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The relationship between Stryd power and running economy in well-trained distance runners

Casey Austin

The Relationship Between Stryd Power and Running Economy
in Well-Trained Distance Runners

by

Casey Austin

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Kinesiology Department

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Approved:

4/17/18
Date

James Hokanson, Ph.D.
Thesis Advisor

4/17/18
Date

Peter M. McGinnis, Ph.D.
Thesis Committee Member

4/17/18
Date

Steve Patrick, M.S.
Thesis Committee Member

5-10-18
Date

Eileen Gravani, Ph.D.
Associate Dean, School of Professional Studies

ABSTRACT

A novel running wearable called the Stryd Summit footpod attaches to a runner's right or left shoe and measures running power output. The developers of the product purport that the footpod's power and form power measures may correlate with metabolic data gathered in a lab. **PURPOSE:** Explore the relationship between power output and running economy at threshold pace. **METHODS:** Seventeen well-trained distance runners, 9 males and 8 females, completed a running protocol at threshold pace. Participants ran two discontinuous four-minute stages: one with their self-selected cadence (SS), and one with cadence lowered by 10% (LC). Metabolic data, power, and form power output were recorded for each cadence condition. **RESULTS:** Average self-selected cadence was 179.60 strides·min^{-1} (±8.43), while lowered cadence was 172.54 strides·min^{-1} (±9.46). Average change in cadence from SS to LC was 3.93%. The average running economy expressed in terms of oxygen cost (±SD) at self-selected cadence was 201.58 ml·kg^{-1}·km^{-1} (±12.80), and at lowered cadence was 204.48 ml·kg^{-1}·km^{-1} (±11.48). Average caloric unit cost at SS was 1.05 kcal·kg^{-1}·km^{-1} (±0.07), and at LC was 1.06 kcal·kg^{-1}·km^{-1} (±0.06). Average power at SS was 4.37 W·kg^{-1} (±0.48), and at LC was 4.42 W·kg^{-1} (±0.49). Average form power at SS was 1.07 W·kg^{-1} (±0.09), and at LC was 1.13 W·kg^{-1} (±0.10). **CONCLUSIONS:** The present findings show that measures of running economy expressed in terms of oxygen cost and caloric unit cost are positively correlated with Stryd's power and form power measures.

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Chapter 1

Summary

Competitive distance running capability may be predicted by three measures: running economy, maximal oxygen uptake, and lactate threshold. Maximal oxygen uptake (VO_{2max}) is the highest amount of oxygen a runner can consume per unit of time (Daniels, Yarbrough, & Foster, 1978). Classical literature attributed improvements in running performance to increased VO_{2max} from training stimuli, though research has shown VO_{2max} does not change significantly over training periods (Daniels et al., 1978). The runner's lactate threshold is the point in exercise when blood lactate concentration begins to increase nonlinearly as intensity increases linearly (Forsyth, Burt, Ridley, & Mann, 2017). Since high blood lactate concentration can cause discomfort during running, it is desirable to maximize ability to clear lactate from the blood (Daniels, 2014). According to Daniels (2014), training at 80-88% of VO_{2max} (lactate threshold pace, or T pace) can help improve the body's ability to clear lactate from the blood.

Running economy (RE) is the amount of oxygen a runner consumes to maintain a given submaximal velocity (Saunders, Pyne, Telford, & Hawley, 2004). RE may also be expressed in terms of oxygen cost or energy cost, with researchers using units of $ml \cdot kg^{-1} \cdot km^{-1}$ and $kcal \cdot kg^{-1} \cdot km^{-1}$, respectively (Fletcher, Esau, & MacIntosh, 2009; Shaw, Ingham, & Folland, 2014; Skovgaard et al., 2018). Since oxygen consumption increases with velocity, improvements in RE mean lower energy demands at a given velocity (Hoogkamer et al., 2016). These lower energy demands, in turn, may lead to improvements in race performance (Saunders et al., 2004). It is desirable for competitive runners to improve RE, but measuring RE usually requires expensive equipment and lab visits (Stryd Team, 2016). However, recent advancements in wearable running technology provide runners with more advanced data than ever (Woodman, Crouter, Bassettt, Fitzhugh, & Boyer, 2017), some of which may be related to RE.

The Stryd Summit running footpod (Stryd, Boulder, Colorado) uses a triaxial accelerometer, a gyroscope, and barometer to provide runners with data for numerous metrics including speed, distance and a novel measure of running power output (K. Li, personal communication, May 26, 2017). The Stryd Team has released two white papers to inform users on the benefits of using power in training and how the footpod measures a runner's power (Stryd Team, 2016; 2017). A runner's external power output may be separated into three components: horizontal (forward moving) power, vertical power, and lateral (rotational) power (Stryd Team, 2017; Vance 2016). The Stryd footpod reports a proprietary measure called form power that is intended to represent the amount of power a runner expends to raise their center of mass upward against gravity with each step (Stryd Team, 2016). Much like running economy, a lower form power value may indicate improvements in running form (Stryd Team, 2016). Since low form power values are contingent upon minimizing vertical and lateral power output through optimization of biomechanical factors (Stryd Team, 2016), it is believed, but not substantiated that improvements in this measure may be related to improvements in RE.

Statement of the Problem

Improving running economy is a desirable outcome of distance running training because better RE may lead to better performance (Daniels, 1985; Williams & Cavanagh, 1987; Hoogkamer et al., 2017). However, measurement of running economy requires expensive equipment that most runners do not have access to. Recent advancements in consumer wearable technology have caused an increase in use of these devices (Meyer & Hein, 2013). As the devices have become more sophisticated, consumers have had access to more fitness data than ever before (Li et al., 2015). While wearable technology has seen an increase in use, there have been few studies examining the use of new proprietary measures. Since RE is considered central to running performance, but can be costly to measure, an alternative metric (form power) measured by a wearable sensor may be useful to runners.

Purpose

The purpose of this study was to measure the correlation between Stryd form power and running economy at lactate threshold pace (Daniels, 2014) in well-trained collegiate distance runners.

Hypotheses

H_0: There is no positive relationship ($r < 0.3$) between Stryd's form power and running economy.

H_a: There is a positive relationship ($r > 0.3$) between Stryd's form power and running economy.

Delimitations

The delimitations of this study include:

1. Participants were "well-trained" runners. "Well-trained" was defined as running an average of 25 miles per week or greater, with minimum VDOT values of 44 $ml \cdot kg^{-1} \cdot min^{-1}$ for women and 50 for men.

2. VO_{2max} was estimated using VDOT values from Daniels (2014, p. 81-82).

3. Threshold (T) pace was set according to the pace tables from Daniels (2014, p. 84-85).

4. Self-selected cadence was measured and participants ran in time with a metronome at their self-selected cadence for the "SS" stage. Participants were instructed to lower cadence by 10% in time with a metronome for the "LC" stage of the running trial. Order of stages was randomized via coin flip.

5. By default, the Stryd Summit footpod system calibrates itself over time to the main user's stride, so the autocalibration on the Garmin watch was set to "OFF" with the calibration factor set to 100.

Limitations

The limitations of this study include:

1. The actual sample size (N = 17) of the study was below the power analysis recommendation of 21 participants due to lack of readily available participants who were inside the required age range and met performance standards.

2. The Stryd Summit sometimes took a few moments to link to the Garmin Fenix 3, and momentarily experienced data dropout of certain metrics. These difficulties did not impact statistics.

3. Technical issues with the heart rate monitors caused unreliable heart rate data for some participants.

4. While participants were instructed to abstain from vigorous activity for 12 hours prior to testing, this could not be controlled.

5. Collegiate athlete participants were in-season and completing their training concurrently with the study.

6. Since it is intellectual property, the specifics of the Stryde power calculation are unknown to the researchers.

7. Some participants had trouble matching their footfalls with the metronome beats causing recorded cadence values to deviate from the assigned cadence values.

Assumptions

The following assumptions were made regarding this study:

1. All participants were assumed to be well-trained distance runners given their answers from the running history questionnaire.
2. Participants were able to hold threshold (T) pace for the trial duration.
3. Decreasing stride frequency changed running economy.
4. Participants abstained from vigorous running and/or weightlifting for at least 12 hours prior to testing.
5. Participants answered the questions on the running questionnaire honestly.

Definition of Terms

Running Economy — Energy demand (VO_2) for a given submaximal running velocity and calculated as the VO_2 per distance run ($ml \cdot kg^{-1} \cdot km^{-1}$, also known as cost of running) (Daniels, 1985; Saunders et al., 2004; Skovgaard et al., 2018). It may also be expressed in terms of caloric cost per distance run ($kcal \cdot kg^{-1} \cdot km^{-1}$) (Shaw et al., 2014).

Stryd Summit Footpod	A small pod that attaches to a runner's shoelaces to record several variables of interest, including power and form power. The footpod can be attached to either the right of left shoe. The power values reported are intended to be a mechanical estimate of running intensity. The footpod uses a triaxial accelerometer, a gyroscope, and a barometer to calculate values reported.
Power	A metric of mechanical output expressed in watts. Power is defined as the amount of work done over a given unit of time. External running power output can be separated into positive and negative components from push off and braking, respectively (Cavagna, Komarek, & Mazzoleni, 1971). The Stryd footpod measures the positive value component of a runner's stride that comes from push-off (Stryd Team, 2017).
Form Power	A Stryd proprietary measure, expressed in watts. Represents the power expended to raise one's center of mass against gravity with each step (Stryd Team, 2016).
Cadence	The number of strides a runner takes per given amount of time. Usually reported in strides per minute (spm).
Ground Contact Time	The amount of time a runner's foot spends touching the ground before liftoff.

Vertical Oscillation	A measure of a runner's vertical displacement of the center of mass from stride to stride (Cavagna et al., 2005).
Leg Spring Stiffness	A measure of stiffness, expressed in kN/m. This measure takes all the muscles, tendons, and ligaments in the lower extremities and applies a linear spring-mass model to them.
VO_2	A measure of oxygen consumed, generally expressed as $ml \cdot kg^{-1} \cdot min^{-1}$. A runner's maximum is known as VO_{2max}.
VDOT	An estimation of VO_{2max} using race performance times (Daniels, 2014).
RER	Respiratory exchange ratio; ratio of CO_2 produced from metabolic activity to O_2 consumed. Can be used to predict fuel sources and is part of running economy when calculated for kcal/km.
Blood Lactate	A measure of lactate concentration in the blood.
OBLA	Onset of blood lactate accumulation; the moment lactate begins to accumulate in the blood.
Lactate Threshold	The exercise intensity at which a rapid increase in blood lactate concentration occurs (Forsyth, Burt, Ridley, & Mann, 2017). Generally expressed as a percentage of VO_{2max}.
Threshold Pace	A running intensity that is difficult enough to increase blood lactate concentration, but is manageable for roughly an hour in

race conditions. Work at this pace is intended to improve the body's ability to clear blood lactate (Daniels, 2014, p. 53-54).

Significance of the Study

Stryd engineered and developed power measurement algorithms based on a runner's body weight and movement data received from the Stryd Summit footpod. While the developer's own testing showed a strong relationship between power and RE (Stryd Team, 2017) it is unclear if this relationship is tied to changes in running technique. If indeed the Stryd footpod measures of power and form power are related to running economy, the footpod could be a useful tool for runners and coaches to monitor running economy. Since changes to RE may lead to changes in running performance (Hoogkamer et al., 2016), a measurable improvement in power or form power over time may improve performance. Therefore, the goal of the present study to examine power and form power's relationship with measured running economy.

