Determining a mathematical way to measure resistance profiles

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N.B.: Figures that require information are explained at the end.

Numerous methods are being used to interpret how much a muscle works during an exercise; like the force output (or torque) of a muscle and the electrical signal transmission (electromyography (EMG)) or *activation* of a muscle. However, measuring torque is often complicated, expensive and does not always fit the goal of the study. On the other hand, EMG is extremely popular but does not represent the amount of tension that is being applied on the muscle and we now know that more EMG does not mean more muscle hypertrophy[1] and that applying tension is the primary hypertrophic stimulus within resistance training.[2] The goal of this paper is to demonstrate mathematically how much tension* is being applied to a specific muscle, what is a resistance profile and what we can do to manipulate the resistance profile of an exercise without changing the exercise. Using an equation to do so would automatically increase our understanding of exercise mechanics, add resistance profile as a subjects of research, explain with accuracy and with a mathematical proof what is a resistance profile, increase the rigor and accuracy of resistance training studies, and reduce the need of a human interpretation when trying to find a conclusion, a causation or an explanation of a specific result.

**The formula used is actually to measure power, not tension. The reason is that I don't know the exact distance between the joint and the insertion attachment (moment arm). The two are however in direct correlation.*

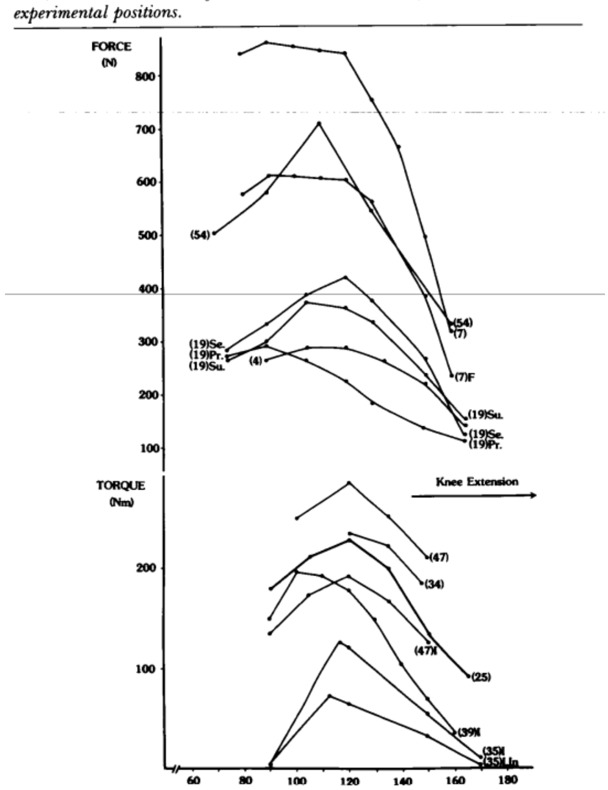
Strength curves and resistance profiles

Strength curves have been subject to a lot of research.[3, 4, 5, 6] Basically, it shows how much a muscle is able to produce force or torque depending on the sarcomere's length. Sarcomeres are the contractile unit of a muscle fiber, their length depends on the angle of a joint. The more you extend your knee, for example, the more you contract your muscle (i.e. quadriceps) therefore the more a sarcomere in a quadricep will shorten. In general, a muscle tends to produce significantly less torque if it is lengthened or shortened compared to its anatomical position. However, certain muscles, like the deltoid, are able to produce a lot of force when they're lengthened, but one thing is for sure, a muscle loses a lot of capacity to produce force as it's being contracted.

Strength curves are useful in our understanding of the musculoskeletal system and exercise mechanics, and can provide important information on how to program resistance training. They are nonetheless independent of the exercise one might be doing and of the resistance training approach you are choosing.

The resistance profile, on the other hand, is the resistance, measured as power, a particular exercise applies on a specific muscle. It is independent, but only to a certain point, of the strength curve of the muscle. Since velocity is involved, if someone contracts a muscle (i.e. changes the angle of a joint) faster or slower at some point of the movement due to an incapacity (or by choice) to produce a constant amount of force, the resistance profile will change.

