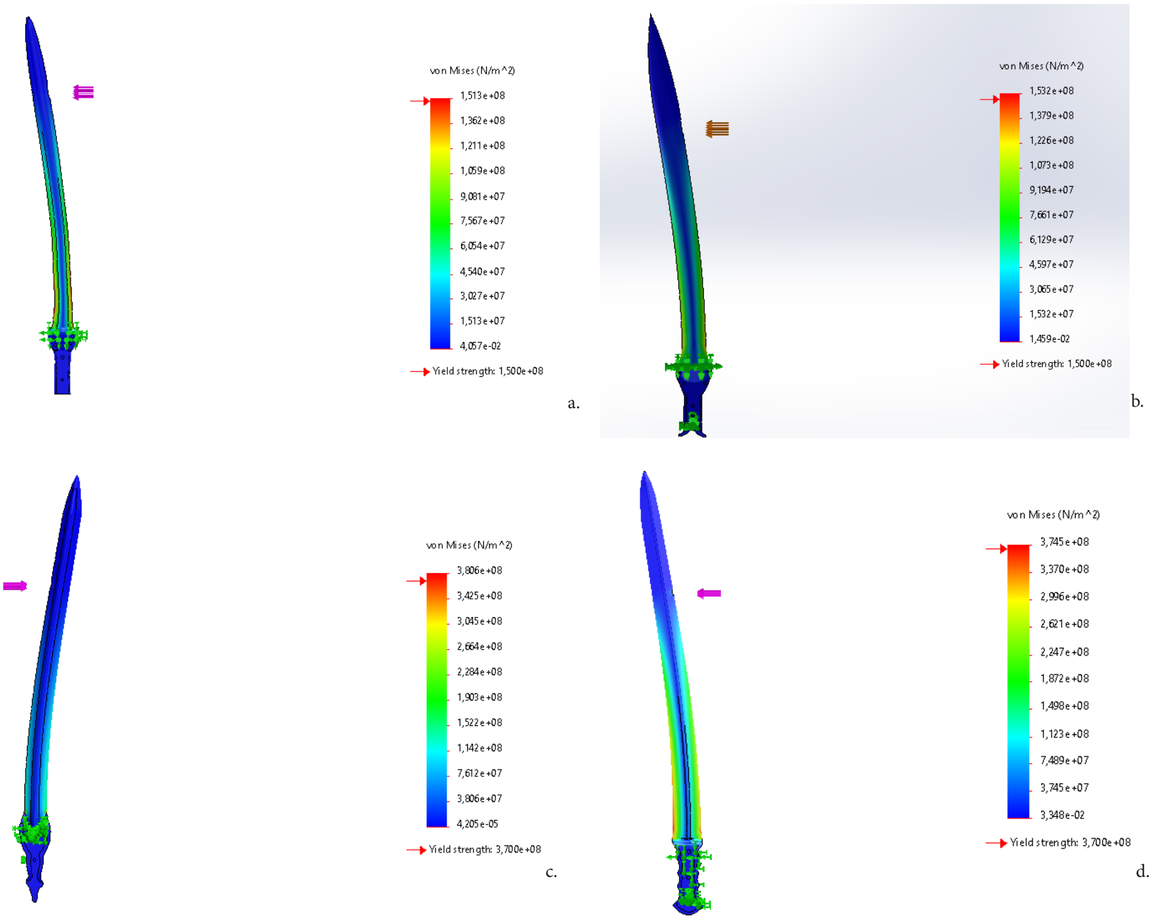

Fig. 2. Cutting attacks: 2a: W.212a (upper left), 2b: W.212b (upper right), 2c: T.210 (down left), 2d: Idalion (down right)

with a broad midrib, which provides greater penetrating power.[34] The difference between the resistances of the swords from Well 212, which are very similar to one another, is also problematic and further analysis is required (Fig. 3).

Sword T.47 shows good cutting performance, even though it is the shortest. As for swords W.212a (Fig. 2a) and T.18, although they are longer and thus theoretically better for cutting,[35] they are more prone to deformation after 100–150 N. This is probably due to their high or broad midribs and thin edges. As Molloy suggests,[36] the reduction or abandonment of the midrib enhances the cutting potential. Indeed, this is confirmed by W.212b (Fig. 2b) and the sword from the Loizou Collection, which do not have high midribs and are of a medium length.

There are similarities in the affected areas across the swords, depending on the type of blow. The tip of the blade is mostly affected during thrusting and the area beneath the guard when cutting. Nevertheless, our analysis shows that all the swords tested could be used both for cutting and thrusting (Figs. 3–4). It seems that swords T.47 and W.212b are equally suitable for both modes. Swords W.212a and T.18 are less effective when used for cutting.

