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Graduate Studies

THE EFFECTS OF PACE VARIATION ON THE COST OF RUNNING IN TRAINED
RUNNERS

A Manuscript Style Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Clinical Exercise Physiology

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By Madeline L. Ranum

We recommend acceptance of this thesis in partial fulfillment of the candidate's requirements for the degree of Master of Science in Clinical Exercise Physiology.

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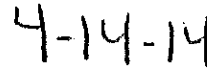
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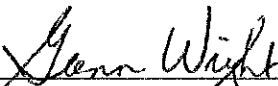
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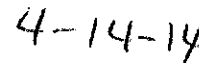
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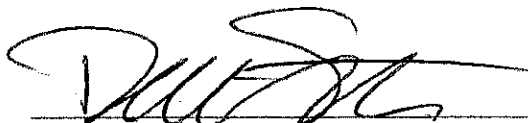
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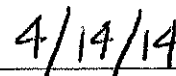
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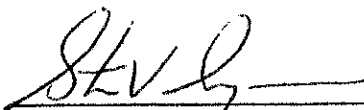


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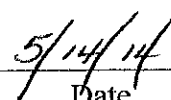


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ABSTRACT

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This study was designed to evaluate the effects of pace variation on the cost of running (CR) in trained runners. Twenty runners (12 males and 8 females) completed a VO_2max test to determine aerobic capacity and ventilatory threshold (VT). Subjects then ran four, 6-minute intervals on the treadmill with 2 minutes of walking in between each interval. One of the intervals was kept at a constant pace which was below the subject's VT (~90% VT) to ensure steady state. The speed of the other three intervals was varied around this local average speed by 0.1 ($0.04 \text{ m}\cdot\text{s}^{-1}$), 0.3 ($0.13 \text{ m}\cdot\text{s}^{-1}$), or 0.5 mph ($0.22 \text{ m}\cdot\text{s}^{-1}$). The pace variations were expressed in relation to the Coefficient of Variation (CV) of running speed to show the extent of variability around each runner's local average speed. The average CV for each pace variation was 0% for the constant speed, 1.4% for a pace variation of 0.1 mph, 4.2% for a pace variation of 0.3 mph, and 7.0% for a pace variation of 0.5mph. Cost of running, heart rate (HR), Rating of perceived exertion (RPE), blood lactate, and stride frequency were measured during each interval. No significant differences were found in CR, HR, RPE or blood lactate. A significant difference ($p < 0.05$) was found in the fast stages of stride frequency across all pace variations but this did not reflect a similar change in CR. Results indicated that pace variations did not significantly affect CR when measured below VT.

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INTRODUCTION

The record performances of elite distance runners have been a major interest to physiologists for over a century. As research has progressed, a few physiological determinants have emerged as the best indicators of performance. These determinants include maximal aerobic capacity, fractional utilization, and the cost of running.

It is well known that endurance athletes must have a high capacity to consume oxygen maximally. Early research demonstrates that athletes competing in endurance-related events such as cross-country skiing, orienteering, and long distance-running have higher maximal aerobic capacities ($VO_2\text{max}$) than athletes in strength or technique related events (Saltin & Astrand, 1967). The necessity of endurance athletes to consume oxygen at a much higher rate than athletes in strength or technique related events is due to the energy requirements of aerobic activity. While strength/technique athletes rely on systems that create energy quickly (the ATP-PCr system & anaerobic glycolysis) endurance athletes must be able to sustain adenosine triphosphate regeneration (ATP) for longer periods of time. This is done through the process of aerobic glycolysis which depends on the availability of oxygen to create ATP. Thus, athletes with high oxygen consumption combined with a high cardiac output ($VO_2\text{max}$) can create more ATP aerobically, giving them the ability to run faster for longer periods of time. Consequently, to compete at the elite level in men's distance running today, runners must achieve a $VO_2\text{max}$ of at least 70-85 ml/kg/min. In women, these values are about 10% lower (Joyner & Coyle, 2008).

While it is well known that $VO_2\text{max}$ is essential to endurance running

performance, it is not considered the single best predictor of performance (Costill, 1973). Rather the ability of a runner to sustain a high percentage of VO_2max throughout the race is a better predictor of performance. This is referred to as fractional utilization or $\% \text{VO}_2\text{max}$. Fractional utilization is defined by the lactate threshold (LT) or the point at which lactate accumulation in the blood exceeds lactate removal. Runners who are able to sustain a high $\% \text{VO}_2\text{max}$ are able to do so because of an increased LT. In trained individuals, LT can occur around 75-90% VO_2max versus 50-60% in untrained individuals (Joyner & Coyle, 2008). This ability of LT to increase with training beyond the point where VO_2max fails to increase is what makes fractional utilization a much better predictor of performance.

When VO_2max and fractional utilization are similar across a field of runners, a third factor comes into play. This is known as the cost of running (CR) which is a measure of the efficiency of a runner. Cost of running which is either expressed as the VO_2 at a common running speed or as the VO_2 required to run one kilometer has been shown to be systematically lower in elite East African runners when compared to elite European runners across a range of submaximal running speeds (Foster & Lucia, 2007). The development of a lower CR in elite East Africans could serve as an explanation for their better performances over other populations of elite runners.

While much focus in the literature has been given to both VO_2max and fractional utilization, it is evident that CR also plays a role in the overall performance of elite distance runners. It has been demonstrated that a lower CR allows runners with lower VO_2max values to have similar performances as those with higher VO_2max values (Pollock, 1977). Additionally, developing a low CR allows runners to improve

performance despite no change or even a drop in VO_{2max} (Jones, 2006). Thus, anything that helps elite runners to achieve a lower CR and thus improve performance is of great interest to athletes, coaches, and physiologists. There are many things that can affect CR including but not limited to body size (Foster et al., 2010), wind resistance (Pugh, 1970), surface (Foster et al., 2010), fatigue (Giminez et al., 2013), and foot strike patterns (Gruber et al., 2013).

One factor that may affect CR that has not yet been studied is pace variation. According to Foster, de Koning, and Thiel (2014), world record performances in the one-mile run are evolving into more evenly-paced races. Previous world record runs in the mile were achieved by a “fast-slow-slowest-fast” lap pattern (Noakes, 2009). However, the more recent world records have been completed with a much more even pacing pattern, possibly to avoid wasting kinetic energy that comes from having to accelerate and decelerate the body. Even though an even pacing pattern has been shown to be highly related to world record performances, it is typically not the pattern of competitive races in which a win rather than a record is the goal. Data published by Thiel, Foster, Banzer & De Koning (2012) from the 2008 Olympics revealed that in the finals of the long-distance events, runners varied their pace frequently throughout the race. When broken down into 100-m segments, the nature of these races was highly stochastic and did not match the even pacing patterns of the world record performances in those same events.

Currently the CR is almost universally measured during a constant pace run of 4-10 minutes. Unfortunately, a constant pace does not reflect the nature of competitive races. Stochastic variations in pace during these races could potentially affect CR and

may be the reason why runners are using even pacing patterns in world record performances. Therefore, the purpose of this study was to measure CR during varied pace running and compare it to the CR of constant pace running. The hypothesis was that CR would be higher during varied pace running, and that the more a runner varied their pace, the higher the CR would be.

METHODS

Subjects

The subjects in this study were 20 trained runners (men n=12, women n=8) from the cross-country and track teams at the University of Wisconsin – La Crosse or well-trained runners from the community. All runners had an extensive background of training and were physically fit and healthy. Physiological data as well as data related to the subjects' training was collected. The volume of training was calculated as the total distance (km) the subjects were accumulating per week in their training logs. Running points were determined from Gardner & Purdy's (1986) running point system and are based on the subject's best recent performance in a competitive race or time trial. Approval was obtained from the Institutional Review Board for the Protection of Human Subjects at the University of Wisconsin – La Crosse. Each subject provided written informed consent prior to the testing. Descriptive characteristics of the subjects are displayed in Table 1.

