Quantitatively measuring power – Reaction Force

A pilot study
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"Measure what can be measured, and make measurable what cannot be measured."
– Galileo Galilei.

Abstract

In this thesis, I have built a prototype machine to measure acceleration produced by Taekwon-do techniques. I used this machine to measure the difference in power between a sitting stance punch performed normally, and a sitting stance punch performed with my off hand restrained in order to find out how much reaction force contributes to power. I found that the average increase in power by using the reaction force was 35%. It must be noted though that this figure was for the average power over the entire impact rather than for the maximum power produced during impact. I was unable to measure the maximum power produced.

Introduction

There are six elements in the theory of power of Taekwon-do. Three of these elements – mass, speed, and concentration – are easily quantified. They describe physically what the power of a technique is made up of. The other three elements of reaction force, concentration and equilibrium are less easy to quantify. Rather than describe in a mechanical sense what the power of a technique consists of, they describe how a student can generate power; how to coax the power out of their bodies. They are student focussed, rather than 'physics focussed'. But the way these latter three elements add to the power of techniques is by acting through the first three. For example, using reaction force applies more of your mass to a technique, it increases the speed you can strike and gives your technique a greater degree of concentration in time. So there is some overlap in the elements of power. Rather than working independently, they all come together to maximise your impact on your target.

The contribution to power of mass, speed and concentration are all well understood by the principles of physics, and can be easily measured. Less easy to measure are the contributions from breath control, equilibrium and reaction force. The aim of this study is to carry out experiments to place a numerical value on the power that can be generated by the reaction force hand in a sitting stance punch.

I wanted to perform a scientific experiment for my thesis that would have value to the taekwon-do community so that I was lending my particular expertise. I chose to measure the reaction force contribution because I felt it had the right combination of three factors: First, as far as I am aware nobody has yet measured analytically how important the reaction force had is in generating power – it is a less well understood question than the importance of mass, speed or concentration. Secondly, of the three remaining elements, reaction force is an easy element to isolate from a technique. And the third factor is the impact to our students. We all know from experience that using reaction force adds to the power of our techniques. We can feel the difference. Now, we will also be able to put a number on it. Instead of saying "use your reaction force hand, you'll have more power!" We can tell our students "use your reaction force hand, you'll have 35% more power!" I feel that putting a number on it like this makes it seem more real to the students, and hopefully they can then see that as a target to strive towards.

Nomenclature

Before going any further, since this is a study intersecting physics with Taekwon-do it's important to clarify the terms I will be using.

In Taekwon-do, we use the word "power" to refer to the effectiveness of our techniques to strike and block our opponents. In physics, the word power refers to the rate of change of energy, which is a similar, but distinct quantity. In the rest of this document, when I use the word "power," I will be talking about the *Taekwon-do* concept of power, not the physics concept.

The idea of power is a slightly complex one, as it partly relies on the interaction of the practitioner with his or her opponent. But generally the goal is deliver maximum of momentum to an opponent's vital spot in a minimum of time and space – this quantity is *pressure* in the language of physics. In any moment of time, the pressure is given by:

$$\text{Pressure} = \frac{\text{change in momentum}}{\text{time} \times \text{contact Area}} \qquad P = \frac{\Delta p}{\Delta t \times \mathrm{A}}$$

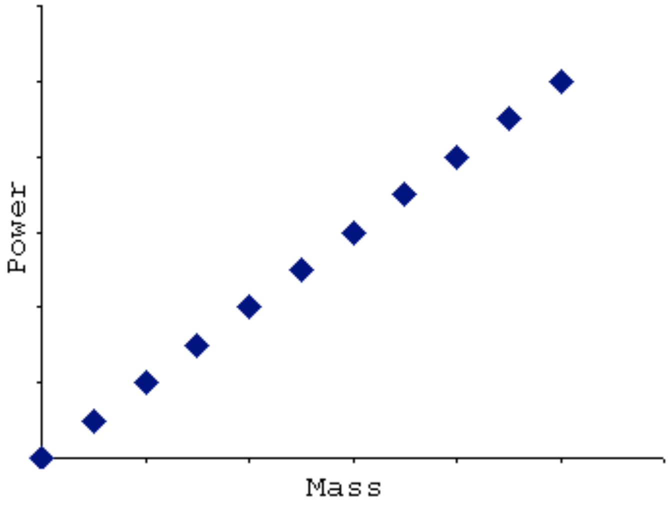
$$\text{Pressure} = \frac{\text{change in (mass} \times \text{speed)}}{\text{time} \times \text{contact Area}} \qquad P = \frac{\Delta(m \times v)}{\Delta t \times \mathrm{A}}$$

I should also point out that the general describes two categories of reaction force in the encyclopaedia: The first he describes is using the equal and opposite reaction force of an opponent's blow against them. The second is the use of reaction forces from your own body. The second type, which I'll call the self-reaction force is what I have measured in this study.

