The Progress of Power: A Narrative Review of the Practical Progression of Running Power Assessment and Application

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Abstract

Power has revolutionized endurance athletics. Power is a function of the amount of force produced in a certain amount of time. Utilized correctly, it can be an effective metric of effort during endurance activities. Cycling saw the first fruits of this metric in the 1980s and 1990s with Tour de France athletes and has continued to provide immense benefits to cyclists. Power when applied to running, however, has seen a much slower progression toward effective use. Various attempts in the 1970s and 80s to use calculations to express running power as a function of multiple different kinematic variables proved futile. In recent years, significant technological developments have led to a revitalization of running power research, particularly in the Stryd pod, which is the most commercially successful "running power meter" available. This technology has been shown to be quite reliable, however results related to metabolic and cardiovascular metrics of effort such as running economy, RPE, and HR have shown a lot of variability and inconsistency. Though sensors such as the Stryd pod have propelled running power research into the 21st century, there is still so much that needs to be done. Perhaps a holistic model utilizing technology from multiple different disciplines in the field of exercise science would provide a more valid and accurate base from which to implement running power in training and racing for a wider range of people and settings.

2.1 Introduction

Power may be one of the most revolutionary metrics applied to endurance sports in recent history, [1]. When the concept was first applied to cycling in the late 20th century, the applications foundationally changed not only the training, but also the competition and assessment of cycling forever [2, 3]. By training based on power, cyclists can make consistent efforts regardless of multiple different conditions that were not possible outside of an indoor ergometer previously. [3, 4, 5, 6]. Power is reported in Watts (W) and is defined as the amount of work done over a period of time, or Joules (J) divided by seconds [2]. Because of the way power is calculated and measured, in cycling it is a more objective measure of effort than a metric such as speed. In addition, it is more rapidly assessed than heart rate due to current technology, and therefore is more applicable in monitoring shorter efforts such as intervals, [2, 4, 5, 7]. Power has also been shown to be highly correlated with metabolic effort measured by VO2, which validates its use in structuring training for aerobic athletes based on the attempts to improve various aspects of aerobic fitness including lactate threshold, VO2max, and economy, [1, 4, 5, 6].

While considerable progress has been made over the last few decades into the validation and application of power for cycling performance, much less advancement has been seen in applying the same concepts to running. This disparity between the two sports is largely due to the nature of measuring power in a rigid body compared to soft tissue. On a bicycle, power can be directly and accurately measured via a strain-gauge placed in the bottom bracket, the crankset, or the pedal, [2, 3, 7]. The rigid nature of a modern bicycle allows forces to be easily conserved and transferred between the pedal and a power-meter. During running, however, determining power produced via a strain-gauge would be not only difficult, but also mildly entertaining. A human body is obviously not fully rigid, containing significant amounts of fluids and soft tissues, making a direct measurement of forces produced immensely complex. Therefore, efforts to develop various indirect measurements of running power have been undertaken to differing degrees of success.

During the early development of running power as a research field, the most widely utilized methods of determining running power were mathematical calculations based largely on variables such as an individual's weight, height, speed, stride frequency, etc. [8, 9, 10]. A downside of these early calculations was the fact that variables could not be assessed and recalculated in real time.

Therefore, this method was much less effective for prescribing training or determining differences of power needed for an individual to run different speeds or efforts.

The new development of accelerometer technology has allowed for real-time measurement of set data points important for calculating power such as leg-length, stride frequency, stride length, vertical oscillation, ground contact time, and others, [11, 12, 13]. An obvious limitation of the accuracy or validation of these types of calculations is the indirect nature of the results. One is not truly measuring the power output during running, but rather measuring other variables to estimate running power.

The purpose of this review, therefore, is to thoroughly assess the literature surrounding power and more specifically running power throughout the decades, discuss the gaps that exist within previous research and current methods, and hopefully provide viable solutions or suggestions to further the research behind running power to further the effectiveness and practicality of utilizing running power as both an assessment and programming tool for training and performance. By furthering our knowledge of how best to collect and calculate running power, we can potentially create a more intuitive way of prescribing training and performance programs based on effort as opposed to something simple such as pace or speed.

