DEVELOPMENT OF A MEASUREMENT SYSTEM FOR THE EVALUATION OF KINEMATICS AND IMPACT FORCES IN HISTORICAL FENCING COMBAT

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This study aims at evaluating the impact forces acting on the blades of swords during a combat. Such forces will be used as input for numerical simulations to estimate the sword durability. Some replicas of the 17th century swords were instrumented with strain gauges and inertial sensors were placed on athletes' joints to reconstruct arm kinematic. The forces along the two relevant axes are calculated by linear regression of two Wheatstone bridges and results were consistent with previsions. The calibration showed small uncertainty (max 11 N) with the transverse sensitivity being directly included in calibration parameters. In addition, the system was fully synchronized between all its parts and the bandwidth seems sufficient to calculate the impacts.

KEYWORDS: fencing, combat, impact, forces, kinematics, strain gauges.

INTRODUCTION: In the past years the metallurgy group of the University of Brescia conducted a study in collaboration with the *Gairethinx* centre for the study and practice of historical fencing. The purpose was to assess the chemical composition and the manufacturing methods used to produce the "Storta", a sword forged in Caino - Brescia, northern Italy - during the early 17th century (Tonelli *et al.*, 2016). The study is now continuing with the aim of measuring the durability of such weapons during a fight: the idea is to apply realistic impact forces as input in a numerical simulation to find how many blows the sword can take and how long it can last before wearing out too much. Replicas of the original swords were produced to match similar geometries and inertias and then used as a measuring instrument to calculate impact forces: two strain gauges bridges were applied, one for each side, trying to independently measure the components of an applied force along the two most significant axes. These axes were identified as the one perpendicular to the blade (x) and the one perpendicular to the faces (z) (see Figure 1). However, it was chosen to use two Wheatstone bridges, each measuring the total force, as obtaining two independent measurements was not possible due to geometrical constraints. The two components of the total force were then obtained by knowing the two total force measurements and the static calibration parameters.

METHODS: The first step was designing a FEM (finite element method) model (using Solidworks) to choose an efficient measuring system and to gain an approximate understanding of the sword's behaviour under mechanical stress. For these purposes, both the description of the original sword and the measures of the two replicas were used, obtaining the result shown in Figure 1.

A vibration test was also performed to obtain the mechanical features of the sword, such as the density and the stiffness of the material: an electromechanical shaker and some accelerometers were used to assess the parameters with a modal updating technique based on the measured modeshapes and natural frequencies.

The updated simulation was then used to emulate a fighting condition by applying a fixed geometry constraint on the handle of the sword. At first, a preliminary strain gauge position was chosen by considering the sword as a cantilever beam. FEM simulations were then carried out by applying different loads in all the three directions and in different points of the sword, with the aim of identifying the static limits of the sword and understanding the best configuration of the strain gauges. The highest strain values were shown near the sword hilt and the neutral axis (with respect to the deflection caused by a force in the x-direction) followed a curved path due to the cross-section changing from hilt to tip. A non-linear dynamic simulation was also carried out to check the impact behaviour with the load being set to 1 kN.

With the aim of determining the forces in the x and z directions, the most sensitive positions of the strain gauges were identified near the hilt, even if the mechanical behaviour was not a-priori defined due to the change in cross-section. A shear strain gauge configuration was chosen to make the bridge output independent from the point of application of the force. At this point, in order to avoid problems arising from measurement sensitivity and bonding error and considering FEM results and literature for the approximate case of a cantilever beam (Ştefănescu, 2011), two strain gauge bridge systems were identified as necessary to measure F_x and F_z. Four rosettes were therefore used, positioned as in Figure 1 (right) on both faces of the sword. However, while the primary objective was obtaining the force measurement in the x-direction, it must be noted that the flexural stiffness in response to a z-force is significantly lower than the corresponding one associated with x-forces. This stiffness difference led to a measuring system with a much higher sensitivity to z-forces than x-forces.

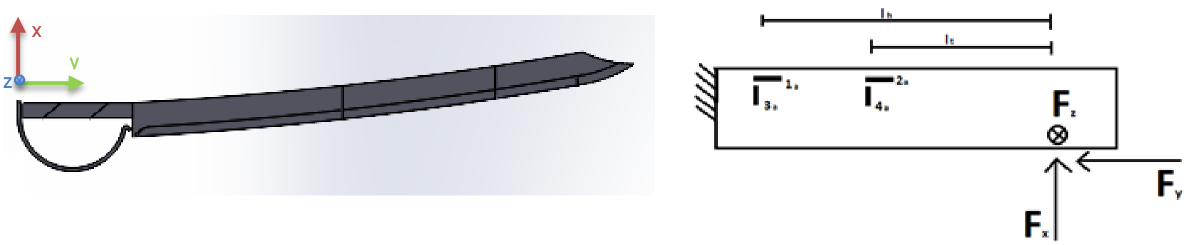

Figure 1: FEM model of the sword with reference system (left) and scheme of the strain gauges arrangement on one side (right). Configuration was replicated also on the opposite face