Background

So let us examine how each of the elements of power contributes to the pressure.

Mass is the simplest of the elements. Mass that you put behind a punch is a factor in its momentum, so it has a positive, linear relationship with pressure. (See the equation above)

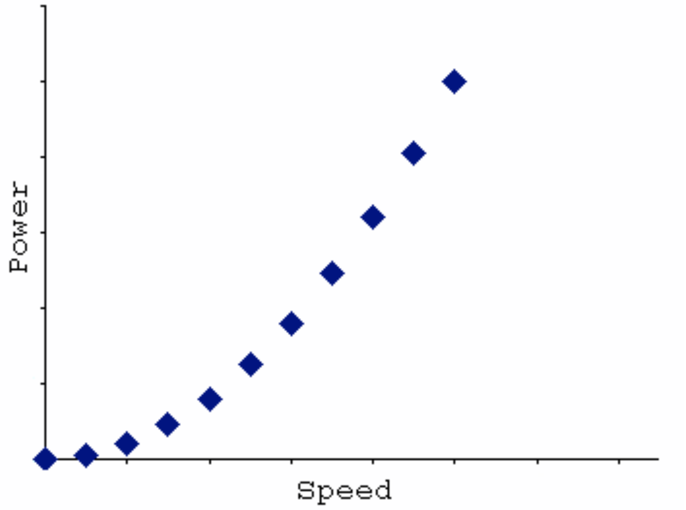


Mass can also be used in a secondary way – via the sine-wave motion, we acquire extra energy from the slight drop in height. Gravitational potential energy is changed to kinetic energy, manifest in the increased momentum we can grant our techniques. Though the source of this extra power is from our mass, the effect is to produce greater speed.

Speed is related to two of the terms in the pressure equation. First, like mass, speed is a factor of momentum. However, the speed of your attacking or blocking tool also contributes to the time term. The faster your strike or block is, the smaller the time factor will be and therefore the larger pressure will be. For the purpose of understanding the contribution, it is useful to rewrite the pressure equation, replacing the time factor with speed as:

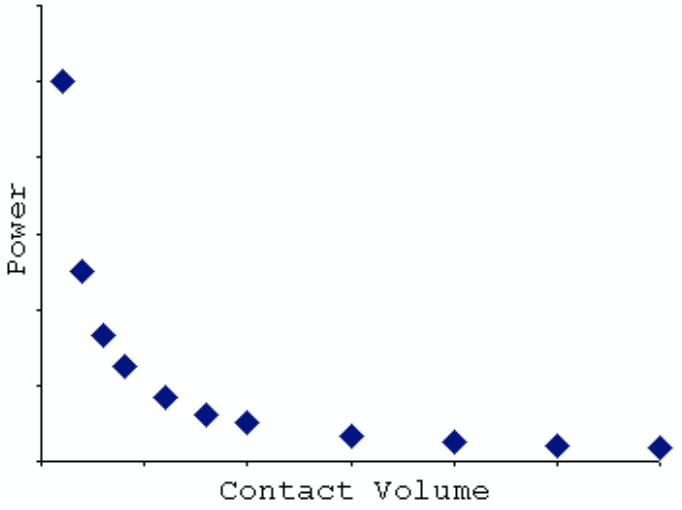
$$\text{Pressure} = \frac{\text{mass} \times \text{speed} \times \text{speed}}{\text{stopping distance} \times \text{Area}} \qquad P = \frac{\Delta(mv) \times v}{d_s \times \text{A}}$$

Now it is easier to see how the speed contributes to the pressure – it multiplies into pressure twice compared with mass, which multiplies in only once.



It is often said that speed is more important than mass for generating power because of this. Certainly, if one was in a position of having to choose between one or the other, one would choose speed. But in reality, to maximise your power it is of course important to master both.