Table 1. Descriptive characteristics of the subject population (n=20)

Subjects	Men (n=12)	Women (n=8)	All (n=20)
Age (years)	20.8 ± 1.9	21.6 ± 1.3	21.2 ± 1.7
Height (cm)	178.8 ± 5.6	168.1 ± 6.2	174.5 ± 7.8
Weight (kg)	69.0 ± 7.1	55.6 ± 6.3	63.7 ± 9.4
VO ₂ max (ml·kg ⁻¹ ·min ⁻¹)	72.8 ± 6.8	57.1 ± 6.0	66.5 ± 10.1
VO ₂ @ VT (ml·kg ⁻¹ ·min ⁻¹)	53.5 ± 6.4	45.8 ± 4.1	5.0 ± 0.6
vVO ₂ max (m·s ⁻¹)	5.4 ± 0.5	4.5 ± 0.3	302.8 ± 37.3
Velocity @ 90% VT (m·s ⁻¹)	3.7 ± 0.4	3.3 ± 0.2	3.5 ± 0.4
CV 1 (%)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
CV 2 (%)	1.3 ± 0.1	1.5 ± 0.1	1.4 ± 0.1
CV 3 (%)	4.0 ± 0.4	4.5 ± 0.2	4.2 ± 0.4
CV 4 (%)	6.7 ± 0.6	7.5 ± 0.3	7.0 ± 0.7
HR _{max} (bpm)	187.7 ± 7.3	185.3 ± 10.5	186.7 ± 8.4
Training volume (km/week)	52.7 ± 19.4	30.6 ± 15.5	43.4 ± 20.7
Average training pace (m·s ⁻¹)	3.8 ± 0.2	3.4 ± 0.2	3.6 ± 0.3
Interval training (sessions/week)	0.8 ± 0.7	0.8 ± 0.9	0.8 ± 0.8
Running points (Gardner & Purdy, 1986)	699.1 ± 193.6	403.8 ± 119.8	574.7 ± 221.0

VO₂max = Maximal oxygen consumption

VT = Ventilatory Threshold

vVO₂max = Velocity at VO₂max

CV 1 = Coefficient of Variation of running speed at constant speed

CV 2 = Coefficient of Variation of running speed with pace variation of 0.04 m·s⁻¹

CV 3 = Coefficient of Variation of running speed with pace variation of 0.13 m·s⁻¹

CV 4 = Coefficient of Variation of running speed with pace variation of 0.22 m·s⁻¹

HR_{max} = Maximal heart rate

Protocol

Each subject performed two trials. Trial 1 consisted of an incremental maximal treadmill test to determine maximal oxygen uptake (VO_2max) and ventilatory threshold (VT). Ventilatory threshold which is known to occur at about the same time as LT (Foster & Cotter, 2006) was determined to ensure that steady state speeds were selected in Trial 2. The purpose of using VT rather than LT was simply the greater ease of detection of VT. The treadmill grade was held constant at 1% to account for the lack of wind resistance in the laboratory (Jones & Doust, 1996). The speed was incremental from walking ($1.3 \text{ m}\cdot\text{s}^{-1}$) to maximal running in increments of 0.5 mph ($0.22 \text{ m}\cdot\text{s}^{-1}$) during each minute. At least 24 hours after the preliminary VO_2max test, each subject completed Trial 2. Trial 2 consisted of four, 6-minute intervals with two minutes of walking between each interval. The average speed of each run was determined as the speed at which the subjects reached 90% VT in their maximal test. This was to ensure steady-state, which is necessary for calculating CR. Each of the intervals was run at a different pace variation around the average speed. The pace variations for each of the intervals were set as 0.0 mph (constant speed), 0.1 mph ($0.04 \text{ m}\cdot\text{s}^{-1}$), 0.3 mph ($0.13 \text{ m}\cdot\text{s}^{-1}$), or 0.5 mph ($0.22 \text{ m}\cdot\text{s}^{-1}$) and the order of the intervals was counterbalanced. The pace alternated above and below the average speed every minute. The slower segments were run first. An example of the protocol for Trial 2 is presented in Table 2. In this example, the subject's speed at 90% VT was determined as 7.5 mph ($3.35 \text{ m}\cdot\text{s}^{-1}$). The first interval was run at a constant speed. The second interval was at a pace variation of 0.1 mph ($0.04 \text{ m}\cdot\text{s}^{-1}$), the third interval was run at a pace variation of 0.3 mph ($0.13 \text{ m}\cdot\text{s}^{-1}$), and the fourth interval was run at a pace variation of 0.5 mph ($0.22 \text{ m}\cdot\text{s}^{-1}$).

Table 2. Sample protocol for a subject whose speed at 90% VT was determined as 7.5 mph ($3.35 \text{ m}\cdot\text{s}^{-1}$).

Time (min)	Speed 1 ($\text{m}\cdot\text{s}^{-1}$)	Speed 2 ($\text{m}\cdot\text{s}^{-1}$)	Speed 3 ($\text{m}\cdot\text{s}^{-1}$)	Speed 4 ($\text{m}\cdot\text{s}^{-1}$)
1	3.35	3.31	3.22	3.12
2	3.35	3.39	3.48	3.57
3	3.35	3.31	3.22	3.12
4	3.35	3.39	3.48	3.57
5	3.35	3.31	3.22	3.12
6	3.35	3.39	3.48	3.57
7 (rest)	0.89	0.89	0.89	0.89
8 (rest)	0.89	0.89	0.89	0.89

To reflect the magnitude of the variation in pace, the Coefficient of Variation (CV) of running speed was determined for variation in pace. The average CV of running speed for the pace variations of 0.0 mph, 0.1 mph ($0.04 \text{ m}\cdot\text{s}^{-1}$), 0.3 mph ($0.13 \text{ m}\cdot\text{s}^{-1}$), and 0.5 mph ($0.22 \text{ m}\cdot\text{s}^{-1}$) were calculated as 0%, 1.4%, 4.2%, and 7.0% respectively.

For all tests, oxygen consumption was continuously measured using open circuit spirometry. Heart rate was continuously monitored using radio-telemetry and recorded as the average HR over the last two minutes of each interval. Blood lactate was measured after the end of each 6 minute interval using dry chemistry in blood obtained from a fingertip. Rating of perceived exertion (RPE) using the 10-point Borg Scale (Borg, 1998) was measured at the end of each 6-minute interval. Stride frequency was calculated as the amount of time it took the right foot to strike the ground 50 times. This was then converted to steps per minute ($50 \text{ steps}/\text{time (sec)} * 60 \text{ sec}/\text{min} = \text{steps}/\text{min}$). Stride frequency was determined during each speed of the varied pace intervals as well as during the constant pace interval. Stride frequency was measured during the first slow

stage as well and the first fast stage of each varied pace interval and also during the constant pace interval. The CR was calculated using the average VO_2 during the last 2 minutes of each interval and expressed as the VO_2 required to run 1 km. CR of each varied pace run was then compared with the CR of the constant pace run.

Statistical Analysis

The difference in CR, expressed in relation to the CV of running speed within each run was evaluated using repeated measures ANOVA. Post-hoc tests were done using the Tukey Test. Alpha was set at 0.05 to achieve statistical significance.

RESULTS

The physiological responses to the pace variations were expressed in relation to the Coefficient of Variation (CV) of running speed. Pace variations had no significant effect on CR (Figures 1&2). Similarly, pace variations had no significant effect on HR (Figure 3), blood lactate (Figure 4), RPE (Figure 5). A significant difference ($p<0.05$) was found for stride frequency for all pace variations (Figure 6).