Knee extension strength curves. Numbers in parentheses identify the sources for data. Unless indicated by one or more of the following letters, curves were obtained under isometric conditions with male subjects: I = *isokinetic torque;* F = *female subjects;* In = *injured knee;* Se., Su., *or* Pr. = *force measured at seated, supine, or prone experimental positions.*



The tempo, which is a predetermined time for the different part of the movement (written 3110 for a 3 seconds eccentric, 1sec pause in the lengthened position, 1sec concentric and no pause in the shortened or fully contracted position†) influences the resistance profile by a lot. This has major implications if trying to compare two groups during a research. A group could, with or without knowing, execute an exercise faster or slower due to different cues given by the team of scientists present. It could probably happen in different studies on mind-muscle connection and range of motion (ROM) where participants are asked to think about a specific goal ("contract the muscle" or "don't go all the way down", for example). If the velocity changes, you can't compare both groups without taking—probably—a massive change in power into consideration. Trying to limit or measure changes in power can be quite difficult and expensive, when it's not the primary goal of a study. However, it would be extremely easy to enter a couple of simple metrics into an equation and it would automatically increase the rigor and accuracy of the study.

†*The eccentric portion of the movement is when the muscle lengthens or stretches, and the concentric portion is when it shortens or contracts.*

The equation

As of right now, the equation can only be applied in single joint movement if a dumbbell or barbell is being used. Upgrading the equation to be able to use it with cable and pulley based exercise will be quite easy. However, to more complex movements like squat and deadlift will be difficult and will need other studies to understand the role of friction. Based on my hypothesis, friction rarely impacts the tension that is being applied on a muscle[7] but it could impact the activation of a muscle.[8] More studies are needed on that topic. It's fundamental to our understanding of exercise mechanics and it has major implications.

Eccentric vs Concentric

$$P = \tau\omega$$

To use the equation, we need to separate the eccentric portion of the movement of the concentric portion. When using the equation, obviously we have to separate both parts of the movement because the velocity might be different, for example with a 3010 tempo. There is however a major difference between the two equations. For the eccentric portion of the movement, we need to use the percentage of the acceleration from gravity used to lower the weight instead of the angular velocity (ω). It's impossible to create acceleration during the eccentric portion unless you contract the antagonist muscle while fully relaxing the *working* muscle. It is however far from something someone should do. If someone does not try to "slow down" the weight during the eccentric, theoretically he uses 100% of the predefined (by gravity) velocity to reach the starting point (e.g. 0° of elbow flexion for a biceps curl). In that case, torque x 0 = 0 watt. Therefore there is absolutely no power produced if someone does not *control* the weight, which makes sense. It is also impossible to use 0% of the predefined velocity unless you don't move. It means that, except at the specific angle where you completely pause (if you do), a certain percentage of the predefined angular acceleration will be subtracted inversely proportionally to the velocity at which you perform the eccentric portion. In other words, the slower you go, during the eccentric portion, the more tension you apply on the specific muscle. It is however the inverse for the concentric portion, the bigger the velocity, the more power you produce.

$$\tau = rF\sin\theta$$

$$F = ma$$

To measure the distance between the weight and the moving joint, perpendicular to the tension (in that case gravity that acts on the weight), you simply need the length of the moving limb (e.g. forearm for a biceps curl) and the ROM. You theoretically use a specific angle, but I coded a program to measure resistance profile, for a ROM at every angle, to facilitate the use of the equation in different contexts (see later paragraphs). So, to measure the distance between the weight lifted and (perpendicular to) the moving joint, you can use the Law of Sines which, in that case, is the length of the moving limb x the sine of the angle at a specific point during the ROM / the sine of 90 (which is 1) because the distance is always perpendicular to the force, it's always 90°. Therefore, with the weight that you are using, the length of the moving limb, the ROM and the tempo, we can quite easily measure the resistance profile.

To measure the percentage to remove from the predefined acceleration (from gravity), you need to divide the velocity of the eccentric portion of the exercise by the velocity that you would get without resisting. In other words, the speed (rad/s) that would result from the totality of the acceleration from gravity. The calculation to get the velocity of the eccentric portion is extremely easy, but to get the "gravitational velocity", you need to use an elliptical integral.[9] The simple pendulum formula doesn't work due to its inaccuracy when the angle gets too big. Anyhow, using the elliptical integral or an approximation of it results in a close enough estimation of the period.[10, 11] The period is the time used for the pendulum to return to its original position. To get the velocity, you simply have to divide the range of motion in radians by the period *used*. So, if you did a 3sec eccentric when the gravitational acceleration was supposed to lead to a 1sec eccentric, you can determine that you used 1/3 of the predefined acceleration, therefore you need to subtract ~33% of it.

