the CrossFit JOURNAL ARTICLES

Human Power Output and CrossFit Metcon Workouts

Tony Leyland

I have had many conversations with CrossFitters, and others, about the efficacy of CrossFit programming. As somebody who teaches about physical conditioning at the university level, I am interested in the unorthodox nature of CrossFit and the results it achieves. While the majority of trainers and athletes easily understand many aspects of CrossFit programming, there is a certain mystique (the infamous "black box") regarding the metcon (metabolic conditioning) workouts.

We all know that a "Deadlift 1-1-1-1-1-1-1" WOD (Workout of the Day) is a strength workout and that "Run 10K" (everybody's favorite!) is an aerobic workout. However, one of my favorite quotes from the CrossFit philosophy is Greg Glassman's injunction to "strive to blur distinctions between 'cardio' and strength training. Nature has no regard for this distinction."

But how does CrossFit blur this distinction given that strength/power training and cardiovascular training are at different ends of the power spectrum? More simply put, when you do "Grace" or "Fran" or "Angie" or even "Linda," what kind of training are you doing? Is it power, strength, or cardio? Can they be combined? To what extent do they overlap? Obviously, they in fact do, and this is one of CrossFit's huge contributions to fitness, but it flies in the face of much of the accepted knowledge in exercise science. How does it work? What are the mechanisms? These are complex questions and the answers depend on many factors.

Human power output

To describe what is going on in CrossFit-type metcon workouts, we must first have a basic understanding of measurements of human power output. While no CrossFitter consciously ponders his power output in the middle of doing "Grace" (at least not if he's doing it with sufficient intensity!), the knowledge of where a particular activity falls on the human power scale provides an excellent basis for understanding how you complete that particular WOD and the resulting metabolic effects.

Table 1 shows the metabolic power, mechanical power, predominant energy system utilized, and time to exhaustion for a healthy male subject on an ergometer where movement velocity was held constant (Knuttgen, 2007). I have added an example of the type of activity for each of these power outputs.

Another way to present this information is to look at the power outputs of selected activities as a percentage of an individual's maximum power output rather than a specific power output in watts. (See Figure 1, next page)

Obviously, elite athletes can easily surpass the mechanical power outputs or times to exhaustion listed in Table 1. A specialized heavyweight Olympic lifter can generate 6,000 watts of mechanical power in a single lift (Garhammer 1993), and Lance Armstrong could ride

Metabolic power (watts)	Mechanical power (watts)	Predominant energy system	Time to exhaustion	Example of activity type
6,000	1,380	Phosphagen	1 second	Olympic lifts
4,000	920	Glycolytic	14 seconds	100-m sprint
2,000	460	Oxidative	6 minutes	2-km row
1,000	230	Oxidative	2 hours	40-mile bike

Table 1. The relationship of metabolic power produced in skeletal muscle to the mechanical power of activity. (Adapted from H.G. Knuttgen, "Strength Training and Aerobic Exercise: Comparison and Contrast," Journal of Strength and Conditioning Research 21, no. 3 (2007): 973-978.)

Notes:

- 1000 watts = 1.36 horsepower = 864 kcal per hour
- The efficiency of converting metabolic (chemical) power to mechanical power (output) is assumed to be 23 percent.
- Only the predominant energy system is listed, but we use all three at most power levels. For example, exercise intensity resulting in exhaustion in 6 minutes would require approximately 20 percent of energy to be obtained from anaerobic systems, and a 14-second sprint would obtain approximately 10% of its energy from the oxidative system.

