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# HIGHLY-CURVED IRANIAN SWORDS: STRUCTURAL PROPERTIES AND SPECIFICATIONS

## ESPADAS PERSAS MUY CURVADAS: PROPIEDADES Y ESPECIFICACIONES ESTRUCTURALES

POR

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## Abstract - Resumen

Iranian highly-curved swords, named *shamshir* (*šamšir*), reached their maximum curve and popularity in 16th -17th centuries and remained the most favored sword of choice on the battlefields for Persian armies. Although, there have been considerable research on their materials and forging methods, to our knowledge, there is no scientific report on their overall mechanical performance and no scientific analysis of their exceptional shape. The following article provides a thorough analysis of the high curve of Persian swords and proves that this high curve provided a maximum cutting ability for a sword and it also enabled certain forms of thrusts which went over and below the shield of the opponent on the battlefield.

Las espadas persas muy curvadas, denominadas *shamshir* (*šamšir*), alcanzaron su máxima curvatura y popularidad en los siglos XVI-XVII y seguían siendo el tipo de espada preferida en los campos de batalla por los ejércitos persas. Aunque se han llevado a cabo numerosas investigaciones sobre sus materiales y métodos de forja, hasta donde sabemos, no existe ninguna investigación científica sobre su rendimiento mecánico general ni ningún análisis científico de su excepcional forma. El siguiente artículo ofrece un análisis exhaustivo de la curva alta de las espadas persas y demuestra que esta curva alta proporcionaba una fuerza de corte máxima de la espada y también permitía ciertas formas de empuje que pasaban por encima y por debajo del escudo del adversario en el campo de batalla.

## Keywords - Palabras Clave

*Shamshir* (*šamšir*); sword; swordsmanship; crucible steel; Persia; curved swords; cutting ability; sabers.

*Shamshir* (*šamšir*); espada; esgrima; acero de crisol; Persia; espadas curvas; fuerza de corte; sables.

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## 1. INTRODUCTION

Straight swords were common in Iranian Plateau at least from 4th millennium BCE (Moshtagh Khorasani, 2006: 375). Slightly curved swords appeared there in 7th century in the northeast of Iran (Chodynski &. Kobylinski, 2000: 59), in the 11th century, they became part of official weapons and in 12th century they became the main weapon of Iranian army (for the development see Alexander, 2001: 193-220; Allan, 1979: 90; Nicolle, 1982). Through the next three centuries, Iranians gradually increased the curvature of these swords (Moshtagh Khorasani, 2006: 375) and these swords reached their high curvature in a gradual process between 15-16th centuries when the most powerful and successful armies in the world were established during the Timurid era (1370 to 1405 CE) (Forbes Manz, 1999; Sela, 2011). Highly-curved swords (figure 1) were the main weapon of armies in greater Iran from 16th until 19th century CE and even during the widespread use of firearms (Moshtagh Khorasani, 2006: 136-145). During this era, many large and wealthy armies used these swords and succeeded in numerous battles and these swords were famous for their extraordinary quality (Verhoeven *et alii*, 2018: 1331-1336) and they were very expensive (Floor, 2003: 242). Western researchers use the term *shamshir* (*šamšir*) to refer to any highly-curved blade from Persia/Iran, but the term *šamšir* is a general term in Persian and it does not refer to any shape of its blade. Prior to the Arab Conquest of Iran and the introduction of Islam in 631 CE, the swords used in Iran were all straight-bladed. This means that the preceding Persian dynasties, namely the Achaemenians (559 BCE-330 BCE), the Parthians (250 BCE-228 CE), and the Sassanians (241 CE – 651CE) all used double-edged, swords with straight blades. As a matter of fact, the origin of this term can also be seen in the Middle Persian Pahlavi, in which it was called *šamšēr*, *šafšēr* and *šufšēr* (Farahvashi, 2002: 336). According to MacKenzie (1971) in *A Concise Pahlavi Dictionary*, the roots of the word *šamšir* can be traced back to the early New Persian language, before it was written in Arabic script. In early New Persian, “sword” was called *sneh* (*snyh*), or *shamsher* [*šamšēr*]. The earlier version seems to be *shafsher* [*šafšēr*] in Manichaen Middle Persian.