2.2 Power Validation: Cycling, VO_2, and HR

Since the late 80s to early 90s, cycling has used power to assess, prescribe, and implement training and racing programs. Anecdotal evidence from Tour de France riders showed promise in the field, but one of the first true research studies assessing the effectiveness of power metrics compared to VO2 measurements was by Coyle et al., in 1991. A group of elite cyclists and sub-elite cyclists both rode a 40 km time-trial. Power and VO2 were monitored during the trial. While VO2max was not significantly different between the groups, the elite cyclists rode faster than the sub-elite. In addition, power and time to finish as well as 1-hr power and blood lactate threshold were significantly strongly correlated. This seemed to indicate that power was more indicative of performance than VO2max [6].

Since then, research delved deeper into the relationships between physiological measures of effort and cycling power. Arts and Kuipers in 1994 showed a significant and strong correlation between power, heart rate, and VO2max, as well as percentages of each, [4]. Less than five years later, Garcin et al., discovered that at consistent submaximal power output, heart rate would remain consistent for a significant period, while rate of perceived exertion (RPE) had a significant linear upward drift, indicating that while power output is an accurate measure of physiological effort, it may not be quite as accurate in determining psychological or perceived effort, [14].

While the concept of “critical power” (CP) or use of power to help prescribe training zones based on metabolic efforts had been discussed previously, [2, 7]. Chidnok et al., took the idea to a direct and practical application. If power can truly be used to assess and prescribe training based on zones such as below “threshold” or above “threshold,” then assigning intervals to varying power zones based on the metabolic zones they reflect would reveal if they indeed are correlated. Cyclists each completed a maximal 3-min test to determine CP, and then completed five separate cycling tests to exhaustion: one with a constant effort, and then four with varying recovery intensities of “severe”, “heavy”, “moderate”, and “light”. It was shown that significant differences in the total duration of exercise was increased as the intensity of recovery decreased, and the total work done above CP was also increased by 46%, 98%, and 220% for the heavy, moderate, and light recoveries, respectively. This showed that the use of power to ascertain critical power was accurate, as the farther from a “calculated” CP the athletes got, the more total work they were able to do, [5].

2.3 Power Progression: Running Power Calculations

The next step is to apply the concept of “power” to running. The interesting fact is that this was attempted long before “power” was applied to cycling. The late 1970s and early 1980s were a ripe time for research into running power. These first attempts were very rudimentary, using solely algorithms and complex equations to try to estimate power. Williams and Cavanagh in 1983 summated a group of running power studies and proposed their own set of equations to calculate power, [10]. The issue is that these calculations were not only rudimentary, but thoroughly indirect. None of them could calculate immediate power, and almost every model assumed different values for various constants such as tendon elasticity, segmental energy transfer, and center-of-mass. As an example, using all the same values for variables and at speeds of 3.6-3.9 m*s-1, the 6 different studies included in Williams and Cavanagh estimated the power output anywhere from 163W to 931W and 1650W.

This study identified three key factors that any running power calculation must be based on: muscular activity, elastic activity, and transfer of energy. These factors need to not only be accounted for, but also accurately assessed (or assumed) for the ending calculation to be valid, accurate, and precise. Muscular activity is a more obvious factor. The force of concentric and eccentric contractions needs to be accounted for to assess the propulsion force during running. A complication of this is that energy is utilized to engage in eccentric contractions. Actions such as the subconscious lateral stabilization of a stride, eccentric quad contraction to contrast landing forces, and even plantar flexion against the ground all require metabolic power without increasing the mechanical power. This was referred to the researchers as negative energy.

Elastic energy consists of the stored energy in tendons and muscles that is released after a relaxation of that tension. The complication of this factor is more obvious; how does one determine exactly how "springy" tendons and muscles are while they are still in the body? The short answer (as shown by the wide range of results from the various calculations in Williams' and Cavanagh's study), is that quantifying the elasticity of *in vivo* tissues was difficult if not impossible.

If these factors can be accounted for, the final step is to assess transfer of energy. If the energy of one segment, (for example the lower leg), increases while another segment such as the upper leg loses energy, this is likely not exclusively due to muscular contracts. It could simply be from a transfer of the energy between segments. The easiest way to think of this concept is to return to a bicycle. As one pushes into the pedal, that energy is transferred from the pedal to the crank arm, to the hub, to the chain, and finally out to the wheel to propel the bike forward. Similar principles can be applied to transfer of energy in the human body during running, however the obvious difference is that more energy is conserved in a bicycle because it is a rigid body. Significant energy can be lost due to dissipation through vibration or heat in the human body, [10].

Even the proposed model by the authors revealed values from 273-1775W for the same variables at a speed of 3.57 m*s-1 depending on the assumed constant values. After this paper, while a few studies were still conducted of this nature, research into representing running power as a mathematical model fizzled out.