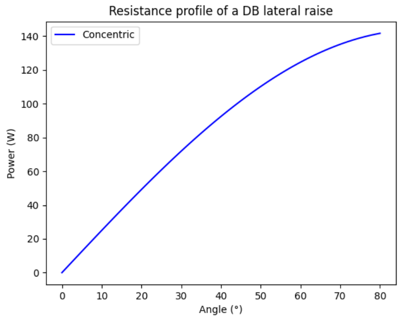
The use of inertia and momentum during an exercise

Something that we often see within resistance training is the intentional use of an increase in momentum, often paired with an increase in inertia. I however tend to recommend an increase in momentum paired with a decrease in inertia. If, obviously, it is in line with the goal of the athlete.

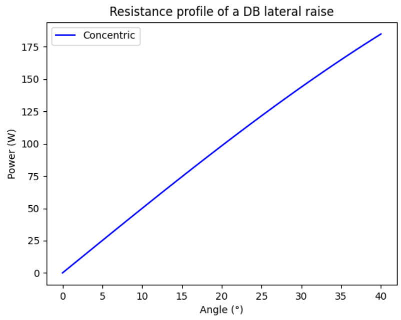
First, momentum is the mass of an object x its velocity, so it is impossible to not have momentum while performing an exercise. What most people do, is that they use their body to create velocity and, due to the law of conservation of momentum, they will only need to produce a minimal amount of contractile force with the specific muscle they want to train to finish the movement. For instance, someone will use their lower body musculature to start a (*deltoid*) lateral raise. One might also simply create a lot of force at the beginning of the movement and let the law of conservation of momentum do most of the rest of the job, but let me get back to that.

The problem is that most people do it for the wrong reasons and while using a specific type of exercise. The most common reason is simply to lift more weight. It's possible to argue that using more velocity and more weight is a good idea because, based on the equation, you would get more power. However, there is a problem with that reasoning. The formula works if you have to produce contractile force, you can't, for instance, throw a weight in the air and say that its mass and velocity are still applying tension on your muscle. Let me repeat: the formula works if you have to produce contractile force.

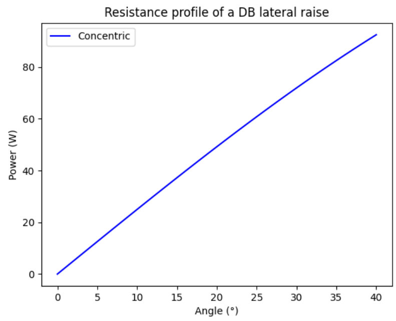
If you produce a constant amount of force to keep the velocity stable during the movement, velocity will be used as a constant and only the distance between the weight and the joint will change the power. Just as an example, let's analyze (*see below*) the different possibilities of a DB lateral raise, a popular exercise for the medial deltoid. Each scenario is using someone with a shoulder to hand length of 70 cm and a DB of 15 kg. Scenario 1 is a standard DB lateral raise with a 1 second concentric and a constant velocity. Scenario 2 is someone who lifts the weight twice as fast for the first half of the exercise and he then uses momentum to not produce any force for the rest of the movement. When comparing those two scenarios, we can see that he reaches a higher amount of power than scenario one. However, if someone can, with the same weight, create that much velocity, I would probably suggest taking heavier dumbbells and using a more complete range of motion, making the comparison between the two scenarios impossible. What actually happens most of the time, is someone generate the most force possible through the muscle he wants to train and uses his body to generate the rest of the momentum, therefore creating a scenario like the third one; (a) there is only power in the part of the movement where his deltoids are working and (b) his deltoids can't create more contractile force than they could in the first scenario.



