

Karate strikes

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(Received 21 November 1974; revised 24 March 1975)

Analysis of a forward karate punch is made as an example of collision mechanics. The energy lost to deformation of an opponent is evaluated, and the deformation is shown to be maximized if contact is made when the fist has the greatest speed. In karate fighting the maximum deformation is obtained by focusing a punch to terminate several centimeters inside an opponent's body. The average impact force is calculated and compared with that needed to break a human bone by stressing it beyond its ultimate bending stress value. Similar breaking forces needed for bricks and wooden boards are also computed. A brief description of breaking demonstrations for the physics classroom is made.

INTRODUCTION

In recent years, considerable popular attention has been directed towards the various Oriental forms of fighting, especially the several forms of karate. One of the peculiar features of karate is that the strikes to an opponent are designed to terminate several centimeters inside an opponent's body, in contrast to the follow-through of the wide swings employed by movie cowboys and most uninitiated street fighters. Here we shall examine the question¹ of whether there is any scientific basis for focusing a strike to terminate just inside the target body.

We shall also examine the forces involved in a strike to a bone of the opponent, for example, a forearm bone. In particular, we shall be interested in the feasibility of a karate expert breaking an opponent's bone much as they break boards, bricks, tiles, blocks of ice, etc., in exhibitions.

Though the martial arts are just now coming into widespread notice in the United States, they have been practiced for several thousand years in the East. Karate is believed to have begun about that long ago in China, spreading later to Okinawa, Japan, and Korea.^{2,3} The principal characteristic of the resulting several styles of karate is the use of one's own body—hands, feet, elbows, head, and knees—as weapons and in defense. People in the West are often unaware of the large impact forces involved in such fighting. Even though a study of karate is immersed in violence, the fighting is graceful and appears to be well grounded scientifically.

DEFORMATION ENERGY

The primary point in striking an opponent is to maximize the deformation damage at the area of contact, and it is only rarely that moving the opponent's body as a whole is desired. In calculating the extent of damage, there appear to be two considerations, one being the amount of energy lost to deformation during the impact, and the other being the impact forces and stresses imposed. Let us first consider the energy lost to deformation.

If we treat the strike as a collision between two free bodies, one (M_1) initially at rest, and the other (M_2) initially moving at speed v , the energy ΔE lost to deformation and heat can be found from the conservations of total energy and linear momentum⁴:

$$\Delta E = \frac{(1 - e^2)}{2} \frac{M_1 M_2}{M_1 + M_2} v^2, \quad (1)$$

where e is the coefficient of restitution. That coefficient is the ratio of the velocity difference of the two bodies after the collision to that difference before the collision. A perfectly elastic collision has $e = 1$, and a totally inelastic collision has $e = 0$. In our development here, we shall neglect the heating of the two impacting masses and treat ΔE as being entirely lost to deformation.

The equation is used by Miller⁵ and by Gray and Gray⁶ in discussions of pile driving and forging. Miller questions whether elastic or inelastic collisions are desired in those activities, and in forging, whether a light or heavy hammer should be used. In forging, one wants to maximize the fraction of the initial energy lost to deformation, the fraction being

$$\frac{\Delta E}{M_2 v^2 / 2} = (1 - e^2) \frac{M_1}{M_1 + M_2}, \quad (2)$$

so that each strike is as efficient as possible. The fraction is largest for $e = 0$, that is, for totally inelastic collisions, as could have been guessed. The fraction is larger for smaller values of M_2 , and thus a light hammer is more desirable than a heavy one. In pile driving, no deformation of the pile is sought, and one attempts to have elastic collisions where $e = 1$. The karate strike is similar to the forging considered by Miller. The karate strike is more complicated, however, because e is strongly dependent on where the opponent is hit. Even though hitting muscle and fat would involve a greater e , and hence less ΔE , than hitting a bone covered by a thin layer of skin, a strike to a high- e area may result in more pain to the opponent. Clearly, a strike to the groin may be more advantageous than one to the leg even though the e for the groin strike is greater. Another problem in the evaluation of any collision is that e may be dependent on v . Unlike Miller's forging, we are not so concerned with the efficient transfer of energy to deformation with each strike as we are with the absolute magnitude of the energy transfer. In forging, we can strike until the job is done; in ka-

rate we may have only one chance. We are therefore interested in (1) rather than (2).