This new definition of pressure is also useful for understanding the contribution of concentration. The two remaining terms in the equation, stopping distance multiplied by contact area, define a volume over which you have contact with your opponent. The smaller you can make this volume, the more pressure will be generated, as per an inverse relationship



Conceptually, it is also useful to think of concentration in time as well as space. Going back to the original statement of pressure, minimising the time factor will increase the pressure generated as well. As you can see, there is some ambiguity over whether this contribution is best described by concentration or speed. Both concepts are useful in instructing us.

Now we come to the more difficult to treat elements. Breath control contributes to power in a few different ways. Proper breath control will help relax a practitioner's muscles during execution of techniques, adding to speed. It can also help muscles to fire in the appropriate order, harnessing the body's natural breathing movements. This can add to the speed as well as to the mass that can be applied. Breath control also aids balance – exhaling at the end of our movements tenses the core muscles in the body, helping it brace to receive impact.

Equilibrium is also important for proper engagement of the muscles – every muscle that's being overused to compensate for poor balance is a bit of force that's not being put into your technique. Related to this is the ability to brace yourself against the ground in order to receive the reciprocal impact of your strikes or blocks. For example, if you are not prepared for an impact, and you bend your knees as a result of the shock then some amount of your momentum is not delivered to your opponent, but rather into your own knees. As well losing concentration of your impact, and therefore lowering power, this can be harmful for you.

Finally Reaction force. As mentioned above, the general categorizes reaction force into two different types. First is the reaction force between yourself and an opponent. This element is about using your opponent's power and momentum against them. It increases your power by adding an external element, which you don't have to produce in your own body. The second is the reaction force of your own body, for example pulling the hand toward your hip as you execute a punch. Doing this increases the speed of the punching hand through equal and opposite reaction force of Newton's third law of motion. It also helps to engage some of the largest muscles in the core that cross over from one side of your body to the other, and increases the mass that can be applied to the technique.

Experimental

The measuring tool used in this study was an accelerometer (3-axis, 100Hz, ±16g range, sparkfun model ADXL345) in the form of a microchip. The microchip was connected to a power source (2xAA batteries) and a readout device which wrote data files onto a microSD card. The accelerometer was affixed to the end of a swinging arm, one end of which was attached to a vertical metal pole weighed down by sandbags. On the other end of the swinging arm is a board padded with mouse pads for safety purposes. This board is the target for the punch. The height of the swinging arm is adjustable to suit any tester.

After warming up, I then measured up to the target in sitting stance. I punched the board normally, aiming for maximum power, then halted the board's swinging motion and restored it to a ready state. The second time time, I punched the board with my off hand restrained inside my pocket, eliminating my reaction force from the technique. The apparatus was again reset, and I continued to punch alternating between normal technique and no reaction-force technique. The data is meanwhile being collected by the accelerometer.

Back of the apparatus, showing accelerometer

Front of the apparatus, showing target

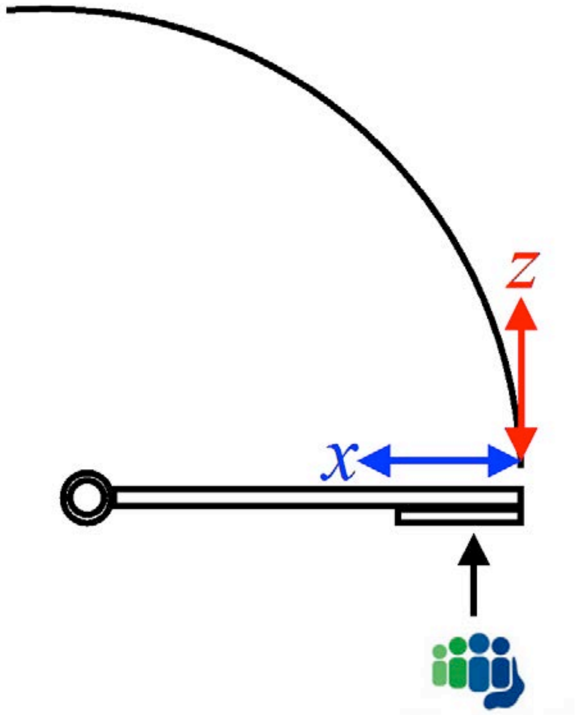
Now, acceleration is what I measure, but it is not the same as pressure, so we need to know the relationship between the two quantities:

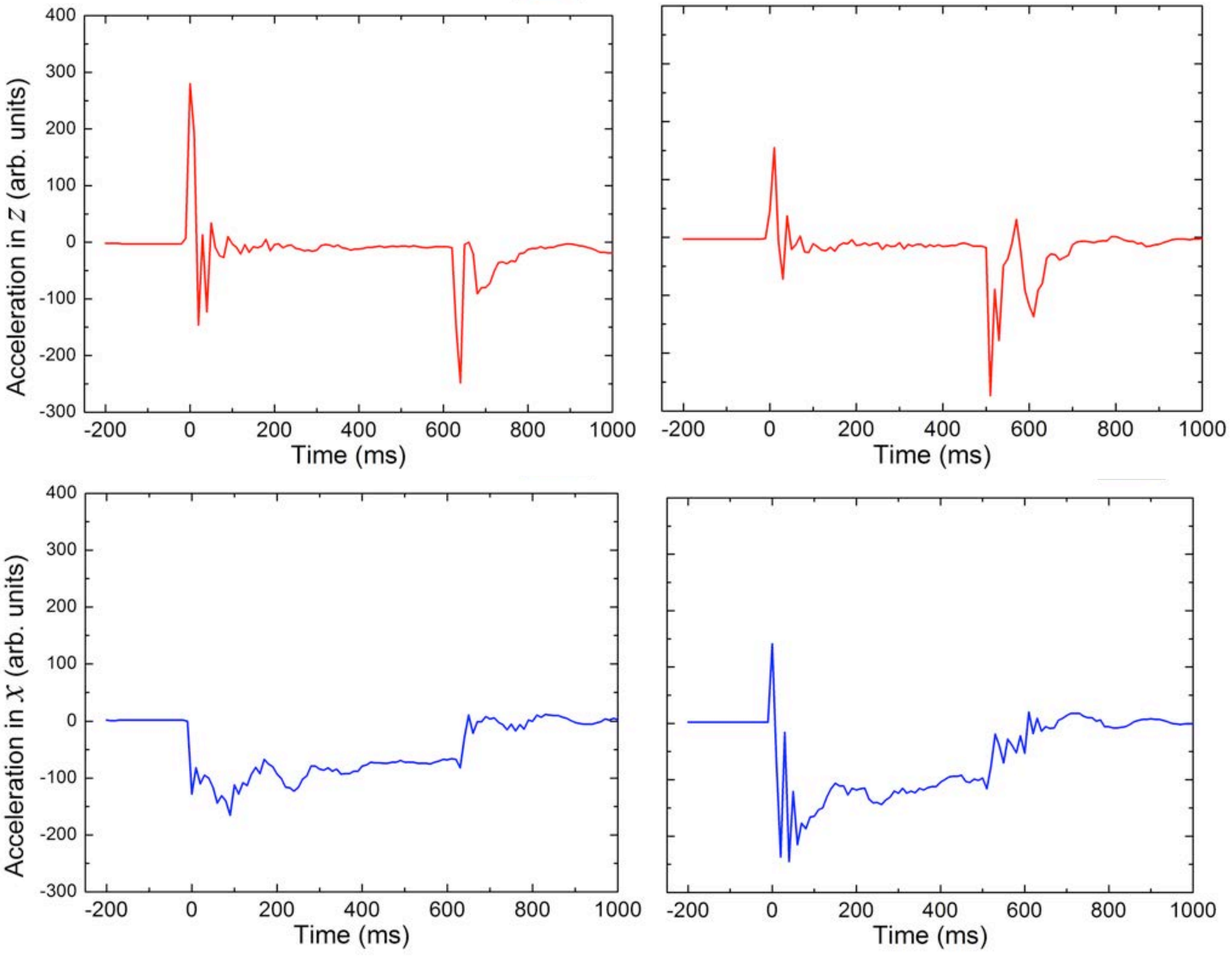
$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{\text{mass}}{\text{Area}} \times \text{acceleration} \qquad P = \frac{F}{A} = \frac{m}{A}a$$

The mass in this experiment is the mass of the swinging arm, which remains constant throughout. The area is the contact area of the attacking tool (fore-fist) with the board. This quantity is unfortunately unknown, with the apparatus I am using I have no way of measuring this during the impact. I can however assume that there is no significant change in the contact area of punches without reaction force and punches with reaction force. Therefore, when comparing one to the other, the area terms will cancel out, and the ratio of one pressure to the other will be the same as the ratio of one acceleration to the other. Acceleration, therefore, is a good proxy measurement for pressure when comparing one impact to another.