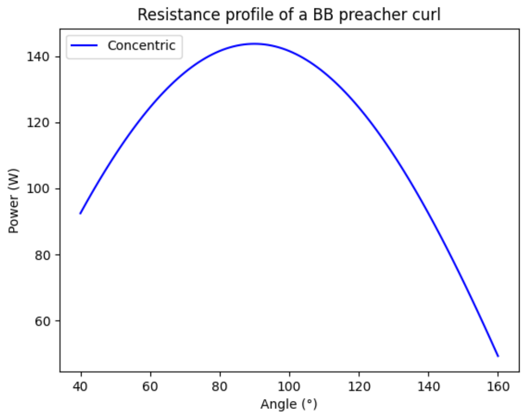
Scenario 1



Scenario 2



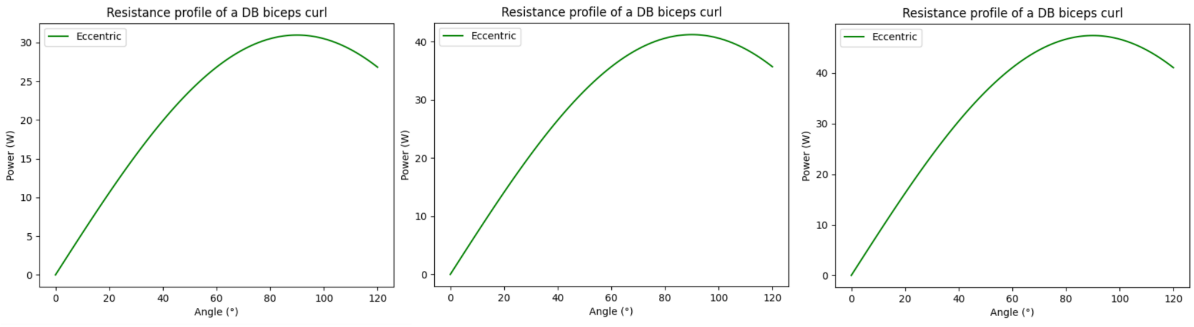
Scenario 3



Those scenarios can not be used to explain every exercise in which you start with a larger acceleration, because a DB lateral raise is part of the group of exercises that I referenced earlier. Why is it the type of exercise that is commonly used for this type of behavior? Because inertia increases as the exercise is performed. Inertia, which increases due to an increase in the distance between the joint and the force (gravity on the DB), determines the object's resistance in a change in motion, while momentum determines the amount of motion. So, the more momentum *and* inertia you have, the less force you have to produce to keep lifting the weight. If you take an exercise that has a lot of power while your muscle is in its lengthened position and it keeps lowering while you lift the weight (i.e. while you contract your muscle), you would theoretically need to keep producing force because the object's resistance in change of motion would be really low. In other words, the effect of gravity will soon make the weight stop moving and you'll have to lift it with the help of your muscle. For instance, doing so in a Preacher curl would be less problematic in terms of losing tension at the end of the movement, simply because you have less inertia at the end of the movement compared with the start.

The eccentric portion

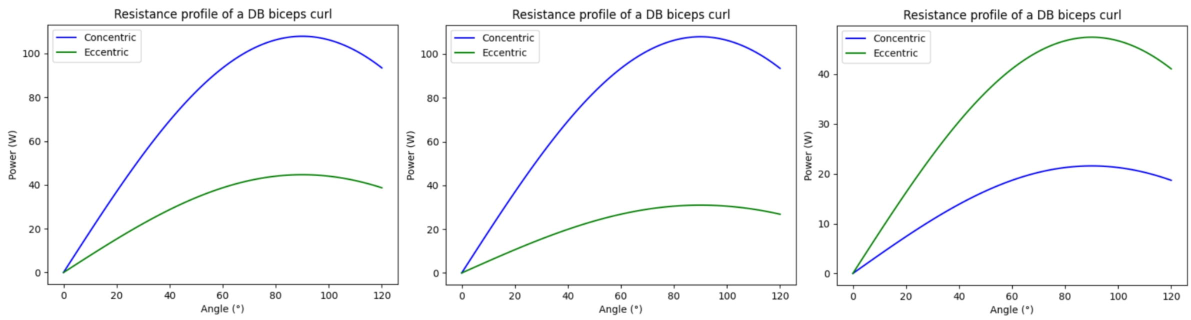
Contrary to the concentric portion, the velocity is inversely proportional to the power for the eccentric part of the exercise. Meaning that the slower you go, the more power you get. However, the difference after a certain point is quite small. We can clearly see, from the graphics below this paragraph, that if you only‡ change the eccentric velocity, the difference between a 1sec to 2sec eccentric is similar to a 2sec to 5sec eccentric. Obviously, a difference of a couple percent at every repetition can lead to major results, but even going from not resisting the eccentric at all to offering a slightly significant resistance can benefit greatly.