<table>
<tr><th>Power Output</th><th>Activity</th><th colspan="2">Energy Systems</th></tr>
<tr><td>100%</td><td>Olympic lifts, high jump, 5-yard maximal sprint, shot put, max plyometric jumps, etc.</td><td colspan="2">Almost exclusively phosphagen</td></tr>
<tr><td>80%</td><td>100-meter sprint</td><td colspan="2">Predominantly phosphagen</td></tr>
<tr><td>60%</td><td>200-meter sprint</td><td colspan="2" rowspan="2">Mix of all three systems but predominantly glycolytic</td></tr>
<tr><td>40%</td><td>400-meter run
100-meter swim</td></tr>
<tr><td>30%
20%</td><td>4-minute-mile run
2000-meter singles row</td><td>VO_2 max Range</td><td rowspan="2">Aerobic</td></tr>
<tr><td>10%</td><td>Marathon pace (elite)
Running (competitive fitness)
Jogging (easy pace)
Walking</td><td></td></tr>
<tr><td>0%</td><td></td><td></td><td></td></tr>
</table>

Figure 1. Percentage of maximal power output that is expended during various activities. (Adapted from H.G. Knuttgen, "Strength Training and Aerobic Exercise: Comparison and Contrast," Journal of Strength and Conditioning Research 21, no. 3 (2007): 973-978.)

up mountains in France generating close to 500 watts of mechanical power for 20 minutes, something the subject in Table 1 above managed for only 6 minutes, and that a typical 25-year-old could do for only 30 seconds (Blakeslee 2005). But how would these athletes do on "Grace" or "Linda"? For a specialized aerobic power beast like a Tour de France cyclist the answer is an obvious "Not very well." However, the Olympic lifter may not do as well as you might think on them either, and a specialized power lifter would also struggle. A specialized bodybuilder, of course, would get completely "gassed" by most CrossFit WODs.

Muscle fiber types and motor units

Before trying to analyze the specifics of what is happening in CrossFit metcon workouts, it would be useful to understand how strength and aerobic exercises compare in terms of motor unit recruitment, muscle cell metabolism, circulation, and the adaptations to the extremes of mechanical power output.

Briefly stated, there are three categories of muscle fibers. Type IIb fast-twitch fibers (also know as Type IIx) are recruited for very short-duration high-intensity bursts of power such as maximal and near-maximal lifts and short sprints. These fibers produce high force levels quickly but they fatigue quickly as well. Type IIa fast-twitch fibers are more fatigue-resistant than Type IIb fibers, but they cannot produce force as rapidly. They are used more during sustained power activities such as sprinting 400 meters or doing repeated lifts with a weight below your maximum (but not with very light weights). Finally, Type I slow-twitch fibers are used in lower-intensity exercises such as very light resistance work aimed at muscular endurance and long-duration aerobic activities such as 5K and 10K runs.

Muscle fibers are organized into motor units and each unit is controlled by a single motor neuron (nerve). All the muscle fibers in a motor unit are the same type of muscle fiber. The cell bodies of Type I neurons have a lower threshold of excitation, which means that if the activity has a low demand for power, only Type I fibers will be stimulated. If the need for force and power development becomes greater, increasing numbers of Type I motor units will be recruited by increasingly larger waves of excitation by the central nervous system (CNS). Eventually, all of the Type I fibers will become involved. This would be at the point where the athlete is reaching his or her maximal aerobic capacity.

Once the demand for power reaches approximately 20 percent of maximal, the CNS stimulation is strong enough to recruit some Type IIa fibers. Evidence of Type II fiber activity is provided by the presence of lactate in the muscle and blood. As the demand for force increases, larger waves of excitation from the CNS eventually result in the recruitment of Type IIb fibers (these have the highest threshold of excitation). To produce maximal force, the CNS produces the largest possible stimulation and all available motor units serving the muscle are recruited (all three types). Note that only trained athletes are actually able to recruit all of the available motor units. This is one of the reasons we see very fast gains in strength with novices to strength training, as they "learn" to recruit more existing fibers.

