Improving Running Economy Through Interventions in Biomechanics and Training

Stryd Team

1. Introduction

Running Economy is a regularly discussed term in both the scientific literature and every day running culture. It has been shown to influence distance running performance in races ranging from 800m to ultramarathon [14,15,23]. Typically defined as the amount of oxygen consumed (in ml/kg/min) at a submaximal running speed below the lactate or ventilatory threshold [4], running economy has been shown to be a better predictor of performance amongst homogenous populations than maximal oxygen consumption (VO_{2max}) [14,19,42]. Runners who consume less oxygen at a standardized speed are said to be more economical, as they require less oxygen per kilogram of body weight to maintain the specific intensity. Decreasing the amount of oxygen one needs to maintain submaximal intensities may lead to enhancements in performance. Because of this, a great deal of research has been focused on better understanding factors that may influence economy. Multiple factors such as anthropometry, physiology, environment, biomechanics, and training [52] have all been shown to affect economy although not all are easily manipulated. Therefore, this article places emphasis on variables such as biomechanics and training, which can most easily be modified in hopes of enhancing running economy and performance.

2. Biomechanics and Running Economy

2.1. Stride Variables

Related biomechanical variables including stride length, stride frequency, ground contact time, and vertical oscillation have all been shown to influence a runner's economy. Running speed is simply the product of stride frequency and stride length [37], so modifying these variables will impact how fast one runs, and possibly the aerobic cost of maintaining that speed. Early exploration of stride length variation found that runners were most economical at their self-selected stride lengths and that deviating from these stride lengths would increase the amount of oxygen consumed at the same speed, thus degrading economy [31]. According to Cavanagh et al. [12], runners likely adopt this stride length based on either perceived exertion at a certain running speed or by adapting physiologically to this stride length over a period of time. Investigations of stride frequency have yielded similar results, as a self-selected frequency has been found to be most economical between the common training speeds of 9-16 km/h [10,12,31]. It is generally believed that increasing the frequency above this can be detrimental to economy despite the corresponding decrease in mechanical power associated with the increased frequency [10]. These results have brought many to the conclusion that the manipulation of stride length and frequency is of little merit, unless the runner exhibits a style that proves to be uneconomical to begin with [4]. There has been research demonstrating that some trained and untrained runners display freely chosen stride lengths and frequencies that are uneconomical and that can be successfully altered to a more optimal combination that will improve economy [40]. Ruiter et al. [49] compared the preferred stride frequency selection of both trained (84.4 ± 5.3 strides per min.) and untrained (77.8 ± 2.8 strides per min.) runners while running at 80% of individual ventilatory threshold. Seven different stride frequencies (self-selected ± 18%) were tested for each subject. Results revealed that trained runners were significantly better than untrained at self-selecting a frequency closer to optimum (87.1 ± 4.8 and 84.9 ± 5.0, respectively). Regardless, both groups seemed to self-select a frequency that was significantly lower than what the findings deemed as most economical, suggesting that both could benefit from an increase in stride frequency [49]. A second research team proposed similar optimal stride frequency numbers stating that most runners would likely benefit from a cadence of near 85 strides per min. [37]. This stride frequency range was shown to both minimize the cost of running (compared to 75, 80, 90, and 95 strides per min.) by reducing braking impulses as well as positively affecting kinematics in ways that could possibly reduce injury risks (reduction of vertical oscillation at the center of mass, ground reaction forces, and accelerations of the tibia at impact) [37]. The claim that this somewhat high stride frequency is conducive to the prevention of running injuries is in agreement with an earlier review of 10 other studies completed by Schubert et al. [53]. It is the author's opinion that there exist optimal parameter values, but they are runner specific, depending on a variety of physiological and conditioning factors.

A higher stride frequency has been shown to lead to shorter ground contact times [43], which have commonly been associated with better running economy [28,45-47,50,51]. Research from Eastern Michigan University's Running Science Laboratory investigated the stride characteristics of highly trained collegiate distance runners and untrained individuals with comparably low BMIs discovering that the collegiate runners demonstrated significantly lower ground contact times at all three tested speeds (3.33, 3.89, and 4.44 m/s) [28]. Although VO_2 was not measured directly, it is generally accepted that highly trained athletes are more economical than untrained individuals at common running speeds [41], suggesting a relationship between shorter ground contact times and better running economy. Variance in ground contact time is a main determinant of leg spring stiffness [43], another metric related to economy [23,35]. Trained runners possess higher stiffness values than untrained individuals [30] and these higher values are thought to be related to better running economy [18,23]. Though high stiffness may be beneficial, some suggest that a tradeoff between internal and external work may result in the selection of a lower stride frequency (hence, lower stiffness) to minimize the displacement of internal organs caused by the high peak leg forces required to maintain greater stiffness [17]. In other words, runners must trade off stiffness against minimizing the internal work necessary to control internal organ displacement [17].