The choice of M_2 for inclusion in (1) depends on not only the fighter's mass but also the type of strike employed. For example, the effective mass involved in a forward punch in which the attacker steps forward is greater than if he remains stationary. In our calculations here, however, we shall employ a typical value for the M_2 involved in a forward punch and not consider variations in M_2 due to stance or movement of the fighter's trunk.

Since (1) depends on v^2 , the karate fighter attempts to maximize the speed of his strike. Let us consider a forward punch (Fig. 1) in which the attacker does not move his feet. The fist starts at the waist with the closed palm upward, and as the fist is hurled forward, it turns over until the closed palm is downward when the arm is fully extended. Karate blackbelts are said to complete this motion in about 0.2 sec with maximum speeds of about 7 m/sec occurring between 70% and 80% of the way through the motion.^{7,8} This range of maximum speed is confirmed in Fig. 2, which is based on data taken from a high-speed movie of a forward punch by the author. In this paper we shall consider the 75% point as that of maximum speed.

Maximum energy transferred to deformation would occur if impact is made at that 75% point. Let us assume that M_2 is the mass of only the striking arm. Miller and Nelson⁹ estimate that the arm is approximately 10% of a man's total mass. Taking $e = 0$, the total mass of both men to be 70 kg, and the maximum speed quoted above, we find from (1) that a maximum of 156 J can be transferred to deformation damage. In absence of a target, the karate expert is trained to terminate the punch when his arm is fully extended. If we assume constant acceleration and deceleration of his fist and if we used the time of



Fig. 1. Forward punch begins at the waist and terminates when arm is fully extended. Contact should be made before full extension.

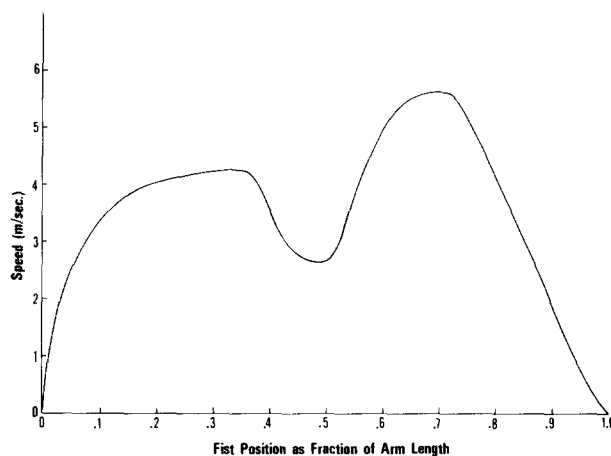


Fig. 2. Speed of fist versus position of fist measured as a fraction of the full arm extension. Data taken from high-speed movie of the author.

maximum fist speed given above, then the maximum speed is reached at 0.75 of the arm's full extension, or typically 10–14 cm from the stopping point. With only (1) considered, then, the maximum energy of about 156 J is delivered to the deformation of the opponent if the attacking fighter focuses his punch 10–14 cm inside the opponent's body. This way impact is made approximately when the fist has the greatest v .

Practically, however, the focus may be only half that distance inside the body since the fist should be fully turned to a palm-down orientation before impact is made to avoid any wrenching of the wrist. Focusing depths of 6 cm or more may be used in other forms of strikes which do not have that practical consideration. The backhand strike to the side involves rapidly pivoting the fist about the elbow while the elbow is rapidly brought from one's front to the side of the body. Contact should be made with the knuckles when the fist is traveling the fastest, and that will be several centimeters before the projected terminal point. In other words, the strike should again be focused several centimeters into the opponent's body.

Since (1) includes the square of the speed, we can see the great advantage of a karate fighter increasing the deformation energy by stepping forward with the punch or by striking when the opponent happens to lunge toward him. If both fighters quickly close, ΔE may even be doubled.

In street fighting there may be a continuation of the punch after maximum speed is obtained and even after contact is reached. Such follow-through is usually not made in karate for two reasons. One, if contact is made sometime during a wide swing, the attacker will probably jeopardize his balance. Two, if contact is made just as the follow-through begins, then the energy transfer during the follow-through results from pushing, and since pushing and displacement do not result in deformation damage, they are normally not worth the loss in the attacker's poise.