Highly curved Iranian swords (figure 1) generally have a wedge-shaped blade without fullers. There are also few examples which have fullers and the others which have a raised back edge (*yalmān*; for the term *yalmān-e tiq* see Moshtagh Khorasani, 2010: 458). The focus of the present article is on the former type of *šamšir* meaning swords with a wedge-shaped blade and without fullers. There are two different types of this version: a) A rare type has a continuous curve to the blade and b) the second type has a blade which is composed of three parts: a section with a slight curved section at forte resembling a straight blade, a highly curved section at the middle of the blade and a short section with a lighter curve near their tip. They are mostly one handed and they were usually carried in a scabbard on the left side of the user’s waist. Most of them were carried edge down via two scabbard fittings (*varband* see Moshtagh Khorasani, 2010: 435), although there are also examples which were carried edge up. Most of them also have a scabbard chape (*tah-e qalāf* see Moshtagh Khorasani, 2010: 383). Their pommel (*kolāh* or *kolāhak* see Moshtagh Khorasani, 2006: 185-186) is usually located at a right-angle to their grip and usually they have a crossguard (*bolčāq* see Moshtagh Khorasani, 2013: 130). Some of pommel caps stand at a slanted angle to the handle. There are different variations of crossguards: a) most of them end up in knob-shaped endings, b) some have spatulated ends and c) some end in downward looking dragons’ heads (see Moshtagh Khorasani, 2006: 178-182).

Although there have been considerable investigations and research on their material (Verhoeven *et alii*, 1998: 58-64; Perttula, 2001: 65-68; Almén *et alii*, 2007; Moshtagh Khorasani & Hynninen, 2013: 157-192), to our knowledge there is no scientific report on their overall mechanical performance and there is no scientific analysis of their exceptional shape, although a proper design of a sword’s shape is necessary for its practical application as well.

This article provides an exhaustive description on physical properties and benefits of the most common type of highly curved Iranian swords from a mechanical point of view. First, we briefly review mechanical properties of the material of four Iranian *shamshir* (*šamšir*), and then we provide an analysis of their dynamic behavior and describe their practicality in thrusting and cutting. For this propose four different Iranian highly curved swords from 16th and 18th centuries, which are kept in Iranian collections, are examined. Their blades and handguards are all made of patterned crucible steel. The blades are about

*Figure 1.* Four swords from 16th and 18th century used here to evaluate mechanical properties of highly curved Iranian swords (Arjmandi Collection).

85 cm ±10 cm long. This is the longest object a normal 180 cm tall person can easily carry in their hand without hitting the ground upon striking.

## 2. MATERIALS

### 2.1. Blade, pommel and handguard material

Blade, pommel and handguard material of these high-quality swords are made of *fulād-e-johardār* or *pulad-e gohardār*. This material in usually called *patterned crucible steel* in English (Figiel, 1991). It was known as a legendary material worldwide in that time and there were many myths about it in Europe and elsewhere telling how easily these swords could cut through heavy armors testifying their effectiveness in battlefields. This material was only produced in Iran, India, Uzbekistan / Central Asia, Kharazm and to a lesser extent in Ottoman Turkey (Moshtagh Khorasani, 2006: 100-111; Emami & Karamad,

*Table 1.* Specifications of the four analyzed swords.

| | **Sword-04** | **Sword-05** | **Sword-06** | **Sword-07** |
|---|---|---|---|---|
| Attribution | 17th century CE | 17th century CE | 18th century CE | 16-17th century CE, King Ismail I |
| *Johar* pattern | Average quality wood grain | Sham | High quality Qum | High quality ladder Mohammad |
| Grip material | Staghorn | Walrus Ivory | Staghorn | Does not exist any more |
| Blade length | 82 cm | 79 cm | 78 cm | 89 cm |
| Weight without scabbard | 735 g | 642 g | 714 g | 741 g |
| COM* distance from shoulder | 27 cm | 16.5 cm | 16 cm | 30 cm |
| COP** distance from shoulder when rotated around handguard | 50 cm | 46 cm | 44 cm | 52 cm |
| Mass of Inertia when rotated around handguard | 0.09 $m^2$.kg | 0.0659 $m^2$.kg | 0.07 $m^2$.kg | 0.134 $m^2$.kg |
| Pendulum frequency around handguard | 0.671 Hz | 0.704 Hz | 0.714 Hz | 0.671 Hz |
| Width near shoulder | 28 mm | 34 mm | 26 mm | 32 mm |
| Width at the middle | 26 mm | 25 mm | 25 mm | 29 mm |
| Thickness near shoulder | 5.3 mm | 5.8 mm | 5.1 mm | 6 mm |
| Thickness at the middle | 4.7 mm | 5 mm | 4.5 mm | 5.5 mm |
| Thickness near tip | 2 mm | 1 mm | 2.5 mm | 2 mm |
| Grip length | 100 mm | 100 mm | 101 mm | 100 m |
| Pommel length | ~ 1 cm | 3 cm | 3 cm | 3 cm |
| Handguard width | 12.5 cm | 11.5 cm | 13.5 cm | 11.3 cm |

* Center of mass. ** Center of percussion (authors' calculations).