Although an abundance of research seems to agree that the aforementioned factors are beneficial to economy, there have been contradictory reports of better economy in those with longer ground contact times [13] as well as studies finding no relationship between leg spring stiffness and economy [29]. That being said, there appears to be sufficient evidence in the literature to reasonably believe that a runner displaying poor economy, a low stride frequency, and long ground contact times may gain substantial benefit from increasing stride frequency [49], reducing ground contact time [28,45-47,50,51], and increasing leg spring stiffness [23,35,46], as all of these factors could possibly lead to improved running economy.

2.2. Flexibility and Stiffness

In addition to leg spring stiffness, Achilles moment arm length and lower body flexibility are also relevant to economy. It is the consensus that stiffer muscles and tendons are better at transferring energy as has been demonstrated by several researchers [5,18,36,55]. A 1998 study by Dalleau et al. [18] fit the spring mass model to eight middle distance runners during treadmill running at 90% VO_{2max}

velocity (vVO_{2max}) to investigate possible relationships between the energy cost of running and leg spring stiffness. It was concluded that the cost of running (running economy) was inversely related to leg spring stiffness ($P < .05$), i.e., that the runners with higher leg stiffness were more economical. These results coincide with a more recent study by Barnes et al. [5], which found a relationship between running economy and leg spring stiffness in a population of sixty-three male and female distance runners. These researchers also found a significant relationship between lower body stiffness and Achilles tendon moment arm length indicating that a shorter Achilles moment arm stretches the tendon to a greater degree. The greater stretch of the Achilles tendon consequently allows for more kinetic energy to be transformed into elastic energy and used to propel the stance leg [5]. Although the length of the Achilles moment arm cannot be altered, the concept of stored elastic energy contributing to propulsion during the stance phase is important, as it also supports the belief that interventions that improve leg spring stiffness will improve economy. Such interventions may include weight [27,39,56], plyometric [46,55,60], or high intensity interval training [3,24]. This concept will be discussed in detail in section 3.2.

Flexibility at other anatomical sites has also been explored to determine possible relationships with running economy. One study recorded nine measures of limb and trunk flexibility on 19 well trained, sub- elite male runners and compared the findings to two separate running economy assessments [16]. Results indicated that more economical runners were less flexible in measures of dorsiflexion ($r = .65$) as well as standing hip rotation ($r = .53$) ($P \leq .05$). A second study found that the running economy of eight collegiate distance runners (four males, four females) was inversely related to the sit and reach scores of each subject at absolute speeds ($r = .826$, $P \leq .05$) revealing that less flexible distance runners are generally more economical [59]. These sit and reach results confirm the findings from a previous study on 34 international standard distance runners [33]. Each of the aforementioned studies associate the better economy of the less flexible runners with the greater ability of less flexible muscles and tendons to return elastic energy, resulting in a more energy efficient means of muscle stabilization and propulsion. Interestingly, research has also shown the opposite relationship [25] or no relationship [6,44] between flexibility and economy although such findings are less prevalent in the literature.

3. Training Effects on Running Economy

3.1. Run Training

Multiple methods of training have been shown to positively influence running economy. As previously mentioned, it is commonly believed that trained runners have better economy than untrained runners and that elite or highly trained runners have better economy than moderately trained or untrained runners at the same speeds [8,41]. This suggests that continued endurance training is related to improved running economy, which is also claimed by several other studies [7,24,32,34,57]. Specifically, when the world record holder for the women's marathon was monitored consistently over a span of 11 years, it was found that along with continued endurance performance improvements, a 15% improvement in running economy also occurred with continuous endurance training whereas VO_{2max} actually decreased over this same time period [34]. Likewise, another group followed highly trained elite runners for one year, finding that running economy increased slowly over this period without any significant changes in VO_{2max} [57]. Interestingly, other studies have provided evidence that continued endurance training did not improve running economy over time [21]. It is worth stating that this particular study was primarily focused on highly trained runners and not moderately trained or untrained runners, possibly leaving less room for continued improvement in the tested population. It is thought there is an upper limit beyond which economy can no longer be improved [20,41], explaining why highly trained runners may see little to no improvement in running economy.