Results and analysis

The four graphs below show typical acceleration data generated from a single punch. The acceleration is in two directions – parallel to the punch (z) and horizontal, perpendicular to the punch (x) – and for two different punches – with reaction force, and without. Each graph has the exact same scale.



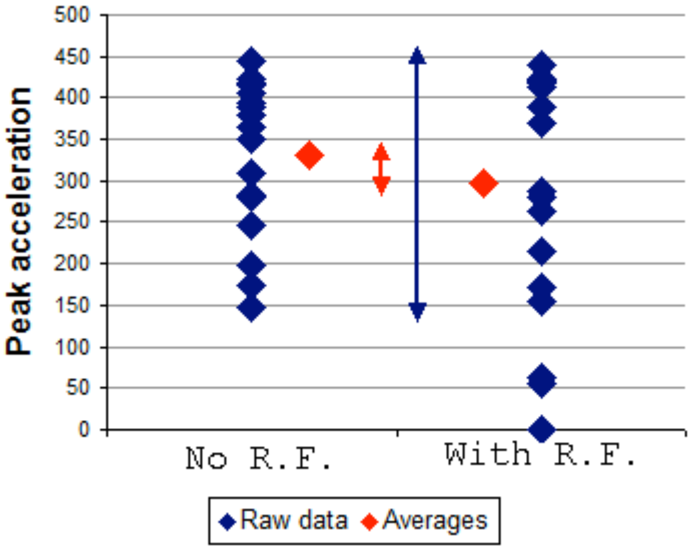

Punch **without** reaction force

Punch **with** reaction force

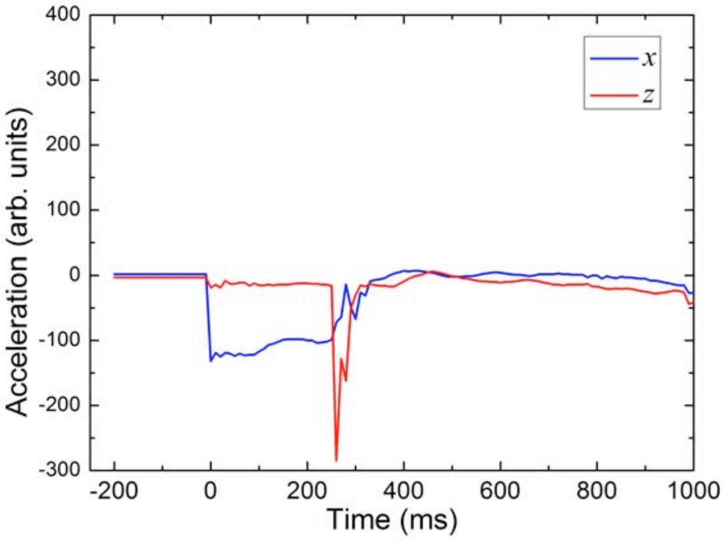
In the z acceleration traces (red) we can see a spike at t=0 corresponding to the impact of the punch. This sets the board swinging. The acceleration in the z direction is then zero for 500-600 milliseconds until the circular motion is manually stopped as seen in the negative peak. From the x acceleration (blue) we see an increase from zero to some finite value corresponding to the speed of the board as it swings around. This acceleration is in a direction toward the centre of the circle, and is the centripetal acceleration of the circular motion. This acceleration ends when the motion is stopped.

Some important things to note about the features shown here: The actual impact of the punch is registered in only a single data point. This unfortunately makes the actual measurement unreliable. It is impossible to tell where in the peak the actual data peak is from. It could be from the top, with the maximum acceleration or it could be from only halfway up and there would be no way to tell.

This is reflected in the data by a high variance of peak acceleration between successive, similar punch events. The figure below shows the peak acceleration of each punch. Comparing the set of peak accelerations with reaction force to the set without gives a result with significantly higher variance within a set (blue arrow) than between the two sets (red arrow). I had hoped to use the peak acceleration as a measure of the power of the punches, but these results show that it will be impossible in this experiment.

