Understanding the Biomechanics of the Karate Punch (*Tsuki*)

By Amy Ballantyne

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Introduction

Kyokushin is a style of karate renowned for the power and strength of its techniques and fast knockouts during *kumite* (fighting). It was developed by Masutatsu (Mas) Oyama (1923-1994) as a full-contact martial art. Oyama was influenced by the Japanese Sumarai maxim '*Ichi Geki Hissatsu'* (one strike, certain death) meaning that fighters should be able to defeat their opponents with their first strike. This affected both how he trained and his development of Kyokushin techniques and philosophy [1].

Years of intensive training (12 hours a day) meant Oyama's technique, strength and power was unrivalled. The immense strength of his punches allowed him to end most of his *kumite* very quickly and often with one strike. As Cameron Quinn explained in 'The Budo Karate of Mas Oyama' this was because the blows of Oyama's punches were so hard that, if they made contact with the opponent, they were able to inflict injury whether or not the opponent blocked. [1]

One way the strength of a punch can be shown is through *tameshiwari* (breaking) techniques. Oyama was a master of breaking techniques and his years of training meant he was able to test the limits of human strength. He performed impressive feats, including novel acts such as the bottle cut and brick break that he had developed himself, for astounded crowds around the world.

The strength of a punch can be measured and analysed through biomechanics. This essay will summarise the collision dynamics of breaking a wooden board with a punch by discussing concepts such as the transfer of energy from the fist to the target, work done, force and power produced. This will be followed by analysing a punch into a boxing bag, and concluded by discussing techniques *karate-ka* (practitioners of karate) can use to increase the strength and power of their punches.

Mechanics of the *Gyaku Tsuki* (Reverse Punch)

Kinetic Energy

The amount of damage inflicted on an opponent or object struck is proportional to the amount of energy in a *karate-ka's* punches. This energy is mostly in the form of kinetic energy (KE) in a straight punch such as the *gyaku tsuki* (reverse punch) as the potential energy and rotational energy are negligible [2]. Kinetic energy is directly proportional to the mass (m) of the object and to the square of its velocity (v) as shown by Equation 1.

$$\text{KE} = \frac{1}{2}mv^2 \qquad \text{(Eq. 1)}$$

In the case of a punch, m is the effective mass of the fist. Intuitively, we know that being hit by a heavier object is worse than being hit by a lighter object travelling at the same speed. (Being hit by a train is worse than being hit by a bike travelling at the same speed). However, not all of a *karate-ka's* mass is put into a punch and the mass of the *gyaku tsuki* is better represented by the mass of the fist and arm [3] [4] [5], which is about 5% of total mass [6]**.** Heavier *karate-ka* tend to have proportionally heavier arms. A study by Wililko *et al.* on the reverse punch performed by Olympic boxers showed that the effective mass increased from 2.3kg for flyweight (51kg) boxers to 5.0 kg for super heavyweight (100kg) boxers [5].

Unlike effective mass, doubling the velocity of the punch produces not twice but four times as much kinetic energy. One of the reasons karate punches are so effective is that a *karate-ka* can train to increase the velocity of their punches through technique. The velocity of a beginners punch is around 5 ms^{-1} [7] but the fist of a trained *karate-ka* in a *chudan gyaku tsuki* (middle section straight reverse punch) has a peak velocity of 6 to 10 ms^{-1} [3].

Inelastic collision

Breaking a wooden board using a karate punch is an inelastic collision [3]. This means that not all the kinetic energy in the fist becomes kinetic energy in the combined system. Instead, some of the energy is expended in deformation, both of the board and the fist. The heavier the target is, the more energy is used in deformation. For example, kinetic energy is mostly conserved while breaking a wooden board, but much more energy is used in deformation of the fist while breaking more massive concrete blocks [3].

Work Done

Work (*W*) is a measurement of the kinetic energy transferred to a target. In the case of breaking a board, it is the kinetic energy transferred from the fist to the board.

$$W = \frac{1}{2}mv^2(final) - \frac{1}{2}mv^2(initial) \qquad \text{(Eq. 2)}$$

The work done on the target is proportional to the kinetic energy of the fist, but also depends on the nature of the target. Properties such as the angle and alignment, cushioning, mass and centre of balance of the target as well as which direction the target is moving all effect the work done on the target.

