



# Running Against the Wind: Adding Air Resistance Costs to Power Estimates in Running

## 1 Introduction

Unlike in sporting competitions consisting of two teams of athletes pitted against one another, the goal in endurance athletics is often more personal, in that one is largely competing against historical versions of one's own previous self. To get the most you can out of the body that you have, you must maximize the effectiveness of your training and/or racing strategy. Endurance athletic competition is therefore often about pushing yourself as far as you can without going over the edge. But how do you know when to push or when to back off in training and racing? To determine this, you need to accurately know: how much effort are you expending?

### 1.1 Running Power

In running, power is absorbed when the foot first hits the ground and produced when the foot later pushes off. Additionally, some of the energy absorbed when the foot hits the ground can be stored in elastic tissues and used to push off later, or used to save energy via what's called the stretch-shorten cycle. Taken together, these mechanisms result in a disconnect between traditionally measured net mechanical power and metabolic power in running.

This disconnect begs the question: how then do we effectively measure effort in running? The main determinant of how hard an activity feels and how far you can go at a given

speed is how much energy/time it costs you to perform that activity, i.e., how many Joules you expend per second, which is defined as metabolic power and expressed in Watts. Of course there are individual muscles that could get fatigued or injured that could affect how hard an activity feels or how well you can perform, but the overarching determinant of effort is metabolic power: how much energy your body has to expend in a given amount of time to perform that activity.

When Stryd's definition of running power was first developed, this idea was kept strictly in mind, as well as the reality that metabolic rate is the main determinant of effort in running. Running power, then, should not necessarily correspond to a mechanically measurable value, but it should correlate very strongly to metabolic power. Stryd's first foot mounted power meter included most of the components that contribute significantly to metabolic power in running. However, it did not yet include the effect of overcoming air resistance when running, let alone the effect of running in windy conditions.

## 1.2 Actual Worldwide Wind Speeds

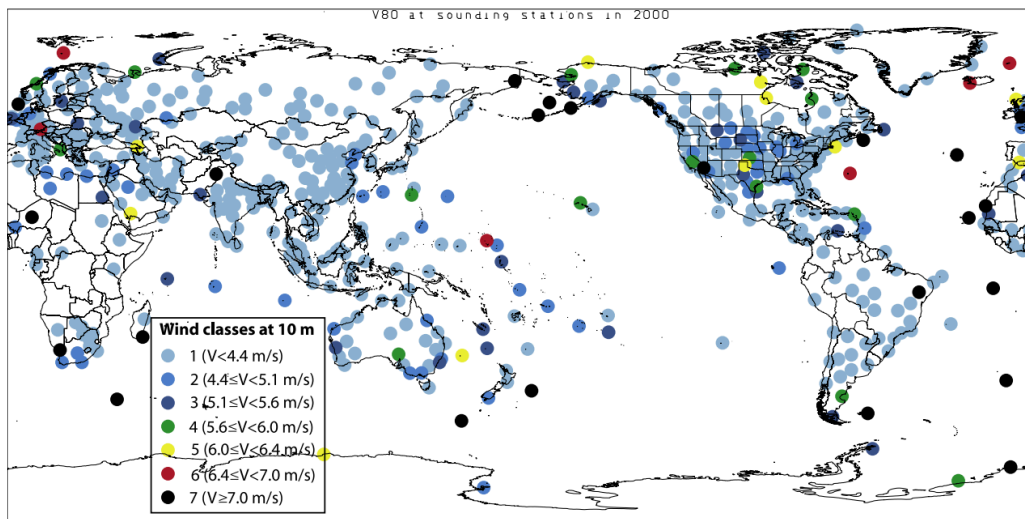


Figure 1: World wind speed values at 10 meters above ground level.<sup>1</sup>

And what is the effect of wind? Qualitatively, we all know how wind affects running. Running into still air at an easy pace all of a sudden becomes prohibitively difficult when a 20 or 30 mph headwind gusts in. Imagine you're given an interval workout on the track, assigned to hit 2:45 for 800 meter repeats. However, on the day they're scheduled, you

<sup>1</sup>Fig. 1 credit from (Archer and Jacobson, 2005).

have a 20-30 mph gusting wind. How should you adjust your pacing to keep the effort assigned that day, to assure you don't blow yourself out or overcorrect and actually under train? Most of us would try to hit the times anyway, but would we be risking overtraining or injury by doing so?

