Impulse of a Kendo Strike

Masahiro Abe and Dhamma Kimpara

Abstract

An expert swordsman struck a target with a kendo sword. The velocity and force of the strike were measured. The relationship between the strike velocity, impact force and effective mass of the sword was investigated. It was shown that the effective mass of the sword remains constant for typical strike velocities.

Introduction

When a kendo sword strikes its target, there is a transfer of momentum and a resultant force. The force of the kendo sword on the target is related to the strike velocity. This collision is not a simple case of conservation of linear momentum because it involves rotational motion, as well as external forces applied during the collision. Since the hands are holding on to the sword, the hands will exert a force throughout the strike. For a complete analysis, one must also consider the rotational motion and elasticity of the sword during the collision. (see figure 1).   Though this collision involves complex motion and several forces, due to the short time of impact and the elasticity of the sword, it is here proposed that the strike can be considered to be effectively a free collision between two objects, since the force exerted by the hand on the sword is not expected to be a significant factor during the

Figure 1 Kendo sword swing[1].

impact. It will be modeled using the concept of impulse and change in momentum during a free collision. In this model, the sword is assumed to be a freely moving object with mass and velocity but, since it is in rotational motion, it is expected that the effective mass of the sword as it exerts an impulse during the collision would be less than the actual mass of the sword.

The effective mass can be found using the equation

$$m_s(\Delta v_s) = F_t \Delta t \qquad (1)$$

Where m_s is the effective mass of the sword, Δv_s is the change in velocity of the sword during the strike, is the force applied by the sword, and t is the time that the force is applied. The change in

momentum of the sword is equal to the impulse exerted by the sword, or the force exerted in the collision multiplied by the time it is applied.

$$m_s(\Delta v_s) = J \tag{2}$$

Where J is the impulse, which is equal to $F_t \Delta t$. This means that the effective mass of the sword is equal to the ratio of the impulse that the sword exerts during the impact to the change in its velocity:

$$Effective\ Mass\ = \frac{J}{\Delta v} \tag{3}$$

If the relationship between the strike speed and impulse is proportional, then it will indicate that the collision is effectively free from outside forces and the effective mass is shown to be constant. If the effective mass stays constant then this implies certain aspects about the nature of the sword. This would imply that the contribution of the force of the hands to the impulse during the collision is effectively zero throughout the range of strike speeds tested. This also implies that the elasticity of the sword, and the short time of impact combine to make this effectively a free collision.