Others have explored the effects of more specific types of endurance training such as interval [7,22,24] uphill running [3,57], and lactate threshold training [54], and their effects on running economy. Denadai et al. [22] found that running economy as well as performance in 1500m and 5000m time trials could be improved by including two weekly sessions of high intensity interval training at 100% velocity at VO_{2max} (vVO_{2max}), for four weeks. These results are in agreement with the previous findings of Billat et al. [7]. The same improvements to running economy were not seen when the intervals were run at 95% vVO_{2max}, suggesting that the higher intensity is necessary for improvements in running economy. The effect of five different types of uphill interval training were observed by a research group from New Zealand in order to understand the effects of different interval lengths and intensities on both physiological and biomechanical parameters and running performance [3]. These investigators reported that the high intensity group, which underwent 12-24 repetitions of short, intense (120% vVO_{2max}) hill intervals (18% grade) ranging from 8-12 seconds in duration, had the greatest improvement in running economy (2.4% ± 1.4%) as well as neuromuscular measures such as leg spring stiffness and eccentric utilization ratio (12% increase). A second group that trained at a slightly lesser intensity of 110% vVO_{2max} for durations of 30-45 seconds, did not see improvements in running economy. Although running economy was only affected by the intervals run at 120% vVO_{2max}, all five interventions were beneficial to 5k race performance [3].

After reviewing the literature, it seems that multiple training intensities can improve economy and that adding variation to one's training regimen could ultimately improve both running economy and race performance. That being said, higher intensity interval training at or above 100% vVO_{2max}, may be most beneficial for running economy [3,22]. Somewhat conversely, other research provides evidence that the greatest improvements in running economy were seen at the intensities of 94% and 106% vVO_{2max}, while training at 132% vVO_{2max} did not improve economy [24]. There are several possible explanations for this. First, training at an intensity as great as 132% $vVO_{2max,}$ may be too high to effectively maintain proper running form and/or complete an appropriate amount of training to provoke a training effect [38]. Secondly, we must consider the ability level of the population being tested. Franch et al. [24] describe the population used in their 1998 study as recreational runners whereas Barnes et al. [3] and Denadai et al. [22] categorize their subjects as "well trained". If the subjects in Franch et al. [24] are lesser trained then the subjects in Barnes et al. [3] and Denadai et al. [22], it is quite possible that different training intensities will elicit different physiological responses and have different effects on running economy. Nevertheless, it is likely that training between the intensities of 95-120% vVO_{2max} will lead to improvements in running economy.

3.2. Heavy Weight and Plyometric Training

Other non-running related interventions have also been shown to improve economy. Weight and plyometric training regimens have been studied to better understand their impacts on running economy and distance running performance over various time periods lasting four to ten weeks [2,27,39,46,56,60]. Early research on this topic observed the effect of explosive strength training on running economy and 5k race performance in trained endurance athletes [46]. Two groups participated in a 5k time trial and running economy measurements both before and after a nine-week intervention in which 32% of the overall training volume in the experimental group was replaced by sport specific explosive strength training compared to just 3% in the control group. Overall training volume was kept the same in both groups. Prior to the intervention, no differences in time trial performance or running economy were seen between groups whereas following the intervention, significant improvements were made in both running economy and 5k performance ($P < .05$) in the experimental group, but not in the control group. Further, results from a similar, six-week study found that a plyometric intervention improved both running economy and 3k running performance [55].

Others have suggested that traditional heavy weight training may be more beneficial to running economy enhancements than plyometric training [2,27]. One study compared 16 well trained runners by randomly assigning them to either a heavy weight training group or an explosive strength training group. Prior to beginning a four-week intervention, both groups performed tests to determine VO_{2max}, running economy, the velocity that corresponded to a blood lactate concentration of 3.5mM, a maximal countermovement jump test, and a one repetition maximum leg press test. Following the four-week training period, the heavy weight training groups showed improvements in running economy whereas the explosive strength training group did not [27]. However, other studies showed improvements with the addition of plyometric training after six weeks [55] and nine weeks [46] suggesting that the plyometric training period used in Guglielmo et al. [27] may have been too brief to see the desired results. It seems that both traditional heavy weight training and plyometric training produce desired improvements in running economy, but over different time periods.

Most studies attribute the improvements in running economy associated with weight and plyometric training to improved mechanical efficiency through increased musculotendinous stiffness, muscle strength, neuromuscular adaptions, and/or motor unit recruitment patterns [2,47,55]. Turner et al. [60] found running economy improvements in 18 trained distance runners after the implementation of a six-week plyometric training program without any changes in the variables associated with improved ability to store and return elastic energy, thus suggesting that the mechanism through which plyometric training improves economy is still unknown. Regardless, there appears to be sufficient evidence to support the addition of weight and/or plyometric routines for the enhancement of economy and race performance.