2012, 86-90; Alipour & Rehren, 2014: 231-261). In these countries it could be more expensive than gold. Although there is evidence of exporting non patterned crucible steel from Iran to the Vikings (Rus) that was supposedly used in forging of *Ulfberht* sword (Fedrigo *et alii*, 2017: 426), patterned crucible steel which was a superior material was not exported and it was not available in other countries (Williams, 2007: 234). In modern times, there were several efforts by scientists and researchers who tried to reproduce it and there are a few claims about partial success in reproduction of or *pulād-e gohardār* in very small quantities (much smaller than a sword) after lifelong efforts and exercises (Verhoeven *et alii*, 1998: 58-64; Perttula, 2001: 65-68; Almén *et alii*, 2007; Moshtagh Khorasani & Hynninen, 2013: 157-192). However, none of them has the exact shape, pattern or properties of their antique counterparts and are no match to their quality, and yet this material is under investigation and there are controversies about it (Sukhanov *et alii*, 2017).

*Pulād-e gohardār* is basically a hypereutectoid crucible melted steel with a pearlitic matrix with spheroidized cementite particles aggregated in a layered arrangement. In other words, this is a solid dispersion of iron carbide (cementite i.e. $Fe_3C$ i.e. extremely hard steel) micro beads in ferrite (soft iron). Iron carbide beads are between 2 to 8 µm big with an average diameter of about 4 µm and show a relatively whitish color in the dark gray (in some cases it is almost black) ferrite background (Verhoeven *et alii*, 2018: 1331-1336).

In *pulād-e gohardār*, the carbide micro beads are concentrated in parallel curves which are visible as lines or curves with lighter color in a darker background with the bare eye. Distance between these lines is generally reduced near the edge of these swords and at the edge usually there is a high concentration of carbide beads. This could indicate a process of hardened and tempered edges which explains a different color of patterned crucible steel close to the edges. Period Persian manuscripts such as *Ta'id Besārat* written by Mirzā Lotfallāh in 16-17th centuries talk about this process. Mirzā Lotfallāh explains,

> The intensity of the color of steel depends on its quenching. If the sword is quenched moderately, the color will be noble. A sword with a moderate quenching cuts very well and keeps a hard and stable edge (*dam-e qāyem*). If the blade edge is thin (*dam-e bārik*) and hits a hard surface, it bends and if it [the thin edge] is too hard, it nicks/breaks off. If the blade edge was not hard enough, it is soft and gives away. A sword which is moderately quenched does not remain bent [after striking], but a sword which is quenched too much with a tendency to moderate quenching cuts very well and also does not remain bent, but if this type of sword hits hard objects there is a possibility of breakage upon bending and also the sword might have a subtle crack (*mu*) [flaw in the blade]. This is called *narre* (uneven) by *mobserān* (experts) from India.

One should note that quenching in this case is likely the temper of blade (Moshtagh Khorasani, 2010: 59). Note that temper is the reheating of hardened steel to some temperature below the eutectoid temperature for the purpose of decreasing hardness and increasing toughness (see Krauss, 1990: 457).

These patterned crucible blades from this study are forged from an egg-shaped ingot or semi-hemispherical ingot of the same dispersion with a Widmanstätten pattern with mean diameter of about 400 µm (see Verhoeven *et alii*, 2018: 1331-1336). Significant amounts of carbon nanotube and cementite nanowires are detected in *pulād-e gohardār* as well (see Reibold *et alii*, 2006: 286). These are advanced materials which are produced in modern world in 1990s and can potentially increase hardness and toughness and decrease mass density of the blade (Salvetat *et alii*, 1999: 255-260; Chen *et alii*, 2000: 301-306). Ultimate tensile strength of *pulād-e gohardār* is more than 1000 MPa (Peterson *et alii*, 1990: 355-374). The toughness of patterned crucible steel in the Charpy impact test is more than 100 J, which is about 67 J/cm$^2$ (Perttula, 2004: 92-97). It means that it is difficult to break a sword made of *pulād-e gohardār* into two pieces in a battlefield (Perttula, 2004: 92-97). Toughness of the best Japanese swords are less than 20 J/cm$^2$ (Misawa & Komazaki, 2002: 119-125). Even in very hard impacts, blades made of *pulād-e gohardār* usually do not break in two pieces at once and only chip at the edge (Verhoeven, 1987: 145-151).