Attempts have been made more recently, however, to create an effective algebraic model for running power. Jenny and Jenny released a paper in 2020 in the Journal of Biomechanics noting papers from the late 80s through current literature in which some headway had been made, [9]. Three factors were identified in creating this model: 1) dissipation of energy due to natural causes such as vertical oscillation, heat, etc., 2) overcoming breaking forces, and 3) overcoming aerodynamic drag. It is important to note that all these factors fall under an interpretation of "negative work" by Williams and Cavanagh, namely intrinsic (dissipation of energy) and extrinsic or environmental negative work. Breaking forces and aerodynamic drag can be considered negative work done by the environment around a runner because it does not require metabolic energy to produce, but it does require metabolic energy to overcome.

This model from Jenny & Jenny was created based on significantly fewer assumptions than previous studies, however similar shortfalls can be said about this study as with all calculation-based running power; namely it is not possible to make a model than accounts for individual and immediate changes without sensor measurement and it is not practical to implement for any training or performance purposes. Thus, the gap still existed between theoretical and practical running power.

2.4 Power Application: Accelerometry

In 2015, a seemingly breakthrough technology was introduced to the community which would change the face of running power and begin a revival of research into the field. This breakthrough is known as the Stryd Pod. The Stryd Pod is an inertial measurement unit or IMU which is able through accelerometry and gyroscopic technology to assess factors including stride length, stride frequency, vertical oscillation, speed, grade, wind speed, and many other factors, [12, 13, 15, 16 17, 18]. Stryd then takes this information and, using a proprietary algorithm, provides users with an estimated numerical value of running power in real-time.

Anthropometric, spatiotemporal, kinetic, and kinematic factors have all been shown to have links between each other. In 2017, Clark et al. produced a study showing that this relationship between vertical ground reaction forces and time-waveform patterns using wearable IMU sensors with body mass included can account for at least 94% of variance between the two, [11]. This provided evidence that wearable technology was theoretically strongly correlated with running forces in the body, and therefore would be a possible avenue for real-time calculations of running power. However, research needed to be done to verify the Stryd sensor specifically.

Research on the updated Stryd Pod began pushing in 2018, with multiple different studies attempting to determine the validity, accuracy, and reliability of the technology. Garcia-Pinillos and company took on the determination of overall reliability and spatiotemporal accuracy of the Stryd Pod, [15, 16, 17, 18]. Kinematic data measured by the Stryd pod showed reliable and valid results for most metrics, but overestimated flight time and underestimated ground contact time, [16]. A follow-up study revealed that the Stryd pod again was relatively valid and reliable, however once again the system overestimated flight time by 15% and underestimated ground contact time by 5% when compared to high-speed video analysis, [15]. Garcia-Pinillos also found high correlations between power and velocity as measured by the Stryd pod, ($r > 0.92$), and found no significant differences in power when measured at different time intervals from a 10-second average to a 180-second average, [17, 18].

Cerezuela-Espejo et al. found that Stryd was the most repeatable unit when compared to four other commercially available technologies on both a treadmill and outdoor track, [19]. In addition, they found that Stryd was also the most valid technology when compared to metabolic effort as measured by VO_2, ($r \geq 0.911$), [19]. In another study, Cerezuela-Espejo's team found that the Stryd power meter showed a high agreement with two proposed running power calculations by Van Dijk & Van Megen's work *The Secret of Running* in 2017 and a white paper released by Skiba in 2016, [8, 20, 21]. The Stryd pod has also been shown to be reliable during different intensities during trail running, [22]. It should be noted that Stryd was not reliable during walking in the same study.

The results show a reliable and valid running kinematics sensor, but what of its accuracy and validity in determining power? The difficulty of determining the validity and accuracy of a technology such as the Stryd Pod is that there is no true "gold standard" in research to compare against. For example, if one were to compare a new body composition technique, it would immediately be compared to hydrostatic weighing. Accelerometry techniques are typically compared spatiotemporally against 3D motion-capture systems. New metabolic technology is compared against widely used metabolic carts. But there is no such "gold standard" in running power. The closest technology to a "gold standard" is an instrumented treadmill such as what was used to assess elite sprinting power by Rabita and company in 2015, [23]. However, instrumented treadmills assess only mechanical power via the ground-reaction forces, and cannot account for inter-segmental forces, nor can it effectively account for any energy lost through heat. Therefore, running power techniques must be compared against the most valid measure of effort that we have, VO_2.

