THE
CrossFit JOURNAL

Work, Power and the Science of CrossFit

Dr. Ken Gall examines the thermodynamics of CrossFit and asks 10 questions worth considering.

By Dr. Ken Gall **February 2012**

Mike Warkentin/CrossFit Journal

While I was an undergraduate research assistant, one of the graduate students in my lab wanted to show me a "thing on the computer" that you could use to "look up information." I took a look at it, reluctantly, because this guy was always wasting my time with annoying things such as balloon animals and ballroom dancing. These were things I had little use for as a student (well, I guess they are of no use to me now, either).

When he showed me his little discovery, I laughed and told him it looked "useless" and I had no interest in wasting time on it. The year was 1994, I was at the University of Illinois, and the software he had shown me was called Mosaic. For those of you unfamiliar with Mosaic, you may better recognize its second-generation name: Netscape. As it turns out, Web browsing and this "terrible annoyance" called the Internet have some use.

I missed the boat. CrossFit's approach is the Mosaic/Netscape of fitness, and I'm not missing something big this time.

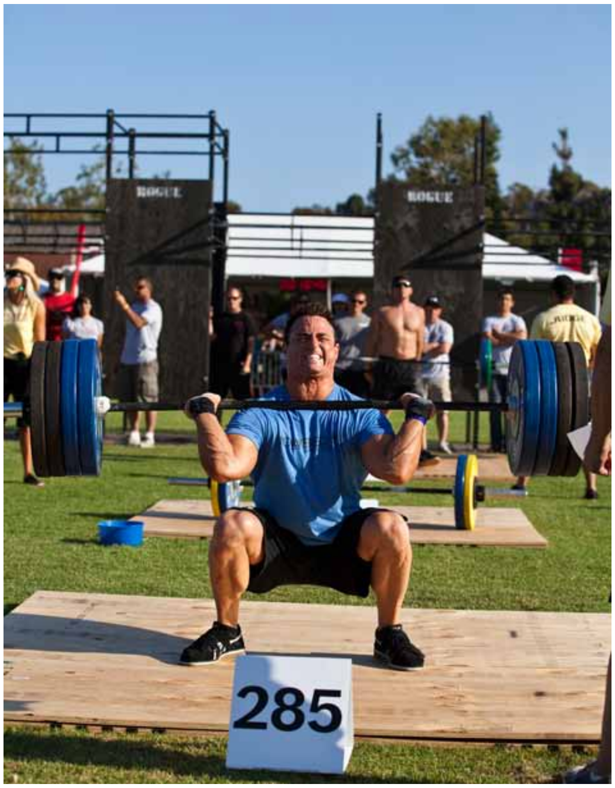
My Ah-Ha Moment

I was first drawn to CrossFit after reading the "What Is Fitness?" article given by Dan MacDougald of CrossFit Atlanta to my wife, Amanda, who had just started CrossFitting and who never lets me forget she started first.

> Greg Glassman and the early adopters of CrossFit have paved the way for us to think about fitness in an entirely new light.

I was already thinking about mechanical work in my workouts. I used to select my weights in my chest and biceps training program to optimize work (not power). By this I mean rather than do 5 sets of 2 reps of 315-lb. bench press, I would do 5 sets of 10 reps at 225 lb. If you do the math, the second grouping is about three times the total mechanical work as the first. I had no clue if this was doing anything for me, but it was how I was planning my workouts, and if I sucked in my stomach you could see my massive chest.

When I first read the CrossFit website I quickly realized that I was missing two other key elements. First, you could select exercises that naturally led to larger ranges of motion, higher reps and heavier loads—like the Olympic lifts and other powerlifting and gymnastic movements.



Staff/CrossFit Journal

To a scientist, the thruster is just a way to move a large load a long distance quickly.

This would lead to more work. Second, if you thought of power (work per unit time), rather than just work, there might be another fitness benefit.

Ah-ha … .

It Works!

I thought the concept of using power to design and measure capacity in workouts was revolutionary, and I believed it would work to make me more physically fit. So I tried it. Turns out … they were right. Within months I felt better. I was leaner, stronger and faster—approaching and surpassing levels of fitness I last felt during my college years as a wrestler. I know this is a common story, but I thought I would at least tell you my version so you would know how massively biased I already am before reading the rest of my article.

Greg Glassman and the early adopters of CrossFit have paved the way for us to think about fitness in an entirely new light. It's a beacon of light in a sea of mediocre fitness businesses, and it can be used to quantify workouts and provide not only great results, but it can also be used to better understand the scientific link between human performance/fitness and training methodologies. Fitness can now be quantified for large groups of athletes over various time domains and movements beyond max load in a single lift or time in single or serial racing events.