Method

Half of a tennis ball, with a diameter of 6.5±0.1 cm, was centered and taped on a Vernier force plate. A high-speed camera, set at 1,200 frames per second, recorded the motion of a kendo sword with a mass of 0.385±0.001 kg. An experienced kendo fighter was used to collect data. The kendo fighter was asked to strike five times with the same strike strength. This was done for four different strike strengths ranging from a very gentle blow to a very hard blow. Using Logger Pro Video Analysis, the position of the bottom of the sword at the point of impact was marked in each frame for a number of frames just before and after the impact as shown in figure 2. The vertical position of that point in each frame was graphed, as shown in figure 3, and the slope of the data was taken as the velocity of that point of the sword during that time. This technique was used to find the incoming and rebound velocities. As shown in figure 3, the incoming velocity of the impact point of the kendo sword for the illustrated trial was -3.1±0.1 m·s⁻¹ while the rebound velocity was 1.5 m·s⁻¹. To record the impulse of the sword as it exerts a force on the ball, data from the force plate was collected (see figure 4) simultaneously to the video recording. Figure 4 shows the 20 peaks in the force readings as a function of time. The integral of the force of each hit with respect to time was determined to find the value of the impulse.   As seen from the figure, the first hit caused an impulse of 0.6 N·s while the last caused an impulse of 1.9 N·s.
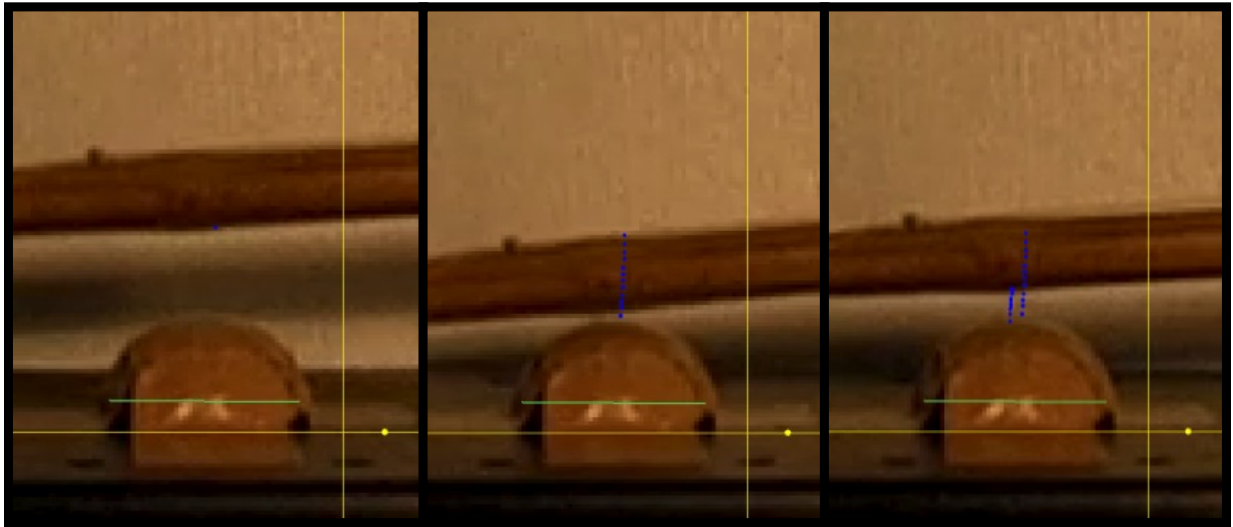
Figure 2 Three individual frames from the video of the sword's motion. Each blue dot indicates the position of the sword at different frames. The line of blue dots on the middle frame indicates the incoming hit velocity of the kendo sword while the left line of dots in the right frame indicate the rebound velocity.
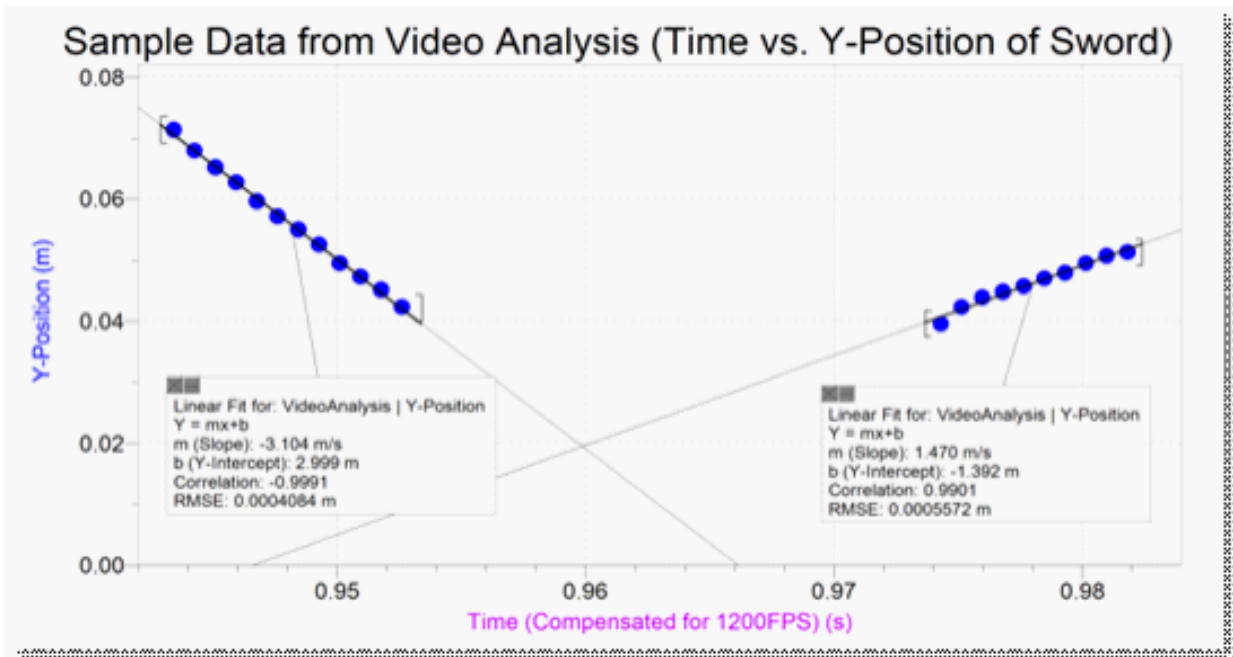