Force

An impact force (*F*) generated when the fist meets the target is proportional to the work done by the fist (and therefore kinetic energy of the fist), but also depends on the distance (*x*) over which the energy is released over.

$$F = \frac{W}{x} \qquad \text{(Eq. 3)}$$

Feld *et al*. found that that wooden boards (1.9 cm thick) bend by about 1 cm before they break, which requires a force of 500 N. From this, we can calculate that the work done is about 5 J. The fist needs to have more kinetic energy than this, however, as some of the energy is lost upon collision as previously discussed.

Breaking wood requires one-fifth the impact force of concrete, but three times more energy. [3] This larger critical energy of wood is because wood requires deflection sixteen-times that of concrete, but may be initially surprising as concrete is renowned for being harder to break than wood. It can be explained, however, by more kinetic energy being used in deforming the fist when it collides with the more massive concrete target [3], so a higher kinetic energy of the punch is required overall.

Feld *et al*. found that the hand of a *karate-ka* can exert a force of more than 3,000 N. For comparison, the maximum limit of a rib is in the region above 600 N [8]. A properly formed fist can easily withstand the resulting counterforce due to the strength of the bones and their connection via viscoelastic tissue, and have been shown withstand up to 25,000 N. [3]

Power

Karate-ka often talk about wanting to improve the power of their punches. A powerful punch does not, however, necessarily impact with the greatest force or do the most damage to a target. These effects are produced by the kinetic energy of the punch and not its power.

Power is the rate at which work is done (Equation 4). Kinetic energy from the fist can be transferred slowly or rapidly to the target. A given amount of kinetic energy can be transferred by a large force acting through a short distance, or a smaller force acting through a longer distance. The later, however, will require more time so that the rate at which the kinetic energy is transferred (power) is less.

$$P = \frac{W}{t} \qquad \text{(Eq. 4)}$$

A powerful punch is not always necessary or desirable for a *karate-ka*. In some situations, usually when there are no time constraints such as for breaking, it is only the amount of work done that is important. In this case, the priority would be for maximum kinetic energy.

At the other end of the spectrum, when time is a factor and there is a priority for speed, it may be desirable for the kinetic energy to be transferred quickly in a powerful punch. One example of this is light contact *kumite* where priority for the *karate-ka* is to score a ‘touch’ point rather than a hard blow.

Self-defence and full-contact *kumite* are likely to have a mix of both types of punches (e.g fast powerful *kiazami-tsuki* or jabs, and strong *gyaku-tsuki* or reverse punches) as well as techniques along the spectrum where there is a need to strike quickly so the punch can’t be blocked or slipped, but have enough kinetic energy to make the blow effective.

Punch Analysis Using a Punching Bag as a Ballistic Pendulum

My own *gyaku tsuki* (reverse punch) into a punching bag was analysed using slow motion video (480 frames-per-second). The impact is inelastic, as seen by the deformation of the bag in Figure 1a, which means we are not able to calculate the KE of the punch itself. But we can estimate the work done by the punch by considering the boxing bag as a ballistic pendulum, a device invented in 1742 to measure the speed of a bullet.

By measuring the height (h) that a boxing bag of mass (m) reaches, and using the gravitational constant (g), we can calculate the potential energy (PE) given to the bag.

$$PE = m \times g \times h \qquad \text{(Eq. 5)}$$

Screenshots of the video were grabbed when the bag was at its highest point (Figure 1b). From this, it could be seen that the bag made an angle of 30 degrees with the vertical. Given a total length of the bag of 1.830 m, a height of 0.245 m was calculated. Using the bag mass of 18 kg and gravitational constant of 9.8 ms^{-1}, a PE of 43 J was calculated when the bag is at its maximum height. Conservation of energy means that this is equivalent to the KE transferred by work done on the bag by the punch. This is significantly higher than the 6.4 J required to break a wooden board that was calculated by Feld *et al.* [3]

We can calculate the average force of the impact by re-arranging Equation 3 to give:

$$F = W \times x \qquad \text{(Eq. 6)}$$

By measuring the distance over which the force is applied from initial contact to final contact with the bag (Figure 2) as 0.2 m, and using the value of 43 J measured for the work done, we calculate that the average impact force is 215 N. This is much lower than the impact force required to break a wooden board (500 N, [3]) but the force is spread out over a longer distance (20 cm compared to 1 cm).