Muscle cell metabolism

In my article "Rest-Recovery During Interval-Based Exercise" I reviewed the three systems whereby a human can produce the energy required to do physical work (*CrossFit Journal* 56, April 2007. These systems were also discussed in *CrossFit Journal* 10, June 2003). I will not repeat a detailed review of those systems here, as I believe that most readers of the *CrossFit Journal* understand that energy for high force/power outputs is supplied by ATP/CP (high-energy phosphates stored in the muscle) and that as exercise intensity is reduced, more energy can be obtained by the glycolytic system and eventually, as exercise intensities are further reduced to levels that can be sustained for several minutes to hours, the oxidative prevails. As an example, 99 percent of the energy expended during a marathon is provided by the oxidative system.

Due to aerobic training and interval work, the oxidative metabolism of Type I fibers can be enhanced by increases in oxidative enzyme concentration and in the size and number of mitochondria (the site of oxidative metabolism). Similarly, anaerobic training will result in increased concentrations of anaerobic enzymes that enhance the anaerobic ability of Type II fibers.

Circulation

Muscle tissue capillarization, blood volume, blood composition, and cardiac output are irrelevant for the highest exercise intensities. Single Olympic lifts, maximal throws, and high jump, for example, do not depend on the delivery of oxygen and substrate to the muscles.

As you move to lower-intensity exercise that can be sustained for longer periods, the need increases for the circulatory system to deliver oxygen and fuel and to remove carbon dioxide (CO_2), waste products, and lactate. As we can see from Figure 1, ongoing power outputs of around 40 to 70 percent of maximum rely heavily on the glycolytic system and the oxidative system, so the delivery of glycogen and oxygen and the removal of metabolites (mostly waste products) from the muscle become increasingly important. By the time exercise intensity is around 30 to 35 percent of maximum, the athlete is in his or her aerobic maximum range, and performance relies heavily on having optimal values for cardiac output, blood volume, muscle tissue capillarization, and hemoglobin concentration (which determines the oxygen-carrying capacity of the blood).

Conventional strength and aerobic training specialization

Most steady, sustained aerobic training occurs around 20 percent of maximal power output and, as discussed above, recruits Type I muscle fibers. Although there may be some small increase in the cross-sectional area of these fibers, this is less important to performance than increases in the oxidative metabolic capacities of the same fibers and increased delivery of oxygen to them. Hence it is not surprising that elite marathon runners and Tour de France cyclists exhibit spare musculature but high blood volume, hemoglobin concentrations, and cardiac output.

Weight lifting prescriptions can be classified as light (12 to 15 rep sets), medium (7 to 12 reps), heavy (3 to 6 reps) and maximal (1 or 2 rep maxes). While specific responses will differ depending on the repetition scheme, it is fair to say that one general adaptation to strength training is an increase in the size (cross-sectional area) of Type II muscle fibers. An important point to understand is that conventional strength training will not improve cardiac function or blood composition and volume. It is interesting to note that there is, however, a change in muscle capillarization. There is not an increase in the number of capillaries, but the size of Type II muscle fibers does increase, which results in the muscle capillaries being moved farther apart. This is called capillary dilution and it is part of the reason very strong athletes who have focused just on strength and power training do not do well at aerobic exercise and CrossFit metcon workouts. (Aerobic training, in contrast, does produce an increase in capillary density that increases the capillary-to-muscle-fiber ratio and improves the muscles' ability to extract oxygen.)

Most athletes who strength train and then do some separate aerobic work tend to focus on running or cycling for their aerobic bouts. While these athletes are slightly better equipped than either pure lifters or pure aerobic trainees to handle some CrossFit workouts, even workouts that emphasize strength and lifting—such as " Linda," for example—are still done for time and are grueling metabolic conditioning workouts (sometimes surprisingly so) that will punish those who specialize at either end of the energy spectrum. CrossFit metcon training requires intense but extended work of all muscle groups. This prevents the capillary diffusion that occurs with a predominant focus on low-rep strength training with long rest periods between sets. Traditional strength training does not challenge the body to deliver oxygen and other fuels and to remove metabolites in the way a metabolic conditioning workout like "Linda" does.