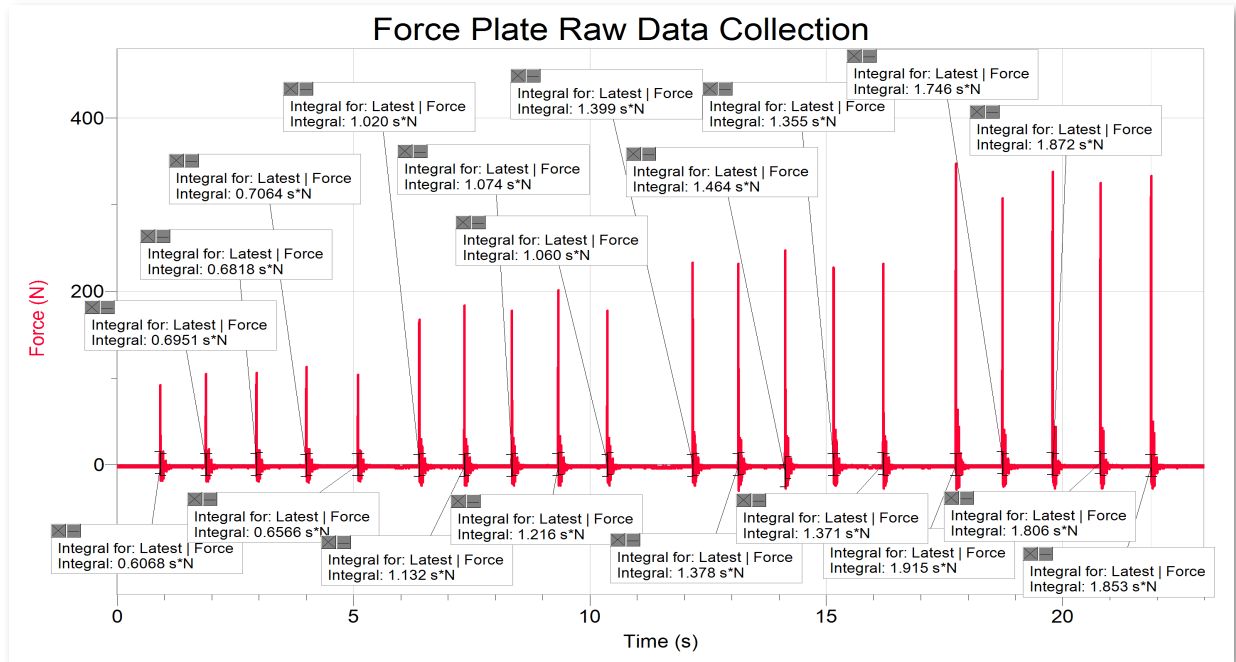**Figure 3** Video analysis of the incoming and rebound velocities of the kendo sword.

Figure 4 Data from the force plate is shown. The integral of each of the hits were calculated to find the impulse of each hit.