The underlying question is: how much does wind really affect effort in running? The answer is that for the majority of time it doesn't make a sizable difference, but when it does, it really does. Average wind speed over land is 7.34 mph, which doesn't affect effort significantly ( $\sim 5$ -10 Watts), but 13% of locations on land have average wind speeds of over 15.43 mph (Archer and Jacobson, 2005). However, even within the 87% of locations with slower wind speeds, there can be months with 5-10 days of gusts of 30+ mph (as much as 100 Watt increase). How can we account for relative air speeds like this and the consequent increase in effort in our training?

Stryd's first foot mounted power meter and its associated algorithms included capabilities to capture the vast majority of the components of running effort, but could not yet accurately account for the cost of air resistance. However, there is a significant difference in metabolic power due to running into a 20 mph headwind than there is in the absence of any wind. The goal with the development of this new technology was, as with all new developments: bring runners closer to knowing their true, objective output power. To do this, we must include an effective measure of air speed relative to runners to allow for increased accuracy of the reported effort involved in running. What follows in this white paper is a testing and accounting of the capability of Stryd's current air resistance capable power meter technology.

### **1.3 White Paper Organization**

The remainder of this white paper is organized as follows. In Section 2, we provide a brief theoretical background and a description of methods used to validate Stryd's relative air power capabilities both outdoors and indoors. Section 3 outlines our experimental methods used to test and validate the Stryd technology. Section 4 provides the results of our validation for air speed detection and power required to overcome air resistance, from controlled settings in wind tunnels and indoors on treadmills to outdoors in real-world conditions against portable anemometers, across runners and shoe placements. Section 5 provides an FAQ to answer most frequently asked questions you might be wondering about, and Section 6 concludes with final thoughts.

## 2 Theory & Background

The force due to air resistance ( $F_A$ ) at the relative air speeds encountered in running can be modeled by the following equation:

$$F_A = \frac{1}{2}\rho C_d A v^2 \quad (1)$$

where  $\rho$  is the air density,  $C_d$  is the coefficient of drag,  $A$  is the cross-sectional area encountering the air resistance, and  $v$  is the relative velocity vector of the runner with the local air mass surrounding them. For instance,  $v$  would be 7 mph if the runner was running 7 mph through still air, but it would be 9 mph if that same runner was running 7 mph into a 2 mph headwind.

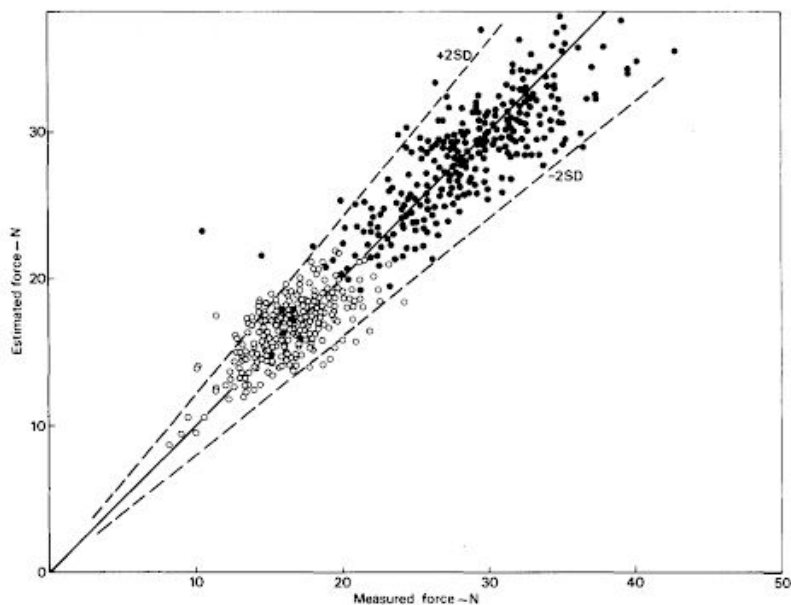


Fig. 7. Comparison between measured and estimated wind forces for all the 331 subjects. ● Facing the wind. ○ sideways to the wind. Dashed lines are shown at  $\pm 2$  standard deviations from the mean ratio of 1.004, and enclose 95% of the points.