Strain gauge data collection was performed using the Shimmer Bridge Amplifier, a specific version of the Shimmer IMU (inertial measurement unit) that also carries an integrated circuit for reading a full Wheatstone bridge (Shimmer Sensing, 2013). The measurement ranges for those sensors were ±2.0 g for the accelerometer, ±500 deg/s for the gyroscope, ±1.3 G for the magnetometer and ±2.5 mV/V for the bridge amplifier. The use of IMUs was in any case necessary to collect kinematic data from the athletes thus making the Shimmer Bridge Amplifier IMUs the optimal choice as they provided both the IMU sensors and the Wheatstone bridge reading. The two Shimmer Bridge Amplifier IMUs were placed on the forearm and on the sword, held in place by a specifically designed 3D-printed case.
Sensor calibration was carried out by clamping the sword and loading with known directions and weights. Weight values were chosen from FEM results and an appropriate safety margin was also considered to avoid reaching sword yielding or strain gauges non-linearity.
In the actual field tests IMUs were placed on the sword and on some of the points used for placing markers in the Plug-In-Gait Protocol (Davis *et al.*, 1991): pelvis (PSI), forearm (RFRA) and upper arm (RUPA) of the dominant side for both the athletes involved in the combat. Data was acquired from accelerometer, gyroscope and magnetometer, in addition to the bridge amplifier for the strain gauges, using a sampling rate of 1000 Hz. A vision system composed by two 3D cameras (Realsense D435i by Intel) was also added to the setup to acquire videos of the sessions with both RGB and ToF (time of flight) sensors, useful for labelling and debugging operations. Each test session included several trials that could be divided into two exercise categories: a “controlled” stroke, in which the athletes agreed on how to execute attack and parry, and a fight lasting one minute, in which athletes were free to decide how to behave.

RESULTS: During the calibration process the sword was loaded on the less flexible axis (x) up to about 200 N in both the positive and negative directions, while for the other relevant axis (z) the maximum static load possible to prevent damage was around 50 N. Calibration results are shown in the left side of Figure 2: in the vicinity of zero load values, the data shows an anomalous behaviour caused by the calibration being performed by loading along one direction only and thus leaving the other axis completely unloaded. The right side of Figure 2 shows the residuals of the linear regression model where a large concentration of error is visible when the sword is unloaded.

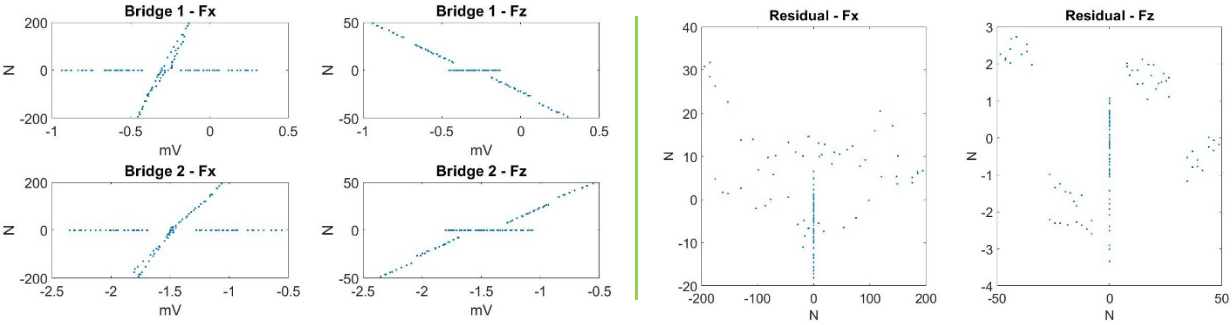

Figure 2: data collected during calibration (left) and regression residuals (right)

The RMSE was also estimated to calculate the error for each axis: F_x error was about 11 N, while F_z error was about 1.5 N. Considering the range of the applied loads, these error values look quite promising, but it must be considered that in the actual tests the impact force will reach values outside of the calibration range.

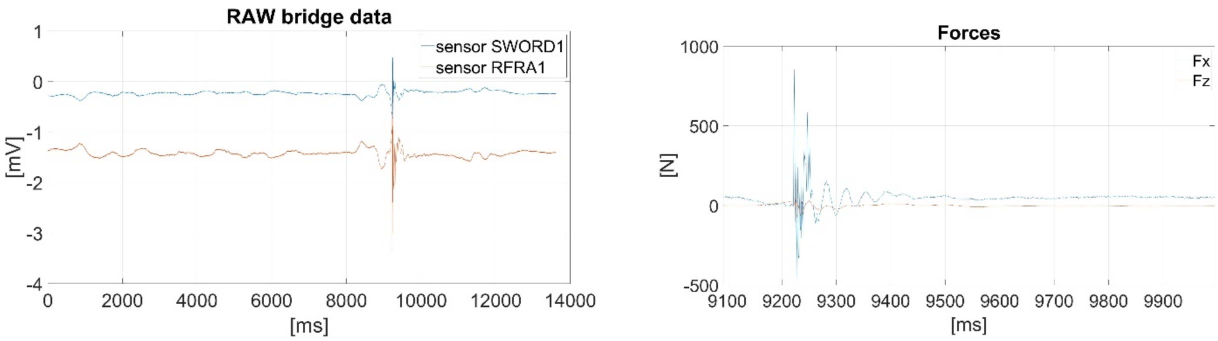

Figure 3: example of data acquired during a controlled hit (left) and forces estimated for the impact section combining values of the two bridges using calibration parameters (right)