Results and Discussion

Figure 5 shows the relationship between the change in velocity of the sword and the impulse of the system.

$$J = (0.160 \pm 0.001 kg)V \qquad (4)$$

The proportional relationship between the change in velocity of the kendo sword and the impulse of the system indicates several key aspects about this particular collision. These results would be a trivial confirmation of Newton's second law if it were a simple linear collision, however in this situation, the swordsman is exerting force during the impact. This is an interesting result because it is not entirely obvious that the relationship would be proportional.
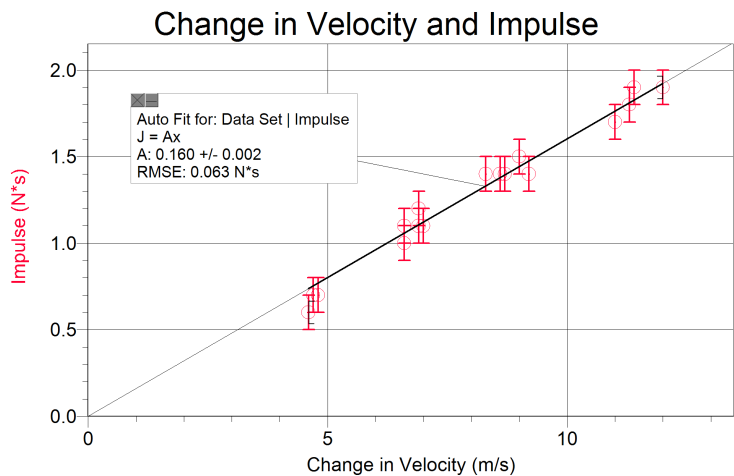

Figure 5 A proportional relationship between the change in velocity of the kendo sword and the impulse of the system.

It can also be concluded that the proportional fit indicates that there are no significant outside forces acting on the sword during the impact. Though the swordsman was exerting force on the sword, due to the sword's elasticity, the force by the hands are not effectively transferred to the point of impact during the short impact time. For a stiff sword, the impulse would be expected to increase at a greater rate than the change in velocity of the sword because the force would be more effectively transferred to the point of impact thus, a greater outside force would be acting on the sword. Additionally, though theoretically there is expected to be a y-intercept due to gravity, it is small enough (order of 1N) compared to the impact forces (100-400N) that the proportional fit is still valid.

Another conclusion that can be reached is that given the proportional fit in figure 5, the effective mass stays constant at all strike speeds since the slope equals the effective mass (in this case). One thing to note is that the effective mass is actually less than the actual mass of the sword. This is due to the fact that the sword is being rotated thus, the velocity at the end of the sword will be much greater than the velocity near the grip of the sword, where most of the mass is concentrated. The part of the sword near the grip will have less of a change in momentum than the tip thus the total impulse needed during the impact is less than the mathematical product of the actual mass of the sword multiplied by the change in velocity of the sword. This makes the effective mass much less than the actual mass. Since the effective mass is largely constant for all hit strengths, it follows that the rotational motion of the sword is constant for all hit strengths.

There are some interesting points to note from figure 4. First the skill of the kendo fighter in controlling the swing can be noticed in the less than 10% variation in incoming velocity and impulse for each "swing strength". Second, a practical observation; that the kendo player can know that his impact speed is linearly related to the impulse exerted.