Figure 2: Height and weight were shown in one study to predict  $C_d * A$  to within two standard deviations of the measured  $C_d * A$  for 95% of subjects.<sup>1</sup>

To determine relative air speed, local air mass density, force of air resistance (and energy cost requirement to overcome it) acting on a runner, Stryd uses microelectromechanical

<sup>1</sup>Fig. 2 credit from (Penwarden, A. D., Grigg, P. F., & Rayment, R. 1978).

systems (MEMS) sensors, both kinematic and environmental, together with user-supplied biometrics and proprietary physical and data-driven algorithms. Coefficient of drag,  $C_d$ , and cross-sectional area,  $A$ , of the runner also must be determined. Most running clothes are designed to fit relatively tightly to the body and typically have a small range of values of coefficient of drag. Likewise, the multi-phase bipedal running motion is shared by all runners, and a similarly tight  $C_d$  distribution also results. To compute cross-section area,  $A$ , Stryd currently asks for two pieces of biometric input, runner height and weight, to feed into our proprietary  $C_d * A$  model. Height and weight are previously known as they are used for other calculations in the power estimation. However, as demonstrated in the example study shown in Figure 2,  $C_d * A$  can be predicted with suitable accuracy based on sparse user information. In this study, across 331 subjects  $C_d * A$  can predict  $C_d * A$  to within 2 standard deviations for 95% of the population.

## 2.1 Stryd Air Power

Stryd accounts for the energy cost of overcoming air resistance by directly measuring the air resistance you encounter while running. When running through calm air, (i.e. air not moving with respect to the ground) the “wind” you encounter, i.e. air moving relative to you, is effectively a wind created by your running speed. Headwinds occur when the air mass you are running through has a velocity with respect to ground and a heading which is counter to the direction you are running in. Running in both calm air and in headwinds, you are always encountering air resistance, and your air power will always include positive additions to your running power to properly account for your energy cost to overcome the air resistance.

A tailwind occurs when the air mass local to you is moving with respect to ground in the same direction that you are running. If you are running faster than the air mass, as is the case in most light to moderate tailwind conditions, you are still encountering a positive air resistance. Tailwinds, including tailwinds presenting positive air resistance, are reducing your energy requirement as it is presenting a smaller air resistance than you would otherwise encounter if you were running through calm air. In tailwinds such as this, Stryd accurately accounts for the energy cost savings you receive and will report a reduced positive air power in the amount necessary to overcome the reduced air resistance.

The increased energy savings from tailwinds are, in actuality, relatively low when compared to the extra power required to overcome the same speed wind encountered as a headwind. For example, running 7.5 mph into a 15 mph headwind might cost you 50 extra Watts, while overcoming calm air at that speed would cost about 6 Watts. Running at 7.5 mph with a 7.5 mph tailwind would save you 0 Watts. Running with a 15 mph tailwind would only save you an additional 6 Watts as compared to the 7.5 mph tailwind. In cases like this, Stryd reports an air power value equal your running speed, which is 0 Watts.

## 3 Experimental Methods

Stryd’s ability to measure wind speed was tested under controlled settings in wind tunnels, outdoors under real-world running conditions in both windy and calm air conditions, and indoors on a treadmill in calm air conditions.

### 3.1 Wind Tunnels

Stryd was tested in controlled settings in multiple wind tunnels around the world. The goals were to test under controlled and known air speed settings, as well as to repeat the controlled tests under multiple elevations and weather conditions found across different testing days and at different geographically placed wind tunnel installations worldwide. Stryd air resistance technology was therefore tested in multiple wind tunnels in North America and in Europe.

During testing, data were simultaneously collected from multiple Stryd devices affixed to multiple shoelace locations on both left and right feet. Trials tested multiple subjects and multiple shoes at multiple speeds and multiple relative air velocities. Indirect calorimetry systems were used, both portable (the COSMED K5) and fixed (the Parvo Medics TrueOne 2400), to capture metabolic energy expenditure of subjects during experimental trials. Multiple different shoe types and sizes, each with unique aerodynamic profiles, across subjects were tested. Runners were subjected to headwinds at speeds of 0, 13, 20, 27, and 35 mph, (0, 21, 32, 43, and 56 kph) across running speeds of 6, 8, and 9 mph.