*Pulād-e gohardār's* macro hardness that mainly comes from ferrite is between 30 to 40 HRC and its micro hardness on the carbide aggregates (specially near its edge) is more than 1506 kg/mm$^2$, which is equal to about 76 HRC (Piaskowski, 1978: 3-30). This is a quite hard edge even compared to modern blades and to our knowledge there were no blade with this hardness in that era. For instance, the highest hardness measured on a

Japanese sword is about 900 kg/mm$^2$ that equals to about 67 HRC (Yaso, *et alii*, 2012: 690-694).

To measure mass density of *pulād-e gohardār*, we used sword-07, which does not have any nonmetallic part (it is missing its handle, etc.). We have measured its volume by dipping it in a large cylindrical jar filled by isopropyl alcohol and measured the volume of alcohol that is displaced due to the insertion of the sword in to the jar. Hereby, the volume of *pulād-e gohardār* used in this sword is measured to be about 100 ml. This item weighs about 740 g. So, mass density of *pulād-e gohardār* should be about 7.4 g/ml that is a relatively low mass density compared to modern blade alloys. The elastic limit of *pulād-e gohardār* is about 0.273% (Piaskowski, 1978: 3-30), which is a high number compared to swords from the same era. For example, the katana's elastic limit is about 0.015% (Okayasu, 2015: 1-6). The maximum tensile elongation of *pulād-e gohardār* is about 10% that is a high number even when compared to the modern steels (Peterson *et alii*, 1990: 355-374). For Japanese swords the maximum tensile elongation is about 5% (Okayasu, 2015: 1-6). If the tip and handguard of an Iranian sword is fixed on a pivot, applying about 60 kgf will bend it reversibly up to 50º (Piaskowski, 1978: 3-30).

### 2.2. Handle material

In these swords, the handle tightly fits one hand between handguard and pommel. The handle is usually covered by walrus ivory, elephant ivory, antler, or buffalo horn grip scales. A few handles are metallic made of silver, iron or steel (Moshtagh Khorasani, 2006: 178-182). Among these materials walrus ivory which is one of the hardest and toughest biological materials and is a nano-porous material was used on most high-quality swords. These handles are known to have good friction with the hand especially when they are wet. The cross-section of these handles is almost circular and its diameter is about 2.5 mm. Usually surface of these handles is smooth. The sword's tang is usually about 4 mm thick near handguard and 1 mm thick near pommel, and less than 15 mm wide. Two pieces of walrus ivory are usually attached to tang by two or three rivets and glued usually by a stone like white material (an adhesive) called *zāj-e sepid*. There are two pieces of spring like steel called *āhanak* (tangbands) covering the tang and the edges of the grip scales (see Moshtagh Khorasani, 2010: 66). There is less than 5 mm of *zāj-e sepid* beneath each *āhanak* between the tang and *āhanak*. Each *āhanak* is precisely soldered from one end to handguard and from the other end to pommel. The pommel itself is filled by *zāj-e sepid* and fixed by a rivet that goes through the tang. The inside of the handguard is hollow and filled by *zāj-e sepid*. The handguard is not welded to tang. The whole handle looks like a precisely designed spring and damper shock absorbing system.

## 3. DYNAMICS AND SHAPE

To analyze the shape and dynamics of these swords, they were digitally scanned and Autocad 2018 (Autodesk Inc.) used to measure their dimensions and angles as depicted in figure 2. In this figure the blades are divided to three curves separated from each other by 10 cm long transition regions. In all of these swords the first curve near the handguard has a very low curvature and it is almost straight. The center of mass (COM) of the swords as shown in figure 2 by a small red dot that is located near the end of their low curvature region. The next region of these blades that is located at their middle has the highest curvature (smallest radius). The radius of this curvature varies from about 51 cm in sword-07 to about 72 cm in sword-04. The center of percussion (COP) of a sword around a pivot is a point on the sword where a perpendicular impact will produce no reactive shock at that pivot. The COP of these swords when their center of rotation is in their handle ($COP_{handle}$) is generally located near the middle of this highly curved region as it is shown in figure 2 by a large red dot. On sword-04, sword-05 and sword-06 a third region with a slightly lower curvature can be distinguished near their tip. However, on sword-07, the second region continues to the tip and there is no third region. The angle between the tip and the forte increases from 39º in sword-04 to 63º in sword-07.

