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Article

An analysis of the mechanical properties of fencing swords, and implications for weapon selection

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SUMMARY

Foil fencing is a competitive combat sport dating back over 500 years. Swords used in fencing are composed of several components, all of which are available with different specifications leading to over 1700 individual combinations, each with distinct characteristics. This study reflects on the art of sword selection and whether this could be founded on a more scientific footing. We investigated relevant properties of blades made from the two most common materials, maraging steel (MS) and low carbon steel (LCS). We hypothesized that there was a statistically significant difference between spring constant, damping behavior, and balance of MS and LCS blades. Our analyses conducted using a cantilever assembly indicated that MS blades were significantly stiffer than LCS blades ($p=0.0004$). MS blades also exhibited more effective damping (and a shorter period of oscillation). This signifies that LCS blades would be better suited to a fencer who favors techniques that require a flexible, springy blade, such as a "flick", whereas MS would better suit a fencer who prefers the excellent tip control and precision afforded by a more rigid blade. These novel findings should prove useful for fencers wishing to make informed, evidence-based blade selections to suit their preferred techniques.

INTRODUCTION

Fencing is a competitive international combat sport that originated in France in the 15th century and has been featured in the Olympics for over 100 years (1). Two competitors, each armed with a sword and dressed in protective clothing, attack one another, trying to score a point by landing a successful "hit", while simultaneously trying to defend themselves against their opponent. Like many sports, participation in fencing fell during the COVID-19 pandemic lockdowns of 2020 and 2021, however, its popularity is rapidly increasing. British Fencing, the national governing body for fencing in the United Kingdom, recorded 6457 members in March 2021 and 11,312 in March 2024, an increase of 75% over three years (2). USA Fencing, the equivalent body in the USA, has also described growth, and recently reported an all-time high of 45,157 members and 752 affiliated clubs nationwide (3). This steady increase in the popularity of fencing as a sport across at least two countries warrants an investigation to provide more robust data to fencers wanting to choose appropriate swords. Sword blades have to be replaced frequently owing to wear and tear, and as such a regular fencer will need to select new sword blades fairly frequently. For competitions, at least two swords must be presented to the referee to demonstrate that if one sword breaks during the fight, the fencer is still able to continue.

Fencing is best split between the three different weapons: Foil, Sabre, and Epee. The focus of this study is foil fencing; however, many of the properties discussed are of similar relevance to the other weapons. The foil is a fine, thin-profiled, lightweight weapon compared to other kinds of swords and is designed for thrusting movements rather than slashing movements (4).

Fencing is an exceptionally high-paced sport, and it is often said that the tip of a fencing blade is the second fastest object in sport, second only to a bullet (5). To allow the referee to accurately award points fencers wear a conductive metal jacket called a lamé and a wire which connects the fencer's sword and lamé to an external system of wires and a box **(Figure 1).** When a fencer successfully hits their opponent with the tip of their sword on their opponent's lamé, they complete an electrical circuit, which causes a light to switch on the box. The light signals that a successful hit was made. This system has been used widely in foil fencing since 1956 (6).

A foil is composed of different sections, including the grip (held by the hand), guard (protects the hand from the opponent's blade), blade (the long section of the weapon) and tip (a compressible button at the apex of the blade that triggers the electrical circuit to complete) (6). While all are

Figure 1. Photograph of a fencer in action. The photograph shows the lamé covering the torso area, which is made from an electrically conductive fabric, and the wire which connects the lamé to the junction box (not shown).

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important and affect the overall behavior and handling of the sword, the most significant is the blade. Blades can be made from different types of steel, with two of the most common types being maraging steel (MS), and low carbon steel (LCS, sometimes informally called Etoile in reference to a popular brand) (7). Both are alloys made primarily of iron and carbon (8). MS has less carbon than LCS and has small quantities of other metallic elements such as nickel, titanium, cobalt, and molybdenum. Additionally, MS is subjected to heat treatments during its manufacture to modify its properties such as flexibility (9). Many fencers begin by learning on LCS blades, which are cheaper, and – some coaches would say – easier for a beginner to handle. There are many specific scenarios when a fencer would choose one or other type of blade, such as the level of competition, whether they are training or competing, their experience level, and blade availability within their club.