Chapter 2

Review of Literature

Running economy (RE) can be defined as the energy demand required to sustain a submaximal velocity, or the energy cost to cover a given distance at a given submaximal running velocity (Daniels, 1985; Saunders et al., 2004). RE in terms of oxygen cost can be calculated using measurements of steady-state oxygen consumption (VO_2), distance traveled, and participant body mass and may be expressed with units of $ml \cdot kg^{-1} \cdot km^{-1}$ (Fletcher et al. 2009; Skovgaard et al., 2018). RE may also be expressed in terms of caloric unit cost with units of $kcal \cdot kg^{-1} \cdot km^{-1}$ if one factors in respiratory exchange ratios (Shaw et al., 2014). According to Saunders et al. (2004), many factors, both physiological and biomechanical, modulate RE in well-trained distance runners. Metabolic adaptations within muscles from training can improve RE (Saunders et al., 2004). Strength training alongside endurance training also has been shown to improve RE (Denadai, Aguiar, Lima, Greco, & Caputo, 2016; Paavolainen, Häkkinen, Hämäläinen, Nummela, & Rusko, 1999; Storen, Helgerud, Stoa, & Hoff, 2008; Berryman, Maurel, & Bosquet, 2010). Recent research by Skovgaard et al. (2018) has indicated that RE may be improved through high intensity interval training (HIIT). It is believed that HIIT may drive a reduction in expression of proteins that have a role in energy intensive processes during exercise, thus resulting in improved RE (Skovgaard et al., 2018). Improving RE is desirable since it is considered one of the primary determinants of running performance (Hunter et al., 2015).

The Stryd Summit footpod is a new piece of wearable technology that is intended to help runners improve their training by using power values. Power values reported by the

Stryd footpod give a near-immediate gauge of intensity to the runner. The Stryd footpod uses Bluetooth wireless technology to pair with either a smart phone or supported GPS watch and uses a triaxial accelerometer, gyroscope, and barometer to record a number of measures related to biomechanical factors. The Stryd footpod measures (or calculates) and reports to users ground contact time (ms), vertical oscillation (cm), leg spring stiffness (kN/M), power (watts), form power (watts) and stride frequency (also known as cadence, measured in strides per min). Form power is one of Stryd's proprietary measures, which is meant to represent the power expended to raise one's center of mass with each step (Stryd Team, 2016).

Running Economy

Running economy is considered an essential component of distance running performance. It is generally considered a better predictor of performance than VO_{2max} among similarly capable distance runners (Saunders et al., 2004). Since RE is related to oxygen consumption at submaximal velocities, improving RE values could mean lower oxygen consumption at faster velocities, which may improve performance (Daniels, 1985).

Running economy and biomechanical factors. Running economy is related to a number of biomechanical factors including vertical oscillation, ground contact time, stride length, and stride frequency. Cavanagh, Pollock, and Landa (1977) compared biomechanical characteristics of elite runners against good runners. The research found that elite runners registered slightly less vertical oscillation, had better biomechanical symmetry, and had better RE values during a submaximal effort run at 10 mph. Mean VO_2 values for the good and elite groups were 55.6 and 52.6 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. The elite runners had a strong correlation between stride length and leg length (r = 0.67), whereas the good runners had no significant correlation (r = 0.10) (Cavanagh et al., 1977). The researchers posited that this discrepancy was due to elite runners taking shorter, more optimal strides that better suited their leg lengths.

Williams and Cavanagh (1987) examined the relationship between biomechanical factors, RE, and performance measures in 31 participants running at a submaximal velocity of 3.6 $m \cdot s^{-1}$ and found that those with the best RE had greater vertical oscillation of the center of mass. However, the researchers were careful to point out that RE is not modulated exclusively by these factors, but instead is influenced by a number of biomechanical factors, with the weight of each factor's influence depending on the individual (Williams & Cavanagh, 1987).

Footwear may have an effect on running economy. Hoogkamer et al. (2016) added discrete weights to running shoes in order cause participants to run with poorer RE. The authors found that 3000 m performance time increased 0.78% per 100g added to each shoe. Recently, Hoogkamer et al. (2017) tested a prototypical marathon racing shoe intended for high energy return (released to the public as the Nike Vaporfly) against already available marathon racing shoes (the Nike Zoom Streak 6, and the Adidas adizero Adios BOOST 2). The researchers tested 18 "high-caliber" male runners who could run 10,000 meters in either 31 minutes or less at sea level or in 32 minutes or less at altitude. The researchers found that over three velocities (14, 16, and 18 $km \cdot h^{-1}$) with all participants completing testing twice, runners used an average of 4.16% less metabolic energy in the prototype shoe compared to the Nike Streak 6, and an average of 4.01% less metabolic energy in the prototype shoe compared to the Adidas adizero Adios BOOST 2 (Hoogkamer et al., 2017).

Cavanagh, Heglund, and Williams (2005) forced lower vertical oscillation on five participants by having them run across fixed force platforms in an aircraft undergoing flight profiles to simulate a gravity value of 1.3g. It was reported that lowered vertical oscillation through simulated gravity resulted in higher stride frequency, lower variation in external energy, and high internal work to move the center of mass.

A runner's velocity is the product of stride frequency and stride length (Lieberman, Warrener, Wang, & Castillo, 2015) and these factors have been manipulated to cause change in RE (Halvorsen, Ericksson, & Gullstrand, 2012; De Ruiter, Verdijk, Werker, Zuidema, & de Haan, 2014; Lieberman et al., 2015).

Stride frequency and running economy. De Ruiter et al. (2014) tested running economy in novice and experienced runners across seven different stride frequencies in addition to their own self-selected stride frequency in order to calculate each participant's optimal stride frequency based on minimum VO_2 values (self-selected frequency ± 18%). The researchers successfully caused a change in RE at ±6%, ±12%, and ±18% of self-selected stride frequency (De Ruiter et al., 2014). The novice runners chose a self-selected stride frequency of 77.8±2.8 strides·min^{-1} and the experienced runners chose a self-selected stride frequency of 84.4±5.3 strides·min^{-1}. Optimal stride frequencies for the novice and experienced runners were calculated as 84.9±5.0 and 87.4±4.8 strides·min^{-1}, respectively. These findings were corroborated by past findings from Cavanagh and Williams (1982) who noted that novice runners typically run at a less optimal stride frequency than more experienced runners.

Halvorsen et al. (2012) studied the effects of reducing stride frequency on running economy in male runners. The researchers set target values for stride frequency to 5 and 10% below self-selected frequencies. VO_2 and stride frequency had a correlation value of -0.19, showing that RE degraded slightly with decreases in stride frequency from self-selected values. The researchers concluded that immediate changes to stride frequency usually have a negative effect on running economy.

Tartaruga et al. (2012) examined the relationship between kinematic variables and running economy in distance runners. It was found that RE was correlated with a number of the kinematic variables measured including vertical oscillation (r =.65), stride length (r =.61), stride frequency (r = -.61), balance time (r =.61), relative stride length (r =.46), range of elbow motion (r = .42), internal knee angle at foot strike (r = .41), and internal ankle angle at foot strike (r = -.32).

Lieberman et al. (2015) tested 14 experienced runners who averaged 30 km or more of running per week at stride frequencies of 75, 80, 85, 90 and 95 strides per minute at a velocity of 3.0 $m \cdot s^{-1}$ with a goal of finding a metabolically optimal stride frequency along with creating a regression calculation to predict optimal stride frequency. Researchers predicted optimal stride frequencies (OSF) for participants by solving for the intersection of two regressions: measured stride frequency versus braking impulse, and measured stride frequency versus maximum hip flexion moment in the sagittal plane during swing phase. The researchers were unable to measure metabolically optimal stride frequency for two subjects and excluded one outlier with very high OSF. Metabolically OSF averaged 84.79±3.62 strides per minute (N = 11) with a range of 79.5-93.4 strides per minute. Predicted OSF averaged 84.7±1.74 (N = 13) and was calculated with all subjects but one outlier. The researchers concluded that many runners have a submaximal OSF of about 85 strides per minute.

Running economy and physiological factors. Running economy is influenced by a number of physiological factors as well. Maximal aerobic capacity (VO_{2max}), lactate threshold, and running economy are considered to be main physiological factors of running performance (Saunders et al., 2004). Bosco et al. (1987) explored the relationship between muscular efficiency and running economy. Since muscle fiber type composition differs between individuals, part of inter-individual differences in RE may be explained by differences in ability to store and use elastic energy from muscle (Bosco et al., 1987). The researchers concluded that runners with higher numbers of type-I muscle might be more economical at slow speeds, whereas faster runners and sprinters might be more economical at faster speeds (Bosco et al., 1987). These claims are corroborated by the findings of Inbar, Kaiser, and Tesch (1981). Inbar et al. recruited 29 males (long distance runners n = 7, short distance runners n = 9, sedentary n = 8, physical education students n = 5). Among the sample, there was a positive correlation between percent of fast-twitch muscle fibers and 40-m sprint time (r = 0.45), and a negative correlation between percent of fast-twitch muscle fibers and 2000-m run time (r = -0.60). It would appear that having a higher percentage of slow-twitch (type-I) muscle fibers is beneficial for distance running performance.

Hunter et al. (2015) found that longer Achilles tendon length, high type-II muscle fiber concentration, and leg strength (as measured by leg press) may have a positive relationship with RE. While running, generation of power comes from elastic energy obtained during the push-off phase of a runner's stride (stretch-shortening cycle [SSC] potentiation) (Hunter et al., 2015). It is believe that energy gained during the SSC can reduce the energy requirements of running (Hunter et al., 2015). As such, it is desirable to maximize elastic energy stored during the SSC to maximize late eccentric force output. The researchers found that type IIx muscle fiber percent and leg strength were correlated to late eccentric force development ($r = 0.70$ and $r = 0.95$, respectively). Achilles tendon length and late eccentric force development were positively correlated with force stored during the SSC ($r = 0.42$ and $r = 0.76$, respectively). Additionally, SSC force was correlated with velocity during SSC, and velocity during SSC was correlated with RE ($r = 0.61$) (Hunter et al., 2015). While the relationship between RE and muscle fiber types is still unclear, the researchers suggest that type-II fibers may be related to improved RE at high speeds due to increased ability to store and use elastic energy at high contraction rates (Hunter et al., 2015; Bosco et al., 1987).

Shaw, Ingham, Atkinson, and Folland (2015) studied the correlation between RE and VO_{2max} in 168 trained distance runners. There was a small positive correlation between RE and VO_{2max} among participants (males $r = 0.26$, females $r = 0.25$). Interestingly, the researchers generally found that among these participants, those with high VO_{2max} values had poorer RE. The study was continued longitudinally with 54 participants and researchers found that over a median trial separation of 203 days, changes in RE were moderately correlated with changes in VO_{2max} ($r = 0.35$). The researchers postulate that those with higher VO_{2max} values likely oxidize lipids at a greater ratio compared to carbohydrates, and that explaining RE in terms of oxygen cost does not account for substrate oxidation (a higher ratio of lipids oxidized equates to higher measured oxygen cost) (Shaw et al., 2015). Therefore, the researchers suggest measuring RE in terms of caloric cost as $kcal \cdot kg^{-1} \cdot km^{-1}$ using RER values to account for substrate oxidation.

Sawka, Pandolf, Avellini, and Shapiro (1983) completed three separate heat acclimation studies to test the effect of heat acclimation on metabolic cost (measured as VO_2) during treadmill walking. The first study tested 15 men in high (40°C, 49°C) and lower temperatures (20°C) before and after a heat acclimation intervention. The second study tested 8 men with the same protocol and factored in time of year to see if seasons had an effect on acclimation. The third study tested 10 men and 9 women to factor in participant gender. The researchers found that across all studies heat acclimation lowered metabolic cost by 3% in hot environments (40°C, 49°C) and 5% in cool environments (20°C). The researchers believed that acclimation to exercise in heat improved oxidative phosphorylation efficiency at the cellular level, but were unsure exactly why (Sawka et al., 1983).