Many athletes, and nearly all of the general public who actually exercise, work at either end of the power spectrum, as described above. Many do both, but, by keeping them separate, they are in effect still specializing—just in two training modalities instead of one. Only athletes who are involved in sports that require frequent recovery from high bursts of power output tend to work at all power levels. For example, an elite soccer player will cover approximately 12 km in the 90 minutes of a match. As a steady running pace this isn't impressive, but the soccer player typically walks for 20 to 30 percent of the match, jogs for 30 to 40 percent, runs at pace for 15 to 25 percent, sprints for 10 to18 percent, and runs backward for 4 to 8 percent of the time. Pretty much every pace is included and we know that recovery from sprints is an excellent way to improve aerobic capacity while also stressing anaerobic systems and Type II fibers. In addition to a variety of running paces, soccer players will have to jump, tackle, brace against shoulder charges, and get up off the floor after being knocked over dozens of times during a match.

Soccer is just one example of a sport with a variety of demands, but in this case, unfortunately, the vast majority of the (still relatively low) strength demands are on the leg musculature. Hence soccer players who do not do any strength training (ideally CrossFit-style) do not display significant strength and power, particularly in the upper body. Rugby, though, requires incredibly varied power outputs from all the body's musculature. Obviously, mixed martial arts and many other sports would similarly tax all muscles, all three energy systems, and all muscle fiber types. My point is that while all athletes will find metcon WODs challenging, athletes who work in anaerobic-based sports with relatively long match durations are better able to handle CrossFit programming at the outset than those coming from purely strength- or aerobic-based training programs.

CrossFit programming and metcon workouts

I, and many others who have looked closely at CrossFit, could write a book on this topic. But for the purposes of this article, what I want to do is begin to explore why CrossFit's metcon workouts are so taxing and effectively train so many aspects of physiological fitness.

In its entirety, CrossFit programming works both ends of the power spectrum (as do a number of other fitness programs). Many workouts focus on strength (e.g., the CrossFit Total, 1- to 3-rep Olympic and slow lifts); others on aerobic capacity (e.g., running and rowing relatively long distances, or sustained calisthenics). In addition, interval training (e.g., 3 x 800 meters, or 4 x 400 meters, or one-minute rounds, or Tabatas) simultaneously improves aerobic function and stresses more Type II fibers and the body's ability to remove metabolites during anaerobic exercise and hence sustain that exercise intensity for longer. But it is the mixed-mode metcon workouts, such as "Linda," "Grace," "Fran," "Helen," and even "Angie" and "Murph" that are particular to CrossFit and one of the keys to its remarkable efficacy at increasing work capacity across broad time and modal domains.

So, what muscle fibers and energy systems do these workouts target? All elite CrossFitters are excellent at working across all their power output levels. They are conditioned to work the entire range, from 20 to 25 percent of their max power output for long periods (aerobic power) to moderate power outputs for extended periods of time, to 90 to 100 percent of their max power output for a few seconds. What the actual maximum power output of any particular CrossFitter is will depend on his or her physical size (total muscle mass) and fitness and skill levels

Obviously though, there are differences among elite CrossFitters. A CrossFitter with a 270-pound clean and jerk is working at 50 percent of maximum load when he does "Grace" (thirty 135-pound clean and jerks for time) and can recruit less of his muscle fibers at the start (maybe only Type I and some Type IIa). Due to the continuous nature of "Grace" these muscle fibers will start to fatigue. But as these fibers tire, he can elicit a stronger wave of excitation and start to recruit additional Type IIa and Type IIb fibers. On the other hand, a CrossFitter with only a 150-pound clean and jerk will have to start with a very large wave of excitation and have to recruit the most muscle fibers available from the beginning of the workout. Hence he will fatigue much quicker and have to rest longer between lifts. This fatigue will definitely have a central nervous system (CNS) component, since intense repeated bouts of strenuous exercise deplete neurotransmitter levels, which results in reduced physical and cognitive performance. All voluntary muscle activities are controlled by the CNS through nerve connections; hence the role of neural fatigue is an integral part of understanding fatigue during metcon workouts.