Some fencers give little or no thought to their choice of blade, and others treat it like an art or even a superstition, saying that certain swords are "lucky" and others "unlucky" or "cursed". Not only is this unscientific, but it can also be problematic. For example, if a fencer's "lucky sword" breaks and they have to use a different one, they may experience psychological consequences, which could negatively impact their performance – even when there is nothing wrong with the new sword. In this study we set out to develop and reflect on the significance of evidence-supported blade selection for practical fencing, and share these insights to support the broader fencing community in adopting a more objective and rigorous approach to sword choice. To assess how blade material might impact the choice of blade for a fencer, we chose to compare the following variables for MS and LCS blades: the spring constant, damping behavior and balance.

We selected the spring constant as the primary property of interest for this study, as it is relevant to the behavior of the sword in a fight, and can be measured in a domestic setting using non-specialist equipment. Our first hypothesis was that the spring constant would be different for the two types of blades, and we considered it likely that MS blades would have a higher spring constant than the LCS blades as MS blades feel more difficult to bend by hand. Our results indicated that MS blades are significantly stiffer than LCS blades, exhibiting less deflection for a given force.

Second, we selected damping – how rapidly an oscillating blade comes to rest when deflected and released - as a property of interest for this study because the fencer's sword hand rapidly accelerates and decelerates the sword in a fight situation. Damping behavior gives an indication of how much lag there is between the motion of the hand and the motion of the tip of the sword – this is something the fencer needs to understand if they aim for accurate tip control. We hypothesized that the MS blades would exhibit stronger damping than the LCS blades. Our results indicated that MS blades exhibited stronger damping than LCS blades, approaching equilibrium more rapidly than LCS blades when deflected and then released.

Finally, we selected balance – the center of gravity in the blade and how far this sits from the hand guard – as a property to explore during this study. Fencers are often heard to declare that a certain sword is "off balance" or has "lost balance", to suggest that the weight is not evenly distributed or the weight distribution has changed owing to use or damage Since this psychological observation is not grounded in fact, we hypothesized that there would be no difference in the balance of MS and LCS blades. Our results indicated that there was no measurable difference in balance point between the MS and LCS blades. Overall, our study indicates that MS and LCS blades differ in the spring constant and damping behavior, but not in balance.

RESULTS

Stiffness and spring constant of foil blades

To investigate whether stiffness differs between MS and LCS blades, we measured the spring constant of 16 sword blades (8 of each material) using a simple cantilever rig to measure deflection **(Figure 2)**. For each blade we applied loads in increments of 10 g, measuring the deflection at each increment, up to a total of 500 g (50 measurements per blade). We repeated this three times with every blade, resulting in 2400 (16*50*3) measurements of the blades under load and several repeated measurements of the blade at rest to ensure it had not been permanently deformed or slipped.

The mean spring constant for MS was 32.1 N m^{-1} (standard deviation 3.82 N m^{-1}) and was 23.7 N m^{-1} (standard deviation 3.39 N m^{-1}) for LCS. Results of an unpaired t-test indicated that MS blades were significantly stiffer than LCS blades ($p = 0.0004$), taking substantially more force to reach a given deflection (i.e., deforming less when a given force is applied **Figure 3, Figure 4**). R^2 values for the linear fits between displacement and load ranged from 0.993 to 1.000, indicating that the data were very close to perfectly linear **(Figure 3)**. With these findings, we confirmed the primary hypothesis that the spring constant of MS blades was greater than the spring constant of LCS blades.

Damping behavior of foil blades

We investigated the damping of the different types of foil blade, as a blade which exhibits prolonged oscillation after it has been subjected to a force will be more difficult to control than one which more rapidly reaches equilibrium. To

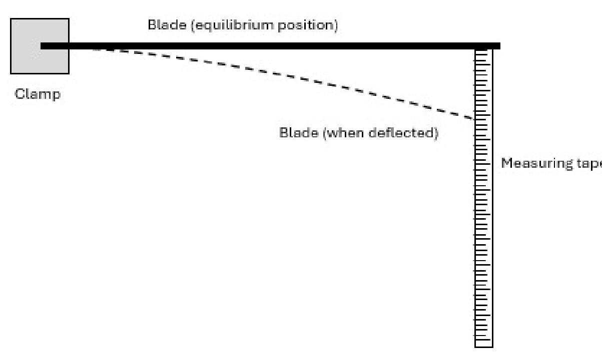

Figure 2. Experimental rig. A schematic showing the cantilever assembly used to measure the deflection and damping of each sword. The blade was clamped at one end with the other end free to deflect when loaded. A vertically mounted measuring tape was used to measure the deflection at a given load. For damping experiments, a smartphone was used to capture the movement of the blade after the load was released, using the same rig.