It is believed that reduced expression of mitochondrial uncoupling proteins (UCPs) may be an adaptation from heat acclimation (Salgado et al., 2017). Mitochondrial UCPs (mainly UCP3 in skeletal muscle) cause proton leakage through mitochondrial membranes, which results in energy loss through thermogenesis (Salgado et al., 2017). During exercise, reduced expression of these UCPs may equate to less energy lost as heat and greater mitochondrial efficiency. Salgado et al. (2017) heat stressed in-vitro myocytes by exposing them to 40°C heat for 24 hours. After being heat stressed, the myocytes showed significantly reduced expression of UCP3 and had increased mitochondrial efficiency. As part of the same study, Salgado et al. (2017) had eight trained male runners and cyclists complete a ten-day heat acclimation protocol and compared exercise economy (cycling) from pre to post test. The heat acclimation protocol involved ten consecutive days with two 50-minute cycling bouts in 40°C heat separated with a 10-minute passive rest. The exercise intensity for the bouts was submaximal and prescribed based on maximal exercise testing. The researchers found no significant change in exercise economy in the sample from pre to post test (Salgado et al. 2017).

Recent research by Skovgaard et al. (2018) tested the effect of a low-volume, high intensity interval training intervention on the running economy of 20 trained runners. The researchers took muscle biopsies before and after the intervention to monitor muscle fiber adaptions from pre to post intervention. The intervention lasted 40 days and featured 10 supervised sessions of 5-10, 30-second maximal effort runs along with 10 non-supervised sessions of moderate-intensity aerobic training (Skovgaard et al., 2018). The total training volume (in running distance) over the 40-day intervention was reduced by 36% compared to before the intervention. Participants completed two 10-km performance runs both before the intervention and after the intervention. One of the 10-km trials was run the day after participants completed a three-hour glycogen depletion protocol, which allowed researchers to force increased fast twitch muscle fiber recruitment for the duration of the 10-km test. Participants showed improved running economy and decreased expression of UCP3 from pre to post test for the normal 10-km trial. However, participants showed no significant change in running economy from pre-to-post test for the glycogen-depleted 10-km trial

(Skovgaard et al., 2018). The researchers believe the improved economy is a result of adaptations in slow twitch muscle fibers elicited by the high intensity, low volume intervention.

Physiological factors and aging. Recent research into aging and running performance has shown that there is a general gradual decline in fitness through aging (Everman, Farris, Bay, & Daniels, 2017; Forsyth et al., 2017). However, the number of athletes older than 35 is steadily increasing as people turn to fitness to fight aging (Forsyth et al., 2017). Everman et al. (2017) conducted a 45-year longitudinal study on 26 elite distance runners. Initially tested in 1968 prior to the US Olympic trials, participants had a mean VO_{2max} value of 78 ± 3.1 $ml \cdot kg^{-1} \cdot min^{-1}$ and mean running economy value of 196 ± 7.0 $ml \cdot kg^{-1} \cdot km^{-1}$. In 1993 and 2013, 22 of the 26 participants returned for testing. VO_{2max} values degraded to 65 ± 6.0 in 1993 and 47 ± 8.1 $ml \cdot kg^{-1} \cdot min^{-1}$ in 2013. RE values increased to 205 ± 16.5 in 1993 and 240 ± 27.0 $ml \cdot kg^{-1} \cdot km^{-1}$ in 2013, indicating higher energy demands at submaximal effort. Researchers concluded that high fitness levels in early years of life seem to contribute to high fitness levels through years of aging (Everman et al., 2017).

Lactate thresholds are also affected by aging (Forsyth et al., 2017). There is a net decrease in blood lactate concentration as aging occurs, so methods of determining lactate threshold that use absolute blood lactate concentrations are unsuitable for veteran runners. The researchers also posit that decreases in VO_{2max} due to aging cause the lactate threshold to shift to a higher percentage of VO_{2max} (Forsyth et al., 2017). It was found that using the maximal deviation method of lactate threshold determination is most appropriate for veteran athletes. This method measures the maximal distance between distance between the line of best fit on a lactate curve, and a straight line that connects the two endpoints of the curve (Forsyth et al., 2017).

Caloric unit cost. While running economy can be defined as the energy demand required to cover a given distance or run a submaximal speed, it can also be expressed in terms of caloric cost (Shaw et al., 2014). Classically, running economy based on energy cost has been expressed in terms of oxygen consumption as $ml \cdot kg^{-1} \cdot km^{-1}$. However, Shaw et al. (2014) suggest that measuring RE as a function of oxygen cost may not be valid at high intensity since at VO_{2max}, oxygen cost will not continue to increase with increasing running speed. The classical RE calculation also assumes that oxygen consumption alone can provide an accurate representation of ATP turnover (Shaw et al., 2014). As such, the authors concluded that expressing running economy as a function of caloric unit cost may be more appropriate because it factors in respiratory exchange ratio. Respiratory exchange ratio (RER) equations were used to estimate substrate utilization (g/min) and energy cost was calculated under the assumption that fat and carbohydrate provided 9.75 and 4.07 kcal per gram, respectively (Shaw et al., 2014).

Running economy on treadmill vs. on track. Since the energy demands differ, running economy may differ slightly between overground and treadmill running conditions. Saunders et al. (2004) posit that 2-8% of energy expenditure during overground running is spent overcoming air resistance depending on race pace and wind. Since running on a treadmill removes most air resistance, energy costs are believed to be lower during treadmill running when compared to overground running. Jones and Doust (1996) recommend using a treadmill grade of 1% to compensate adequately for the extra energy demand air resistance presents. However, Mooses, Tippi, Mooses, Durussel, and Mäestu (2015) found that competitive European distance runners had significantly better RE on a running track when compared to a treadmill with a 1% incline. The researchers found that recorded VO_{2max} values were identical on the track and treadmill, but participants were running at a higher percentage of their VO_{2max} while on the treadmill. All participants were habituated to treadmill running, but still had better RE on the track (215.4 ± 12.4 on track, 236.8 ± 18.0 $ml \cdot kg^{-1} \cdot km^{-1}$ on treadmill). It is believed that the relationship between RE and running surface changes depending on the participant demographic and the biomechanical adjustments they make between surfaces (Mooses et al., 2015).

Running economy and weight training. It has been generally agreed that running economy can be improved with concurrent endurance and strength training (Denadai et al., 2016). Paavolainen et al. (1999) implemented a nine-week explosive strength training intervention for a group of 10 experimental participants. The experimental group replaced 32% of their training volume with 15-90 min explosive strength training sessions consisting of different sprint and jump exercises. A control group (n = 8) replaced just 3% of their training volume with explosive strength training. The experimental group saw a significant improvement in RE and 5k performance time (from 18.5 to 17.8 min) (Paavolainen et al., 1999).

Storen et al. (2008) supplemented normal endurance training with an 8-week heavy weight training program. Participants performed half squat sets three times a week over the intervention and it was found that the participants improved their RE by about 5% when running at 70% of VO_{2max}. Berryman et al. (2010) had 35 well trained male distance runners assigned to either plyometric, weight training, or control interventions over an 8-week period. All participants performed the same endurance training program. The researchers found that plyometric training lead to a larger improvement (218 ± 16 to 203 ± 13 $ml \cdot kg^{-1} \cdot km^{-1}$) in running economy when compared to the weight training group (207 ± 15 to 199 ± 12 $ml \cdot kg^{-1} \cdot km^{-1}$), though both groups saw a significant improvement. The control group saw no change.

Wearable Technology in Running

Use of wearable technologies (wearables) like GPS watches, fitness trackers, and pedometers has increased in recent years (Woodman et al., 2017). Researchers have studied wearables as a means to increase physical activity, but have found that sometimes users face barriers in usability and acceptance of technology (Meyer & Hein, 2013). However, wearables have been cited as an exciting advancement since they provide more precise data than self-assessment can (Meyer & Hein, 2013). Wearables have been seeing increased use in performance settings as well, with sports teams and high level athletes taking advantage of technological advancements to track data over time to pinpoint areas for improvement (Li et al., 2015). Recent advancements in wearables are leading to novel metrics that may or may not be useful to athletes trying to improve their performance, much like Stryd's form power.

Stryd Summit footpod. The Stryd Summit (Stryd, Boulder, Colorado) footpod is a novel wearable sensor for competitive runners and triathletes and reports pace, distance, vertical oscillation, cadence, leg spring stiffness and ground contact time data. The Stryd footpod is unique in that it also reports proprietary running power and form power measures to users (Stryd, Power Meter for Running).

Running power output can be separated into horizontal, vertical, and lateral components (Vance, 2016; Stryd Team, 2017). The Stryd Team points out in their 2017 white paper that running is a cyclic activity and that within a complete stride, net work done is roughly equal to zero (power = work $\cdot$ time^{-1}, therefore, net power output is also roughly zero). Negative external work is applied the runner by environmental forces like gravity, ground friction, and wind resistance (Stryd Team, 2017). The team explains that positive external work done during running is a result of the runner working against environmental forces by pushing off the ground. The Stryd footpod uses a triaxial accelerometer, a gyroscope, and a barometer embedded into a small shoe-mounted chip to measure the power output from the positive component of the runner's net work completed (K. Li, personal communication, 2017; Stryd Team, 2017). The Stryd Team purports that this positive component of external work is directly correlated with metabolic energy expenditure (Stryd Team, 2017). To compare power values against metabolic expenditure, the Stryd Team tested nine runners from the recreational to sub-elite level at eight different speeds (8 $km \cdot h^{-1}$ through 20 $km \cdot h^{-1}$ increasing by 2 $km \cdot h^{-1}$ per stage) for three minutes each while recording power output and oxygen consumption. The team found that power ($W \cdot kg^{-1}$) was strongly correlated with metabolic cost (VO_2 in $ml \cdot kg^{-1} \cdot min^{-1}$) in their sample ($r^2 = 0.96$). The exact methodology behind the power calculations is unknown to the researchers since the power calculation algorithm is part of Stryd's intellectual property.

Form power is explained as the power to raise one's center of mass against gravity with each stride (Stryd Team, 2016) and can be considered as a factor of vertical and lateral components of positive external work (Stryd Team, 2017). It is believed that a runner may be able to improve their biomechanical efficiency over a long period time through monitoring power and form power values both acutely during daily runs and longitudinally over training periods (Stryd Team, 2016). Improvements in biomechanical factors can also improve RE, and over time may help a runner perform better in competition (Williams & Cavanagh, 1987). The Stryd Team posits that runners who train with the Stryd footpod while monitoring power values may be able to monitor changes in running economy through changes in power and form power (Stryd Team, 2016).

Chapter 3

Methods

Running economy is the energy demand required to run at a given submaximal pace or cover a given distance (Jones & Carter, 2000; Saunders et al. 2004). It may also be expressed in terms of oxygen cost or energetic cost, with units of $ml \cdot kg^{-1} \cdot km^{-1}$ and $kcal \cdot kg^{-1} \cdot km^{-1}$, respectively (Fletcher et al. 2009; Shaw et al., 2014; Skovgaard et al., 2018). It is a well-known measure associated with running capability, but is fairly difficult to measure. A new running wearable sensor that has been released, the Stryd Summit footpod, that attaches to a runner's shoe and records power output during runs. It also records its own proprietary measure of efficiency called form power. Form power is a metric that is meant to represent power that raises one's center of mass against gravity with each step (Stryd Team, 2016). Form power may have a relationship with running economy. The product is attractive to runners and triathletes alike because it may provide a relatively low-cost alternative to monitoring running economy through lab testing using expensive equipment. Improvement in running economy and efficiency usually leads to better performance (Williams & Cavanagh, 1987). As such, runners monitoring Stryd power readings may more easily see improvement over time, and may be able to narrow down training methods that improve economy.