Van Dijk and Van Megen in their book *The Secret of Running* took to compare the Stryd power and VO_2 data in a private study and found a coefficient of determination of 0.96 between the two, [21]. The next year saw two studies produce quite different results. Aubry found that amidst three different efforts both indoor and outdoor, an *R-value* of only 0.29 was found both a group of recreational and elite runners, and that no significant correlations were found between running power and VO_2 when the groups were separated, [24]. It should be noted that a follow-up manuscript from the researchers at Stryd proposed major methodological flaws in the above paper, [25] however, the article was never rescinded. In another study, a positive correlation of 0.6 was found in seventeen well-trained athletes between Stryd power and running economy, [26]. As mentioned above, Cerezuela-Espejo et al. found a correlation of at least 0.911 when testing the Stryd pod compared to VO_2 data, [19].

A study in 2021 compared the Stryd pod to "gold standard" determinations of VT1, VT2, and MAP via ventilatory criteria at specific speeds and found high correlation with speed at each threshold, but no significant correlation between these speeds and VO_2, suggesting that the Stryd Pod's "power" calculations are more related to speed than actual metabolic effort, [27]. In addition, a study based on New Zealand competitive U20 runners assessed running power via the Stryd pod on three separate surfaces including road, dry cross-country course (XC-dry), and wet cross-country course (XC-wet) [28]. Earlier research has already suggested that it requires more energy and therefore more power to run on more difficult terrain than on firmer terrain, accounting for a 150-180% increase in the energy required to run the same speed, [29, 30]. In the same way, one could assume that running at the same energy, speed would reduce by roughly the same amount. Therefore, one would suppose that the power required to run on XC-wet would be the highest, followed by XC-dry, and lastly road.

However, according to the results, the highest power values were found in the exact reverse order. In addition, the speeds for each surface from firmest to softest were found at 5.0 $m \cdot s^{-1}$, 4.8 $m \cdot s^{-1}$, and 4.4 $m \cdot s^{-1}$, [28]. If we follow the principles of previous research and assume that the athletes were giving similar efforts, the slowest surface should have had a race speed of 3.33 $m \cdot s^{-1}$ or 1.5x slower than the road surface. Obviously, the runners completed the race on average much faster than this. These results, in addition to the wide range of correlations found in previous studies, call into question the validity of utilizing Stryd power or any similarly related IMU to assess effort, and therefore to prescribe training or assess performance.

2.5 Power Gaps: Where Research Needs to Go

As we have seen, problems remain in running power, and many of these issues stem from the same roots as running power calculations. Muscular energy is still being accounted for via kinematic data. While kinematic data has been shown to have high correlations with kinetic data such as power, [8, 10, 11, 21, 31], it is still obvious that the most direct way to determine power would be via kinetic data. This kinetic data would allow for a much more accurate and valid assessment of the force produced by muscles, (as has been shown in cycling), [2, 4, 6, 7], which in turn fulfills one of the three parameters of running power calculations by accounting for muscular energy.

Elastic energy and transfer of energy are still calculated the same way. Assumptions are made to satisfy the requirement of the variable in an algorithm, but no progress has been made in determining the true values of either for the purposes of calculating running power.

What is needed is a novel approach. During the time of running power calculations, authors attempted what they could with the technology they had, however it was consistently obvious that the thoughts were not implementable due to lack of technology. Today we have the means to truly make a valid, accurate, and reliable determination of running power. A full, comprehensive, and interdisciplinary model has never been proposed, and up until now there has been good reason. It has not been feasible previously to combine multiple technologies and fields of exercise science towards the goal of a single metric. However, with the revitalization of running power research due to the advent of the Stryd Pod and other technologies, as well as the commercial interest in running power products, I believe that now is the time to dive into broadening the horizons of what power can do in distance running.

By creating a model that is not only reliable, but also can accurately and immediately account for the objective effort of individual athletes as well as the progress of a team, we can begin to construct a framework for a new running boom. The sport of distance running could see a revolution in training not observed since cycling discovered power for the first time. Not only the elite of the elite, but your everyday jogger trying to qualify for Boston, your high school cross-country athlete, or the master's competitor still trying to stay healthy will benefit from such a drive forward.

Progress is not arrival. The improvement of a certain field does not mean that we can settle for "good" when we could chase what is "great." We have the tools, technology, and the support to create a true measure of running power. It is time to chase it.

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