We can also estimate the average power of the punch by estimating the time that that the fist is in contact with the bag as 500 ms, and use Equation 4 to calculate an average power of 86 W.

For context, the most powerful punch ever recorded produced 69 kW and was by Francis Ngannou (UFC) [9].

Figure 1. Screenshots of a video taken during a *gyaku tsuki* into a punching bag: (a) maximum deformation of bag and (b) peak height/angle of bag.

Figure 2. Screenshots of a video taken during a *gyaku tsuki* into a punching bag: (a) initial contact and (b) final contact of fist with bag.

Improving Punch Performance Through Technique

The strength of the punch can be improved by increasing the KE of the punch, either through increasing the mass or the velocity of the fist.

Effective Mass

As previously discussed, the effective mass of experienced *karate-ka* can be approximated by measuring the mass of the fist and arm. However, this is only true if the wrist is kept rigid. Wililko *et al* showed flexing of the wrist reduces the effective mass to an amount approximating the mass of the fist. [5]

Velocity

The peak velocity of the fist when it collides with a stationary target can be increased through kinetic linking [10] [11]. A *gyaku tsuki* by an experienced *karate-ka* consists of the rapid execution of a sequence of body movements where each body segment moves faster than the previous body segment [10], [12]. It begins with leg extension, followed by hip and trunk rotation, and then arm extension (proximal to distal order). The large muscles of the legs and back accumulate and transfer energy to the much smaller fist, increasing its velocity as the mass decreases like the cracking of a whip [11]. The key to obtaining maximum velocity is precise timing to bring each new body segment into play when the proceeding body segment has reached its maximum velocity. Simultaneous blocking (or halting) by the front foot may also be used in order to increase the velocity of the fist [11] [13]. Generating maximum velocity for each segment is the reason *karate-ka's* train for tight, explosive muscles throughout the body.

It is important that the collision of the fist with the target occurs when the fist is at peak velocity, usually just before full extension [3]. For this reason, *karate-ka's* often train by visualising their fist punching through the target.

Reach has also been found to affect velocity. Kimm *et al.* found that boxers with longer reach were able to produce a higher peak velocity of the fist. This was explained by more distance for the fist to travel and therefore more time for the fist to accelerate to a higher velocity even though the total time taken to reach the target may be longer. [12]

Traditional karate techniques

The traditional *gyaku tsuki* includes rotation of the fist (from palm up at the hip to palm down at full extension as seen in Figure 2b) and the *hikite* (simultaneous pullback of the opposite fist). Although these actions are not primarily intended to provide additional strength or power to the punch (they instead have alternative purposes and potential applications), they may contribute marginally [14]. Venkatraman *et al* showed that fist rotation has minimal effect on velocity but does increase the impact force by 6-12% [4] and has been mathematically shown to increase kinetic energy due to an increase in rotational energy [2].

Conclusion

The strength of a punch is determined by its kinetic energy, which can be increased by optimising effective mass or velocity of the fist through fine-tuning punching technique and training for explosive muscles. Maximum strength is not always desirable for a *karate-ka* and there are circumstances where it is advantageous to prioritise power over strength.

Although this essay has focussed on the strength of the *gyaku tsuki*, the damage inflicted on an opponent depends significantly upon the properties of the target including: the opponents balance and angle to the punch, cushioning of the target, and the size of the target and the opponent. The relative velocity can be increased by pulling the opponent towards the punch, or connecting when a target is moving forward.

Finally, the purpose of karate *kumite* is to transfer maximum energy while receiving minimum injury, and defence to avoid or block attacks is a major component of a *karate-ka's* training. An effective defence followed immediately by strong and powerful counter attack to an appropriate target often determines the outcome of a fight.

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