Improvements in running economy may largely be attributed to improvements in biomechanical running form. In its simplest form, a runner's velocity is their stride length multiplied by stride frequency (Lieberman et al., 2015). While running economy is related to these factors, it is modulated by many additional biomechanical factors. Tartaruga et al.

(2012) found correlations between many biomechanical factors and running economy including vertical oscillation, stride length, stride frequency, balance time, and knee and ankle angles. It is difficult to tell which factors improve running economy the most. For example, some researchers have reported lower vertical oscillation leads to improvements in RE (Cavanagh et al., 1977), while others report those tested with best economy have higher vertical oscillation (Williams & Cavanagh, 1987).

Running economy often changes based on the running surface. Most believe running economy to be highest on a treadmill because of lack of air resistance (Saunders et al, 2004; Jones & Doust, 1996). However, Mooses et al. (2016) found that high-level runners actually had better running economy on a running track compared to a treadmill even though the participants were habituated to treadmill running.

The purpose of this study was to measure form power and running economy and assess the relationship. It was hypothesized that form power would be positively correlated with running economy.

Methods

Participants. A correlational power analysis was run to determine a required sample size using G*Power 3.1.9.2 (Universität Düsseldorf, Germany). With effect size set to .60, $\alpha < .05$, and power set to 0.95, a total required sample size of 21 participants was recommended. A total of 17 participants were recruited and took part in the study. Participants were recruited from the SUNY Cortland cross country team and the SUNY Cortland kinesiology department. Participant VO_{2max} values were estimated and reported as VDOT using the participant's most recent race performance times and VDOT estimation charts from Daniels (2014, p. 81-82). "Well-trained" was defined as running an average of 25 miles per week, with a minimum VDOT of 44 $ml \cdot kg^{-1} \cdot min^{-1}$ for women (a 22:15 5k) and 50 $ml \cdot kg^{-1} \cdot min^{-1}$ for men (a 19:57 5k). Informed consent was obtained, and a physical activity readiness questionnaire was completed before the running trial.

Instruments. Testing took place at the SUNY Cortland exercise physiology lab. A Parvo Medics TrueOne 2400 metabolic analyzer (Parvo Medics, Sandy, UT) was used to record gas exchange measures. Gas exchange data were recorded on a Dell desktop computer running Windows 7. Form power and cadence were recorded by a Stryd Summit footpod (Stryd, Boulder, Colorado). The footpod was paired via ANT+ to a Garmin Fenix 3 (Garmin Ltd., Olathe, Kansas) with the Stryd Run Data Field loaded. Testing was completed on a Trackmaster TMX425c treadmill (Trackmaster Treadmills, Newton, KS).

Design and procedures. Participants completed a running history questionnaire (Appendix C), an informed consent form (Appendix B) and a physical activity readiness questionnaire (Appendix A) in the SUNY Cortland exercise physiology lab prior to testing. Height and weight were measured and subsequently entered into the Stryd application to calibrate the footpod to the participants' anthropometric data. Threshold pace was set according to Daniels' VDOT pace table (Daniels, 2014, p. 84-85). This table lists VDOT values (estimated VO_{2max} predicted using race performance times) and corresponding training paces for the values.

Before testing, participants were given a brief overview of the protocol and instructed about how they should time their strides to match a metronome. The participants then put on the gas analyzer mask and heart rate monitor, and the Stryd footpod was attached to the runner's left shoe. The Stryd footpod uses a clip-on mount that locks to a runner's shoelaces. The Stryd footpod was mounted approximately equidistant from participants' malleolus and the toe of their shoe. If there was an obstruction on the tongue of the shoe that prevented ideal placement, the Stryd footpod was placed on the next row of laces distal from the malleolus. The same researcher mounted the Stryd footpod for all participants.

Participants completed a two-stage discontinuous running protocol. Metabolic and power data collection began with a five-minute warm-up run with all experimental equipment donned to acclimate participants to running while connected to the analyzer. The participants' self-selected cadence was determined during a one-minute run at assigned threshold pace at the immediate conclusion of the five-minute warm-up. After the warm-up and cadence measurement, participants took a 3-minute rest. During the rest, researchers calculated a cadence value 10% lower than the participants' self-selected cadence for them to replicate during the experimental protocol using a Microsoft Excel Spreadsheet. A coin was flipped to determine the order of testing protocol stages (SS then LC, or LC then SS):

Self-selected cadence (SS) stage – Participants ran four minutes at assigned threshold pace. Participants attempted to match their cadence with a metronome set to replicate their self-selected cadence from the warm-up period.

Lower cadence (LC) stage – Participants ran four minutes at assigned threshold pace. Participants attempted to match their cadence with a metronome set to a value that is 10% lower than their self-selected cadence from the warm-up period.

After the warm-up rest period, participants began the first stage of the experimental protocol with a metronome clicking at a beat corresponding the cadence stage (SS or LC). Participants were instructed to match their strides with the beat of the metronome. Upon completion of their first randomly assigned stage, participants rested for three minutes. After the first stage's rest period, participants began their second randomly assigned stage with the metronome clicking at the appropriate cadence value. Upon completion of the second stage, participants rested for one minute and data collection ceased. The Stryd data and metabolic data were then extracted from the final minute of each stage based on event time points noted by the researchers. Ratings of perceived exertion were recorded at the completion of the SS and LC running stages. Running economy (in terms of O_2 cost and caloric unit cost), average power, average form power, and average cadence were calculated from the last minute of each running stage.

Statistical analysis. Statistical analysis was completed using IBM SPSS Statistics version 23. A bivariate correlation analysis was run to determine if there is a relationship between running economy, power, and form power.

The Relationship Between Stryd Power and Running Economy In Well-Trained Distance Runners

Abstract

A novel running wearable called the Stryd Summit footpod attaches to a runner's right or left shoe and measures running power output. The developers of the product purport that the footpod's power and form power measures may correlate with metabolic data gathered in a lab. **PURPOSE:** Explore the relationship between power output and running economy at threshold pace. **METHODS:** Seventeen well-trained distance runners, 9 males and 8 females, completed a running protocol at threshold pace. Participants ran two discontinuous four-minute stages: one with their self-selected cadence (SS), and one with cadence lowered by 10% (LC). Metabolic data, power, and form power output were recorded for each cadence condition. **RESULTS:** Average self-selected cadence was 179.60 strides$\cdot$min^{-1} (±8.43), while lowered cadence was 172.54 strides$\cdot$min^{-1} (±9.46). Average change in cadence from SS to LC was 3.93%. The average running economy (±SD) at self-selected cadence was 201.58 ml$\cdot$kg$^{-1}\cdot$km^{-1} (±12.80), and at lowered cadence was 203.89 ml$\cdot$kg$^{-1}\cdot$km^{-1} (±11.48). Average caloric unit cost at SS was 1.05 kcal$\cdot$kg$^{-1}\cdot$km^{-1} (±0.07), and at LC was 1.06 kcal$\cdot$kg$^{-1}\cdot$km^{-1} (±0.06). Average power at SS was 4.37 W$\cdot$kg^{-1} (±0.48), and at LC was 4.42 W$\cdot$kg^{-1} (±0.49). Average form power at SS was 1.07 W$\cdot$kg^{-1} (±0.09), and at LC was 1.13 W$\cdot$kg^{-1} (±0.10). **CONCLUSIONS:** The present findings show that measures of running economy expressed in terms of oxygen cost and caloric unit cost are correlated with Stryd's power and form power measures.

Introduction

Running economy (RE) can be defined as the energy demand required to sustain a submaximal velocity, or the energy demand to cover a given distance at a given submaximal running velocity (Daniels, 1985; Saunders et al., 2004). RE in terms of oxygen cost can be calculated using measurements of steady-state oxygen consumption (VO_2), participant body mass, and distance traveled and may be expressed with units of $ml \cdot kg^{-1} \cdot km^{-1}$ (Fletcher et al. 2009; Skovgaard et al., 2018). RE may also be expressed in terms of caloric unit cost with units of $kcal \cdot kg^{-1} \cdot km^{-1}$ respiratory exchange ratios (Fletcher et al. 2009; Shaw et al., 2014).

Running economy is considered an essential component of distance running performance and is modulated by factors both biomechanical and physiological (Saunders et al., 2004). It is generally considered a better predictor of performance than VO_{2max} among similarly capable distance runners (Saunders et al., 2004). Since RE is related to oxygen consumption at submaximal velocities (Shaw et al., 2015), improving RE values means lowering oxygen consumption at faster velocities, which may lead to improved performance (Daniels, 1985;Williams & Cavanagh, 1987; Hoogkamer et al. 2017). Therefore, it is desirable for competitive distance runners to improve their economy by lowering the energy cost of running.

Running economy is related to biomechanical factors including vertical oscillation, ground contact time, stride length, and stride frequency (Cavanagh et al. 1977, Tartaruga et al., 2012). A runner's velocity is the product of stride frequency (cadence) and stride length (Lieberman et al., 2015) and these factors have been manipulated to cause change in RE

(Halvorsen et al., 2012; De Ruiter et al., 2014; Lieberman et al., 2015). De Ruiter et al. (2014) tested runners over seven cadence values (self-selected frequency ± 18%) and successfully elicited a change in RE at ±6%, ±12%, and ±18% of self-selected cadence. RE is also related to physiological factors including muscle fiber composition, achilles tendon length, and oxidative phosphorylation efficiency (Inbar et al., 1981; Sawka et al., 1983; Bosco et al., 1987; Hunter et al.; 2015). As such, a runner can improve RE through optimization of biomechanical and physiological factors competition (Williams & Cavanagh, 1987). Past studies have shown RE improvements with the addition of strength/explosive training interventions in addition to normal endurance training (Paavolainen et al., 1999; Storen et al., 2008; Berryman et al., 2010; Denadai et al., 2016). A recent study by Skovgaard et al. (2018) found that a low-volume, high intensity interval training intervention improved RE of 20 trained runners.

Use of wearable technologies (wearables) like GPS watches, fitness trackers, and pedometers has increased in recent years (Woodman et al., 2017). Wearables have been cited as an exciting advancement since they provide more precise data than classic self-assessment can (Meyer & Hein, 2013). Wearables have been seeing increased use in performance settings as well, with sports teams and high-level athletes taking advantage of technological advancements to track data over time to pinpoint areas for improvement (Li et al., 2015). Recent advancements in wearables are leading to novel metrics that may be useful to athletes trying to improve their performance.

The Stryd Summit (Stryd, Boulder, Colorado) footpod is novel wearable sensor for competitive runners and triathletes and reports pace, distance, vertical oscillation, cadence, leg spring stiffness and ground contact time data. The Stryd footpod is unique in that it also reports running power and form power measures to users. The Stryd footpod uses a triaxial accelerometer, a gyroscope, and a barometer embedded into a small shoe-mounted chip (K. Li, personal communication, 2017) to measure the power output from the positive component of the runner's net work completed (Stryd Team, 2017). The Stryd Team purports that this positive component of external work is correlated with metabolic energy expenditure (Stryd Team, 2017). To compare power values against metabolic expenditure, the Stryd Team conducted internal testing. The team found that power ($W \cdot kg^{-1}$) was strongly correlated with metabolic cost (VO_2 in $ml \cdot kg^{-1} \cdot min^{-1}$) in their sample ($r^2 = 0.96$). External mechanical power output has been measured in previous research using videography and force plates (Cavagna, Komarek, & Mazzoleni, 1971; Fukunaga et al., 1980; Schepens et al., 2001).