### 3.2 Outdoor Running

Stryd was tested outdoors in everyday running conditions. The goals were to test and validate the real-world outdoor running scenario across runners, terrain, wind patterns, elevations, and weather patterns. Stryd’s technology for reporting relative air speed was tested against a head-mounted anemometer (relative air speed measurement device) during outdoor running. The anemometer device used was the AAB ABM-200 (Airflow velocity range & accuracy specification: 0.5–140 mph  $\pm$  0.5%). The anemometer was connected via Bluetooth to a custom smartphone application designed to record time-aligned relative air speed simultaneously from both the Stryd power meter and the anemometer. The anemometer was affixed with epoxy to the brim of a baseball cap, such that the fan orientation was orthogonal to both the forward running velocity and to Earth ground. To minimize dynamic bias in anemometer fan orientation introduced via head turning, subjects were instructed to keep their head both level and pointed forward while running for the duration of the testing. Tests were completed on both windy and calm days. Subjects completed long runs, interval session runs, on track, trail, and road surface conditions.

Subjects ranged in height (and therefore also the anemometer placement location), from 160-198 cm.

### **3.3 Indoor Treadmill Running**

Stryd was tested while running indoors in calm conditions on a treadmill. The goal for this scenario was to verify that when running on a stationary treadmill indoors and in the presence of calm air, no extraneous power are added into the total power value reported by Stryd. Instead, power due to overcoming air resistance should be very close to zero, or zero, because when running on a treadmill placed in an indoor environment, it is expected that a runner will be stationary on a treadmill and therefore should not be overcoming any air resistance.

## **4 Results**

### **4.1 Wind Tunnels**

Stryd was tested against controlled and known wind speeds in multiple wind tunnels located around the world in North America and in Europe. Figure 3 shows aggregated results from multiple subjects' running trials performed on a treadmill placed in the wind tunnel at multiple fixed running speeds across four wind speeds relative to the runner (13, 20, 27, and 35 mph). Data was taken from both left and right feet of runners, and four pod locations were simultaneously tested and reported. Here, "percentage error" is defined as the deviation in percent of Stryd's wind speed measurement from the applied wind speed setting of the wind tunnel.

The four tested pod placements are as follows. One pod was placed on the left foot, and three pods were placed together on the right foot. In Figure 3, "left bottom" indicates a pod placed on the left foot, centrally located on the laces and on the set of laces closest to the toe. This location experienced the lowest error and is therefore considered to be the ideal location with the highest wind measurement accuracy, however all tested locations are considered suitably accurate for practical use.

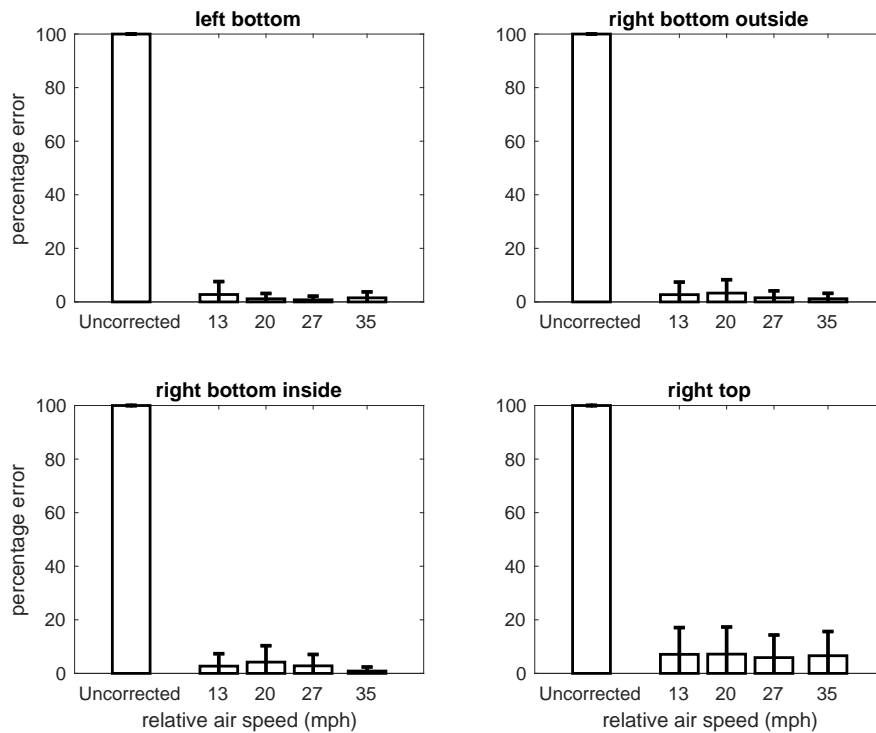


Figure 3: Relative air speed error across shoelace placement locations and various wind speeds as compared to the error found in a non-wind capable (“Uncorrected”) Stryd power meter.