It is generally believed that a higher curvature makes a sword more favorable for cutting because more curvature decreases the initial contact area between its edge and opponent's armor. Thus, the initial pushing pressure on target i.e. exerted force on the target divided by the contact area, increases and the sword's ability to initiate a fracture in

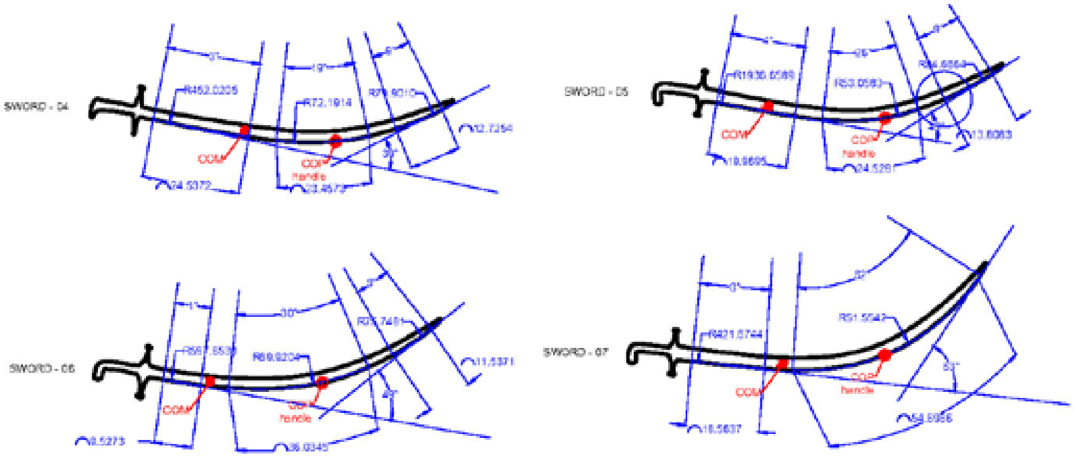

*Figure 2.* Dimensions and angles of four highly curved Iranian swords. The numbers after letters "R" are the radius of curvature, and the numbers after half circles are arc lengths. Numbers with degree sign are showing the angles in degree (authors' calculations).

armor increases as well. Moreover, an important factor in cutting is the ratio of slice to push velocities ( $\xi$ ) and therefore, no matter how sharp a blade is, it is easier to cut with a combined slicing and pressing. Especially when cutting a ductile steel with low friction coefficient (i.e. typical high quality armor), having a large $\xi$ is very important in initiation of fracture in target at lower pushing pressures and results in a deeper cut even with a lower pushing pressure (see Atkins, 2006: 2523-2531).

In the modern world, cutting technology is still important in design of various cutting tools. On these modern tools we know that having a blade with variable curvature rotating around a pivot point with a zero or nonzero linear velocity, the highest $\xi$ can be achieved by a blade with a low curvature (large radius) region near pivot point, and a high curvature (small radius) region next to the low curvature region (Atkins, 2006: 2525-2526). Apparently highly curved Iranian swords are precisely designed based on this criterion. As it is shown on figure 2, these swords have low curvature near their handguard and a high curvature next to this first section. So, these highly curved swords not only can apply a higher initial drawing pressure (draw cut) to cut, they can initiate and deepen a cut in materials which are normally harder to cut by increasing $\xi$ by their variable curvature.

For a swordsman, it is generally desired to apply the maximum force (drawing pressure) on his target and receive the minimum reaction shock force on his sword's handle. When the reaction shock on the user's hand is minimum, the sword's vibration will be minimum as well (Cross, 2004: 622). These are necessary for reaching a maximum damage on the target and a minimum fatigue on the user's hand. For a straight sword that rotates around its grip, ratio of the reactive shock force on the user's hand ($F_U$) to the force exerted on the target ($F_T$), can be calculated from the following equation (Cross, 2004: 622):

$$\frac{F_U}{F_T} = \frac{-I_{COM}}{m.L_{COM}^{\ 2} + I_{COM}} + \frac{m.L_{COM}}{m.L_{COM}^{\ 2} + I_{COM}} r \qquad (1)$$

where $I_{COM}$ is the sword's moment of inertia, $m$ is its mass, $L_{COM}$ is the distance between its center of mass and grip, and is distance between the impact point and center of mass. For a curved sword like sword-07 this ratio can be calculated as follows (parameters are defined in figure 3):

$$\frac{F_U}{F_T} = \sqrt{\cos^2 \beta \cdot \left[ \frac{D \cdot m \cdot L_{COM} - I_{COM} - m \cdot L_{COM}^{\ 2}}{I_{COM} + m \cdot L_{COM}^{\ 2}} \right]^2 + \sin^2 \beta} \qquad (2)$$

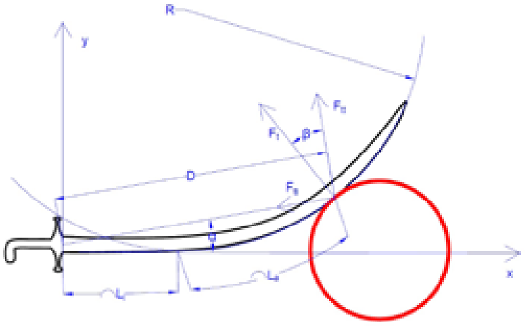

*Figure 3.* Force and geometrical analysis of impact between sword-07 (black line) and a target (red) (authors' calculations).