Introductory karate students often believe that the rotation of the fist in the forward punch described above significantly adds to the energy delivered to the opponent. If we treat the arm as a solid, uniform cylinder of radius $r = 3$ cm and use the arm mass and punching time from above, we find that the rotational energy E_r is

$$E_r = M_2 r^2 \omega^2 / 4 = 0.4 \text{ J}, \quad (3)$$

which is negligible compared to the 156 J calculated before. Similarly negligible results are obtained for punches in those styles of karate in which the fist is rotated immediately before contact rather than continuously throughout the punch. So, the fist rotation appears to be largely for the most comfortable use of the arm muscles.

IMPACT FORCE

The second aspect to be analyzed in evaluating the damage to the opponent is the impact force and the resulting stresses in the opponent's bones if bones are struck. Again, if we consider a forward punch with the arm as a free mass of about 7 kg, the maximum momentum of the punch is approximately 49 kg m/sec. Nakayama¹⁰ reports that contact time appears to be 10 msec or less. If the fist comes to a complete stop within that time owing to the collision, then the average impact force can be as large as 4900 N. Since the collision occurs so quickly, it is approximately correct to neglect the muscular accelerations during the collision.

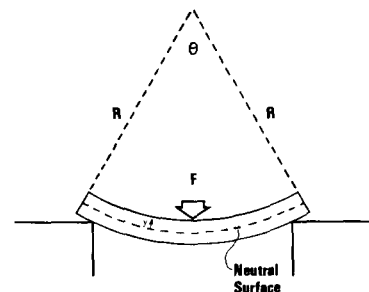
To evaluate roughly the effect of such an impact force, let us consider the resulting acceleration of the head if the strike is made there. Miller and Nelson⁹ give the head's mass as typically 8% of a man's total mass. If we again assume that the total mass is 70 kg, the average impact force would give an average acceleration of about 875 m/sec², or about 89 g, to the head. This result is consistent with that of R. L. Le Fevre, as related to Benedek and Villars,¹¹ on the acceleration of a dummy's head when struck by a prizefighter. The peak acceleration of the dummy's head was 80 g. Such a blow, according to Benedek and Villars,¹² would be a factor of 2.5 times too low to be fatal to the average person but could result in unconsciousness. The blow from the prizefighter is spread over a rather large glove. The karate fighter impacts primarily only two knuckles, those of the first and second fingers, and the force can be considered to be applied at a single point. For our purposes here, would such a karate punch made directly to a bone, such as in the forearm, result in breakage?

To answer the question, we first must calculate the stress created by the impact force and then compare that value with the maximum value that can be withstood by a human bone. Our development follows Clements and Wilson¹³ and Benedek and Villars.¹⁴ If a static force F is applied to a material over an area A , then the stress σ on the material is F/A . If a straight bone is pulled at each end by a force F , then the bone will be elongated by an amount δl that is proportional to the force and the initial length L . The ratio $\delta l/L$ is the strain ϵ and is related to the stress by a constant E , the Young's modulus of elasticity:

$$\sigma = E\epsilon. \quad (4)$$

This linear relationship between stress and strain holds up to a point called the proportional limit. In our work here we shall continue to use (4) even up to the rupture point, but we shall partially compensate our error by eventually incorporating experimental stress data.

Fig. 3. Deflection of a supported bone is made by an applied force.



If a static force causes bending of a bone supported as shown in Fig. 3, then there will be compression along the inside of the curve and elongation along the outside curve. Somewhere inside the bone will be a surface called the neutral surface along which there is neither elongation nor compression. The magnitude of strain anywhere in the bone is expressed as a function of the distance y away from that neutral surface by

$$\epsilon = \delta l/L \approx y\theta/R\theta = y/R, \quad (5)$$

where θ is the angle shown in Fig. 3 and R is the radius of curvature of the bent bone. The stress σ as a function of y follows from (4):

$$\sigma = E y/R. \quad (6)$$

The external forces on the bone cause torques on the bone, and since we are considering a static case, all those torques must be in equilibrium. Consider the cross section of the bone on the near side of the imaginary cut indicated in Fig. 4. The stresses over the cross section cause a torque on the cross section about the axis OO . The bone does not turn about that axis, however, because there is an equal and opposite torque, $(F/2)(L/2)$, about OO due to the support force at the end of the bone. In relating the torque from the stresses on this cross section to the torque from the support force, we can eventually calculate a maximum force that can be endured by the