The other three subplots indicate error seen from the pod locations tested on the right foot. “right bottom outside” indicates a pod on the right foot which is placed towards the outside of the foot and the set of shoelaces closest to the toe. “right bottom inside” indicates a pod on the right foot which is placed towards the inside of the foot and the set of shoelaces closest to the toe. “right top” indicates a pod on the right foot which is placed centrally and on the set of shoelaces closest to the ankle.

Stryd’s wind capturing technology can correctly report relative air speed within 2.5 mph for an optimally placed pod in the center of the laces and towards the toe of the shoe. While the error does increase for other, less optimal pod placement locations, it does not go above 5.5 mph, and only reaches this magnitude at the highest relative air speed when it is placed high up on the foot.



## 4.2 Outdoor Running

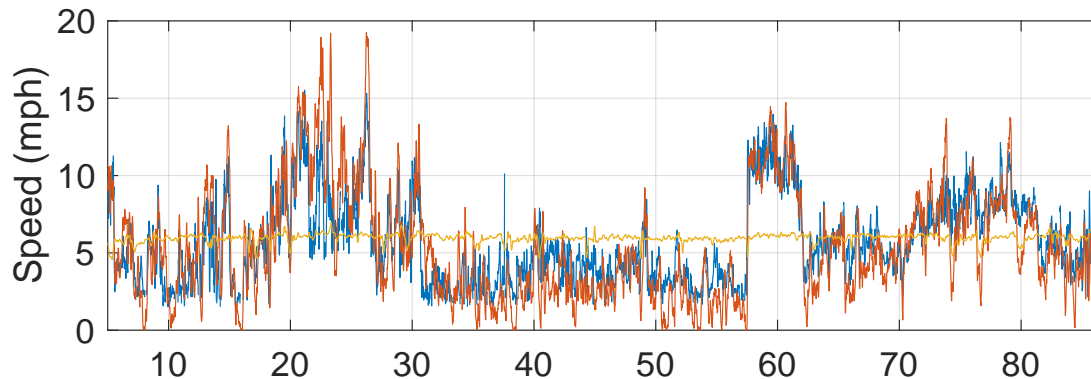


Figure 4: Relative air speed values of a subject running outdoors. Stryd real-time air speed (red line) as compared with a head-mounted anemometer (blue line), along with real-time running speed (orange line).

Stryd was validated in its ability to accurately capture naturally occurring outdoor head winds, cross winds, tailwinds and calm air conditions by comparing concurrently taken Stryd wind speed measurements to measurements from a head-mounted anemometer. In Figure 4, representative data is shown from one of the outdoor runner subjects' outdoor running trials. The test course followed a winding trail with elevation gain and loss, located near Boulder, CO, USA. The data shown in the figure had average disagreement between Stryd and the head-mounted anemometer of 1.61 mph, while over all test subjects, the average disagreement between Stryd (placed at the foot) and the anemometer (placed at the head) was 1.96 mph.

The dataset in Figure 4 contains headwinds (red and blue traces which exceed running speed), tailwinds (red and blue traces lower than running speed), and crosswinds (many cases throughout, as the runner followed a winding trail). No matter the magnitude and directionality of the wind relative to the runner, Stryd and the anemometer track well against each other. Note that, the anemometer used has  $\pm 0.5\%$  error across its measurement range, and is subject to error introduced by involuntary head turning during running and is not regarded here as an absolute ground truth. However, the high correlation between sensors shows the utility of such a test, as well as the ability of Stryd to respond well in swirling, gusting, and real-world winds which dynamically and unpredictably change in both amplitude and direction.