Stryd's form power is explained as the power to raise one's center of mass against gravity with each step (Stryd Team, 2016). It is believed that a runner may be able to improve their biomechanical efficiency over a long period time through monitoring power and form power values both acutely during daily runs and longitudinally over training periods (Stryd Team, 2016). The Stryd Team posits that runners who train with the Stryd footpod while monitoring power values may be able to monitor changes in running economy through changes in power and form power (Stryd Team, 2016).

Improving running economy is a desirable outcome of distance running training because better RE may lead to better performance (Daniels, 1985; Williams & Cavanagh, 1987; Hoogkamer et al. 2017). However, measurement of running economy requires expensive equipment that most runners do not have access to. Recent advancements in consumer wearable technology have caused an increase in use of these devices (Meyer & Hein, 2013). As the devices have become more sophisticated, consumers have had access to more fitness data than ever before (Li et al., 2015). While wearable technology has seen an increase in use, there have been few studies examining the use of new proprietary measures. Since RE is considered central to running performance, but can be costly to measure, an alternative metric (power or form power) measured by a wearable sensor may be useful to runners. As such, the purpose of this study was to measure the correlation between Stryd form power and running economy at lactate threshold pace (Daniels, 2014) in well-trained collegiate distance runners.

Methods

Participants. A correlational power analysis was run to determine a required sample size using G*Power 3.1.9.2 (Universität Düsseldorf, Germany). With effect size set to .60, $\alpha < .05$, and power set to 0.95, a sample size of 21 participants was recommended. A total of 17 participants were recruited and took part in the study (nine males, eight females). Participants were recruited from the university cross country team and the university's exercise science department.

Participant VO_{2max} were estimated using race performance times and reported as VDOT based on the VDOT estimation chart from Daniels (2014, p. 81-82). This chart lists performance times for race distances from 1500m up to a marathon and provides VO_{2max} estimates based on them. Reported VDOT for each participant was based on the race performance time that gave them the highest VDOT according to the chart. "Well-trained" was defined as running an average of 25 miles per week, with a minimum VDOT of 44 $ml \cdot kg^{-1} \cdot min^{-1}$ for women (a 22:15 5k) and 50 $ml \cdot kg^{-1} \cdot min^{-1}$ for men (a 19:57 5k). Average participant age (±SD) was 20.59 years (±2.29). Average height was 1.75m (±0.08). Average mass was 62.42 kg (±6.91). Average VDOT was 56.59 $ml \cdot kg^{-1} \cdot min^{-1}$ (±8.21). Informed consent was obtained, and a physical activity readiness questionnaire was completed before the running trial.

Instruments. Testing took place at the university exercise physiology lab. A Parvo Medics TrueOne 2400 metabolic analyzer (Parvo Medics, Sandy, UT) was used to record gas exchange measures. Gas exchange data were recorded on a Dell desktop computer running Windows 7. Prior to each testing session, the metabolic analyzer was powered on for at least 30 minutes to warm up, then O_2 and CO_2 sensors were calibrated based on known gas tank concentrations and room air. Flowmeter calibrations were then completed using a 3.0L syringe. Form power and cadence were recorded by a Stryd Summit footpod (Stryd, Boulder, Colorado). The footpod was paired via ANT+ to a Garmin Fenix 3 (Garmin Ltd., Olathe, Kansas) with the Stryd Run Data Field loaded. Testing was completed on a Trackmaster TMX425c treadmill (Trackmaster Treadmills, Newton, KS).

Design and procedures. Participants completed a running history questionnaire, an informed consent form, and a physical activity readiness questionnaire in the exercise physiology lab prior to testing. Height and weight were measured and subsequently entered into the Stryd application to calibrate the footpod to the participants' anthropometric data. Threshold pace was set according to Daniels' VDOT pace table (Daniels, 2014, p. 84-85).

This table lists VDOT values (estimated VO_{2max} predicted using race performance times) and corresponding training paces for the values.

Before testing, participants were given a brief overview of the protocol and instructed about how they should time their strides to match a metronome. The participants then put on the gas analyzer mask and heart rate monitor, and the Stryd footpod was attached to the runner's left shoe. The Stryd footpod uses a clip-on mount that locks to a runner's shoelaces. The Stryd footpod was mounted approximately equidistant from participants' malleolus and the toe of their shoe. If there was an obstruction on the tongue of the shoe that prevented ideal placement, the Stryd footpod was placed on the next row of laces distal from the malleolus. The same researcher mounted the Stryd footpod for all participants.

Participants completed a two-stage discontinuous running protocol. Metabolic and power data collection began with a five-minute warm-up run with all experimental equipment donned to acclimate participants to running while connected to the analyzer. The participants' self-selected cadence was determined during a one-minute run at assigned threshold pace at the immediate conclusion of the five-minute warm-up. After the warm-up and cadence measurement, participants took a 3-minute rest. During the rest, researchers calculated a cadence value 10% lower than the participants' self-selected cadence for them to replicate during the experimental protocol. A coin was flipped to determine the order of testing protocol stages (SS then LC, or LC then SS).

For the self-selected cadence (SS) stage, participants ran four minutes at assigned threshold pace while attempting to match their cadence with a metronome set to replicate their self-selected cadence from the warm-up period. For the lower cadence (LC) stage participants ran four minutes at assigned threshold pace while attempting to match their cadence with a metronome set to a value that was 10% lower than their self-selected cadence from the warm-up period.

After the warm-up rest period, participants began the first stage of the experimental protocol with a metronome clicking at the cadence value appropriate for the stage (SS or LC). Upon completion of their first stage, participants rested for three minutes. After the first stage's rest period, participants began their second stage (SS or LC) with the metronome clicking at the appropriate cadence value. Upon completion of the second stage, participants rested for one minute and data collection ceased. The Stryd data and metabolic data were then lined up based on event time points noted by the researchers. Ratings of perceived exertion were recorded at the completion of the SS and LC running stages. Running economy (in terms of O_2 cost and caloric unit cost), average power, average form power, and average cadence were calculated from the last minute of each running stage.

Statistical analysis. Statistical analysis was completed using IBM SPSS Statistics version 23. Paired t-tests were run to determine if statistically significant differences occurred in variables of interest between the two cadence conditions. A bivariate correlation analysis was run to determine if there was a relationship between running economy, power, and form power.

Results

Mean data (±SD) for cadence, oxygen consumption (VO_2), respiratory exchange ratio (RER), rating of perceived exertion (RPE), and ventilation (Ve) separated by cadence condition are reported in Table 1. One-tailed paired t-tests were run on these variables to find if significant differences occurred between the two cadence conditions (SS or LC). There were statistically significant differences between cadence conditions in the following variables: cadence, $t(15) = 6.573$, $p = 0.000$; VO_2, $t(16) = -1.856$, $p = 0.041$; RER, $t(16) = -1.962$, $p = 0.034$. There were no statistically significant differences between cadence conditions for the following variables: RPE, $t(16) = -1.515$, $p = 0.075$; Ve, $t(16) = -1.495$, $p = 0.77$.

Table 1
Cadence, VO_2, RER, RPE, and Ve by Cadence Condition

	Cadence (strides·min^{-1})	VO_2 (ml·kg^{-1}·min^{-1})	RER	RPE	Ve (L·min^{-1})
Self-selected cadence	179.60 (±8.43)*	52.81 (±8.68)*	0.96 (±0.06)*	11.65 (±1.66)	93.80 (±19.34)
Lowered cadence	172.54 (±9.46)*	53.44 (±8.54)*	0.98 (±0.06)*	12.12 (±1.65)	96.00 (±18.38)

Note. Data reported as mean (±SD).
* Paired T-test is significant at the 0.05 level (one-tailed).

Mean data (±SD) for running economy, caloric unit cost, power, and form power are reported in Table 2. One-tailed paired T-tests were conducted to determine if significant differences occurred between the two cadence conditions (SS or LC). There were statistically significant differences between cadence conditions in the following variables: running economy $t(16) = -2.017$, $p = 0.031$; caloric unit cost $t(16) = -2.093$, $p = 0.027$; power, $t(16) = -6.349$, $p = 0.000$; form power $t(16) = -5.664$, $p = 0.000$.

Table 2
Running Economy and Power by Cadence Condition

	Running economy ($mL \cdot kg^{-1} \cdot km^{-1}$)	Caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$)	Power ($W \cdot kg^{-1}$)	Form power ($W \cdot kg^{-1}$)
Self-selected cadence	201.58 (±12.80)*	1.05 (±0.07)*	4.37 (±0.48)*	1.07 (±0.09)*
Lowered cadence	204.48 (±10.65)*	1.06 (±0.06)*	4.42 (±0.49)*	1.13 (±0.10)*

Note. Data reported as mean (±SD).

* Paired T-test is significant at the 0.05 level (one-tailed).

The results of the bivariate correlation of cadence, running economy, caloric unit cost, power, and form power are shown in Table 3. The correlation was run on all data collected between the two cadence conditions combined. It should be noted that the target lowered cadence of 10% below self-selected cadence was not realized.

Table 3
Bivariate Correlation Matrix of Cadence, Running Economy, Caloric Unit Cost, Power, and Form Power

	Cadence	Running economy	Caloric unit cost	Power	Form power
Cadence	-				
Running economy	-0.441**	-			
Caloric unit cost	-0.482**	0.985**	-		
Power	-0.383*	0.560**	0.554**	-	
Form power	-0.858**	0.523**	0.542**	0.707**	-

* Correlation is significant at the 0.05 level (one-tailed).

** Correlation is significant at the 0.01 level (one-tailed).

There were moderate, negative, linear relationships between the following variables: cadence and RE; cadence and form power. There were moderate, positive, linear relationships between the following variables: RE and power (Figure 1); RE and form power (Figure 2); CUC and power (Figure 3); CUC and form power (Figure 4). There was a moderately strong, positive, linear relationship between power and form power. There was a strong, negative, linear relationship between cadence and form power.