The average CR for each CV of running speed is presented in Figure 1. No significant difference ($p=0.49$) in CR was detected among the pace variations (227.1 ± 16.2 at 0% CV, 227.8 ± 16.6 at 1.4% CV, 225.9 ± 13.5 at 4.2 % CV, and 227.0 ± 15.7 at 7.0% CV). No significant difference ($p=0.35$) was noted between genders (Males: 227.9 ± 20.5 at 0% CV, 228.2 ± 21.2 at 1.4% CV, 225.4 ± 16.9 at 4.2%, and 226.0 ± 19.6 at 7.0% CV; Females 226.9 ± 7.3 at 0% CV, 227.3 ± 6.6 at 1.4 % CV, 226.9 ± 6.8 at 4.2% CV, and 228.4 ± 7.8 at 7.0% CV)

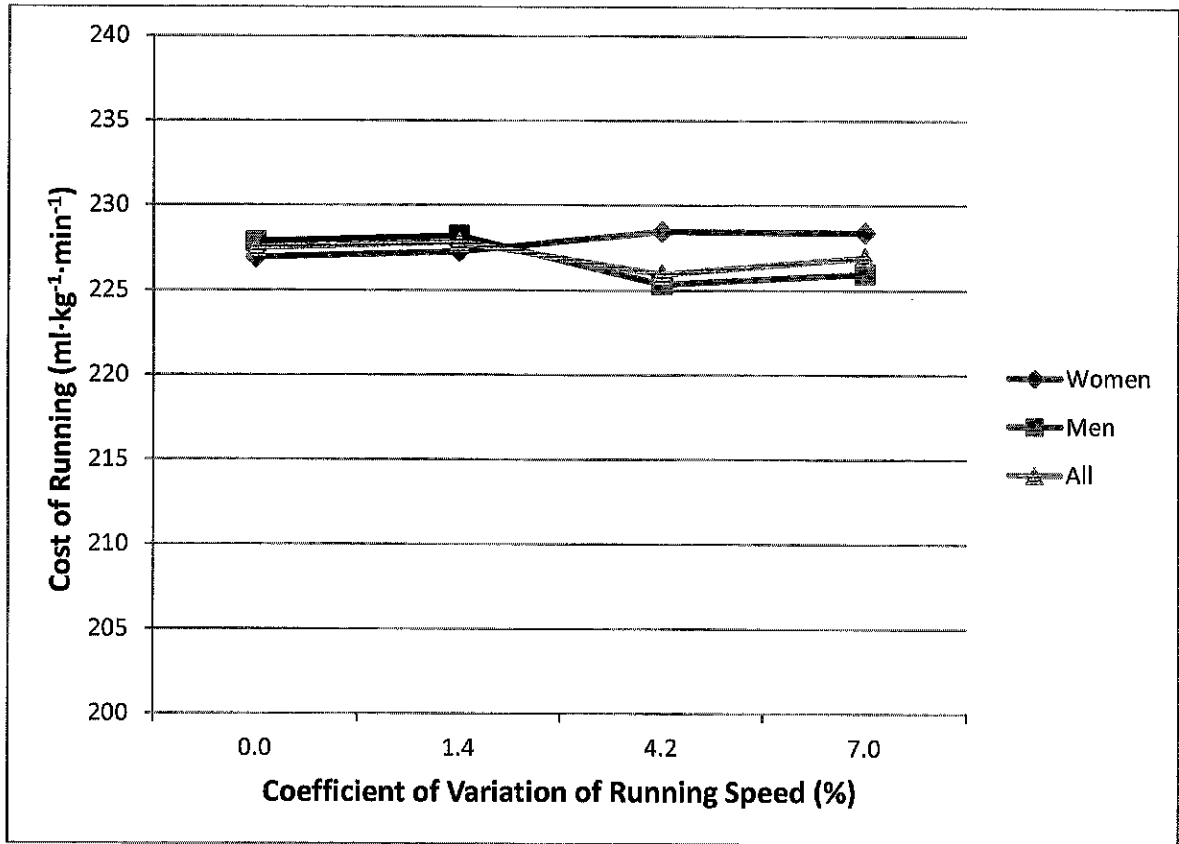


Figure 1. Average Cost of Running in relation to the Coefficient of Variation of running speed separated into categories of Men, Women and All.

The CR for each subject is displayed in Figure 2. There there was a wide variance in CR within the sample. The dashed line represents the average CR for each average CV of running speed. The smaller solid lines represent each individual's CR and CV of running speed. Two subjects had a very high CR indicating that they were inefficient compared to the rest of the group. The rest of the subjects were more efficient with CR values between 200-240 ml/kg/km. However, there was no evidence of a systematic variation in CR in relation the CV of running speed.

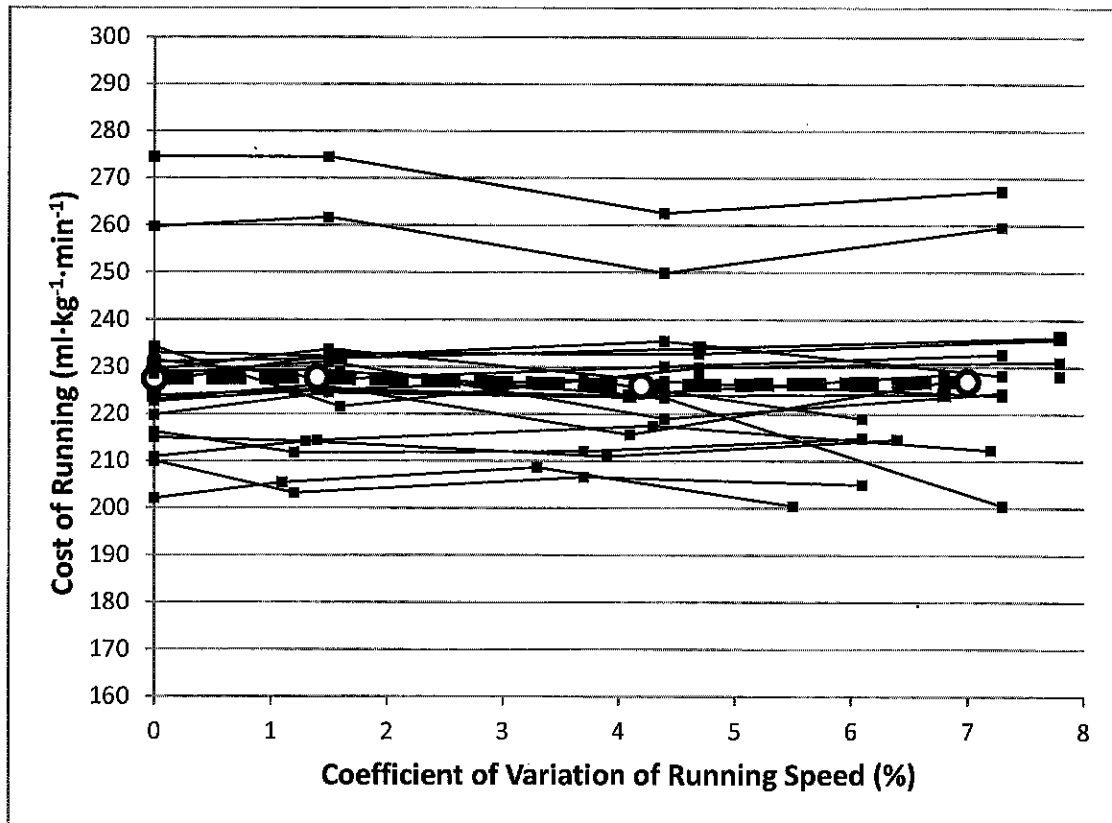


Figure 2. Super subject graph of each subject's Cost of Running with respect to the Coefficient of Variation of running speed.

The average HR in relation to the CV of running speed is presented in Figure 3.

No significant difference in HR was detected among the pace variations ($p=0.055$).