Were x and y are denoting coordinates of the impact point and:

$$\begin{aligned}
&\beta = {}^{L_a}\!/\!_{R} - \arctan {}^{y}\!/\!_{x} \\
&D = \sqrt{x^2 + y^2} \\
&x = L_l + R \cdot \sqrt{\frac{\tan^2\left({}^{L_a}\!/\!_{R}\right)}{\tan^2\left({}^{L_a}\!/\!_{R}\right) + 1}} \\
&y = R - R \cdot \sqrt{1 - \frac{\tan^2\left({}^{L_a}\!/\!_{R}\right)}{\tan^2\left({}^{L_a}\!/\!_{R}\right) + 1}}
\end{aligned} \qquad (3)$$

Figure 4 compares ratio of sword-07 with a similar straight sword. As it is seen on this figure, for both swords the $\mathrm{COP}_{\mathrm{handle}}$ is about 50 cm away from the grip. On the straight sword, when the impact point gets away from $\mathrm{COP}_{\mathrm{handle}}$, the reactive shock force increases linearly (red line on figure 4). However, on a highly curved Iranian sword (sword-07) by getting away from the $\mathrm{COP}_{\mathrm{handle}}$, the reactive shock force on the user's hand increases more gradually. In other words, these highly curved swords are more tolerant in choosing the impact point and generally reflect less force to the user's hand, and they transmit more force and push pressure to the target. Thus, such a highly-curved sword will make a deeper cut and more damage on the target compared with a straight sword of similar velocity, mass and length. Use of such a highly curved sword will generate less fatigue on the user's hand as well.

The axis of rotation of a sword can be on its handle, its user's elbow, its user's shoulder, or somewhere behind the user when he has a large linear velocity (running or riding on a horse). If the swordsman uses his sword while riding on a horse, by increasing the horse's speed, the sword's center of rotation moves further away in his back. According to the parallel axis theorem, when the axis of rotation goes away, COP gets closer to COM (see Brody, 1986: 640). Therefore, if a sword is designed for infantry and its center of rotation is somewhere between the user's fingers and shoulder, its COP will not get close to COM by very much and it is more likely to be close to the $\mathrm{COP}_{\mathrm{handle}}$ (COP when the sword is rotating around its handle). Thus, using the region of the blade that is close to its $\mathrm{COP}_{\mathrm{handle}}$ probably was more favorable for infantry. Therefore, this region should have the highest ability to cut and have the highest curvature, similar to sword-04 and sword-05. On the other hand, if a sword is designed for cavalry, it will probably have a COP that is moved towards COM. Such a sword needs to be highly curved all the way from $\mathrm{COP}_{\mathrm{handle}}$ to COM like sword-06 and sword-07. Therefore, we can conclude that swords with maximum curvature closer to COM are more suitable for the cavalry and swords with maximum curvature closer to their tip, are more suitable for the infantry. When the highly curved region is longer, the corresponding arc's angle increases and the angle between the tip and forte increases as well, which can be another indication of suitability of a sword for cavalry.

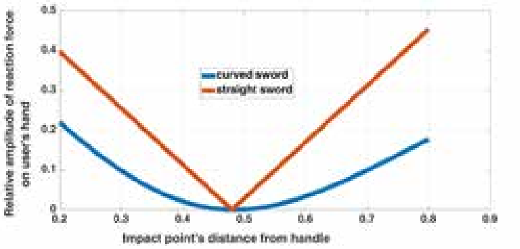

*Figure 4.* Ratio of the reactive shock force on the user's hand to the impact force on target as a function of impact point's distance from handle for sword-07 (blue) and a similar straight sword (red) (authors' calculations).

Mistakenly, there is a feeling among some practitioners of European swordsmanship that highly curved swords are not suitable for thrusting. However, according to the period literature, they were effectively used for thrusting as well (Moshtagh Khorasani, 2013: 161-162). Even when highly curved, the curvature makes it possible for a sword to turn around a shield and thrust at a target behind it. However, thrusting techniques in Iranian swordsmanship of that era were different from the common thrusting techniques used in rapier, smallsword or modern fencing. In fencing in the lunge thrusting technique, a linear velocity is given to the sword on a straight path along the sword's axis to the target. The maximum linear velocity a human can give in such a way is about 10 m/s (Kimm & Thiel, 2015: 502-506). To achieve more damage on the target by a thrust (highest push pressure at the sword's tip), it is necessary for the sword's velocity to be along its axis near the tip at impact time. To do so, in Iranian thrusting technique, rotational and linear velocities are given to the sword's tip at the same time and consequently the impact speed of the sword's tip during this thrust technique can be higher. Figure 5 shows one of several thrust techniques in Iranian swordsmanship. As it is seen here, the user first gives a linear velocity towards the target to the sword. Then, he adds an annular velocity to it to hit the target along his sword's axis. Hereby, not only he gives the thrust maximum push pressure by aligning his sword's axis, he also increases the total velocity of his sword by about 10 to 20 percent. However, this improvement comes at the cost of increasing the sword's path length and giving more time to the target to react.