The left graph of Figure 3 shows an example of the raw data covering the whole duration of a “controlled” test: one bridge was more sensitive to the weight of the sword also showing higher oscillations due to the handling of the sword before the hit, while the other remains closer to zero. This behaviour can be ascribed to sword interactions being primarily in the directions of the sword edge, as expected especially during a controlled gesture performed avoiding as much as possible to being hit on the flat side of the sword. The right side of Figure 3 shows a plot of the estimated forces: the sensor didn’t saturate and the peaks of F_z never exceeded 90 N, being about one order of magnitude lower than F_x and indicating that values along the z-axis may be almost negligible in many cases. Considering bridge output values, force results were in line with the previsions derived from the numerical simulations. Finally, the same graph also shows that the blow acts like a second order wave with two components: the impact force F_z associated with a very damped response and the transverse force F_x associated with a much less damped behaviour.

DISCUSSION: The RMSE value obtained from calibration data shows that the developed measuring instrument has a very low calibration uncertainty, being orders of magnitude lower than the impact forces. In addition, a proper calibration method was chosen to compensate the high transverse sensitivity of the system: the transverse sensitivity is in fact included directly in the static calibration parameters as the strain gauge bridges were used together to estimate both F_x and F_z.

Great attention was also paid to the fact that all the data acquired were to be calculated on the same time base: using the same sensor to acquire both strain gauges data and kinematic data allowed ensuring a complete synchrony of the system. In addition, during the configuration process, all the sensors were automatically synchronized at the absolute time of the computer they were connected to.

The main limitation of the developed system is the rather low bandwidth, especially considering the goal of measuring impulsive phenomena that by definition are always under sampled. Considering that the Shimmer Bridge Amplifier sensors integrate an antialiasing filter, their bandwidth is 500 Hz. Considering the sword as a dynamic force sensor with a high damping, it is actually possible to estimate its bandwidth at roughly 23 Hz. This bandwidth compromise was chosen to facilitate the integration of the various devices and maintain a simple experimental setup. Moreover, the current setup allowed not to significantly alter sword weight which is a very relevant point considering the great variability and dynamicity of the athletic gestures involved.

Finally, the experimentally measured forces can be considered as very reasonable preliminary input data for future numerical analyses despite the limited bandwidth of the developed measurement system. Furthermore, the raw strain gauge output could also be used as an additional way to validate such numerical analyses without worrying about the reduced bandwidth.

It should also be pointed out that the actual force-measuring system bandwidth of 23 Hz would be sufficient for measuring the forces transferred by the sword over the athlete during the impact because human gestures are typically performed and measured at < 6 Hz frequencies.

CONCLUSION: In this study strain gauges were applied for the first time to the estimation of impact forces during historical fencing, using the sword itself as a force sensor and developing a measurement system able to provide accurate data. Although some aspects can be improved, the results obtained are satisfactory and open the way to a new line of studies related to the estimation of the strength and durability of the weapons and to the measure of forces involved during the impact between swords. The resulting force values could also be used to compare different types of weapons and to estimate the athletic performance of fencers, providing feedback and helping their training. In addition, although the current study focused on medieval weapons, the same approach could potentially be applied to any sword or even to all combat sports that involve the use of some weapon or instrument.

REFERENCES

Davis, R. B. I. *et al.* (1991) 'A gait analysis data collection and reduction technique', *Human Movement Science*, 10, pp. 575–587.

Shimmer Sensing (2013) 'Shimmer3 Bridge Amplifier + Expansion Board User Guide', *Shimmer 2015*, Rev 1.5(Realtime Technologies Ltd), pp. 1–14.

Ştefănescu, D. M. (2011) 'Strain gauges and Wheatstone bridges - Basic instrumentation and new applications for electrical measurement of non-electrical quantities', in *International Multi-Conference on Systems, Signals and Devices, SSD'11 - Summary Proceedings*. doi: 10.1109/SSD.2011.5767428.

Tonelli, G. *et al.* (2016) 'Historical and Metallurgical Characterization of a "Falchion" Sword Manufactured in Caino (Brescia, Italy) in the Early 17th Century A.D.', *Jom*, 68(8), pp. 2233–2249. doi: 10.1007/s11837-016-1920-3.

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