4. Stryd for the enhancement of performance

4.1. Diagnosis

The Stryd foot pod can be used to diagnose form problems and provide feedback on running biomechanics previously shown to influence running economy. Metrics such as leg spring stiffness, form power, cadence, ground contact time, and vertical oscillation are measured with a Stryd device to help runners modify form during the run or analyze form improvements over an extended period of time. As shown in the presented research, increased leg spring stiffness [18,27], shorter ground contact times [28,45-47,50,51] and lower vertical oscillation [11,58] have all been linked to good running economy. Using Stryd to monitor these metrics provides a reliable way to assess the strength of one’s training plan as a means of improving running economy. For instance, one may see that, over a period of six weeks, ground contact time has decreased and leg spring stiffness has increased. These results suggest that running economy has improved as a result of a decrease in the amount of braking that occurs with a longer stance phase. Less time spent braking is thought to contribute to smaller losses in speed and improved economy [45].

Two recently added metrics, form power and leg spring stiffness, can be used to assess postulated improvements in economy without undergoing intensive physiological testing. The form power metric can be used to monitor form changes in real time or after the completion of a run. This metric is defined as the power to raise one's center of mass against gravity with each step and is independent of speed and gradient. Altering form to decrease this number at similar training speeds will generally be associated with improved economy as it will also reduce vertical oscillation. However, lowering these values too much would negatively affect the body's ability to utilize higher amounts of recycled energy through higher leg spring stiffness. In other words, it is likely that each runner possesses an "optimal" range in which low levels of form power are achieved without drastically decreasing stiffness. Stiffness levels that are too high or form power levels that are too low will negatively affect the other metric in a way that would degrade running economy. Knowing this, it is important to understand that these two metrics should be used on an individual basis as there is not yet strong evidence that advocates for an optimal combination suitable for all runners.

Not all runners should expect to make significant form changes, as many are economical at their freely chosen stride length and frequency [10,12,31]. In this case, both metrics can still be of benefit. The form power metric can be used during a run to monitor changes in running gait that may occur with fatigue while the leg spring stiffness metric can be used alongside a Stryd training plan to assess improvements over time.

4.2. Utilization

Stryd training plans include plyometric/weight training routines as well as different types of run training previously shown to increase leg spring stiffness and performance [3,46,55]. Increases in the leg spring stiffness value over a period of weeks or months provides some evidence that the training approach is improving economy. Although increasing stiffness is typically deemed as beneficial, values which are too high may lead to increased risk of bony injury, as shown by Butler et al. [9]. Their study suggests that there may be an optimal stiffness range for each individual in which performance is high without significantly increasing the risk of injury. Values outside of this optimal range (either too high or too low) may lead injury and reduced training.

The power metric, which is also supported by the Stryd Pioneer, continues to be an excellent training tool to be used with or without pace and heart rate. Running with power has substantial benefits for those who frequently train on varying terrain and/or in varying temperatures. While pace and heart rate are still extremely important training and racing tools, they may be affected by outside factors such as weather, terrain, elevation, accumulated fatigue, and supplement use. Power on the other hand, is less susceptible to external factors; it will generally better reflect the true effort level. This is because power can be used as a real-time measure of the amount of effort being exerted to do a certain amount of work.

Athletes racing on varying terrain will benefit from pacing with power rather than pace. If an athlete wants to average 6:00 per mile over the duration of a run and attempts to hold this pace during a particularly hilly section of the course, too much energy will be expended during this segment, causing rapid fatigue. Instead, staying in a prescribed power zone associated with the 6:00 mile pace while running on the flat will allow the athlete to maintain the same intensity while running at a slightly slower pace thus preventing overexertion and the early onset of fatigue, and enabling higher speed later in the run.

Heart rate can be influenced by outside factors that are not true measures of training intensity such as core temperature [1], dehydration [1], and caffeine consumption [26,48]. Using heart rate as a gauge of intensity in these situations could lead to the overestimation of intensity. Power is not affected by these external factors and would provide more reliable feedback for monitoring intensity no matter the conditions.

5. Conclusion

Running economy is affected by several factors, some of which can be manipulated with the goal of improving economy and performance. Biomechanical variables can be monitored using a Stryd foot pod to make necessary changes both during a run and over an extended period of time. Changes in leg spring stiffness and form power can be observed while using different types of run and/or plyometric/weight training approaches throughout an extended training cycle. Using these newly included metrics in conjunction with those such as power, vertical oscillation, cadence, and contact time previously presented on the Stryd Pioneer, this new device can be reasonably believed to track improvements in running economy during day to day training without requiring intensive laboratory tests.

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