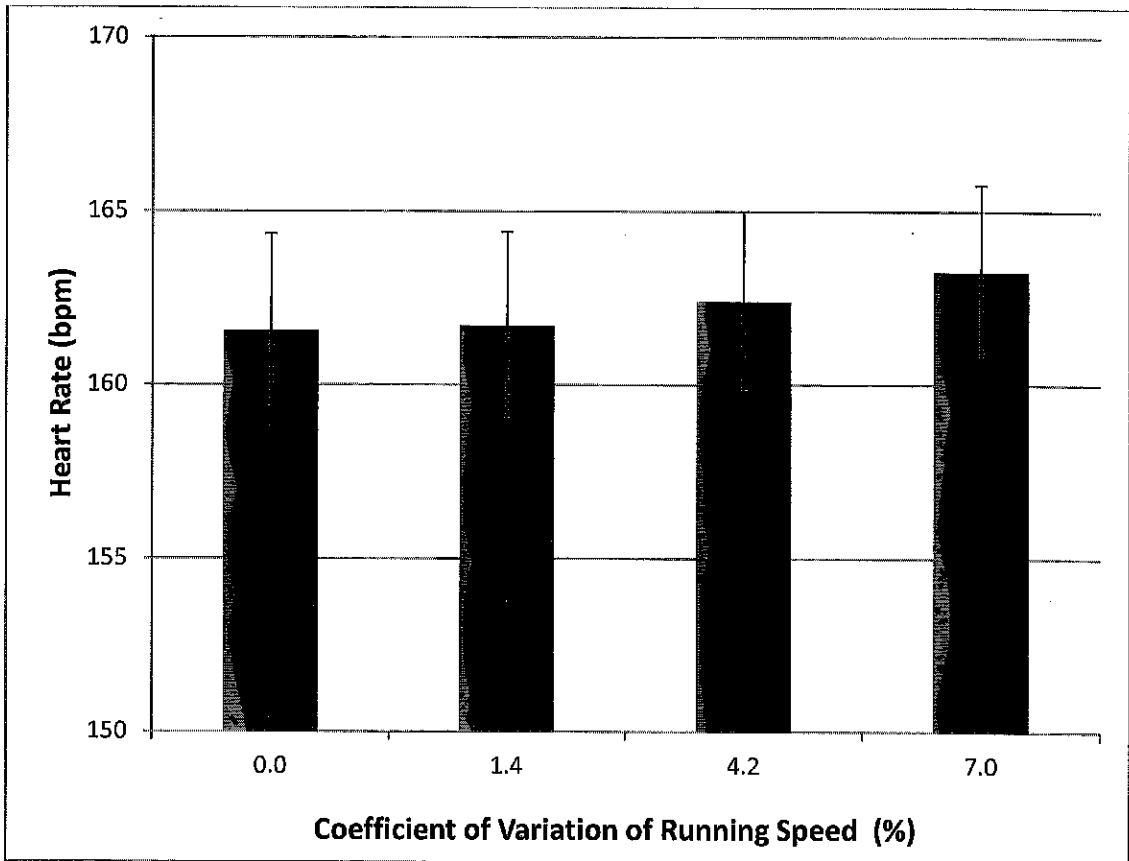


Figure 3. Average heart rate response for each Coefficient of Variation of running speed.

The average blood lactate samples are displayed in Figure 4. No significant difference was found in blood lactate concentration among the pace variations ($p=0.52$).

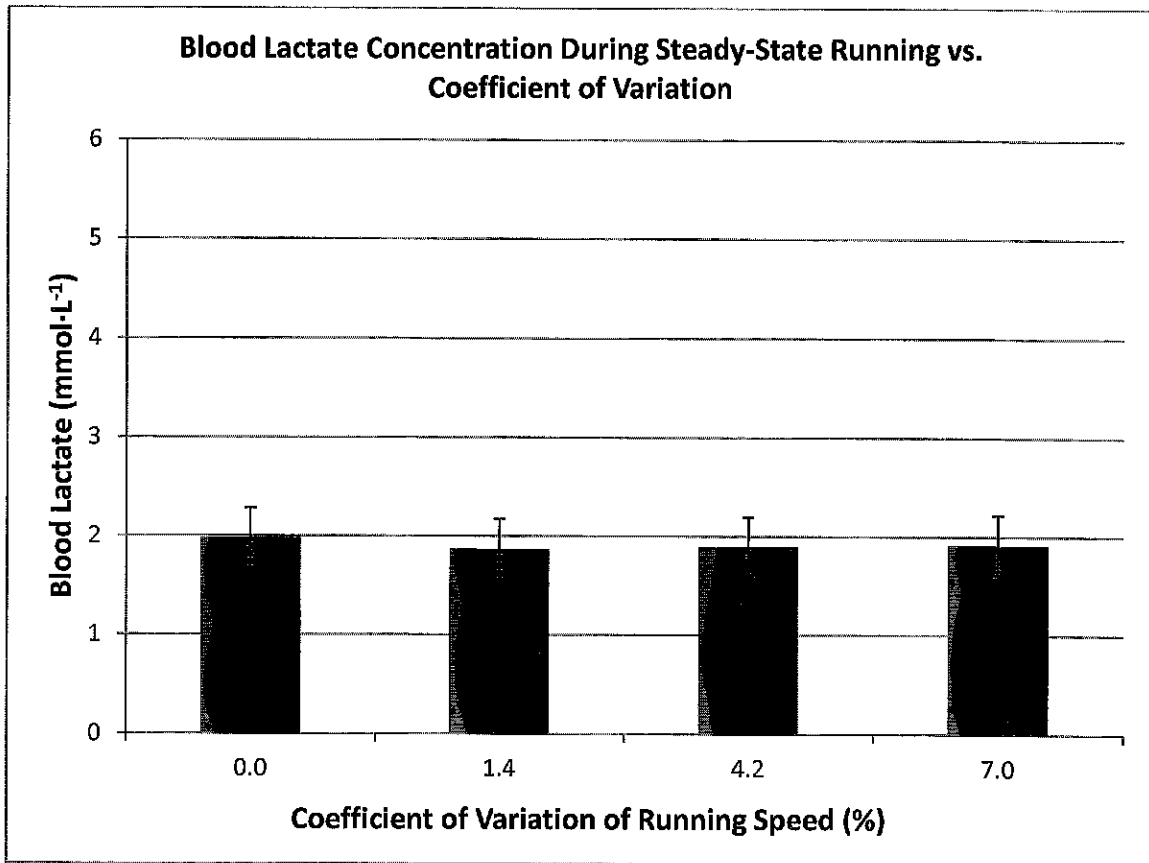


Figure 4. Average blood lactate responses to each Coefficient of Variation of running speed.

The average RPE in relation to the CV of running speed is presented in Figure 5.

No significant difference in RPE was found among the pace variations ($p= 0.053$).

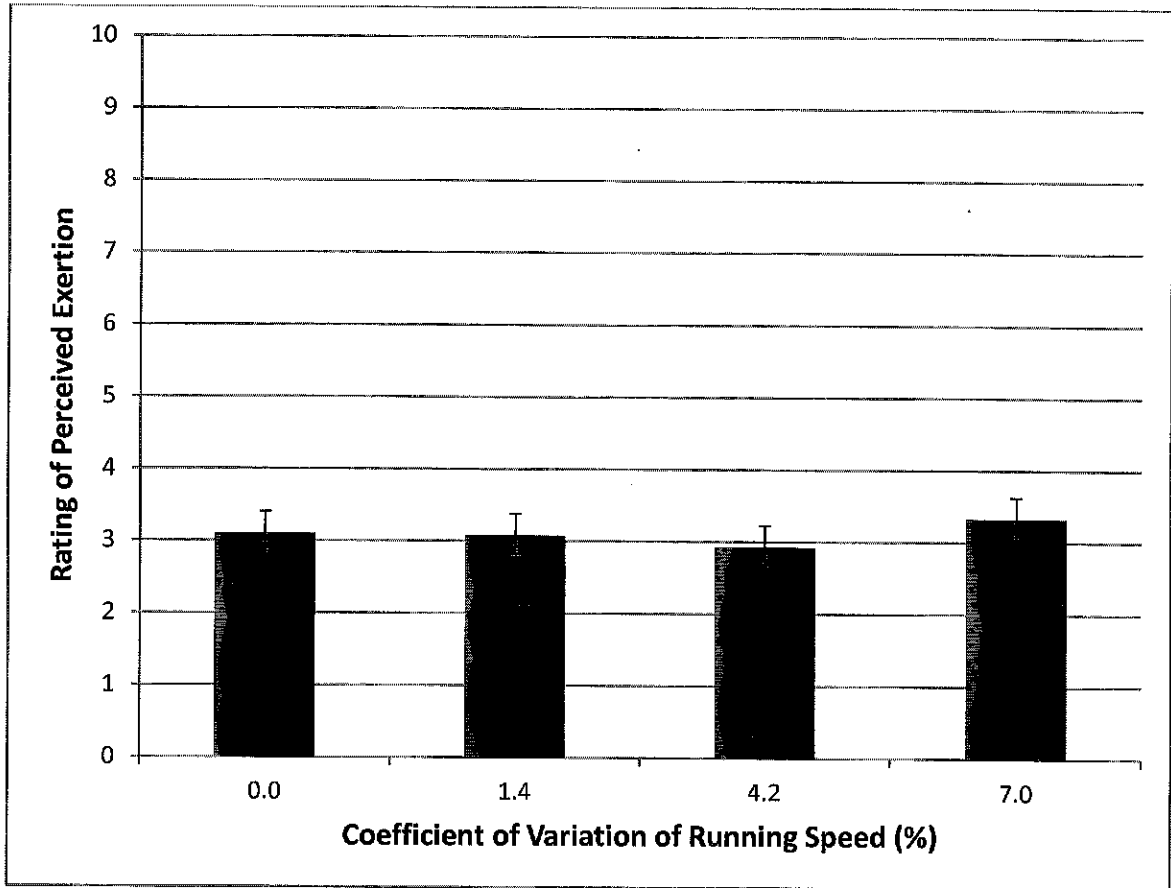


Figure 5. Average Rating of Perceived Exertion in response to each Coefficient of Variation of running speed.