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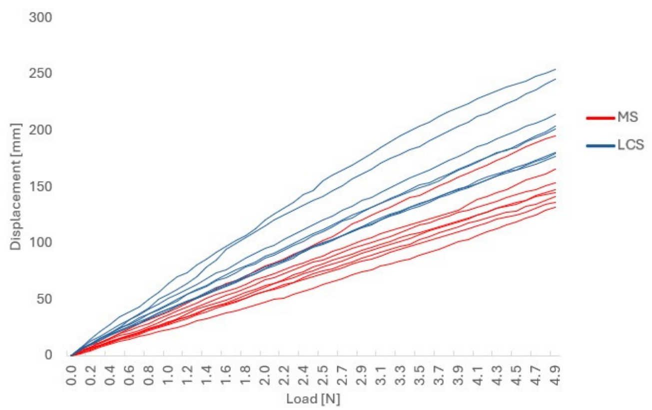

Figure 3. Displacement of fencing swords as a function of the applied load. Each curve is the mean of three separate load-displacement data sets for each given blade. Red lines signify maraging steel (MS) blades and blue lines low carbon steel (LCS) blades. Displacement was measured by applying a series of loads and measuring the position of the end of the blade on a vertically mounted linear scale at each load. The data show that for a particular load, LCS blades deflect more than MS blades, indicating that LCS are more flexible and MS are stiffer. The fit to linear was generally good, with R^2 values for MS in the range 0.998-1.000 and for LCS in the range 0.993-0.999.

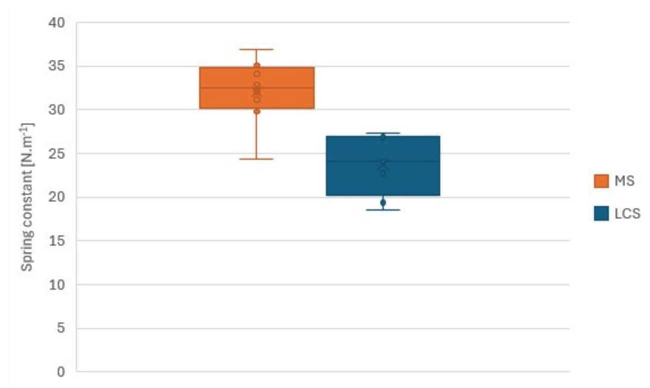

Figure 4. Box and whisker plot showing the spring constant data for maraging steel (MS) and low carbon steel (LCS) blades (n=8 blades for each group). We calculated the spring constant using the gradient of the load displacement data shown in Figure 3. The spring constant of MS was significantly higher than that of LCS blades (un-paired t test, *p=0.0004*).

investigate damping, we clamped a MS and a LCS blade in a vice and held it at a set 20 cm deflection from equilibrium. We then released the blade and recorded the movement of the sword tip in slow motion (120 frames per second), observing how it moved over time after being released.

We found that the amplitude of the MS blade oscillation decays more rapidly than that of the LCS blade over a time interval of 2.52 s **(Figure 5)**. We calculated the envelope of the decay manually from the raw data by selecting the peak amplitude in each oscillatory cycle, and plotted the natural log of the envelope points against time to generate a straight line, so that the gradient of which represents the decay constant for the blade. Relative decay constants equaled 0.0587 for MS and 0.0312 for LCS. Note that these are relative decay constants, not absolute values, as the position of the blade tip was measured using arbitrary units and therefore it was not possible to calculate the absolute decay constant but only the relative values of the two blades. This was necessary because the camera setup for the moving blade could not be calibrated to record absolute position, only change in position, and is the reason that units are not provided. We recorded the mean oscillatory period (i.e., the time for one complete oscillation, starting at the equilibrium point, to the maximum deflection in one direction, to the maximum deflection in the other direction, and back to the equilibrium point) by calculating the time elapsed between each of the envelope points and found this to be 0.147 s for MS (standard deviation 0.005 s) and 0.167 s for LCS (standard deviation 0.004 s).The blades exhibited simple harmonic motion, tracing a sinusoidal curve that decays over the observation interval, as the frequency (the inverse of the period) was consistent over the measurement interval **(Figure 5)**. As such, we confirmed the secondary hypothesis that there is a noticeable difference between the damping behavior of MS and LCS fencing foil blades.