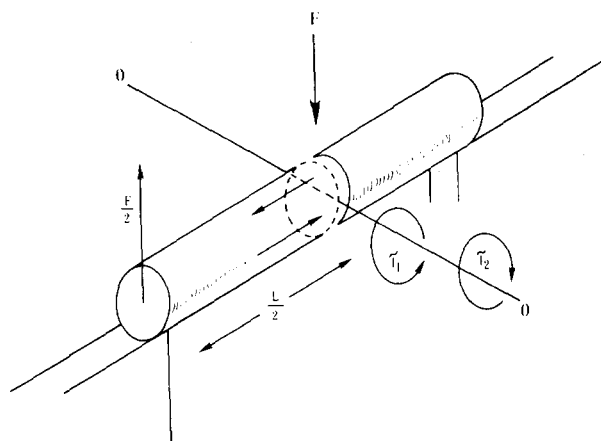


Fig. 4. The cross section on the near side of the imaginary cut through the bone experiences two torques about the axis OO . τ_1 is due to the stresses over the cross-sectional area indicated by the vectors. τ_2 results from the support force $F/2$.

bone without the stresses causing breakage.

The torque on the cross-sectional area element dA at a distance y from the axis OO due to stress is

$$d\tau = y\sigma dA. \quad (7)$$

The total torque on the cross section about OO due to stress is

$$\tau = \int y\sigma dA.$$

By using (6), this expression is

$$\tau = (E/R) \int y^2 dA = (E/R)I, \quad (8)$$

where

$$I = \int y^2 dA, \quad (9)$$

and for equilibrium (Fig. 4), we must have

$$(F/2)(L/2) = \tau = (E/R)I. \quad (10)$$

The maximum stress occurs at the bone surfaces along the inside and outside of the curve. If the stresses there exceed the ultimate bending stress σ_u , which is also called the modulus of rupture, then the bone ruptures. We approximate the distance between the neutral surface and the surface of the bone along the inside curve to be the radius a of the bone. The maximum force that can be endured follows from (10) and (6) as

$$F_{\max} = 4IE/LR_{\min} = 4I\sigma_u/La, \quad (11)$$

since, by (6),

$$\sigma_u = Ea/R_{\min}.$$

Benedek and Villars¹⁵ give the ultimate bending stress from Yamada¹⁶ for wet human long bones as being approximately 2×10^8 N/m². If the bone is assumed to be a uniform cylinder 1 cm in radius and 20 cm in length, then $I = \pi a^4/4$ and $F_{\max} = 3142$ N. The center of the bone is deflected by less than 1 cm.

This result for F_{\max} means that, if a bone is supported at both ends and if our static analysis is approximately equivalent to a situation in which the force is quickly applied to the bone, a karate fighter could easily rupture the bone with a punch. Of course, in a fight a bone such as an arm bone is unlikely to be broken. Good targets are the ribs and, if the opponent has mistakenly placed a foot firmly on the ground, the lower leg of that foot. Since the bone in the above calculation is deflected by less than 1 cm, the bending of a bone is in itself no reason for a fighter to focus a strike several centimeters into the body.

In karate demonstrations boards, bricks, tiles, blocks of ice, and other materials are broken rather than bones. Let us calculate the force needed to break a pine board of di-