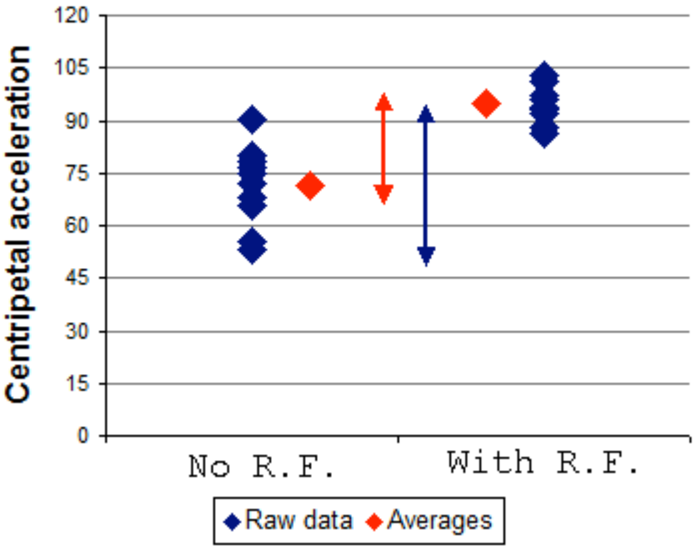


The speed of the punched was occasionally so fast that not even a single data point was registered above zero! See the below figure (of a punch *with* reaction force), with both x and z acceleration plotted on the same graph. You can still see the centripetal acceleration, but there is no corresponding red peak.



What this means is that the entire impact of the fist on the board took place between two consecutive data points – in less than 10 milliseconds!

I will use instead the average centripetal acceleration to measure the power of the punches. Centripetal acceleration is proportional to the square of the momentum. It misses out on the time information, but still gives be a figure for the total momentum transferred from the practitioner to the board. I discuss the implications of this in a later section ("Limitations of this study")



Raw data is shown in the figure above, and one can instantly see that it is a more coherent measure than the peak acceleration – the arrows are this time approximately the same length. To turn this data into data on the pressure, we first of all need to know the relationship between centripetal acceleration and pressure:

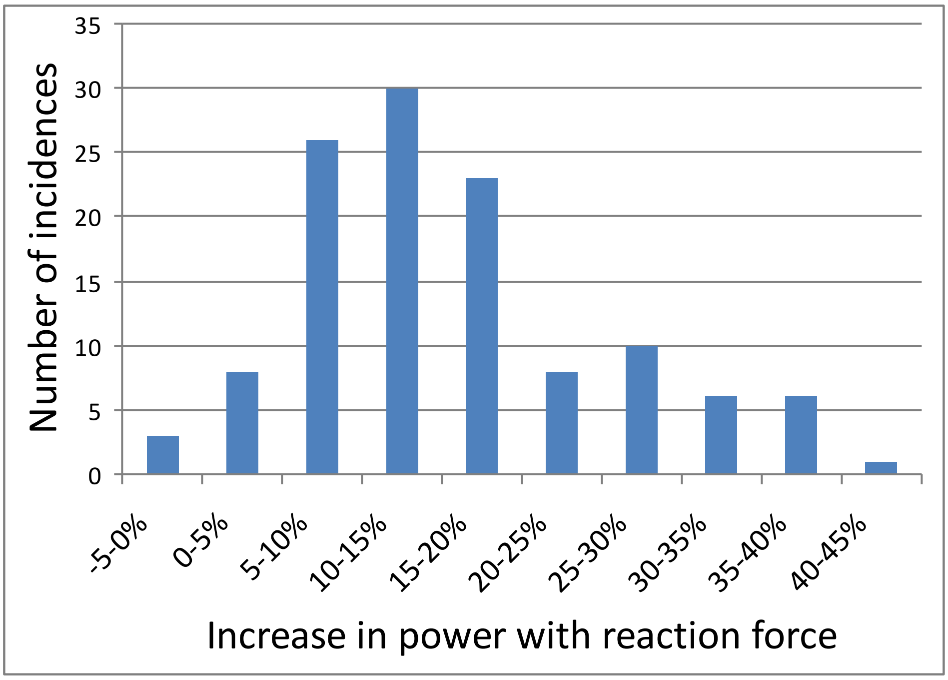
$$\text{centripetal acceleration} = \frac{\text{mass} \times \text{circular velocity}^2}{\text{circle radius}} \qquad a = \frac{mv^2}{r}$$

$$= \frac{\text{momentum}^2}{\text{mass} \times \text{radius}} \qquad a = \frac{p^2}{mr}$$

$$\text{pressure} = \frac{\text{momentum}}{\text{time} \times \text{area}} \qquad P = \frac{\Delta p}{\Delta t \times \text{A}}$$

$$\text{pressure} = \frac{\sqrt{\text{mass} \times \text{radius} \times \text{centripetal acceleration}}}{\text{time} \times \text{area}} \qquad P = \frac{\sqrt{mra_c}}{\Delta t \times \text{A}}$$