Balance and center of gravity of foil blades

Finally, we considered the balance of the sword blade, specifically the point at which the center of gravity can be found. Balance is a property often mentioned by fencers, when considering how a sword "feels" in the hand. Fencers often speak about a blade being balanced or "off" and it is plausible that variation in the center of gravity owing to different materials, manufacturers or other factors might explain this. To assess balance, the balance behavior of 16 swords was assessed (8 of each material), and it was found that the center of gravity was 260 mm from the base of the blade in both groups, with no measurable difference between blade types. We consider the accuracy of our measurement to be +/- 5 mm.With these findings, we confirmed the tertiary hypothesis that there is no difference between the balance of MS and LCS fencing foil blades.

DISCUSSION

Our study highlighted important differences between the properties of two commonly used fencing blades. The spring constant of MS blades was 36% higher than that of LCS blades (32.1 N m^{-1} for MS and 23.7 N m^{-1} for LCS), and the difference was statistically significant (*p=0.0004*). Thus, we concluded that MS blades are considerably stiffer than LCS blades. The dimensions of the blades, including the cross-sectional areas and shapes, are similar but not necessarily identical and different manufacturers are at liberty to make blades that are slightly thicker or thinner, or more or less tapered, within reasonable limits. So, while one could refer to literature values of elastic moduli for different varieties of steel, it is difficult to infer the properties of sword blades which have complex geometries. The oscillatory period was also shorter for MS blades than for LCS blades (0.147 s for MS and 0.167 s for LCS). When other factors such as mass and length of the object are equal, a shorter oscillatory period often indicates a stiffer object. As such, these two data sets, acquired using different techniques, are consistent and support one another. This represents a new finding that to the best of our knowledge has not previously been quantified or analyzed.

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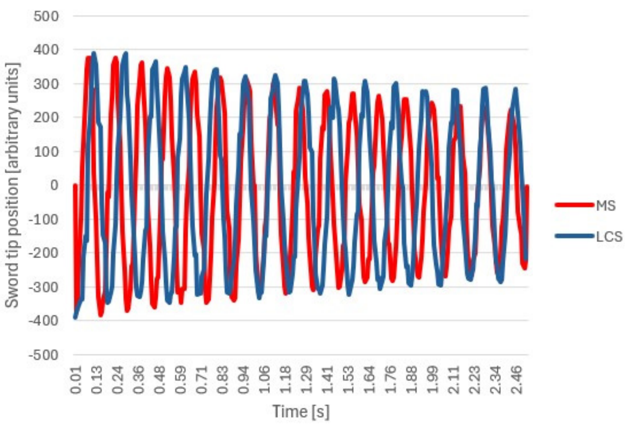

Figure 5. Oscillation of maraging steel (MS) and low carbon steel (LCS) blades after they are released from a set deflection of 200 mm from at rest. The x axis represents time in seconds, and the y axis represents deflection from equilibrium position and is in arbitrary units. The envelope of the decay was calculated manually from the raw data and was used to calculate the decay constant as set out in the Materials and Methods section. One blade was used for each type. Relative decay constants equaled 0.0587 for MS and 0.0312 for LCS. Mean oscillatory period was 0.147 s (standard deviation 0.005 s) for MS and 0.167 s (standard deviation 0.004) for LCS.

This finding has great significance for foil fencers. A fencer who relies on flicks and whips as part of their skillset will find that such moves require less strength and force with a LCS blade and more strength and force with a MS blade. It is not to say that such moves cannot be executed with MS blades, but they are likely to take more strength, practice, and time to perfect, and if a fencer usually fights with LCS and makes an abrupt change to MS, they are quite likely to find that their flicks fail. Although once thought controversial, the flick remains a popular move in modern fencing and is used by some of the sport's most accomplished competitors (13).

On the other hand, a fencer who instead prefers a more clinical, precise approach, will find that a stiffer blade exhibits less "lag" – where the tip of the blade doesn't move completely in sync with the fencer's hand but instead lags behind. Stiffer MS blades with less lag are therefore better suited to a fencer who prioritizes good "point control", allowing them to place the tip of their blade with precision and control. Point control is often described as one of the most important things one can practice as a developing fencer, and this data illustrates that this may be easier to practice, and achieve, using MS blades (14).