34 Jung and Mehofer 2008, 123.

35 Snodgrass 1964, 109; Molloy 2010, 416.

36 Molloy 2010, 419.

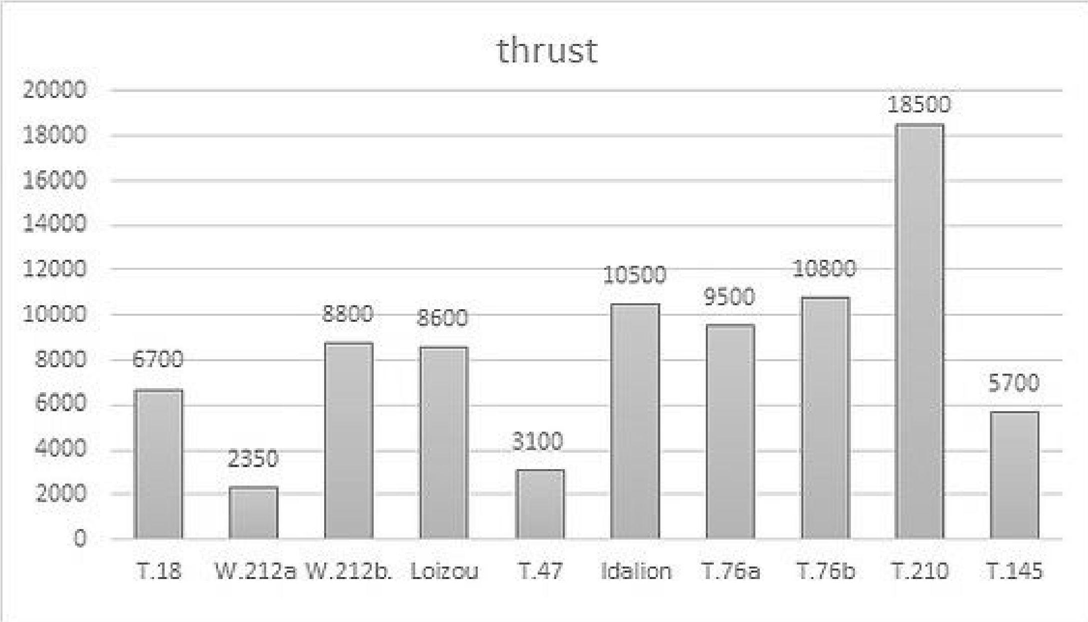

Fig. 3. The resistance to force (in Newton) of all swords in thrusting blows until the yield point.

TEST RESULTS: STEEL SWORDS

Regarding the steel swords, the same methodology was followed, and the yield point was identified. Therefore, the applied force in each case is the maximum sustainable before plastic deformation starts.

In thrusting attacks, all swords show great performance even though their length varies (Fig. 3). Sword T.210 (Fig. 1c) can handle almost three times the load of force of T.145, even though they belong to the same sub-type. The first sword is ca 20 cm longer and has a prominent midrib, while the second seems to lack one. Nevertheless, all the swords, as noted above, can handle large force loads while thrusting, thus this difference between the two swords is probably not an essential one. As for cutting attacks (Fig. 4), swords T.76b and T.145 have the greatest resistance, most probably due to the absence of a midrib on T.76b and the presence of a low one on T.145. On the contrary, T.76a and T.210 (Fig. 2c) present very low resistance due to their prominent midribs. The sword from Idalion is different morphologically to the other examples. The problematic area during the cutting blow is larger, but it can handle a significant force load (420 N) (Fig. 2d). Its surprisingly long length, at almost 80 cm, together with the fact that it has a midrib of rhomboidal section, may be the reason for this, since length with proper support is a great asset in a cutting weapon.[37]

CONCLUSIONS

The first conclusion that emerges is that all swords can handle a much greater force while thrusting than cutting (Figs. 3–4). Nevertheless, they are all capable of being effective in both modes, as has already been suggested.[38] Regarding the *thrusting blow*, the superiority of the iron swords is evident (Fig. 3). Among them, sword T.210 can sustain a truly impressive load of force. The bronze swords can also handle great force, but there are more