But It's Complicated

Putting on my academic hat, I would argue that the human body is just a mechanical system that converts chemical (or metabolic) energy to mechanical work. If we think of ourselves as a mechanical system, it is ideal if we can move heavy loads over long distances quickly. Who doesn't like fast cars and big trucks? And what if there was a truck that could haul 10 tons and was faster than the Audi R8? It would be pretty useful—well, at least to me. I believe that CrossFit works because we are training ourselves to do things we were built to do: perform work.

Even though I am 100 percent convinced CrossFit works, it is still important to understand some of the more subtle details so we can set up a framework as to why it works and continually strive to train optimally. The human body is a complex system, and work and power are slightly more complex for us than a car. Let me provide two examples.

Mike Warkentin/CrossFit Journal

In a barbell lift, the athlete's mass is an important part of the system even though we usually only consider the mass of the barbell.

Example 1: Load up a barbell with 225 lb. In Test 1, see if you can do 10 back squats in 30 seconds. This is a relatively high mechanical power output for your center of mass and the barbell. In Test 2, let's extend the time frame to 10 minutes and make it one back squat, but you have to make the entire rep take five minutes on the way down and five minutes on the way up. Most people who can successfully do Test 1 will fail Test 2, even though the latter is much lower mechanical power output for you and the bar compared to Test 1.

> In squat cleans, relative work is often compared by the bar movement only, even though in a real energy calculation we would need to consider you as part of the system.

Example 2: This comes from Louie Simmons' book: deadlift a set weight as many times as you can as fast as you can in one minute (high power output). Then, based on this number of reps, try to do slower, controlled deadlifts at half the rep speed (lower power output). You will be unable to do as many reps in the second instance, and in fact you will notice that there is a certain time frame over which you start to lose capacity to do the reps regardless of how many you have performed before.

In Example 2, there is a contribution of total work due to hitting the bar off the ground more violently (elastic energy from outside the system of you and the barbell), but you can eliminate this by starting the weight from a dead stop at the ground, and you will usually perform more reps while maintaining reasonably fast rep speed.

Work and Power

In thinking about work and power, it is best to use the field of thermodynamics. Thermodynamics is about as boring as it sounds, but essentially it is a field of study that uses energy balances to shed light onto the behavior of energy conversion. The first thing to determine is what is in the thermodynamic "system" you are analyzing. Is it just you? You and the barbell or weight? The floor? The pull-up bar? The floor and pull-up bars can store and release elastic energy, so they can be important in some situations.

We typically consider the system to be us (with our own mass) plus the barbell (or other external mass). We can also define a system that is only our body mass and consider the barbell an external mass to our system. In this case, our system transfers work to this second system (the barbell).

The importance of the choice of your thermodynamic system changes for different workouts. In a pure pull-up workout, the only thing that is really important is our body as the system. In a power-clean workout we primarily perform work on the bar, and we often "calculate" power for the bar only.[1] In squat cleans, relative work is often compared by the bar movement only, even though in a real energy calculation we would need to consider you as part of the system because of the squat of your body weight in each rep. Online CrossFit power calculators are available to do these type of calculations that account for athlete mass and height along with movement type.

Let's step back a bit and go back to the beginning—this will help us explain the two examples I brought up above.

If we consider your body and whatever barbell or weight you are holding a system, we can define the Gibbs Free Energy, G, as:

$$G = U + pV - TS$$

U is the internal energy, p is pressure, V is volume, T is temperature, and S is entropy. We can effectively ignore the pV term because we are not going to perform work by changing pressure or volume of the system (much more relevant for a gas, like performing work by compressing propane into one of those little vessels), and we will likely not change the temperature or entropy of the system (unless you want to throw your weights all over the room at the start of the workout, which will increase the randomness, or entropy, of your system before starting). This leaves us with internal energy, U, and we can broadly write internal energy in a form useful for our system as:

$$U = U_{mech} + U_{chem}$$

Mike Warkentin/CrossFit Journal

With movements like kettlebell swings, the eccentric part of the movement has important effects on the amount of work performed.


Staff/CrossFit Journal

Two athletes with the exact same weight often move it very differently.

In this equation, "Umech" and "Uchem" are mechanical and chemical energy. The first law of thermodynamics states that the change in internal energy (δU) is equal to the amount of heat provided to the system (δQ) minus the amount of work performed by the system on its surroundings (δW). Ignoring the temperature rise, this basically means that the work done within our system is equal to the changes in mechanical and chemical energy.

Work done = δW = δUmech + δUchem

CrossFitters already know the δUmech part of this equation as "mechanical work," and assuming you stop or reverse the weights at the top and bottom of your reps[2], it is best calculated through force, F, times the distance an object is moved, δx:

δUmech = F δx

The most common force, F, in CrossFit is a weight, and the displacement is typically a vertical move (gravitational potential energy). Exceptions exist, such as work done against a frictional resistance: rowing, running, prowler pushes, etc. The chemical-energy term, δUchem, is very hard to quantify, but it is there and is also known as "metabolic energy." Our body is constantly converting chemical energy to mechanical work, and the transfer between chemical and mechanical energy happens regularly during a workout.