MS and LCS blades exhibited damped simple harmonic motion when held at a fixed deflection and then released. Simple harmonic motion is defined as a periodic oscillation where an object moves back and forth around an equilibrium point, where the acceleration is directly proportional to the displacement from this point and acts in the opposite direction to displacement, driven by a restoring force. The damping behavior of the MS and LCS blades differed noticeably, with MS blades exhibiting a decay in their oscillation that was more rapid than LCS blades. The difference was substantial; the relative decay constant was 0.0587 for MS and 0.0312 for LCS (dimensionless) – that is, MS exhibits a decay constant 88% greater than LCS. A stronger damping is typically considered to be better, as a rapidly oscillating blade is less predictable and more unwieldy. Given how fast fencing is, one can understand that a sword that continues to oscillate after deflection will be in the wrong place when the fencer tries to rapidly progress to their next move, compromising their chances of scoring a point. As such, it is harder to score a point with a blade that has a lower damping, so in this respect, an MS blade may be considered more controllable.

The balance of a sword is something often discussed in fencing circles, and fencers will claim that some swords have good balance and others are "off". We therefore explored the center of gravity of a selection of MS and LCS swords to first assess whether they differed between the materials and secondly whether there was a lot of variation within the groups. Neither was found to be the case – we found that the center of gravity of the 16 swords investigated was a consistent 260 mm from the blade base. This finding suggests that fencers who claim their sword is "off balance" are either mistaken, or could be referring to blades which have been worn or damaged over time, as damaged swords often exhibit dramatic bends and visible surface defects which could plausibly affect balance. New swords appear to have a consistent balance, at least within the limits of this study.

There is surprisingly little data on fencing swords in the scientific literature. Most research on fencing focuses on injuries, fatigue, and on methods to improve performance such as strength and conditioning regimes and concentration techniques (15-18). In terms of sword selection, therefore, it is not surprising that most fencers resort to habit, personal recommendation, or superstition.

The aim of this study was to take the first steps in building up a repository of data that developing fencers can use to aid their selection and understanding of their sport, and that aim has been achieved. The limitations of the study include the sample size, which was limited by the time and the number of swords available. Future studies could expand on this work, by considering damping for a larger number of sword blades, as damping could only be investigated for one sword from each blade material inf this study, due to the time-intensive nature of the investigation and the fact that the swords were only available to us for a short period of time. A further limitation to this study was the limited number of properties that were assessed, which was due to a lack of access to specialist equipment, restricting which properties could be measured. Further studies could assess a wider range of properties if access to more equipment could be secured, such as the effect of fatigue and extreme bending on blade properties. Furthermore, this study assessed some of the most common sword parameters, but there are other options that might affect the handling and behavior of the sword that could be explored with more time and access to these swords. Further studies could explore other sword components such as the impact of different grip designs (pistol and French grip, hollow, porous and solid construction, aluminum and titanium), and the interaction of factors such as blade material and grip material, blade age and material, and grip design and handedness. In addition, heavily used sword blades often exhibit bends, surface defects, and discoloration. Thus, it would be interesting to explore the properties of aged blades, for example to test whether balance is more variable

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in older, damaged blades than in new blades, and whether damping behavior changes over the lifetime of the blade, perhaps owing to work hardening after repeated deflection. However, it would be difficult to control for how "aged" a blade is as blades are not typically distinguishable by unique codes or numbers and are usually stored in a large container with many mixed in together, so it would be necessary to plan carefully and measure the hours of use of each blade to have a coherent sample.

In conclusion, our study indicated that MS blades are stiffer than LCS blades and have a shorter period of oscillation. These findings may help fencers select blades, especially when considered in light of the fencer's preferred style and maneuvers.

MATERIALS AND METHODS

Stiffness and spring constant of foil blades

Spring constant was selected as the single most impactful and important property that would influence sword behavior in a fight situation, with the properties of damping behavior and balance as secondary properties of interest.

The relationship between the spring constant (k), force (F) and deflection (x) can be described by Equation 1 (10):

$$F = k * x \quad \text{.....[Eq 1]}$$

The spring constant is measured by taking a rod of material, securing one end, and applying a force to the other end **(Figure 2)**. Force (F) is the force applied to the material, which could be done by applying weights of known mass, or some other means. Deflection (x) is the distance moved by the unattached end of the rod, and hence the spring constant (k) is an indication of how much the material bends or deforms when the force is applied.