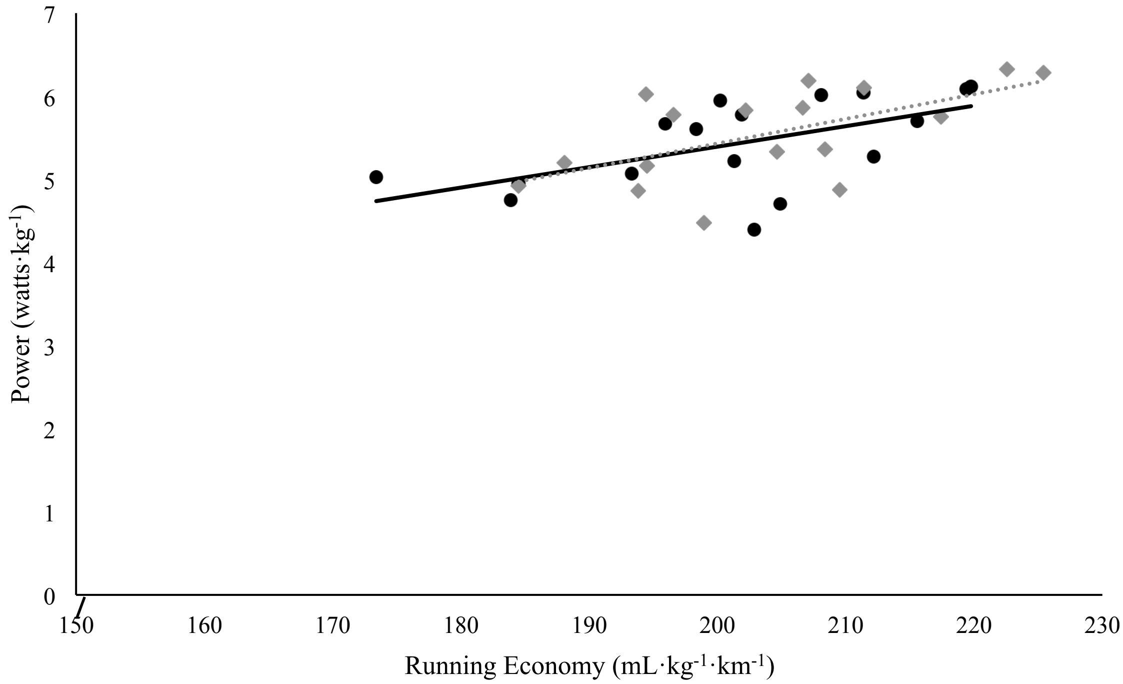

Figure 1. Correlation scatterplot for power and running economy. The black circles and solid line of best fit represent the SS condition. The gray diamonds and dotted line of best fit represent the LC condition. Data recorded during the last minute of each stage.

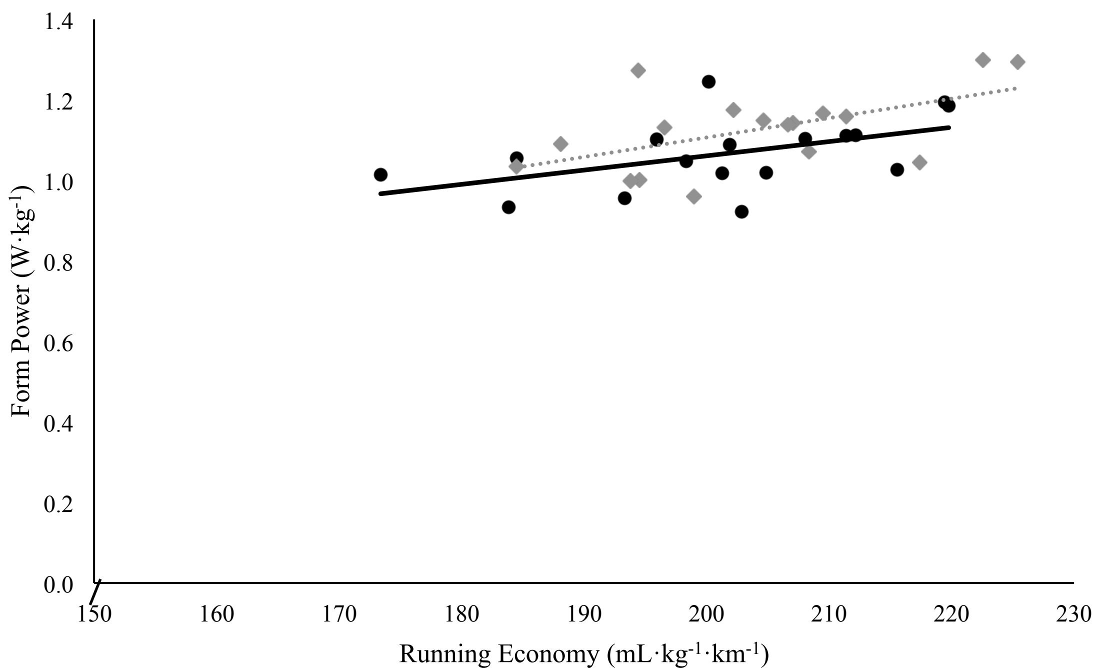

Figure 2. Correlation scatterplot for form power and running economy. The black circles and solid line of best fit represent the SS condition. The gray diamonds and dotted line of best fit represent the LC condition. Data recorded during the last minute of each stage.

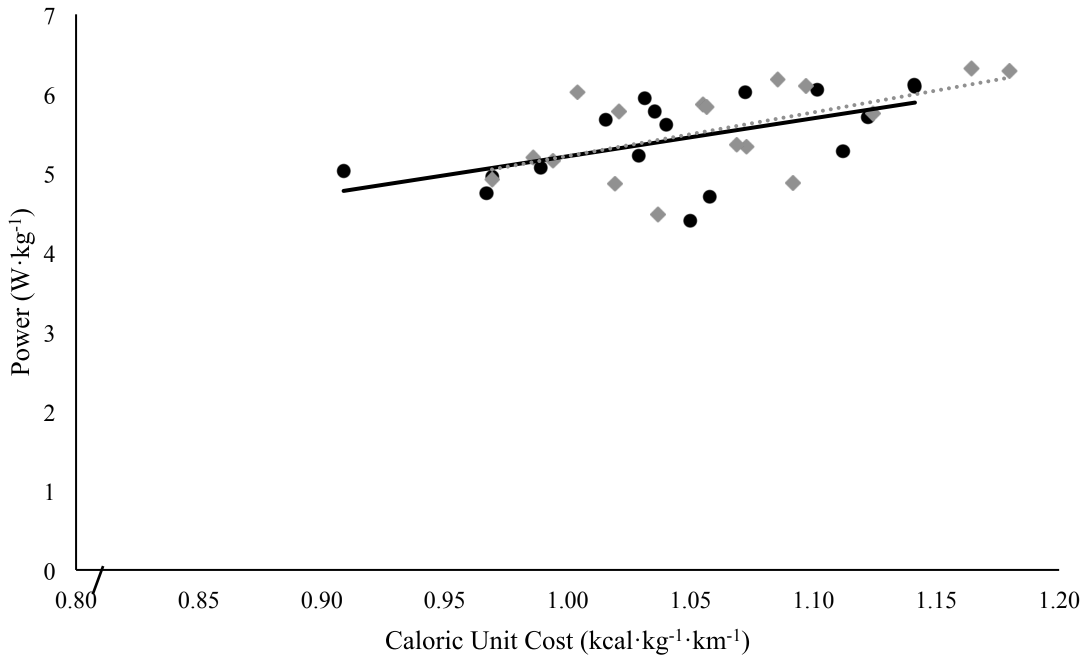

Figure 3. Correlation scatterplot for power and caloric unit cost. The black circles and solid line of best fit represent the SS condition. The gray diamonds and dotted line of best fit represent the LC condition. Data recorded during the last minute of each stage.

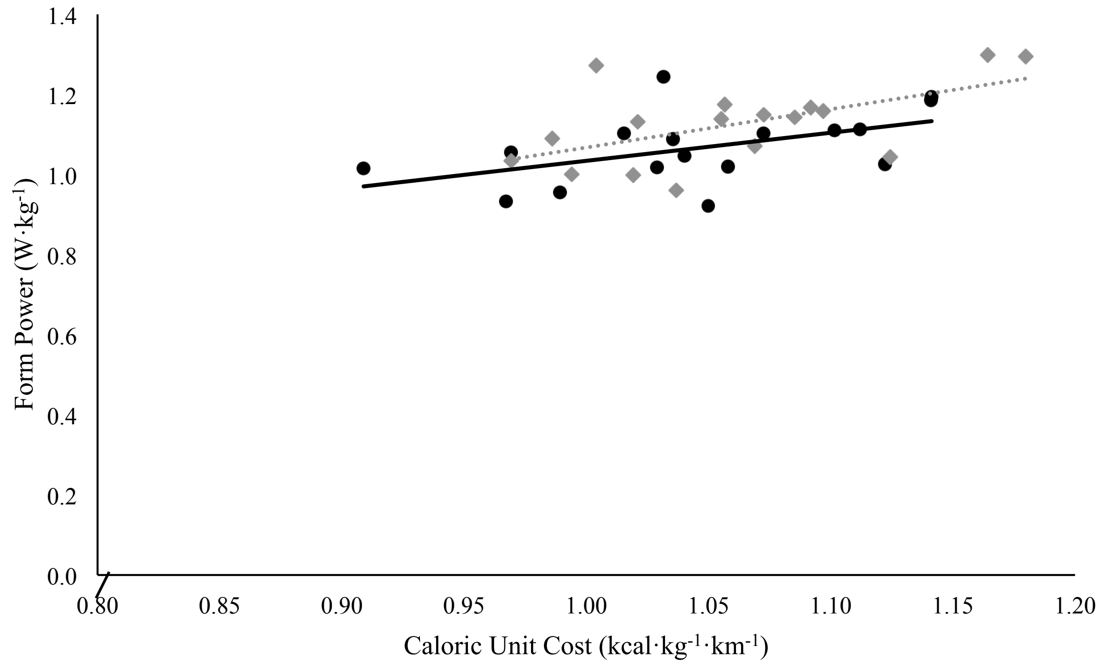

Figure 4. Correlation scatterplot for form power and caloric unit cost. The black circles and solid line of best fit represent the SS condition. The gray diamonds and dotted line of best fit represent the LC condition. Data recorded during the last minute of each stage.

Discussion

The purpose of this study was to explore the relationship between established measures of running economy (oxygen cost, caloric unit cost) and Stryd's proprietary power measures (power, form power). In the company's white papers, the Stryd Team (2016; 2017) purport that athletes using power measurements in training may be able to monitor changes in running economy through changes in power values. The present researchers aimed to elicit a significant change to participants' running economy and power by forcing a 10% decrease in cadence using a metronome. The actual decrease in cadence was just 3.93%. It is believed that this smaller cadence change is the reason there was no significant difference in oxygen cost or caloric unit cost between the two cadence conditions. However, the moderate positive correlation that was found between running economy and Stryd's power and form power is encouraging. These findings suggest that there is a relationship between Stryd's power metrics and running economy.

Cadence had a strong negative correlation with form power and a moderate negative correlation with both measures of running economy. Previous studies have found a relationship between cadence and RE (Halvorsen et al., 2012; Tartaruga et al., 2012; Lieberman et al. 2015), though form power may be more sensitive to changes in cadence. The percent change in RE from self-selected cadence to lowered cadence was 1.13%. The percent change in form power from self-selected cadence to lowered cadence was 5.31%. Form power's apparent greater sensitivity to cadence change may be due to the mechanical nature of the power measure.

Stryd represents a novel method of measuring running power. Previous research by Cavagna, Komarek, and Mazzoleni (1971) involved using videography along with force plates to calculate external mechanical work and running power. The researchers measured average forces during push off and braking phases of runners' strides and used video footage to measure the distance and velocity traveled by each participant's trunk between strides. This method resulted in power values of 2500-3000W for subjects running at 9.5 $m \cdot s^{-1}$ (Cavagna, Komarek, and Mazzoleni, 1991).

Should power be related to economy, it may be desirable for runners to monitor power values for improvement both acutely and longitudinally. Previous studies have used various strength-oriented interventions for improving running economy (Denadai et al., 2016), and similar interventions are necessary to test for improvements in power values. Interventions that have improved running economy in previous studies include heavy weight training (squats) (Storen et al., 2008), explosive strength sessions (sprinting and jumping) (Paavolainen et al., 1999), and plyometric training (Berryman et al., 2010).

Conclusion

The present study suggests there is a relationship between Stryd's power and form power, and running economy expressed in terms of oxygen cost and caloric unit cost. While target lowered cadence values were not met, it would appear that form power is more sensitive to changes in cadence and may be more sensitive to biomechanical changes than RE or CUC.