So pressure is related to the square root of centripetal acceleration. I now have two sets of data, each of sixteen members. The first set is of the punches with reaction force, the second set of the punches without. I then want to ask: If I compare a random punch in the first set to a random punch in the second set, how much more power does the punch with reaction force have? The answer to that question is displayed below:



Most of the pairs yielded a value of between 5% and 20% increased power, with the average increase in power of 16.1%. This graph also shows the distribution of possible values around the average. For the last part of the analysis though, I'll just deal with that average figure of 16.1% increased power.

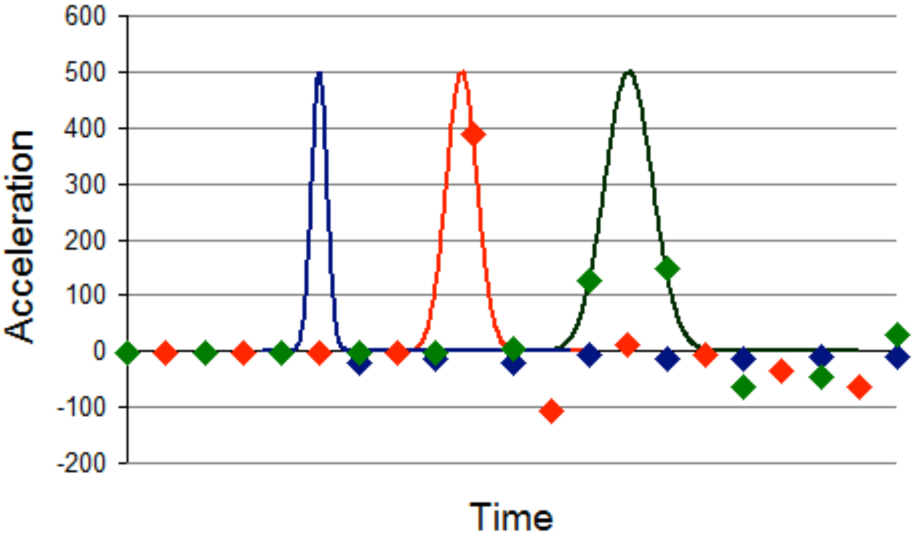
As mentioned before, I was unable to directly measure the acceleration of the punch impact. Going back to our equation for the power:

$$\text{Pressure} = \frac{\text{change in momentum}}{\text{time} \times \text{contact Area}} \qquad P = \frac{\Delta p}{\Delta t \times \text{A}}$$

We know now the change in momentum, but although we know that the board swings faster, we don't have information on the impact time itself. Can we do anything to add this information in?

I would intuitively expect that we would find that the time is shortened with the use of reaction force. Higher power, higher speed, shorter contact time. This would mean that the figure of 16.1% consistently underestimates the real increase in power. Does the data present me any evidence that this is the case?

Low though my time resolution is, I can still pick out three distinct types of event: Where the impact is measured in zero, one, and two intervals. These will correspond to shorter or longer contact times. Examples of each type are shown in the figure below.



The curves are Gaussian function fits to the data, and are only rough guides for the eye. The heights of these peaks are arbitrary, but the widths should be fairly accurate representations of the contact time. By counting the numbers of zero, one, and two interval events in the sets I can have some idea about the relative contact time in each case. Sure enough, without reaction force we see more two interval events, and the zero interval events disappear entirely.