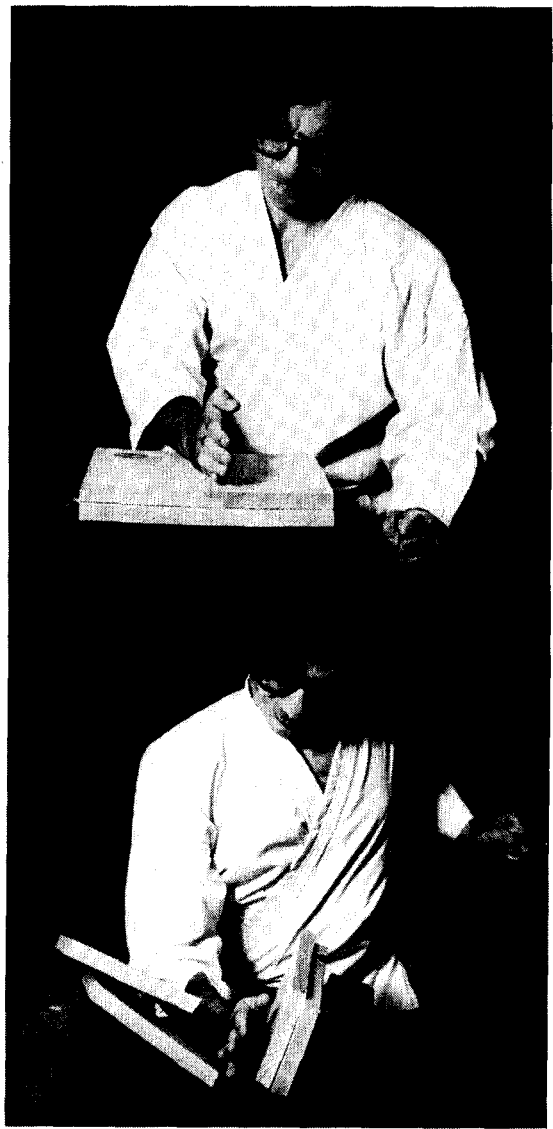


Fig. 5. Horizontal boards broken by a hand chop.

mensions $1 \times 20 \times 30$ cm and a brick of dimensions $4 \times 10 \times 20$ cm. The symbol I from (9) for rectangular objects is $Wh^3/12$, where h is the height and W is the width. The ultimate bending stress is about 7×10^7 N/m² for pine¹⁷ and can be about 6×10^8 N/m² for brick.¹⁸ The board and the brick are each considered to be supported at the ends of their long sides and with the smallest dimension vertical (Fig. 5). The results of (10) for rupture are 3111 N for the pine and 3200 N for the brick, each of which is less than the average force of a punch by a karate blackbelt as calculated above.

At this point we can see why a karate demonstrator always chooses to break several thinner boards rather than a single board of the same total thickness. With the multiple boards, rupture can proceed successively through the boards, each such rupture involving a smaller value of h in the calculation above than if a single thick board were used.

We can also understand why a karate fighter accelerates his striking foot, fist, etc., before contact is made. The total elapsed time for a forward punch is at least 20 times longer than the contact time, which means that the force accelerating the striking fist is at least 20 times less



Fig. 6. Vertical board broken by a forward punch. Note that the punch terminates about 6 cm after contact with the board.

than the impact force and hence is too small to break bones, boards, and bricks. Significantly damaging strikes can be made even if the attacking fighter does not push against the ground during impact if the striking fist, foot, etc., has already received a large acceleration.

Karate demonstrations in a physics classroom by a blackbelt can bring the students to their feet in anticipation of the violence of the boards and bricks breaking. Board breaks are easier if the boards are horizontal and have solid supports on their ends (Fig. 5). The strike should be with the grain of the wood. If students hold the boards vertically (Fig. 6), several students are normally needed to hold the board firmly enough. A single student usually flinches and yields when the board is struck, and an embarrassing amount of pain to the striking hand can result. Bricks should also be supported horizontally. To protect the hand from the rough brick surface, bricks are often wrapped in a thin cloth.

The breaks are best accomplished by chopping with the side of the hand. If the fist is used, the wrist should be kept straight upon contact to avoid wrenching the wrist, and contact should be made on the knuckles of the first and second fingers. Unless the skin over the knuckles has previously been toughened, such punches will probably break the skin somewhat, and although any bleeding will greatly heighten the drama of the demonstration, punching should be avoided for this reason.

Proper and intelligent caution should always be exercised in any breaking demonstration and any simulated karate fighting, and unless a teacher holds a blackbelt, he should not attempt one of these demonstrations himself. With the popularity of karate increasing, there is a fair chance some physics students will hold blackbelts and can give the demonstration. If not, an instructor from a local karate school could be invited. Since many blackbelts have only an intuitive feel for the physics behind karate strikes, they may be very interested in cooperation just so they can finally see the scientific basis of their fighting styles.

ACKNOWLEDGMENTS

I would like to thank Frank Stanonik and Professor Karl J. Casper for many helpful comments on this paper and Ed Celebucki for posing in the photographs. This work was supported in part by an Instructional Assistance Grant from the Center for Effective Learning at the Cleveland State University.

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