Figure 6 shows with confidence that kendo sword fighters can increase the force of their swing by simply increasing the speed at which they swing. However, it is suggested that, given the difference between the effective mass and the actual mass of the kendo sword, a less elastic sword such as a bokken may exert higher forces at the same hit velocities.
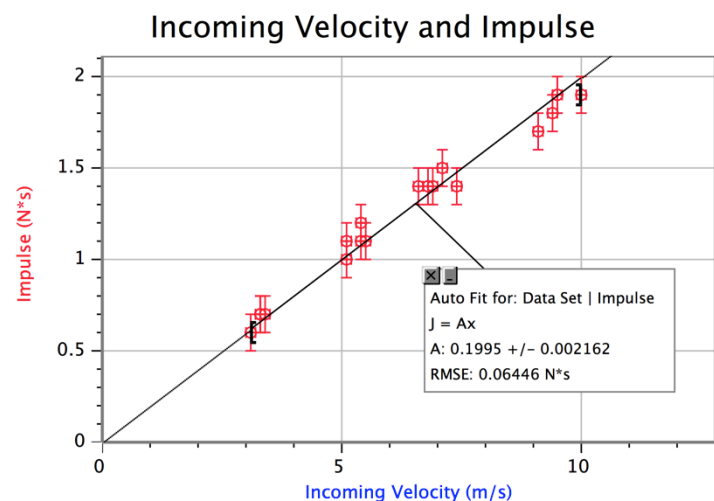

Figure 6 A linear relationship between the hit velocity of the kendo sword and the impulse of the system.

Figure 7 shows a proportional relationship between the impact kinetic energy and the loss of energy of the kendo sword. The kinetic energy was calculated using the effective mass of the sword and the incoming and outgoing velocities of the sword. Further work is needed to confirm this.

It is important to note that the proportional relationship shown in figure 7 does not necessarily follow from the previous discussions of figures 5 and 6. One possible explanation is that if the sword obeys Hooke's law, the maximum

Figure 7 Incoming Kinetic Energy and Loss of Kinetic Energy after impact. Mass defined as the effective mass (see figure 5) and velocities were the incoming and outgoing velocities.

displacement of the sword on impact would be proportional to the incoming kinetic energy (simple harmonic oscillation). In addition to this, if the work done by internal friction in the sword is proportional to the displacement of the sword, then the loss of energy would be proportional to the incoming kinetic energy. Similarly, in the object being struck, a similar situation would occur. To confirm this, high speed video would have to be taken, allowing careful analysis of the displacement of points along the sword and the compression of the impacted object. Further study is needed to clearly explain the relationship shown in figure 7.

A possible improvement in the investigation is to increase the range and intervals of the hit velocities. Because there is a limit on the accuracy of the human swinging the kendoka, a machine could be used to swing the sword in the same way as a human but with more accuracy and higher range and systematic control of velocities. In this research, only one section of the kendo sword shaft was used to hit the target. Further investigation could be to examine the impacts at different points on the kendo sword.

Conclusion

The relationship between the strike velocity of the kendo sword and its effective mass was shown to be that the effective mass of the sword is constant when the hit velocity increases. Usually it is expected that the hand will apply a greater force for a greater force of impact. The results of this investigation are surprising because it implies that the force of the hand during the impact is negligible or is constant for all strike velocities. This relationship applies to the full range of velocities used during normal kendo sparring.
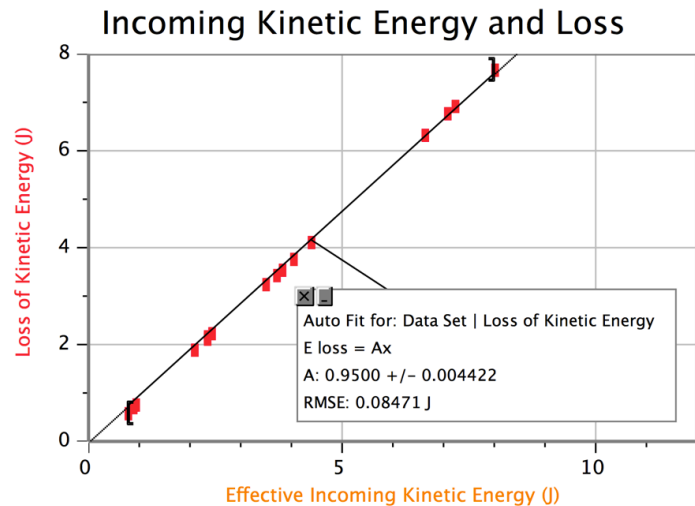
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