### 4.3 Indoor Treadmill Running

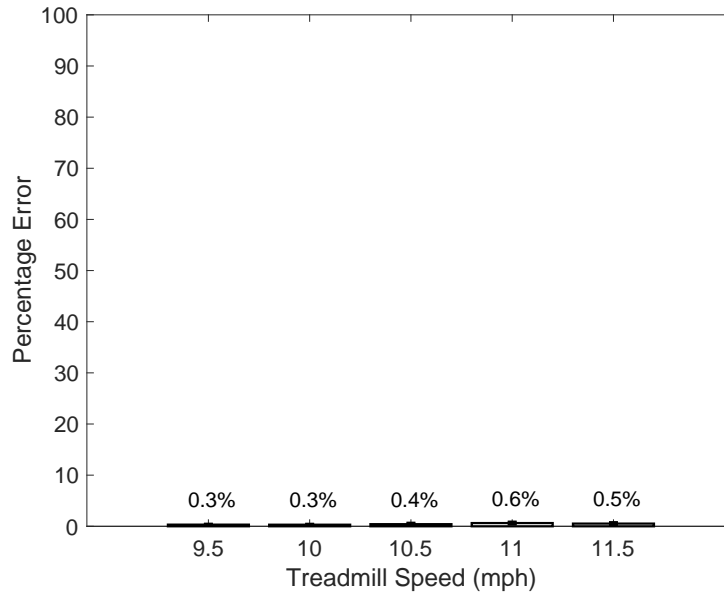


Figure 5: Treadmill:

When running on an indoor treadmill, a runner largely stays in place and therefore has no air resistance to overcome. The expectation is for Stryd to report no additional power due to overcoming air resistance. The results of the indoor treadmill validation testing, shown in Figure 5, confirmed that very little to no extraneous power was introduced across subjects when running on a stationary treadmill indoors in calm air. All speed trials yielded under 1% extraneous power as compared to a non-wind capable Stryd power meter.

### 4.4 Energy Cost of Air Resistance

Stryd air power due to overcoming air resistance was compared against data-derived models from the literature (Pugh, 1970; Davies, 1980) on subjects running on treadmills inside wind tunnels and under various wind speeds. In Figure 6, two representative subjects' total power as reported from Stryd are shown as compared with both high and low envelopes set by results reported in the literature. The envelopes were created by applying the maximum and minimum expected metabolic power from a statically defined wind speed (e.g., 13, 20, 27 or 35 mph) from the combined literature to the uncorrected power reported by Stryd. Stryd's data reported in the figures were derived from real-time wind measurements,

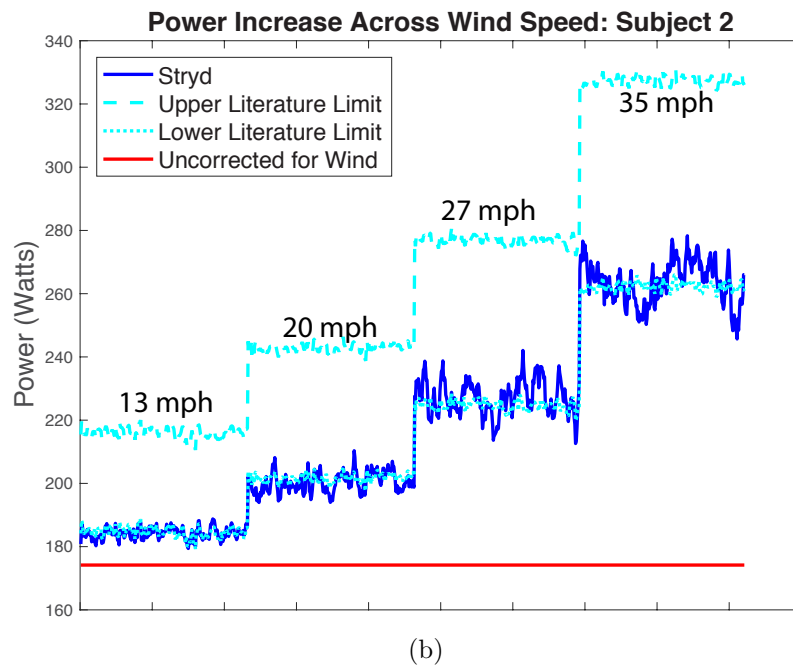
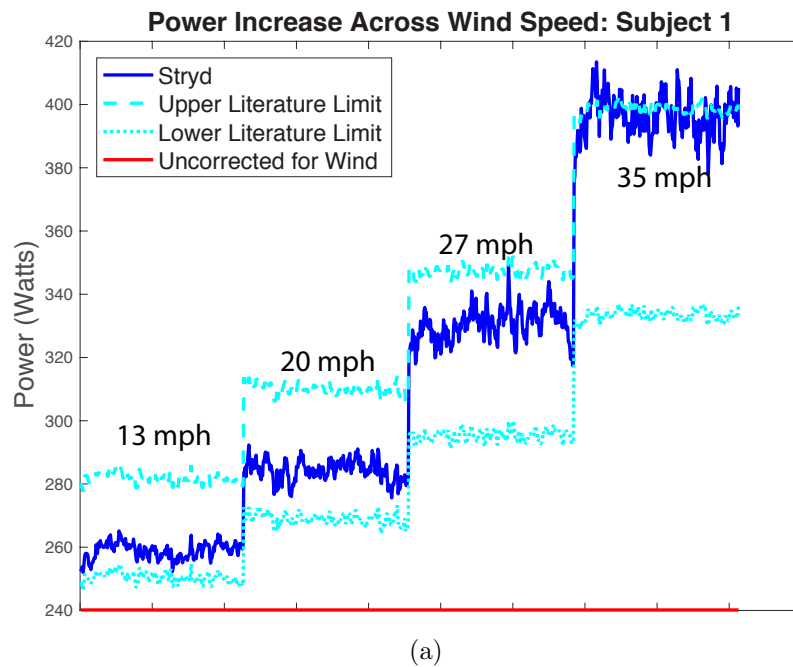