The CNS fatigue will affect lightweight or weaker CrossFitters more during heavier lifts as they require more muscle stimulation to achieve each lift. However, the lightweight CrossFitter will have an advantage in workouts like "Angie," "Helen," "Murph," and possibly "Fran" as well, which are made up largely of bodyweight exercises, with only relatively light external loads, since the lower bodyweight means there is less total work to accomplish. Body dimensions also play some role, and a tall athlete will do more work during exercises like Tabata squats and floor-to-overhead lifts than a shorter athlete of the same weight.

Another distinguishing element of CrossFit programming and the variety of workout types it includes is that we have to exercise through the entire power range in so many muscle groups. What other training program would ask you to do something like "Linda"? Although circuit training has been around for a long time, it typically entails individually working different small muscle groups fairly hard for a fixed time and then resting before starting another round. CrossFit "metcons," though, are metabolically demanding combinations of full-body, multi-joint, high-power movements that you just blast through for time with no rest. They typically challenge all muscle fiber types and all energy systems at once. Clearly they are predominantly anaerobic, with the aerobic system helping recovery. Only those who can blast through 26+ rounds of "Cindy" with no rest periods can claim that it is primarily aerobic. Maybe "Cindy" and "Murph" have more aerobic flavor than some of the metcon workouts but, for most of us, as those push-ups start to fatigue the Type I fibers, we have to resort to whatever fibers the CNS can manage to stimulate. Twenty-five minutes into "Murph" the strain is felt in a lot of different muscle fibers and the circulatory system, whereas twenty-five minutes into a hard 10K run, the strain is limited to legs and circulatory systems.

Another important challenge presented by many of the metcon workouts is the instant switching of activities that many of them require. During the fast 400-meter run in "Helen," for example, the body pushes blood to the working leg muscles, which means that capillaries in these muscles open up, while capillaries in the gastrointestinal tract and other organs not essential to exercise are restricted. There is only so much blood to go around, and if resistance into all the body's capillary beds dropped, you would pass out due to low blood pressure. To prevent this, blood flow to the upper body is also restricted. Then you hit the kettlebells, and the body has to switch blood flow to the upper body quickly. It isn't easy.

If you haven't already experienced this yourself, try this experiment: warm up and then do your max set of pull-ups. A day or two later, warm up and go for a hard 1K run followed immediately by another max set of pull-ups. You will not be able to do as many. Why? I think there are (at least) three factors. For one thing, the blood flow to your "pull-up muscles" will be slightly lower after the run, as the closing down of capillary beds in the legs is not instantaneous, and this will delay opening up of capillaries in the arms. Keep in mind the body has been trying hard to get oxygen and fuel to the legs and remove CO_2, metabolites and lactate from them, and now, suddenly, you are telling it you have "changed your mind and would like it to focus on the arms please!" Second, there is a challenge to the CNS to re-coordinate the activity, switching to pull-ups from the run. And, third, I think there is also a psychological/mental difficulty component, as it just plain feels harder to do pull-ups (especially fast, powerful kipping ones) when you are busting a lung already.

Obviously the hormonal response to the metcon workouts is also a huge and complex factor in their efficacy. Strength training has been shown to increase anabolic hormones (hormones that promote tissue building). These hormones are insulin, insulin-like growth factor, testosterone, and growth hormone. Research with young males has shown that several factors appear to increase acute serum testosterone levels during and after workouts. These factors are:

- Large muscle group exercises (e.g., deadlifts, cleans, squats)
- Heavy resistance work (1- to 3-rep-max sets)
- Moderate to high volume of exercise (Note that this research finding does not necessarily mean just long duration but also multiple sets and multiple exercises.)
- Short rest intervals
- Two or more years of resistance training

Does the above list apply to metcon workouts? Rhetorical question; no need to answer.