Figure 6 displays the average stride frequency for each pace variation during the fast and slow stages. Statistical analysis showed a significant difference ($p < 0.05$) among all of the pace variations for stride frequency during the fast stage. However, the differences between the means were small and could not explain a significant difference in CR. Therefore, this finding was considered practically insignificant. There was no significant difference ($p = 0.09$) in stride frequency during the slow stage.

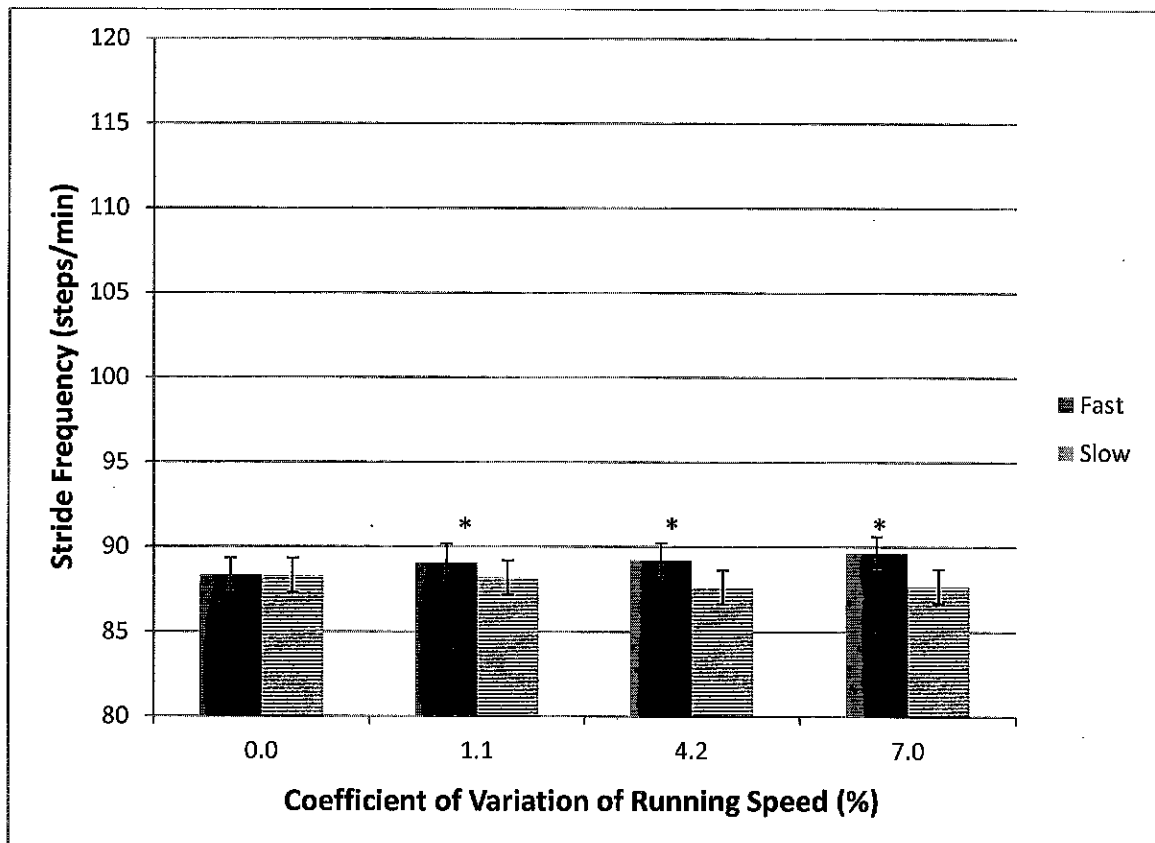


Figure 6. Average stride frequency during fast and slow stages for each interval in response to each Coefficient of Variation of running speed.

* Indicates a significant difference from stride frequency (fast) at 0.0% CV of running speed.

DISCUSSION

The primary purpose of this study was to investigate how small variations in pace around a local average speed affect CR. In order to do this, subjects completed 6 minute intervals in which the pace was increased and decreased every minute around a local speed that coincided with 90% VT (to ensure steady-state). The changes in speed ($0.04 \text{ m}\cdot\text{s}^{-1}$, $0.13 \text{ m}\cdot\text{s}^{-1}$ and $0.22 \text{ m}\cdot\text{s}^{-1}$) coincided with an average CV of 1.4 ± 0.13 , 4.2 ± 0.40 , and 7.0 ± 0.67 % of running speed. A fourth interval was run with no changes in speed (0% CV) as a control. It was found that with an average of 1.4, 4.2, and 7.0 % CV in running speed, there was no significant change in CR when compared with constant pace running. In addition, the pace variations had no significant effect on HR, blood lactate, or RPE. However, a significant difference in stride frequency across all pace variations was found.

The hypothesis was that pace variation would increase the CR because of the energy it requires to accelerate and decelerate the body. However, results did not support an increase in CR with an increase in the CV of running speed. Based on these findings, the hypothesis that pace variation around a local average speed increases CR was rejected. Results for HR, blood lactate, and RPE supported this finding. If pace variations had significantly increased CR during each interval, then significant increases in HR, blood lactate, and RPE should have also been present at each interval. Results for stride frequency showed a significant difference across the pace variations but since the

differences were small and were not matched with similar differences in CR this finding was considered practically insignificant.

Cost of running, which has only been measured at a constant pace up until the present study, is a popular topic in distance running research because of its relationship with successful performance. Pollock (1977) measured running economy (VO_2 at a fixed speed) showed that it was the reason for similar performances between elite runners despite large differences in their maximal aerobic capacities. More recently, Jones (2006) found that it could explain Paula Radcliffe's continuously decreasing times by decreasing CR over a 6 year period despite a decrease in $\text{VO}_{2\text{max}}$. In addition, the dominating performances of Elite East Africans at the global level can be explained by a significantly lower average CR compared to the average CR of European and North American runners (Foster & Lucia, 2007). When compared to these elite groups the runners in the present study had a much higher (i.e. worse) CR (Figure 8). When compared to an average runner's CR based on ACSM calculations, the runners in the present study were only slightly more efficient.