Figure 6: Uncorrected average power (red), and Stryd power values (dark blue) with increasing air speed for an example subject. Cyan (light blue) shows the expected power min and max envelope, as taken from the literature.

which are representative of the true dynamic conditions (e.g., wind turbulence around the treadmill or the subject moving forward or backward on the treadmill). The result is that Stryd's power data encompasses the subject variability represented in both Pugh and Davies data and largely fits within upper and lower bounds they define for metabolic power. While Stryd's air power estimate was found to match the theoretical model very well, it further improves by allowing for more individual subject input and variation than the literature models, explaining more personalized accuracy than the single theoretical model alone.

## 5 Frequently Asked Questions (FAQ)

**Q: Does Stryd maintain accuracy at high and low altitude locations? How does Stryd handle daily fluctuations in temperature and humidity? What about different weather patterns, e.g. low pressure zones in stormy conditions or high pressure zones during a bright and sunny day?**

A: Stryd maintains accuracy across all of these cases. Because Stryd measures the air mass local to you, the exact air which you are running through, all of the above variations in conditions are captured and accounted for.

**Q: I have several different shoes that I cycle between in my training. Will my Stryd work on all of my shoes?**

A: Stryd's algorithm has been validated to show it can determine relative air speed across different shoe sizes and types.

**Q: I'm small and thin, but my boyfriend is tall and heavy, acting like a sail in the wind. Will Stryd work in windy conditions accurately for both of us?**

A: Yes. Stryd adjusts power reporting based on user data, including height and weight, to provide accurate air power reporting across body shape and size.

**Q: How does my running form affect the air power measurement?**

A: Stryd uses instantaneous data from your foot movements to separate external air speed from what is due foot movement. The result is that Stryd works robustly across running forms.

**Q: Does the placement of the pod on my shoelaces make a difference in accuracy?**

A: Yes, but not by very much (see Figure 3). Though Stryd works well in many pod place-

ment locations around the laces on your shoe, it has been optimized for placements closer to the toe of the foot and with the small end of the pod facing forward. While still sufficiently accurate, placing Stryd higher up on the laces will lead to slightly less accurate data.

**Q: Can the current algorithms handle crosswinds and tailwinds?**

A: Yes. While Stryd is currently optimized for headwinds, as these affect metabolic power the most, Stryd does respond to crosswinds from both the front and rear and to tailwinds up to and including your running speed.

**Q: How quickly does Stryd work in real-time?**

A: Stryd updates power values much faster than many physiological responses, e.g. heart rate, and faster than at least every stride you make. It therefore allows you to update your pacing as quickly as you conceivably can.

**Q: How does Stryd work on a treadmill?**

A: Stryd will give accurate values both indoors or outdoors, on or off the treadmill. Since on a treadmill you are running in place, there is no air resistance to overcome. Stryd will naturally measure a lack of air resistance and your power will accurately reflect it as such.

## 6 Final Thoughts

Stryd's air power technology is the first to offer runners the real-time power they are using in the moment to overcome their unique local air mass resistance, including when running in both calm and windy conditions, and when running indoors and outdoors. However, the Stryd technology reported on in this white paper is continuously under improvement, as is with all run power technology at Stryd. As new improvements become available, they will be delivered to Stryd power meters as part of firmware updates that are designed to continue to give runners the most accurate, precise, and user-specific power data possible.