Chapter 5

Summary, Conclusions, Implications, and Recommendations

Summary

The purpose of this study was to measure the correlation between Stryd form power and running economy at lactate threshold pace (Daniels, 2014) in well-trained collegiate distance runners. Participants were 17 well-trained distance runners (nine male, eight female). The researchers hypothesized that there would be a moderate relationship between form power and running economy. This hypothesis was confirmed, though the researchers goal of eliciting a significant change in running economy through forced changes in cadence was unsuccessful. Data from the metabolic cart were used to examine average values for VO_2, VCO_2, Ve, and RER. Running economy expressed in terms of oxygen cost was calculated using VO_2 values and time it would take the participant to run a kilometer at their assigned pace. Caloric unit cost was calculated using Peronnet and Massicotte's (1991) table of nonprotein respiratory quotients. Data from the Stryd footpod was used to examine average values of cadence, power, form power, ground contact time, vertical oscillation and leg spring stiffness. Form power had a moderate positive correlation with running economy ($r = 0.524$) and a moderate positive correlation with caloric unit cost ($r = 0.541$).

Conclusions

It was concluded from this study that:

1. There were moderate, negative, linear relationships between the following variables: cadence and RE ($r = -0.426$); cadence and CUC ($r = -0.478$).

2. There were moderate, positive, linear relationships between the following variables: RE and power (r = 0.571); RE and form power (r = 0.524); CUC and power (r = 0.556); CUC and form power (r = 0.541).
3. There was a strong, negative, linear relationship between cadence and form power (r = -0.858).

Implications

The results of the present study could be of use to coaches and athletes aiming to expand their data tracking with wearable technology. The Stryd Summit footpod appears to accomplish the developers' claim of providing users with "an accurate, reliable device to provide real-time metabolic cost estimation" (Stryd Team, 2017) through the mechanical measures of power and form power output as evidenced by the moderate positive correlations that exist between these metrics and running economy. However, the participants' inability to elicit a significant change in running economy through changes in cadence leaves some question as to how well the Stryd footpod can measure intraindividual changes in economy.

Should the relationship between running economy and power hold up across a range of running economy values, then Stryd could be an exciting new tool for coaches and runners. Power may give runners a real-time estimation of metabolic activity in the field, allowing them to estimate their running economy both acutely during daily runs and longitudinally over long training periods. With the cost to buy a Stryd Summit being relatively low (MSRP $199.99), power metrics present a possible alternative to expensive testing using established methods with metabolic carts in labs.

Recommendations

Future research involving the Stryd Summit footpod should focus on both acute and longitudinal methods in a similar manner to running economy studies. It would be useful to examine the validity and reliability of the biomechanical factors that Stryd reports (ground contact time, vertical oscillation, leg spring stiffness, and cadence) against established measurement methods. It may also be necessary to explore the effect footwear has on power metrics in a similar fashion to how Hoogkamer et al. (2016, 2017) tested footwear's effect on running economy.

It may be beneficial to further explore the effect of cadence on power and running economy. While the present researchers lowered cadence by 10%, past research has examined running economy over ranges of cadences (De Ruiter et al., 2014; Halvorsen et al., 2012; Lieberman et al., 2015). Lieberman et al. (2015) tested participants from cadences between 150 and 190 strides per minute and used a regression to find a metabolically optimal cadence. A similar study to find optimized cadences for power values should be conducted.

Past research has explored the effect of strength training interventions on running economy (Paavolainen et al., 1999; Storen et al., 2008; Berryman et al., 2010; Denadai et al., 2016). Longitudinal studies involving similar weight training and plyometric interventions should be conducted to explore the effect of said interventions on participant power values. If power and form power have a relationship with running economy and tend to be influenced by the same factors, then strength training may allow runners to run at lower power values for given paces, much like running economy. If all these factors are explored, we could get a more complete view of the relationship between Stryd's power and form power and running economy.

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Appendix A – Physical Activity Readiness Questionnaire (PAR-Q)

Physical Activity Readiness Questionnaire - PAR-Q (revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	**1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	**2. Do you feel pain in your chest when you do physical activity?**
☐	☐	**3. In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7. Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____

SIGNATURE ____________________________ DATE ____________________

SIGNATURE OF PARENT ____________________________ WITNESS ____________________
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

1:12

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Appendix B – Informed Consent

Document of Informed Consent
Department of Exercise Science
State University College at Cortland

TITLE: The relationship between running economy and Stryd form power in well-trained distance runners

STUDENT INVESTIGATOR: Casey Austin, (518) 929-6939

FACULTY SUPERVISOR: James Hokanson, PhD., (607) 423-1854

PURPOSE: The purpose of this study is to determine the relationship between running economy and Stryd form power in well-trained distance runners at lactate threshold pace.

PROCEDURES: The data gathered from the testing will be used to determine the running economy, average form power, and average stride frequencies of each participant. As a test subject, you will report on one occasion for testing. Anthropometric data (height, weight) will be recorded and exercise testing will take place at the exercise physiology lab. You will be familiarized with the ParvoMedics TrueOne 2400 metabolic analyzer and Stryd Summit Footpod prior to testing. To start, you complete a 5-minute warm-up run at a pace that is easy for you, then complete a minute at a calculated "threshold pace" (similar to half marathon pace).

After the warm-up, you will complete an 8-minute run protocol at your calculated "threshold pace". The 8-minute run will be split into 4-minute stages. One of the 4-minute stages will be run at a self-selected cadence. The other 4-minute stage will be run with a cadence lower than your self-selected value by matching your footsteps with a metronome. The order of the trials will be randomized. There will be a three-minute rest between stages. After the protocol is complete, you will rest for three minutes and data collection will be completed.

RISKS: The proper precautions will be to taken to ensure that the testing area, as well as all of the equipment being used, is safe for all participants involved in the study. The possibility of injury in this study is minimal.

BENEFITS: The results of this study may indicate whether Stryd's form power has a correlation with running economy. Form power is unique as a novel measure of mechanical running efficiency and could be a useful training metric for runners.

CONFIDENTIALITY: All data from the experiment will be stored in a locked cabinet, and the data on the computer will be stored anonymously with your identity protected.

FREEDOM OF CONSENT: Participation in this study is completely voluntary, and you may withdraw from the project at any time. Individuals may withdraw in writing or by telephone (518 929-6939).

The student responsible for this research project is Casey Austin, who will be working in conjunction with the faculty members of the SUNY Cortland Kinesiology Department. For questions concerning the rights of human subjects, please contact, Human Subjects Committee at SUNY Cortland, (607)753-2511.

I have read and understand the activities required for my involvement in this project, and I consent to participate.

Name: _______________________________ Telephone#:
____

Signature: ____________________________________ Date:
____

Appendix C – Running History Questionnaire

Running History Questionnaire

Name: ____________________ ID: ______________

How long (years) have you been running competitively? _________________

What are your three **most recent** race performance times (minutes:seconds, race distance)?

_________________ Approx. date:

_________________ Approx. date:

_________________ Approx. date:

What is your approximate normal, everyday running pace (min/mile)? ____________

How many miles per week have you been running over the past two months (circle one)?

1-20 miles **20-40 miles** **40-60 miles** **60+ miles**

How many days per week have you been running over the past two months (on average)?

1 day **2 days** **3 days** **4 days** **5+ days**

POST-TEST: Which stage of running did you prefer (low cadence or high cadence)?

Appendix D – Supplemental Tables and Figures

Table 4.
Cadence, Ground Contact Time, Vertical Oscillation, and Leg Spring Stiffness by Cadence Condition

	Cadence (strides·min^{-1})	Ground Contact Time (ms)	Vertical Oscillation (cm)	LSS (kN·m^{-1})
Self-selected cadence	179.60 (±8.43)*	205.94 (±14.03)	7.53 (±1.14)*	9.56 (±1.38)
Lowered cadence	172.54 (±9.46)*	206.37 (±14.26)	8.53 (±1.49)*	9.69 (±1.42)

* Paired T-test is significant at the 0.05 level (2-tailed).

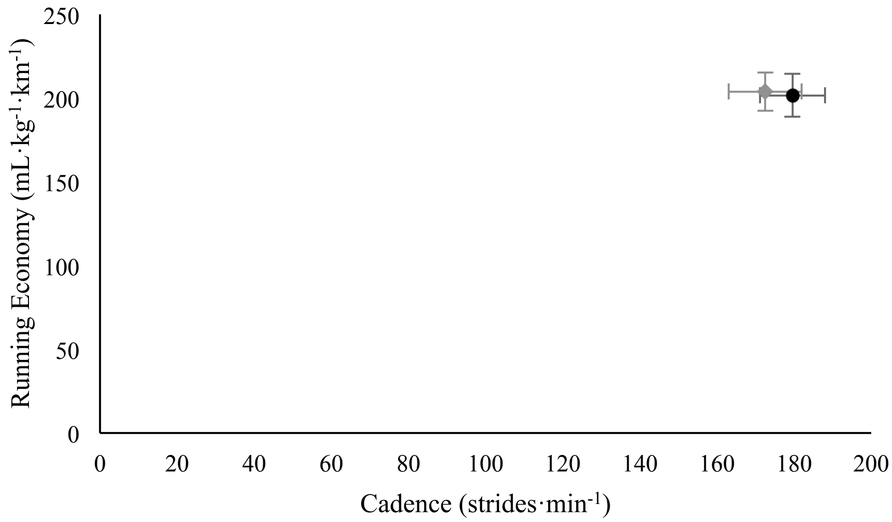

Figure 5. Running economy and cadence averages by cadence condition

The black circle represents SS cadence condition. The gray diamond represents LC.

Data reported as means. Error bars represent standard deviations.

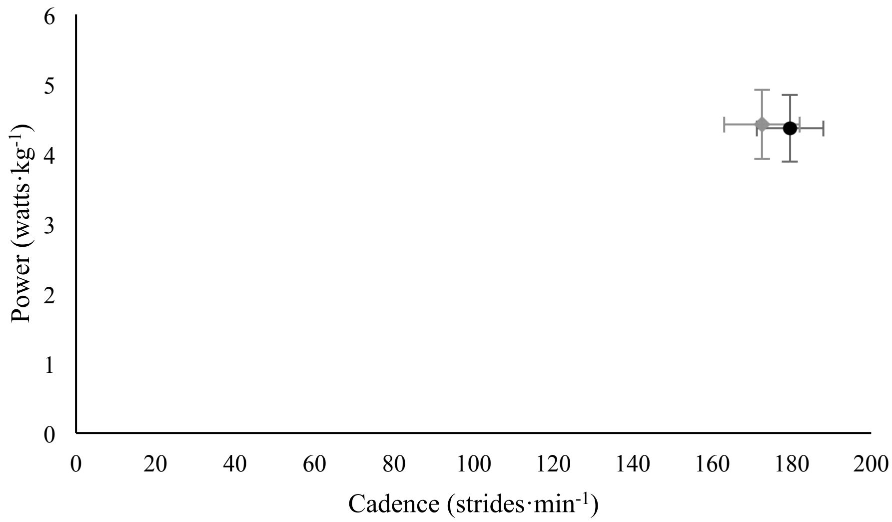

Figure 6. Power and cadence averages by cadence condition.

The black circle represents SS cadence condition. The gray diamond represents LC.

Data reported as means. Error bars represent standard deviations.