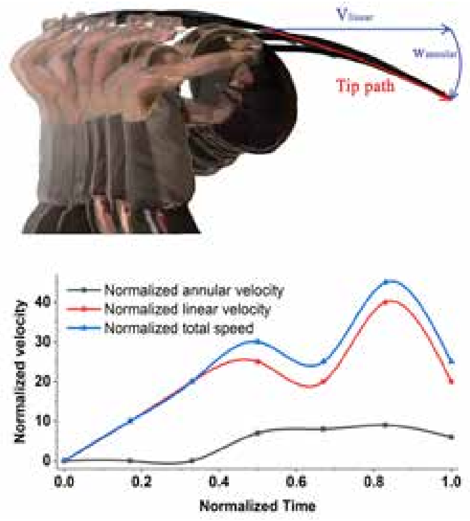

*Figure 5.* Analysis of one of thrust techniques in Iranian swordsmanship. The upper picture depicts the motions of a swordsman and below curves show linear, annular and total velocity of his sword's tip (authors' calculations).

Figure 6 depicts force and power of a typical human muscle as a function of its velocity. Generally, the contraction velocity of human muscles decreases by increasing the applied force or torque and at some point in between there is the maximum exerted power (Roberts, 2016: 266-275; Callahan & Kent-Braun, 2011: 1345-1352; Andersen *et alii*, 2006: 2523-2531; Bahill & Karnavas, 1989: 89-97). Thus very heavy swords or swords with a very high moment of inertia which require more force, are slow and cannot deliver much energy to damage the target (especially when moved upward). Very light swords or swords with very low moment of inertia are very fast. However, such light swords will not acquire enough energy to make significant damage on the target. There is an optimum value for a sword's mass and moment of inertia at which it acquires maximum energy and can cause the maximum damage on the target. Having a heavier sword may look pointless, considering the fact that such a heavier sword will have less energy to damage a target and it is considerably less agile, less quick, less maneuverable and less fast. However, in some cases a sword's mass is not chosen to optimize its energy or velocity as there were other considerations such as toughness, length (range), etc. On the other hand, depending on conditions, a sword's energy (damaging power) may be traded for maneuverability, agility and speed. In practice there are swords weighing from 200 g (fencing foil that needs no energy to damage and needs to be quick and maneuverable) to more than 4000 g for very long and heavy European great swords (see Higgins Armory Museum, HAM# 3133).

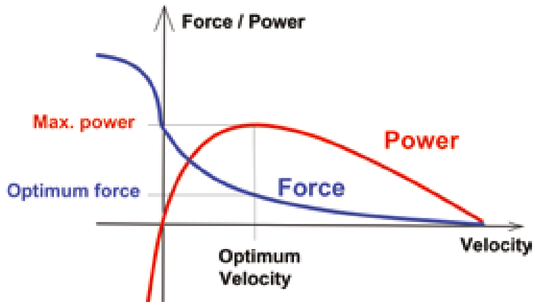

*Figure 6.* Force and power (energy exerted per unit time) of a typical human muscle as a function of its velocity extracted from (Roberts, 2016: 266-275; Callahan &. Kent-Braun, 2011: 1345-1352; Andersen *et alii*, 2006: 2523-2531; Bahill & Karnavas, 1989: 89-97; Christensen & Aagaard, 2005: 87-94). Scale of axes may vary depending on the muscle, age and previous trainings.