This formula asserts that the force applied to an object is directly proportional to the displacement from its position of equilibrium, which is true of most alloys as long as the force applied does not cause the stress in the object to exceed the yield stress of the material (11). Fencing swords are subject to large forces during use – for example, in certain moves, a sword is moved rapidly through the air and then decelerated very rapidly whereby the inertia of the blade causes the tip to continue moving after the hand has stopped. The blade will thereby distort or "whip", bending up to 90°. Further details on this technique, including the specific kinematic processes at play, have been described elsewhere (12). How much the blade distorts when subject to rapidly changing forces will have implications for many maneuvers, especially those which rely on the sword "whipping" or bending when rapidly accelerated then decelerated.

Eight MS foil sword blades and eight LCS foil sword blades were removed from their grips and guards and inspected to ensure no damaged blades were used. To measure spring constant, a blade was clamped at the base in a vice secured firmly to a work surface. A vertically mounted measuring tape was positioned such that the measuring marks were aligned with the tip of the blade. The blade was initially positioned such that it was horizontal, and the starting position as measured on the measuring tape was recorded **(Figure 2)**.

A set of weights of mass 10 g were placed, one at a time, in a small cloth bag of mass 4 g equipped with a drawstring, and the bag was positioned, using the drawstring, at the end of the blade. The blade tip prevented the bag from slipping off the end. After each weight was added the new position of the blade tip was recorded with reference to the measuring tape. After each of the five weights were added (that is, after each 50 g was added), all weights were removed to check that the equilibrium position of the sword was the same as it had been at the start. This served two purposes: (1) to ensure that the blade had not slipped in the vice and (2) to ensure the blade had not suffered any permanent deformation. This process was continued to a maximum total mass of 500 g. This was carried out in triplicate on each blade, for the eight MS and eight LCS blades (1200 measurements in total for each of MS and LCS blades; 150 measurements per blade). This led to three triplicate measurements of the spring constant for each blade, of which we took the average, creating 8 measurements for each of MS and LCS blades to be used in the statistical analysis.

The three observations for each blade were combined to find a mean deflection at each successive load, and the gradient of the load-displacement curve was calculated by applying a line of best fit. R-squared values were recorded to assess the fit to linearity. The data were subjected to an unpaired t-test to ascertain whether there was a statistically significant difference between the spring constant of MS and LCS blades.

Damping behavior of foil blades

To investigate damping behavior, blades of MS and LCS were fixed in the same vice as described above and a smartphone, mounted on a tripod, positioned at a fixed location, was set to record the position of the blade. A small piece of blade tape (often placed on the end of the blade in a competition) was attached to the tip of the blade to allow the software to easily discern the sword tip from the rest of the blade and the background. The blade was deflected to 200 mm from equilibrium then released, and the smartphone recorded its position as it oscillated, capturing 120 frames per second. Note that it was only possible to investigate one blade of each sword type in this phase of the study, owing to the time intensive nature of the investigation and the fact that the swords were on loan from a busy fencing club, and only available for a limited time. To quantify the differences between the behavior of the two blade types, the envelope of the oscillatory curves was calculated by manually sifting through the data to select the peak amplitudes, recording magnitude and time for each oscillation. The natural log of these envelope points was then plotted against time and the negative of the gradient recorded. The negative of the gradient is defined as the decay constant, which indicates how rapidly an oscillating object is being damped and approaching equilibrium. In this instance, only the relative decay constant could be measured as the absolute position of the sword tip was not known, as the experimental apparatus only allowed for measurement of position in arbitrary units. When the blade was subject to force and displacement measured for the spring constant calculation it was stationary during measurements, allowing for measurement of absolute position, whereas when

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it was displaced and released allowing it to oscillate it was in continuous motion during the measurement period which did not permit measurement of absolute position. Nevertheless, as the positioning of the blade and smartphone camera was the same for the two blades, the two data sets are directly comparable and relative decay constant is an appropriate way to compare the behavior of the two blade materials. The time at which the peak amplitude was reached was also recorded and the mean of these was calculated to indicate the oscillatory period.

Balance and center of gravity of foil blades

To investigate balance, a strong thread with a loop at one end was attached to a beam such that it hung vertically over an open space. Sword blades (n=16, eight of each material) were placed through the loop, the loop tightened against the blade, and the position of the loop adjusted laterally until the blade hung horizontally. The position of the loop at which the blade balanced horizontally was considered the center of gravity and was then measured with respect to the blade end nearest the guard (the base) using a standard ruler. Note that it was not possible to do statistical analysis on this data as all swords returned the same measurement of 260 mm within measurement limits (+/- 5 mm).

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