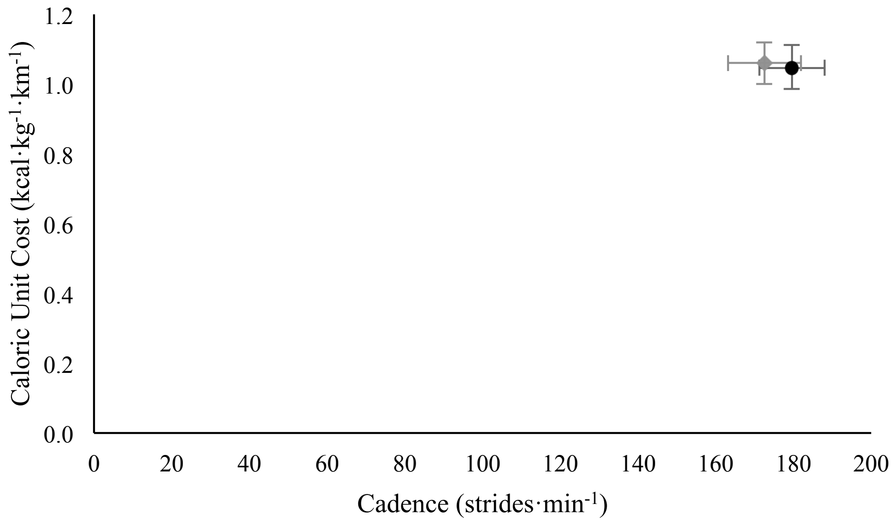

Figure 7. Caloric unit cost and cadence averages by cadence condition.

The black circle represents SS cadence condition. The gray diamond represents LC.

Data reported as means. Error bars represent standard deviations.

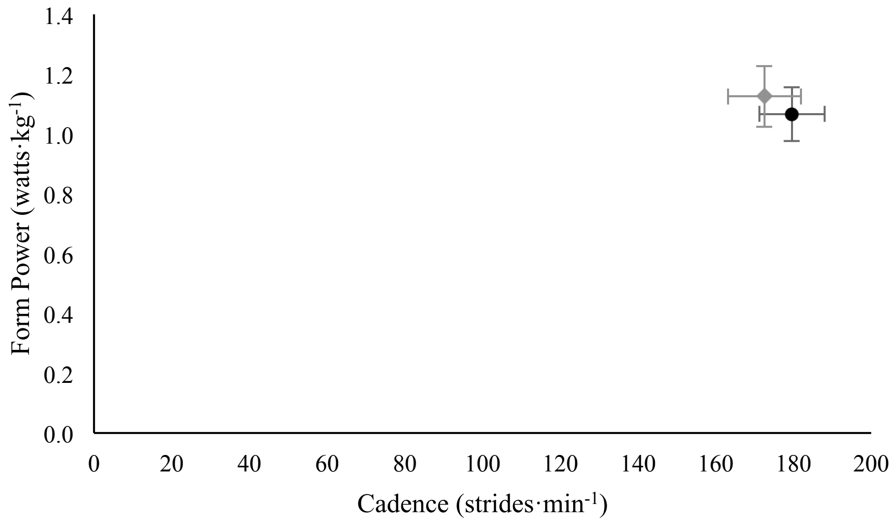

Figure 8. Form power and cadence averages by cadence conditions

The black circle represents SS cadence condition. The gray diamond represents LC. Data reported as means. Error bars represent standard deviations.

Appendix E - Pilot Data Results

Prior to the writing of this proposal, a case study has been performed along with some pilot data gathering. For the case study, a change in running economy was elicited using a high knee running technique. Researchers instructed the participant to raise their knees to be parallel to the ground while running in order to increase cost of transport. For the pilot data, a change in running economy was elicited by lowering cadence by 5% as the literature showed this could cause meaningful change to economy (Halvorsen et al., 2012). Data were collected in two separate sessions with the same participant. One session was run at 8.5 mph and the second was run at 9.5 mph.

Case study – High knee method. Before beginning the protocol, the participant was given a brief overview of the protocol and instructed on proper high knee running technique ("Lift your knee enough for your thigh to be parallel to the ground…").

The participant then put on the gas analyzer mask and recording in Breeze was started. The participant stood at rest on the treadmill for 2 minutes, then the Stryd app began recording and the treadmill belt was turned on to a speed of 7.5 mph. The participant ran at this speed for 3 minutes then began a 3-minute high knee running period to force a change in energy demand and running economy. The treadmill belt was then slowed to 6.5 mph and the participant was instructed to resume normal running technique for 3 minutes. Finally, for the last 3 minutes, the participant resumed high knee running to complete the 14-minute protocol. The Stryd application recording and Breeze collection were stopped at the same time and time points were lined up after testing.

All measures were collected from steady state exercise during the last 30 seconds of each stage of the protocol. The following measures are reported as mean ± standard deviation (if applicable). Steady state VO_2 increased as expected when running condition was changed ($7.5_{mph} = 35.65 \pm 0.41$ mL·kg^{-1}·min^{-1}, $7.5_{high\ knee} = 44.73 \pm 0.38$, $6.5_{mph} = 33.65 \pm 0.55$, $6.5_{high\ knee} = 41.61 \pm 0.52$) (Figure 1). Since VO_2 changes were successfully incited by the high knee conditions, running economy changed as well ($7.5_{mph} = 177.41$ mL·kg^{-1}·km^{-1}, $7.5_{high\ knee} = 222.55$, $6.5_{mph} = 192.64$, $6.5_{high\ knee} = 238.33$) (Figure 2).

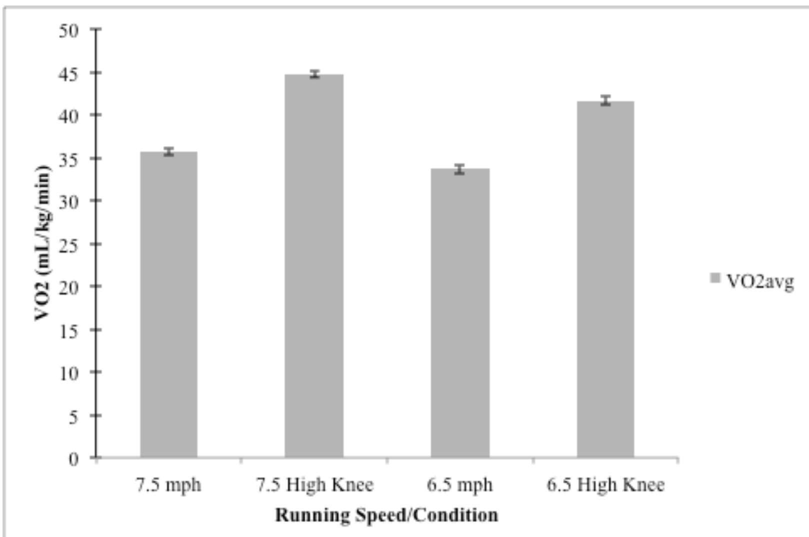

Figure 1. Steady state VO_2 values by running speed/condition. VO2avg is steady state VO_2 over last 30 seconds of stage. Data reported as means, error bars represent standard deviation.

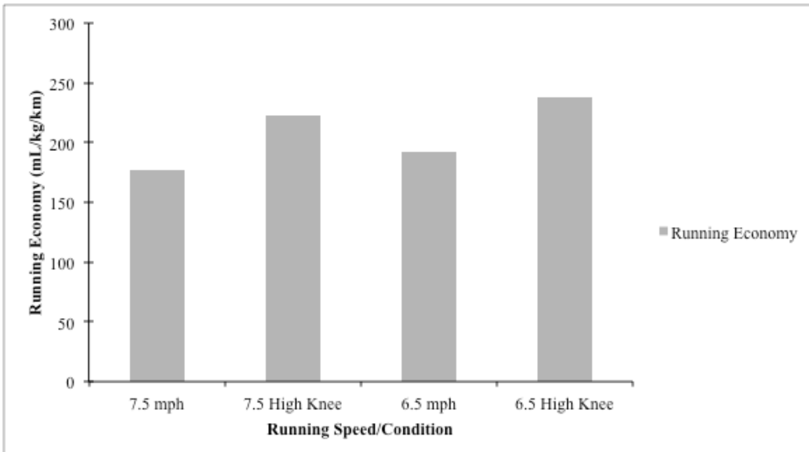

Figure 2. Running economy by running speed/condition. Data reported as means.

Stryd's form power measure changed slightly between running conditions, but there did not appear to be a relationship between form power and running economy (7.5 mph = 57.64 ± 1.21 watts, $7.5_{\text{high knee}} = 56.36 \pm 0.5$, $6.5_{\text{mph}} = 55.55 \pm 0.52$, $6.5_{\text{high knee}} = 57.36 \pm 0.67$) (Figure 3).

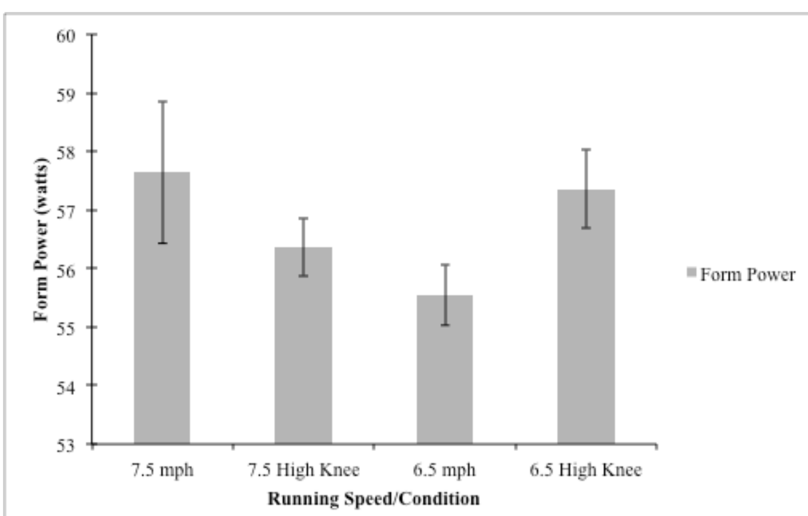

Figure 3. Form power values by running speed/condition. Form Power averaged from steady state during last 30 seconds of stages. Data reported as means, error bars represent standard deviation.

Pilot study – Stride frequency alteration method. For the pilot testing of this study's protocol, a participant ran two separate sessions at different running speeds while making alterations to stride frequency. Sessions were done of the treadmill in the SUNY Cortland exercise physiology lab, and the participant's gas exchange was measured through the MedGraphics Ultima analyzer. The results from testing can be found in Table 1. The participant ran for three minutes then reduced stride frequency by approximately 5% to induce a change in running economy (Halvorsen et al., 2012). At 8.5mph, running economy improved when stride frequency was lowered by about 5%, but form power degraded. At 9.5mph, both running economy and form power degraded when stride frequency was lowered by 5%.

It is believed by the researcher that form power's meaningful change at both speeds shows biomechanical degradation brought about by the decrease in stride frequency. Running economy may have improved at 8.5mph because the pace was not demanding enough for the runner to increase cost of transport by lowering stride frequency. As such, it will be important to choose a pace that is appropriately demanding for further research.

Table 1

Results of Cadence Alteration Method at 8.5 mph and 9.5 mph

	Form Power	Running Economy	Cadence
8.5 mph	65.97 (.17)	181.34	85.06 (.57)
9.5 mph	66.50 (.50)	178.72	87.33 (.83)
8.5 mph low cadence	70.58 (.85)	161.93	80.94 (1.26)
9.5 mph low cadence	71.75 (.67)	192.35	82.34 (.81)

Notes:

Form power reported in watts, running economy reported in $mL \cdot kg^{-1} \cdot km^{-1}$, cadence reported in spm

Data reported as means (± SD) where applicable

Data gathered from last minute of each stage