37 Snodgrass 1964, 109.
38 Snodgrass 1964, 93; Molloy 2011, 74.

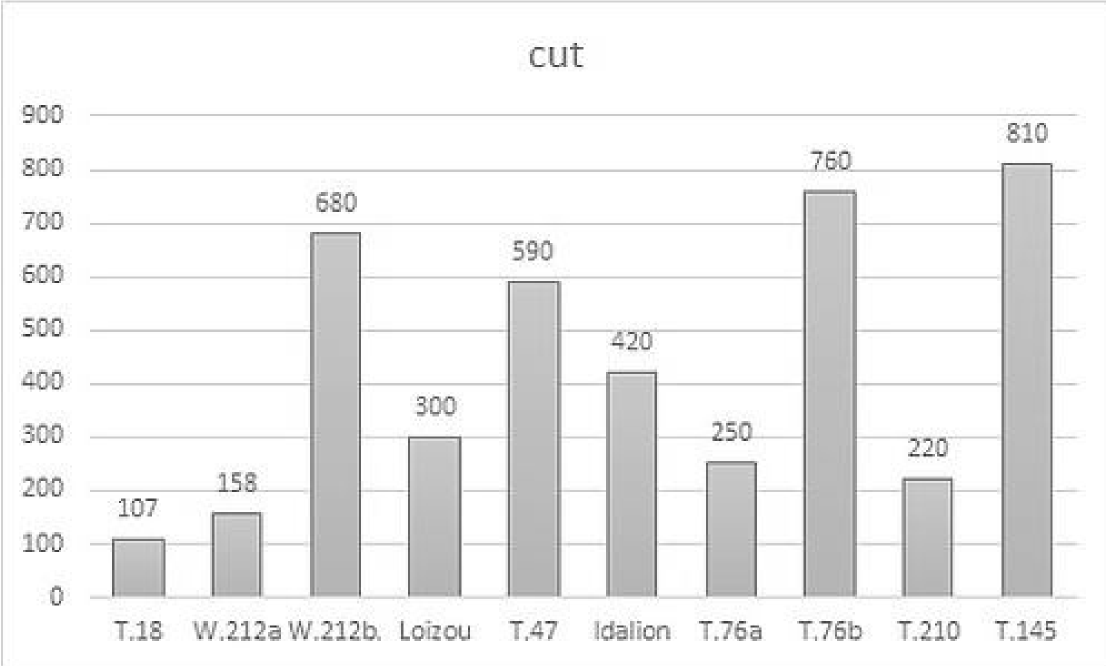

Fig. 4. The resistance to force (in Newton) of all swords in cutting blows until the yield point.

variations among the models. For example, the big difference in resistance observed between the two almost identical swords, Well 212 and T.18, and the rest of the bronze swords cannot be explained only by the geometry of their shape. It seems that thrusting attacks depend on many variables. The kinetic energy of a sword, calculated by its mass and the speed of delivery of the blow, and the fact that this energy goes to work (W) depending on force and distance, shows how many factors have to be considered. First of all, the weight of a sword affects its acceleration in thrusting,[39] as well as the location of the centre of the mass (or balance point).[40] Another parameter to consider is the moment of inertia, determined by the axis of the sword and the distribution of the mass along the sword.[41] Finally, the geometry of the blade, meaning its length, cross-section, width and elements like the pommel, seriously affect its thrusting capability.[42]

Regarding the *cutting blow* (Fig. 4), iron swords seem generally more efficient than bronze ones with the exception of bronze swords T.47 and W.212b. These can handle similar forces, perhaps because of their relatively short length and broad width (T.47) or the absence of a midrib (W.212b). This is an interesting observation in that it implies that bronze swords could be equally efficient for cutting as their iron successors. The reason for this might be a thickened cross-section which helps to absorb the impact force.[43]

The problematic areas are common to both materials when the same type of blow is applied. All swords are prone to damage in the area below the guard on each side of the midrib in the case of a cutting blow; this part needed to be of thicker construction, and so reinforced with more metal. In the case of a thrusting blow the problem is observed at the tip of the sword, but in this case the force they can handle is much greater. Thus, there is no problem with their functionality when used for thrusting. The Naue II swords show greater variability in length and shape. With respect to their morphology, the iron versions are more likely to have rounded shoul-

39 Turner 2002, 7.

40 Jung and Mehofer 2008, 118, 124; Molloy 2011, 74.

41 Turner 2002, 7.

42 Jung and Mehofer 2008, 118, 124.

43 See also Jung and Mehofer 2008, 131.

ders and a flat grip-tongue.[44] The sword from Idalion (Figs. 1d, 2d) is a special example with scalloped edges on the tang. Its mechanical performance is quite impressive, even though it dates to the beginning of the EIA. It resembles Levantine daggers, and it has therefore been suggested that it is not an early attempt to produce an iron Naue II sword.[45]

FINAL REMARKS

This paper has presented some initial results of our analysis of ten swords from Cyprus. We will continue our research by constructing more 3D models of swords from the Eastern Mediterranean and running mechanical tests on them. By the end of our research project, we hope to have a better understanding of the role of swords as status symbols and weapons, and to be able to assess possible links between technological advancements and the sociopolitical background of the transition from the LBA to the EIA.

One of the biggest problems we face is the limited number of existing archaeometric analyses, especially of iron swords. Metallographic analyses are necessary to reveal the steps in the process of making steel. Furthermore, mechanical testing of swords is not without its disadvantages, since we cannot assess a series of factors. These in many cases cannot be calculated even with the help of experimental archaeology. Another important limitation is the fact that SolidWorks shows the yield point of an object and thus the beginning of its plastic deformation, without being precise about its degree and oscillation. On the other hand, by using SolidWorks we can at least design the object and understand the advantages and disadvantages of a sword's morphology and its resistance to stress, which in some cases renders it almost useless after just a few blows.

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44 Vonhoff 2013, 202.
45 Palermo 2018, 235.

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