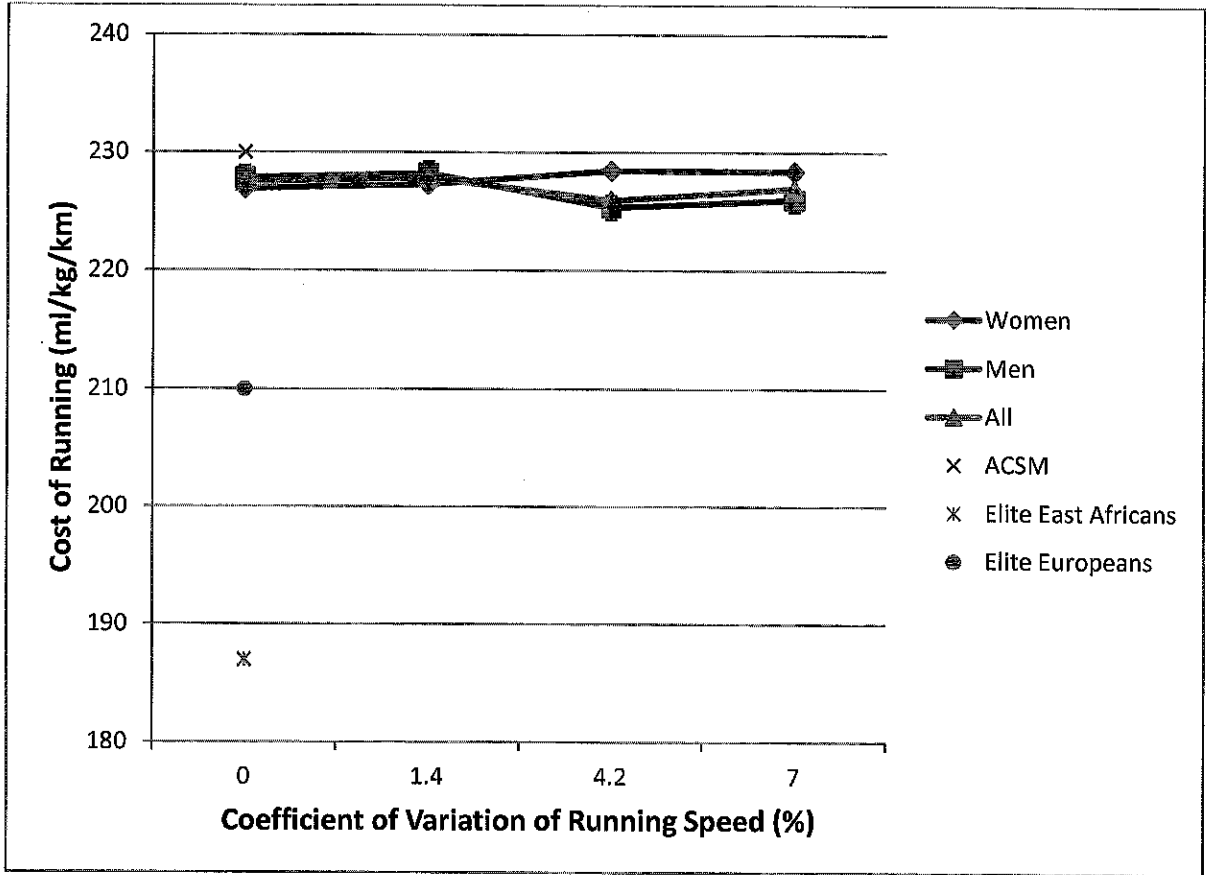


Figure 8. Cost of running of subjects in the present study compared to elite European, East African, and ACSM reference values.

There are numerous significant factors that can affect CR, but the present study is the first to assess the relationship between pace variation and CR. No previous studies have investigated CR in regards to pace variation and further research is needed to investigate its effects. It could be suggested to repeat the same study on an outdoor or indoor track surface since on a treadmill an athlete's center of gravity is neither accelerated nor decelerated. However, Basset et al. (1985) found no significant differences in aerobic energy requirements between uphill track and treadmill runs when at constant speeds of 180-260 m/min. This argues that repeating the present study on a different surface would likely produce similar results to the present study.

As previously mentioned, the world-record pattern in the mile run is evolving into an evenly-paced race rather than the classic "fast-slow-faster-fastest" lap pattern that was common in the past (Noakes et al., 2009, Foster, 2013). From the present data, we have demonstrated that small variations in pace do not significantly affect CR when below the VT/LT. We may assume these results extrapolate to higher speeds but more research is needed to explain how pace variations affect performance at higher speeds. Above VT/LT, CR can no longer be measured due to VO_2 drift and more factors that may come into play. An alternative explanation to running an even pace is that it may simply help the runner to avoid wasting his or her kinetic energy by high velocity on the final lap when that same energy could have been used to help the runner achieve an overall faster pace throughout the entire race.

CONCLUSION

CR is an important determinant of success in the performance of highly trained and elite runners. Athletes, coaches, and physiologists should pay attention to the factors that significantly decrease or increase CR. This study demonstrated that small variations in pace, representing a CV of running speed from 0 to 7% do not significantly affect CR. Additionally there was no effect on HR, blood lactate, RPE. A significant increase in stride frequency was found across the pace variations but these results did not line up with a significant difference in CR and were therefore considered practically insignificant. Further research is needed to investigate the effects of pace variation on CR at more competitive speeds, but the findings of the present study support the current method of measuring CR at a constant pace as a robust approach when measuring VO_2 below the VT/LT.

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APPENDIX A
INFORMED CONSENT

INFORMED CONSENT for “The Effects of Pace Variation on the Cost of Running in Highly Trained Runners.”

I, _____, give my informed consent to participate in this study designed to determine the effects of pace variance on the energy cost of running. I have been informed that the study is under the direction of Carl Foster, Ph.D. who is a Professor in the Department of Exercise and Sport Science at the University of Wisconsin-La Crosse. I consent to presentation, publication, and other release of summary data from the study that is not identifiable with me.

I have been informed that my participation in this study will:

- a. Require me to perform one maximal treadmill test and one sub-maximal treadmill test both of which will require me to wear a snorkel-like device to analyze my breathing and a heart rate monitor, strapped around my chest, to monitor heart rate.
 - b. Require me to have my performance measured quantitatively by measuring my oxygen cost of running, heart rate, blood lactate and rate of perceived exertion. I understand that my individual results will contribute to overall group data that may eventually be published. However, any information released will not identify me personally.
 - c. Require approximately 3 hours total time over two days and take place in the Human Performance Lab, Mitchell Hall, UW-L.
2. I have been informed that there are no risks associated with this study other than the fatigue and muscle soreness associated with higher intensity exercise, and the minor

discomforts associated with drawing blood from the fingertip and wearing the snorkel-like oxygen device.

3. I have been informed that there are no primary benefits to myself other than knowledge of my VO₂max, Ventilatory Threshold, oxygen cost of running at both even and varied paces, and my physiological responses such as heart rate, blood lactate, and rate of perceived exertion. I understand that while this study has no direct benefit to me, it does provide free exercise testing that I normally would not have available to me. Based on the results of this study, we may be better able to understand the energy cost of running by measuring it at a varied pace rather than a constant pace, adding to the existing research.
4. I have been informed that the investigator will answer any questions I have regarding the procedures throughout the course of the study.
5. I have been informed that any personal, identifiable information will be kept confidential and will not be shared with anyone outside of the research staff and thesis committee who are responsible for analyzing the data. Only average data, or data blinded to individual identity, will be published or presented.
6. I have been informed that I am free to decline to participate or to withdraw from the study at any time without penalty.
7. Concerns about any aspects of this study may be referred to:

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Questions regarding the protection of human subjects may be directed to the UW-La Crosse Institutional Review Board for the Protection of Human Subjects, (608-785-8124 or irb@uwlax.edu.)

Investigator: _____

Date: _____

Participant (print name): _____

Signature: _____

Date: _____

APPENDIX B
RATING OF PERCEIVED EXERTION

RATING OF PERCEIVED EXERTION

RPE	DESCRIPTION
0	No Effort (standing at rest)
0.5	Very, Very Easy
1	Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	
7	Very Hard
8	
9	Very, Very Hard (near maximal)
10	Maximal

Source: Borg, G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

APPENDIX C
REVIEW OF THE LITERATURE

REVIEW OF THE LITERATURE

The purpose of this paper is to review the literature regarding the physiological determinants of distance running performance, including maximal aerobic capacity, fractional utilization of $VO_2\text{max}$, lactate threshold, and cost of running.

Aerobic Capacity

Maximal aerobic capacity ($VO_2\text{max}$) is known as the best objective laboratory measurement of cardiorespiratory endurance. $VO_2\text{max}$ is defined as the highest rate of oxygen consumption achieved during maximal or exhaustive exercise, and it is measured as the point at which oxygen consumption plateaus, despite an increased intensity of exercise (Wilmore, Costill, & Kenney, 2008). The early research of Hill and Lupton (1924) first described $VO_2\text{max}$ and its relationship to the limits of human endurance performance. Further findings by Saltin & Astrand (1967) supported this relationship. In their study, over 100 elite Swedish national team athletes underwent maximal treadmill testing. Results showed higher $VO_2\text{max}$ values for athletes competing in endurance related events (e.g. cross-country skiing, orienteering, and long distance running) and lower $VO_2\text{max}$ values for athletes competing in strength and technique related events such (e.g. wrestling, gymnastics, and weight lifting). Thus, high $VO_2\text{max}$ values were considered necessary for successful performance in endurance events, but not necessary for success in strength and technique related events.