The specific hormonal response to training is in itself another long article, but it is important to note that only muscle fibers that are activated by resistance work are subject to adaptation due to these hormonal effects. This is yet another obvious benefit of CrossFit programming and yet another reason to ask, "Why bother doing biceps curls?"

Chronic long, slow, distance training, however, can actually decrease testosterone levels in males and estrogen levels in females. This fact may be an additional reason for the effectiveness of CrossFit's directive to train hard and smart, not just long and longer. It is certainly part of the reason CrossFit has had such good results training endurance athletes with much less mileage than traditional endurance programs prescribe. Tough metcon workouts can be as short as two minutes and as long as 50+ minutes, but none will have you pounding the pavement for hours upon hours.

Benchmark CrossFit Workouts Mentioned in this Article

"Angie"

100 pull-ups
100 push-ups
100 sit-ups
100 squats

One round, for time. Complete all reps of each exercise before moving to the next.

"Cindy"

5 pull-ups
10 push-ups
15 squats

Complete as many rounds as possible in 20 minutes.

"Fran"

21 thrusters, 95 pounds
21 pull-ups
15 thrusters, 95 pounds
15 pull-ups
9 thrusters, 95 pounds
9 pull-ups

For time.

"Grace"

30 clean and jerks, 135 pounds

For time.

"Helen"

400-meter run
21 kettlebell swings, 1.5-pood (24 kg)
12 pull-ups

Three rounds, for time.

"Linda" (a.k.a. "Three Bars of Death")

Deadlift, 1.5 times bodyweight
Bench press, bodyweight
Clean, .75 times bodyweight

10/9/8/7/6/5/4/3/2/1-rep rounds (ten rounds, starting at 10 reps and decreasing by one rep per round). Set up three bars and storm through for time.

"Murph"

1-mile run
100 pull-ups
200 push-ups
300 squats
1-mile run

For time. Partition the pull-ups, push-ups, and squats as needed. Start and finish with a one-mile run. If you've got a twenty-pound vest or body armor, wear it.

For the complete list of CrossFit's "named" workouts, see the CrossFit FAQ.

Subscription info at http://store.crossfit.com
Feedback to feedback@crossfit.com

The utility of CrossFit results

Ultimately any training program should be able to boast that it is preparing its trainees for whatever life—or a game or a mission—throws at them. I think this is one of the easier things to explain about CrossFit.

I once had a student in an exercise physiology course who looked to be an out-and-out bodybuilder type—until he ran seven laps of a 400-meter track during a 12-minute run test (Cooper Test). I was impressed. I talked to him and he admitted that two years earlier he was just a bodybuilder. But then he went on hikes with his girlfriend only to be left out of breath and in the dust. He spent hours upon hours in the gym each week and got his ass kicked on a hike! After that experience he had to ask himself, "What is the use of having a Cadillac body with a Volkswagen engine?" I thought that was a great statement but I will modify it to be more accurate in light of my discussion above. Our muscles are in fact the engines that drive our mechanical power output. So a better way to rephrase my student's quote might be to ask "What is the point of having a Ferrari engine with a lawnmower fuel pump?"

Have I answered the $64,000 question of what is going on inside the black box of CrossFit programming? Of course not. But I hope I have clarified some of the mechanisms at play. So far, there is not any research (that I am aware of) that has really got to what I think is at the heart of that question: namely, "Why is the whole greater than the sum of the parts"? By this I mean that—even if we can start to dissect how CrossFit metabolic conditioning challenges all muscle fiber types, all energy systems, the central coordination of muscle groups, and the nerve transmission systems themselves, as well as eliciting a variety of hormonal responses that in turn benefit all muscle fibers—the question still remains as to exactly how and why CrossFit's particular blurring of the distinctions between "cardio" and strength training consistently produces such a stunning blend of athletic abilities.

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