> I know many of us have experienced the situation where by going slower we somehow feel worse during a workout than when you just get the reps over with.

However, chemical energy is the energy term your active muscles are burning even while you hold the deadlift weight in the top position (essentially an isometric), or the term that is still burning at a certain rate when your rep speed is very slow. If we exclude the barbell from our system calculation, we can inefficiently perform work on it by burning extra chemical energy in our body by, for example, moving the reps very slowly.

In this situation, we do little work on the barbell but still exhaust chemical energy in our body.

So if we now think of power we have the following:

Power = F δx/δt + Pchem

It is the chemical-energy term of total work and power that explains why isometrics (think bottom-to-bottom Tabata squats) and slow rep speeds can sometimes catch up with you and make an otherwise-low-power-output workout "harder" than just going faster within certain limits. This term can contribute to power output even when you are not performing measurable mechanical work on an external mass or your own center of mass.

I know many of us have experienced the situation where by going slower we somehow feel worse during a workout than when we just get the reps over with by effectively using our chemical-energy reserves to do the mechanical work. So in essence, if you want to perform optimally at CrossFit, you need to maximize the mechanical term of the power equation above, but you need to be aware of the chemical-energy term because it can contribute to your total power generation as a human system.

Unfortunately, the chemical-energy term does not "count" in CrossFit, where we often measure work performed on a barbell or your own center of mass as the only component of work. Exceptions to this exist, such as competitions when isometric holds are used. For example, holding a deadlift weight for max time constitutes minimal mechanical work and is just a measure of your chemical-energy reserves to keep several muscle groups contracted under load. For similar reasons a farmers carry (on flat ground) also tests our chemical-energy reserve without performing much "gravitational" mechanical work.

So What?

In the end, an athlete needs to effectively convert chemical energy to mechanical work. There is a balance that exists—an optimal combination of rep speed, technique, and cadence for specific time domains and movements that minimizes workout time. If you transfer chemical energy ineffectively, you may fizzle out faster and ultimately end up with a slower time. Your body may have actually performed more work, but it will not "count" in your assessment.

In terms of conserving chemical energy, many of the elite athletes know the "tricks" already. We have already discussed rep speed, and if you move the reps too slowly you sometimes end up worse than if you just moved quickly through the reps. Poor technique can also lead to ineffective burn of chemical energy, something that really catches up with athletes in workouts longer than a few minutes. The "negative" of reps is also a very interesting burn of your chemical energy that is converted into useless mechanical work (often slowing the bar down). Depending on the movement, the negative is advantageous from repetition-speed point of view (e.g., deadlift, kettlebell swing, pull-up), and it would be ridiculous to try and drop off at the top of each of these movements. However, in competition there are instances, particularly for the Olympic lifts, where dropping reps will, in the end, conserve chemical energy and result in a faster time than trying to cycle every negative. A notable exception to this is something like Grace, where the time domain is so short that steadying and repositioning the weight takes more time than you have at your disposal.

Basic Science Opportunities

When I was a kid, my father only let me ask three questions a day. I guess I got pretty annoying. My two favorite questions were:

1. Which is tougher: fire or rock?
2. Why do birds fly higher than bees?

Deep. Now I always try to tell my father that asking questions is the cornerstone of science, and he always tells me that it's a good lesson to be able to only ask a limited number of them.

Mike Warkentin/CrossFit Journal

How does an increase in absolute strength result in an increase in work capacity with submaximal loads?

Mike Warkentin/CrossFit Journal

What exercises are best for overall fitness?

Either way, questions motivate the scientific method aimed at understanding the behavior of the world around us. Along these lines, my favorite *CrossFit Journal* article is "Fooling Around With Fran." In his article, Greg Glassman writes, "We cannot, yet, derive fundamental principles more valuable than measure, think, and experiment."

> Should people trying for general overall fitness always maximize power output to become fit?

I completely agree, and "Fooling Around With Fran" is a prime example of applying the scientific method to CrossFit. CrossFit enables experimentation in fitness across new time and movement domains and with much larger groups of people. I am not an exercise physiologist or exercise scientist, so I am not an expert in this literature; however, I have read a fair number of articles on the topic, and although there are studies supporting high-intensity fitness and interval training (think Tabata intervals based on the study published by Dr. Izumi Tabata in 1996), there is plenty of room for studies that incorporate CrossFit methodologies. We all know the overall results are there, but we still do not understand all the details of what works better/faster and why when you open up to the range of movements and time domains in CrossFit.