1 sec eccentric | 2 sec eccentric | 5 sec eccentric

‡ *Each scenario is using a 0° to 120° ROM, 15kg dumbbells, and 35cm forearms.*

Another important significance in understanding the impact of velocity in resistance profiles, is understanding how to prioritize a specific part of the movement. Below this paragraph, you can easily see how a change in tempo can lead to an increase—or decrease—in power during the eccentric or concentric portion. During the last one or two decades, there has been an increasing interest in comparing both parts of an exercise, to better understand their specific benefits.[12, 13] To prioritize the concentric portion, you need to perform the eccentric and the concentric relatively fast. Inversely, to prioritize the eccentric portion, you theoretically need to do both slowly. However, doing so would result in a massive increase in time under tension (TUT) during a period of high metabolic demand, therefore leading to an increase in metabolic stress, which is what prioritizing the concentric portion leads to.[14, 15] Nevertheless, in most cases, I think that voluntarily performing the concentric slowly is not the best idea. The concentric *will* slow down if you reach proximity to failure, in that case, you will recruit high threshold motor units, leading to more hypertrophy.[16, 17] That is why I would recommend a training partner if the goal is to make the eccentric portion the main focus.

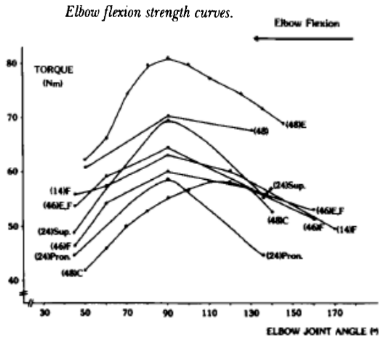


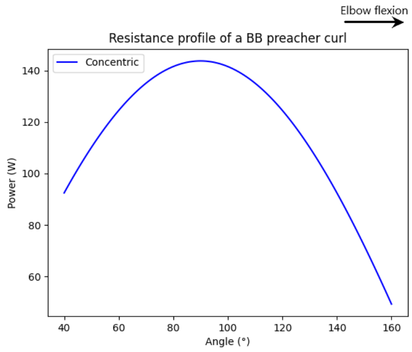
Tempo : 3010 | Tempo: 1010 | Tempo: 5050

Each scenario is using a 0° to 120° ROM, 15kg dumbbells, and 35cm forearms.

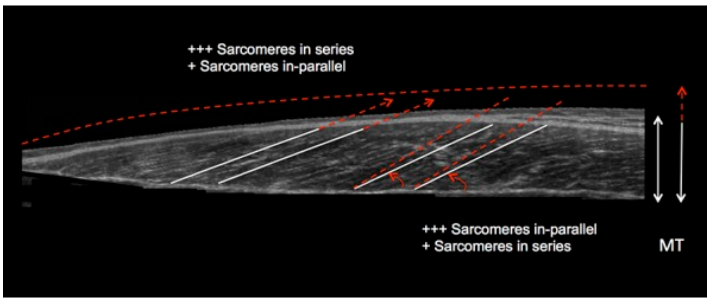
Linking strength curves and resistance profiles

An increasingly popular belief is that "resistance profiles should (or must) be similar to the strength curve". I want to provide information as to why I do not think of it as a good ideology. But, before laying potential reasons, I want to explain the reasoning behind the ideology—which is not necessarily completely wrong. Certain coaches or trainers recommend to select exercise that has a resistance profile similar to the strength curve of the muscle that is being trained because that is a perfect scenario to be able to generate the maximal amount of force, therefore producing high mechanical tension (or stress), which seems to be the primary stimulus for muscle hypertrophy within resistance training.[2, 15, 18, 19, 20, 21] Because, you could, in that case, use a weight that is maximally challenging during the entirety of the movement. The power would be at its highest when your muscle is able to produce the most contractile force possible and the power would lower while the muscle would weaken. For instance, we could say that "the resistance profile of a BB preacher curl (using a preacher bench with a 40° angle) matches the strength curve of the biceps (or elbow flexors)". I however find it difficult to say, based on this statement, that the preacher curl is automatically one of the best exercises for the biceps.