Pollock (1977) investigated the differences in the submaximal and maximal

metabolic characteristics of a sample of elite runners in order to observe if there were any specific differentiations between various types of runners. Results showed that elite runners (ER) when compared to moderately trained runners and untrained runners had superior VO_2max values. However, when the ERs were separated into marathon and middle to long distance runners (M-LD), the M-LD group had significantly higher VO_2max values while the marathon group had significantly lower submaximal VO_2 values than the M-LD group. These findings showed that subtle differences do exist between different types of ERs while also demonstrating the superior aerobic capacities of ERs when compared to amateur runners.

Levine (2008) investigated numerous studies on VO_2max . According to Levine, VO_2max is an important determinant of performance because of its relationship to cardiorespiratory capacity and its ability to be measured in any individual at any given level of fitness. Additionally, he describes VO_2max as a primary distinguisher in the characteristics of elite endurance athletes because it allows them to run faster for long periods of time as a result of a well-developed cardiac capacity and the ability to generate a large stroke volume. Lastly, Levine explains how VO_2max helps to understand the limits of endurance performance because of what is happening functionally once it is reached. Once VO_2max is reached, it cannot be sustained for long periods of time because of functional alterations at the local muscle that limit oxygen transport and eventually lead to the cessation of central motor drive and voluntary effort.

Joyner & Coyle (2008) discussed the physiology of endurance athletes citing VO_2max , LT, and performance VO_2 as the most important determinants of success. Additionally, they laid out the performance requirements of VO_2max for current elite

runners. For current endurance athletes, a VO_2max value of 70-85 ml·kg⁻¹·min⁻¹ (10% lower in women) is required to perform at the elite level. Additionally, elite athletes should be able to work at 75-85% VO_2max before reaching their LT.

Fractional Utilization

While VO_2max is known as an important component in endurance related events, it is not considered the best indicator of performance. Rather, the ability to utilize a large fraction of aerobic capacity (% VO_2max) is a better predictor of performance. This was supported by Costill, Thomason, and Roberts (1973) who studied a group of highly trained runners of similar aerobic capacities and discovered a high correlation between running performance and the fraction of VO_2max achieved. After maximal and submaximal testing was completed on the subjects, they competed in a 10-mile road race. The runners who finished with faster times achieved higher % VO_2max but did not always have the highest VO_2max values in the group. Conley and Krahenbuhl (1980) studied % VO_2max in 12 of the top 19 performers in the 10k. The subjects in this study underwent maximal treadmill testing followed by submaximal treadmill testing at three different speeds that correlated to their running speeds in the 10k race. Those who achieved a higher % VO_2max at the submaximal speeds also had better performances in the 10k race. From this study it was concluded that 65.4% of the variation observed in the performances of the runners in 10k race was due to their differences in % VO_2max .

Weston, Mbambo, and Myburgh (1999) measured running economy by calculating % VO_2max in African and Caucasian 10k runners of similar body mass and performance. The subjects completed one peak treadmill test and two 6-minute submaximal tests, one at a common speed of 16.1 km/h and the other at 10k race pace.

Results showed VO_2peak values to be 13% lower in the African runners than the Caucasian runners. At 16.1 km/h, the Africans were 5% more economical. This study showed that while Africans had much lower VO_2peak values, their similarity in performance to their Caucasian counterparts was related to rather to better running economy or the ability to employ a higher % VO_2peak . This study further demonstrated how % VO_2max can compensate for lower VO_2max values in runners and still produce successful performance.

Hoyos, Pérez, Santalla, and Chicharro (2002) completed a study on world class cyclists to determine the relationship between VO_2max and cycling economy/efficiency during intense, sub-maximal exercise. Eleven male cyclists performed a maximal test for VO_2max determination followed by a constant-load test of 20 minutes at a fixed power output. The main finding of this study was that both cycling economy and gross mechanical efficiency were inversely correlated to VO_2max . Thus, a higher cycling economy and gross mechanical efficiency could compensate for lower VO_2max values in cyclists. These studies clarify that in addition to a high VO_2max value, the best performers in endurance related events must be able to achieve a high % VO_2max . Joyner & Coyle (2008) provide values for the % VO_2max required for various elite distance races. In the marathon elite runners must be able to compete at 85-90% of their VO_2max . In the 10k, the % VO_2max required should be near 95%, and in the 5k % VO_2max should be very close to or at 100% VO_2max .

Lactate Threshold

Lactate threshold (LT) is an important physiological marker associated with endurance performance. Lactate threshold in trained individuals allows them to exercise at a higher %VO₂max before lactate begins to accumulate in the blood (Wilmore, Costill, & Kennedy, 2008). In addition to %VO₂max, LT is strongly associated with the speed that a runner can generate (Joyner & Coyle, 2008). Therefore, it can be concluded that the higher the LT, the better the aerobic performance. The ability to work at higher rates with little lactate accumulation has been shown to be related to both a reduced lactate production as well as an increased lactate clearance (MacRae, Dennis, Bosch, & Noakes, 1992).

An early study conducted by Costill (1970) on the relationship of blood lactate to %VO₂max examined the changes in blood lactate in a group of highly trained runners during prolonged, exhaustive running at varied intensities and durations. The tests consisted of maximal and submaximal treadmill runs from 5 to 120 minutes. Determinations of lactate were also made after competitive distance races that ranged from 1.61 to 42 km. Based on these measurements, an inverse curvilinear relationship between race distance and blood lactate concentration was discovered. Lactate accumulation was found to be higher for shorter races than it was for longer races. Costill found that when %VO₂max was less than 70%, there was little to no increase in lactate. The same was true in two hours of running between 55-67%. The best runners in this study were able to achieve 90% VO₂max for 25-30 minutes with only moderate accumulation of lactic acid.

In the same study that Costill et al. (1973) found a correlation between %VO₂max

and performance, a correlation with blood lactate concentrations was also found. The faster runners in this study were not only able to achieve higher % VO_2max values but were also able to run at higher speeds with significantly less lactate than the slower runners.

Allen, Seals, Hurley, Ehsani, and Hagberg (1985) also conducted a study on the relationship of blood lactate to % VO_2max in older well-trained runners compared to younger non-trained runners. Because these two groups had shown to achieve similar performances in 10k road races, a study was done to compare the physiological determinants of each group. The older well-trained runners were matched with younger non-trained runners based on similar performances and both groups underwent maximal and submaximal treadmill testing. The submaximal testing consisted of several 10-minute bouts of treadmill running ranging from 60-100% VO_2max with one of the bouts performed at a velocity equal to the subject's running speed during their competitive 10k road race. The results of these tests indicated that running economy was not different between the two groups. However, the well-trained older athletes reached their LT (defined as 2.5 mM blood lactate) at a higher % VO_2max than the younger runners even though this lactate level was achieved by both groups at the same speed and oxygen consumption. In conclusion, the older well-trained athletes were able to have similar performances to the younger runners because of their ability to work at a higher % VO_2max before reaching LT.

Svedenhag and Sjodin (1985) further demonstrated a relationship between LT and running economy in their study involving 10 elite male runners from the Swedish national track and field team. This study investigated the physiological changes that

occurred in these runners over one year of training including VO_2max , % VO_2max , and running velocity corresponding to blood lactate concentrations. Treadmill testing was completed on four occasions: in January, in May, during the highly competitive summer months, and the following January. VO_2max increased successively throughout the season with the highest values obtained during the summer period. From the end of the summer period to the next winter period, VO_2max values significantly decreased. Running economy was shown to improve throughout the year, with better values occurring in the summer period than in the first January, and with even lower values being achieved by the time of the second January. Following a similar pattern, running velocity corresponding to a lactic acid concentration of 4 mmol L^{-1} increased significantly from January to May and then remained at this higher level for the remainder of the year. This effect seemed to be caused by the improvement in running economy since VO_2max and % VO_2max were similar to the values obtained at the beginning of the year.

Furthermore, Jacobs (1986) examined several studies that contrast the relationship of VO_2max to endurance performance and the relationship of blood lactate concentration to the same endurance performance. In every study, the lactate variable was shown to have more correlations with performance than VO_2max . Additionally, Jacobs discussed the marked effectiveness of using the LT to prescribe exercise intensity rather than % VO_2max or maximal heart rate.