For those of you unfamiliar with the "Fooling Around With Fran" article, it goes after one of the most interesting and fundamental training dilemmas regarding CrossFit: power output. The article's focus is on comparing the power output of Greg Amundson doing Fran with three thruster weights, 75, 95 and 115 lb. As you may expect, Amundson's average power output was highest on the lightest Fran and lowest on the heaviest Fran. The conclusion of the article (not proven but hypothesized) was that to improve Fran time at 95 lb. the athlete should do Fran at heavier weights more often than at lighter weights.

Why do I find this interesting? Because it gets to the very nature of why CrossFit works—but it also makes me think of basic questions for which we do not have answers. For starters, a few come to mind. If you have more questions than answers, you are in a scientific field ripe for the picking. It's harvest time.

1. Is the "Fooling Around With Fran" conclusion true—or can you improve at heavier workouts by doing lighter weight, higher power output workouts (assuming you are far from your 1RM weight)?
2. How does an increase in 1RM strength translate to improved work capacity over other time domains? Does it only matter if the weights are within a certain percentage of your 1RM? What is this critical percentage?
3. How does increased work capacity at one time domain translate to other domains? Can you train high power output CrossFit movements in only the five-minute domain and be proficient at 10-minute workouts, 20-minute workouts and 40-minute workouts?
4. What exercises are the best for overall fitness and translation to other movements? If the thruster has a higher power output than the clean and jerk at light weights, should we use that to train more than clean and jerk in certain weight ranges? Sure, they are different movements, but if it is total power output we want to maximize, why not primarily train with the optimal movement?
5. Should people trying for general overall fitness (not elite competition) always maximize power output to become fit? In other words, how much should they scale before their 1RM in a movement is far enough from the prescribed weight?
6. How fast should we perform reps? Always as fast as possible for all weights? Or for lighter weights should we control rep speed relative to heavier reps because the chemical energy burn is different for different weights? Where does this transition occur for different athletes?
7. For clients trying to look better (which is why many people first start in the gym), what fraction of their 1RM should they be working to optimize (read: make it happen as fast as possible) the development of lean muscle mass?
8. On the completely other side of the spectrum, what are the optimal weights to determine the fittest person on the planet? Those that maximize power output for a given time domain? Or should the workouts be strength-limiting even in longer time domains? If they should be strength-limited, what group of athletes determines this limit?[3]
9. How does body type (weight and height) influence maximum power output in typical CrossFit workouts? Should workouts be varied to test power output for various body types to avoid modal bias (we want to be good over broad time and modal domains)?[4]
10. How do you balance calculations and controlled experiments into your programming with an intuitive/random approach by a good coach?

Staff/CrossFit Journal

How does height influence maximum power output?

Endnotes

1. In a pure power-clean workout, no one cracks out a calculator and determines power when comparing to another athlete, as you may be kicked out of the gym. However, this calculation is "implied" when competing. If two athletes do 30 power cleans for time at the same weight, then the only variables left are distance and time. Time becomes the determining factor over who displayed more "average power" in the workout. However, the dilemma is that the taller athlete will have moved the bar farther (times 30) and thus has higher power output for equivalent time. More on this later.

2. We also have the issue of kinetic energy, which is not typically considered in CrossFit power calculations. When you stop reps at the top and bottom and completely reverse the direction of motion, kinetic energy can be dropped, and you can calculate work just using force and distance moved as changes in gravitational potential energy. In the throwing of mass for max distance (without reversal and repetition) the amount of kinetic energy you impart to the object is, obviously, important.

3. In some CrossFit competitions, weights have become heavier over the past few years—even for longer workouts. Weights above a certain threshold, for longer time frames, have relatively low power output. In the limit, using excessively heavy weights would be analogous to employing strict pull-ups vs. kipping pull-ups.

4. For example, if we use thrusters, the taller athlete may actually generate more power than the shorter athlete even though in competition this is not accounted for. When you have to throw a heavy object a set distance in the air, the taller athlete's power advantage would now "help", as it does in wall-balls. How do we choose unique competition movements that account for total power output better, independent of body type? Appropriate mixtures of movements do this to some degree—like thrusters and pull-ups—but this only offsets body weight differences, not height differences. Of course, I don't have any good answers here, but if power generation is our measure and body type influences actual power output greatly, we need some innovative ways to test for this that don't bore people to death in watching a competition.

Courtesy of Dr. Ken Gall

About the Author

Dr. Gall is a professor at the Georgia Institute of Technology with joint appointments in the School of Materials Science and Engineering, the Woodruff School of Mechanical Engineering, and the Bioengineering Program. He has taught engineering mechanics, materials science and bioengineering for well over a decade. He has over 140 peer-reviewed journal publications with an h-index of 38 and has given over 200 professional lectures. He has served as a consultant to over a dozen large companies and both the United States military and intelligence community.