There are two major reasons why I tend to object to this statement. First, I think that choosing various exercises with different resistance profiles is a good idea in the long term. There seems to be an advantage in prioritizing the shortened position if you specifically want to hypertrophy the medial part of a muscle.[22] Also, I would hypothesize that having a resistance profile that challenges the shortened position, when the muscle is at its weakest, would increase metabolic stress to a significant level, because being able to generate enough contractile force would be quite metabolically demanding. Contrarily, choosing an exercise that almost exclusively has power when the muscle has the largest capacity to generate force would be a lot less metabolically demanding, therefore serving different purposes. We know that periodized training tends to be better for muscle hypertrophy and strength,[23, 24] and I think that including resistance profile in our periodization could be even more beneficial in terms of stimulus variation and specificity, and even for the simple benefits of the increase in motivation with exercise variety.[25]



Secondly, I would argue that the strength curve of a muscle might differ with an increase in fatigue and a change in muscle architecture due to a resistance training protocol. We know that sarcomeres, the contractile units of the muscle fibers, undergo a slow change in angle during a workout (figure to the left).[26] We do not know for sure if it impacts the strength curve, but it would be surprising if the change in angle would not modify the capacity to generate contractile force. Nevertheless, I could also argue that with metabolite accumulation, an hypoxic environment, and lower energy availability, it would be astonishing that one is still able to produce a proportional amount of contractile force in the shortened position compared with the lengthened position, like prior to the workout. Therefore, suggesting that one must choose exercises that "matches" the resistance profile is most likely a bad idea. I would tend to suggest choosing an exercise with a resistance profile that "matches" the goal stimulus.

Conclusion

In conclusion, I think that a fundamental understanding in exercise mechanics could help coaches and trainers make better decisions for their clients and athletes. I also think that it could help scientists gain important knowledge that could be applied in increasing the rigor and the accuracy of future studies. Mechanical stress has an essential role in muscle hypertrophy and we currently have no serious understanding of the underlying physics of it. Being able to make mathematical predictions would revolutionize resistance training science.

If you want to get the program (code) that I used to calculate the resistance profiles, you can copy it from the PDF below and paste it in Python. Please remember that (as of right now) it can't use every exercise, only those with one rotating joint, and that use a dumbbell or a barbell.

Python program used for the graphics

Current limitations

As of right now, there are a couple limitations concerning the practicality and efficacy of the equation:

1. If there's a lack of control for the changes in directions (between the eccentric and concentric, and vise-versa), the lost in power is currently not accounted for;
2. The current equation does not support the use of cable and pulley systems, nor does it support the use of multi-joint—or full-body— exercises;
3. The amount of power lost when the tension is not in line with the primary muscle is currently not known.[§]

§ Another major lack of understanding is regarding factors that determines which muscle receives most—if possible *all*—of the tension. Some people, myself included, would say that you need (a) the power directed in a way that increases tension, not compression, and (b) that the power is lined up with the aimed muscle fibers. Therefore, the future formula must take into consideration a 4D model of the exercise: (1) Is the force increasing tension? (2) Is the force in line with the aimed muscle? (*this dimension is the one that the formula is lacking*) (3) This is where you add the angle of the moving joint, the distance (radius), etc. and finally (4) you must add velocity.

Figure 1 is from Kulig, Kornelia; Andrews, James G.; Hay, James G. (1984);
Figure 2 means: Power (in Watts) = Torque x Angular velocity;
Figure 3 means (from the top): Torque = Length of the moving limb x Force x Sine of the angle, and Force = Mass x Acceleration (gravity);
Figure 5 is a scenario with a forearm of 35 cm, 20 kg barbell, 1 sec concentric, a preacher bench of 40° and a range of motion at the elbow of 0° to 120°;
Figure 8 compares the strength curves of the elbow flexors (left) with the resistance profile of a preacher curl (right)
Figure 9 shows MT (Muscle thickness) before a workout (white) and after a workout (red). Diagonal lines show sarcomeres angle (before and after).

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