The importance of the LT to endurance training is perhaps best summarized by Foster & Cotter (2006) who describe three practical reasons for its significance. First, they point out that LT is highly related to the % VO_2max that a person can sustain which

is able to “increase with training beyond the point where $VO_2\text{max}$ fails to increase.” As a result, it may be possible for the LT to detect changes in fitness due to training much more sensitively than $VO_2\text{max}$. Second, they indicate that LT is strongly associated to performance in endurance-related activities and may provide a better measure of endurance capacity than $VO_2\text{max}$. Third, they discuss that LT could potentially provide better guidelines for exercise intensity during training as many physiologists and coaches are now using it to set the upper-limit intensity for exercise training in their athletes. This is being done because it provides a high rate of aerobic metabolism without the adverse effects that result from disturbing the acid-base balance in the body during intense exercise. Training at intensities associated with the LT is thought to optimize performance while training above the LT could potentially be a detriment to performance.

Cost of Running

It is evident that $VO_2\text{max}$, $\%VO_2\text{max}$, and LT are important determinants of distance running performance (Joyner & Coyle, 2008). At the elite level, however, all of these determinants will be similar across a field of runners. When all of these determinants are the same, the best indicator of performance is known as the cost of running (CR). CR is calculated by extrapolating running economy to a common speed or by expressing it in terms of the oxygen consumption required to run one kilometer (Foster & Lucia, 2007). This allows for comparison of CR amongst a field of runners and helps to determine the better performers by identifying those with lower CR values.

Bosch, Goslin, Noakes, and Dennis (1990) conducted a study to investigate the disproportionate success of African runners. In this study they compared the

physiological characteristics of nine black and ten white sub-elite South African runners. The test subjects first completed a VO_2max treadmill test and after rest completed a treadmill marathon. The running speed during the treadmill marathon was determined based on each subject's ventilatory threshold and both groups ran at 86-88% of the speed that they had recently achieved in a competitive marathon race. Measurements such as body weight, blood lactate, skin temperature, oxygen consumption, respiratory exchange ratio (RER), and heart rate (HR) were measured during the treadmill marathon. Important findings showed that the black South African runners were shorter and lighter than the white runners and also had lower relative VO_2max values. Despite their lower VO_2max values the black South African runners were able to achieve a significantly higher % VO_2max during the treadmill marathon race, but the reason for this remained unclear.

Weston, Mbambo, and Myburgh (1999) further investigated this topic by measuring the running economy, % VO_2max and blood lactate concentrations in African and Caucasian runners. The runners in this study were matched in both 10k performances and size. Anthropometric measurements were taken in addition to a VO_2max treadmill test. A sub-maximal test consisting of two different workloads, one at 16.1 km/h and the other at 10k race pace was also completed by the subjects. Significant findings in this study showed that African runners had lower VO_2max values than Caucasian runners but were able to achieve the same performance because of their ability to achieve a higher % VO_2max . The better running economy helped to further explain the unbalanced success of elite African distance runners. However, the reason behind the better running economies of the African runners continued to remain unclear.

Lucia et al. (2006) were the first to demonstrate a correlation between running

economy and body size. This study compared elite Eritrean runners to elite Spanish runners and found an inverse correlation between the maximal calf circumference and oxygen consumption at a common running speed. This correlation was discovered throughout the entire group (Eritrean and Spanish runners) suggesting that CR had a stronger relationship to body circumferences than to racial distinction. The Eritrean runners, however, were found to have smaller calf circumferences in general, which helped to explain their superior running economy.

Foster et al. (2006) demonstrated that CR was not just related to small calf circumference but to an overall smaller body size. This finding diffused the notion that the dominance of elite Africans in long-distance running events was related to race. This review helped to explain why in general, runners tend to be smaller people, regardless of origin. While it is scientifically supported, it is also not difficult to understand on a common sense level, how running for a smaller individual would result in a lower energy cost to the body than it would for a larger individual. Thus, it can be concluded that the lower CR in elite Africans is more indicative of a smaller body size than a racial distinction.

Perhaps some of the best indicators that CR is a function of small body size are studies on world famous runners who were small in stature. One of these studies was conducted by Costill, Branam, Eddy, & Sparks (1971) on top Australian distance runner, Derek Clayton. Clayton, who was achieving world record records at the time, had only an average VO_{2max} but was found to be expending less energy than his competitors due to the development of a very low CR. Further research by Pollock (1977) demonstrated a notable finding in the comparison of two American long-distance runners, Steve

Prefontaine and Frank Shorter. Both runners had nearly identical times in various long distance races, yet Shorter had a $VO_2\text{max}$ of 71.2 ml/kg/min while Prefontaine obtained a value of 84.4 ml/kg/min. Shorter's performance was attributed to a low CR, while Prefontaine's performance seemed to depend more on his high $VO_2\text{max}$.

Further research by Jones (2006) on the current women's marathon world record holder, Paula Radcliffe, also demonstrated the significance of a low CR. One of the most notable findings was that Radcliffe's CR improved over the 5-year course of the study while her $VO_2\text{max}$ had decreased. Despite the drop in $VO_2\text{max}$, she was able to achieve an 8% improvement in her 3k time by developing a lower CR.

In 2007, Foster & Lucia calculated the CR in a group of elite East African runners and a group of elite European and North American runners. The data revealed a generally lower CR in the elite East African population than the elite European and North American population. When running economy was extrapolated to a common running velocity of 268 m/min (6-minute mile pace) Elite East Africans were consuming oxygen at a rate of 49 ml/kg whereas the elite European/North American were around rates of 55 ml/kg. A lower CR was also shown when running economy was expressed in terms of the oxygen consumption required to run 1 kilometer. For elite East Africans, the CR was 187 ml/min/kg while it was 210 ml/min/kg in the elite European/North American population. Based on this information we can see why elite East Africans tend to dominate long distance running events but we now know that it is a function of their smaller body size rather than a racial distinction.

Implications for Trained and Elite Runners

A recent review published by Coyle & Joyner (2007) explains the current criteria for optimal performance in highly trained and elite long-distance runners. We now know that these runners must have high VO_2 max values and be able to work at a high % VO_2 max over the duration of their event. These two factors come together to create the performance VO_2 , which is homogenous in groups of highly trained and elite runners. The determining factor in these groups then is the CR. The best performances will be obtained by the runners who are able to achieve the lowest CR and thus generate faster speeds without becoming fatigued.

Based on this information, CR has become the most important factor to highly trained and elite distance runners. Anything that affects CR is currently a popular topic of research in distance running performance. Many factors have been found to affect the CR, including uneven terrain, wind resistance, and thermal stress (Costill, 1972).

Daniels, Foster, Daniels, & Krahenbuhl (1977) demonstrated the importance of surface and altitude to the CR. They found that at similar speeds, track running is more demanding than treadmill running. They also found that track and treadmill running at sea level is more demanding than track and treadmill running at altitude.

Jones & Doust (1996) compared the cost of outdoor running to the cost of indoor treadmill running. They found that a 1% treadmill grade most accurately reflects the cost of outdoor running, and compensates for the lack of wind resistance when running indoors. This study has been widely accepted and implemented in training and testing protocols requiring the use of a treadmill. Recent research by Sassi et al. (2010) found that the CR is higher for natural grass and artificial turf surfaces than it is for asphalted

track surface while Umberger, Braun and Hamill (2013) showed that rear foot strike patterns as opposed to front foot strike patterns in endurance events result in lower relative contribution of carbohydrate oxidation to total energy expenditure.

Another factor that could affect the CR but that has not yet been studied is pace variations. Thiel, Banzer, Foster, and de Koning (2012) broke down each distance race from the 2008 Beijing Olympics into 100m segments. The data showed that the runners competing in these events had a stochastic pacing pattern throughout the race. Such a pacing pattern is thought to be the result of various tactics used within a competitive race that require runners to accelerate or decelerate their mass.

According to Foster et al. (2013) the evolutionary pattern of world-record one-mile performances has evolved into an even pacing pattern. In contrast to the classic lap pattern of “fast-slow-slower-fast,” runners are now achieving better world record times at more even lap patterns. The theory behind running an even pace is to conserve kinetic energy used to accelerate and decelerate the body for the purpose of using it at the end of the race during the final kick. While this pattern seems to be associated with world record performances, highly competitive races such as the Olympic finals are clearly not following this seemingly more efficient, even pacing pattern.

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