If the maximum power an athlete can exert for a short time considered to be about 1500 W (see Lakomy, 1993: 376) and if when striking with an empty hand (a 0 kg sword), it takes about 0.1 s for his hand to reach its maximum velocity (see Kimm & Thiel, 2015: 502-506) and the maximum hand speed of an athlete be about 10 m/s to 20 m/s depending on his gesture and path (Kimm & Thiel, 2015: 502-506; McEvoy, 1998: 216-221) according to conservation of energy one can write:

$$\begin{aligned} &E_{sword} = \tfrac{1}{2}.M_{sword}.v^2 = P.t \\ &\tfrac{1}{2}.M_{sword}.(20m/s)^2 \approx 1500W.\frac{1}{10}s \qquad (4) \\ &M_{sword} \approx 0.75kg \end{aligned}$$

Thus, the hardest impact an athlete can deliver on a target will happen when his sword's mass is about 750 g. Highly curved Iranian swords weigh between 600 g to 1200 g and most of them are about 700 g to 800 g. Medieval European swords are usually between 1000 g to 1500 g (greatswords weigh up to 4000 gr but they were used vs pikemen formation to create an opening) and Japanese katana swords usually weigh about 950-1200 g. Highly curved Iranian swords can be used single handed and are fast because they are light; and they can be light because their material (*pulād-e gohardār)* has very high micro hardness and toughness and does not need to be thick to be tough.

We have calculated moment of inertia of these highly curved Iranian swords by measuring their pendulum frequency and their mass based on De Motu (Turner, 2002: 148-150). The moment of inertia on these swords is usually between 0.05 to 0.1 $m^2$.kg when rotating around an axis that goes through handle perpendicular to it. A fencing foil's moment of inertia is 0.027 $m^2$.kg, the typical Viking swords' moment of inertia is about 0.084 $m^2$.kg, Swedish two handed long (152 cm) swords have a moment of inertia of about 0.23 $m^2$.kg, and European Albion Ringeck sword have a moment of inertia of 1.44 $m^2$.kg (Turner, 2002: 14).

These Iranian swords usually have a cross-shaped handguard with two semi spherical masses (about 1 cm diameter) at the end of each quillon. Such a handguard not only provides some protection for hand, but it also increases the sword's moment of inertia around its longitudinal axis (along the sword's length) without any significant increase in its mass. This high moment of inertia around longitudinal axis, reduces the sword's tendency to rotate around this axis in the user's hand. This is useful for curved swords because if they are struck on their side, the impact point's distance from longitudinal axis (y in figure 3) is large. Thus, the rotational torque ($\tau$) that is generated by this impact is large ($\tau = y.f$ where $f$ is the impact force). In straight swords y is always small and consequently this torque is negligible. In other words, a straight sword does not tend to rotate in its user's hand when struck on its side. However, a highly curved sword is prone to rotate in its user's hand around its longitudinal axis when it is struck on its side near its tip, and a high moment of inertia around this axis is needed in these swords to help its user to prevent this rotation. The pommel of these swords reduces the reaction shock force on the user's hand as well (Denny, 2006: 943-950).

## 4. CONCLUSION

The present article presented an analysis of four highly curved Iranian *shamshir* (*šamšir*) with wedge-shaped blades without fullers from Iranian collections. All these swords were digitally scanned and Autocad 2018 (Autodesk Inc.) was used to measure their dimensions and angles. The scans and measurements showed that the blades are divided into three curves. Although the first section at the forte of the blade looks straight to the naked eye, the scans and measurements showed that even this section has a slight curve to it. This means that in all of these swords the first curve close to the handguard has a very low curvature. The center of mass (COM) of the swords is located near the end of this low curvature region. The next region of these blades, which is located at their middle has the highest curvature (smallest radius).

The article has shown that the center of percussion (COP) of these swords, when their center of rotation is in their handle ($\text{COP}_{\text{handle}}$), is generally located near the middle of this highly curved region. On sword-04, sword-05 and sword-06 a third region with a slightly lower curvature can be distinguished near their tip. However, on sword-07, the second region continues to the tip and there is no third region. The angle between tip and forte increases from 39° in sword-04 to 63° in sword-07. The article has concluded that swords with maximum curvature closer to COM are more suitable for the cavalry and swords with maximum curvature closer to their tip are more suitable for the infantry. When the highly curved region is longer, the corresponding arc's angle increases and the angle between the tip and forte increases as well. This means that in swords suited for cavalry, this angle is larger.

Further, the article has demonstrated that special shape of these swords makes them more favorable for cutting by decreasing the initial contact area between its edge and target and increasing the initial drawing pressure on target, increasing the ratio of slice to push velocities ($\xi$) and easier initiation of fracture in target and obtaining a deeper cut, and by reducing the ratio of reaction shock force to the user's hand to the force applied to the target ($F_U/F_T$).

Moreover, we have shown mass of these swords is optimized for delivering maximum energy to the target. Furthermore, in thrusting these swords, the target may be hit slightly harder and may be performed from above or below the opponent's shield. However, may give more time to the opponent to defend.

Future research on different cutting tests performed by *shamshir* (*šamšir*) will shed more light on cutting and thrusting capabilities of this type of swords and further investigation on their handle may provide a better insight to the shock absorbing system that is incorporated in their handle.

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