With a theoretical reason to suspect faster impacts, and with some evidence to support this I feel comfortable in making an estimate of the magnitude. We know the average difference in centripetal acceleration between the two sets of punches, and therefore the average difference in speed. Assuming that the impact occurs over the same distance, the contribution to power of the faster impact can be calculated:

I'll label the acceleration of punches without reaction force: a_1. Then, the acceleration of punches with reaction force is $1.35a_1$.

$$a_1 = \frac{\text{mass} \times \text{circular velocity}^2}{\text{circle radius}} \qquad a_1 = \frac{mv_1^{\,2}}{r}$$

$$\mathrm{a}_1 = \frac{\text{mass}}{\text{circle radius}} \times \left(\frac{\text{contact distance}}{\text{time}} \right)^2 \qquad \mathrm{a}_1 = \frac{m}{r}\left(\frac{d}{t_1}\right)^2$$

$$\text{therefore, time} = \sqrt{\frac{\text{mass}}{\mathrm{a}_1 \times \text{radius}}} \times \text{distance} \qquad \therefore t_1 = \sqrt{\frac{m}{a_1 r}}\,d$$

$$\text{and shorter time} = \sqrt{\frac{\text{mass}}{(1.35 \times \mathrm{a}_1) \times \text{radius}}} \times \text{distance} \qquad t_2 = \sqrt{\frac{m}{1.35 a_1 r}}\,d$$

$$\text{short time} = \frac{1}{\sqrt{1.35}} \times \text{longer time} \qquad \therefore t_2 = \frac{1}{\sqrt{1.35}}\,t_1$$

Now that we have a figure for the new, shorter time, we can plug it back into our equation for power along with the increased momentum to get an estimate of the final result. The subscript 1 denotes values without reaction force, and the subscript 2 denotes values with reaction force.

$$\text{Pressure} = \frac{\text{change in momentum}}{\text{time} \times \text{contact Area}} \qquad P = \frac{\Delta p}{\Delta t \times \mathrm{A}}$$

$$P_1 = \frac{\Delta p_1}{\Delta t_1 \times \mathrm{A}} \qquad P_2 = \frac{\Delta p_2}{\Delta t_2 \times \mathrm{A}}$$

$$P_2 = \frac{(1.16 \times \Delta p_1)}{(0.86 \Delta t_1) \times \mathrm{A}}$$

$$P_2 = 1.35 \times P_1$$

According to my data, using my reaction force hand in a sitting stance punch adds 35% to my power on average.

Limitations of this study

At the start of this study, I had hoped to be able to measure the maximum pressure value reached in the process of a sitting stance punch, and to compare punches with reaction force to punches performed without reaction force using that figure. In the end, due to limitations in the equipment I used, I was only able to compare *average* pressures over the entire punch impact, rather than maximum. This lowers the usefulness of the study somewhat.

Targets for punches such as wooden boards, and human bones typically have some critical tolerance for pressure, after which they will rupture. Maintaining this high pressure is not important in achieving the goal of a break, only reaching it for however short a time. So the maximum pressure is undoubtedly a more useful measure than the average, given the application of the technique, and it’s not entirely clear that the maximum pressure should be affected in the same way as the average pressure by the use of the reaction force.

The other main limitation of this study is that it had only one test subject – myself. The result I get from my reaction force may not be the same as the result another taekwon-doin. Factors such as weight, build, age and technique could all have a significant impact on the power the reaction force grants. For example, I hypothesise that if I were to repeat the experiment using a yellow belt as my test subject, the power granted by the reaction force would come out to be lower than when testing on myself. I expect that this early in the student's training they will not have learned to use their reaction force to its full potential. I would very much like, after making some improvements to the apparatus, to take myself along to a regional or national event to repeat the experiment on a wide variety of different taekwon-doin.

Finally, this pilot study covered only one technique: a sitting stance punch. I have no doubt that the contribution to the power would differ for other techniques. Even the hip position in a walking stance punch might be sufficiently different from sitting stance that a different reaction force power would be measured.

In terms of the apparatus used, in a newer model I would want to use an accelerometer with kilohertz or faster readout. This would hopefully allow me to measure the peak acceleration directly, and also to see the difference in the shape of the impact over time. It could be possible to explicitly measure the area of contact of the punch as well, but that would require a more drastic change in the apparatus. This can be more of a long term goal.

Conclusion

In conclusion, I undertook experiments using an accelerometer to measure numerically the contribution to my power that reaction force gives me. A sitting stance punch was used as the model, and the result was that a punch with reaction force was, on average, 35% more powerful than a punch with no reaction force. These experiments were something of a pilot study, to test the feasibility of making measurements this way. I have identified some improvements that could be made to the equipment and the method. Once a sufficiently fast and stable measurement system has been created, one can imagine any number of interesting impact experiments that could be done. My aim at the moment is to get an electrical engineering student at my university to build such a device as a project, and to set it up as an on-going resource available to itkd.

Special thanks

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