12-2021

Effects of Varying Warmup Stimuli on Running Economy

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Presented to the Faculty of the Graduate School of

Stephen F. Austin State University

In Partial Fulfillment

Of the Requirements

For the Degree of

Master of Science

STEPHEN F. AUSTIN STATE UNIVERSITY
December 2021

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ABSTRACT

Purpose: The purpose of this study was to determine the effects of two potentiating warm-up stimuli (weighted-vest strides and plyometrics) on running economy (RE) over short (5-10 minutes) and longer durations (30+ minutes) of exercise in trained distance runners. **Methods**: Five recreationally trained male runners were recruited to participate in this study. Each trial consisted of a 10-min self-paced warm-up on the treadmill followed by baseline RE test and baseline leg-stiffness. This was immediately followed by one of two intervention warmup protocols. The protocols consisted of either a series of plyometric movements, 6 x 10-sec strides with a weighted-vest equal to 20% body mass, or a control intervention. Following the intervention, a 10-minute resting period was included to elicit the effect of waiting in a coral pre-race. Following the resting period, a post-intervention RE test and leg-stiffness test were recorded. A 30-min endurance run on the treadmill followed the post-intervention RE and leg-stiffness tests followed by a final RE and leg-stiffness test. HR and RPE were recorded throughout the RE portions of the trials. **Results**: There was no statistical significance supporting the effect of condition (p=0.535) or time (p=0.238) on RE or on power (p=0.061) as a result of the interventions. There was a statistically significant effect of time on RE from the post-intervention to post-30-min run (p=0.012). **Conclusion**: There was no statistically significant effect of intervention condition on RE or power via leg-stiffness in recreationally trained distance runners.

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INTRODUCTION

Endurance running performance is influenced by three primary physiological factors including, lactate threshold (LT), VO_{2MAX}, and running economy (RE) (13). The LT indicates the point at which the production of lactate exceeds the rate of lactate removal, while VO_{2MAX} is utilized to determine the maximum quantity of oxygen that the cardiorespiratory system can utilize at a time. RE, defined as the oxygen or energy cost to run at a given speed, is of greater consideration when determining distance performance due to the variation in RE in individuals with otherwise similar physiology. Variation of up to 30% in RE can occur in athletes with comparable performance factors (8). This indicates that the variation of RE in athletes should receive greater attention due to its potential to increase performance. Factors that affect RE include anthropomorphic factors, environment, training, and equipment (3). One primary physiological factor affecting RE is an increase in leg stiffness which causes an increase in muscle tendon elasticity. This increase in muscle elasticity increases the rate and degree of musculotendinous energy return causing increased efficiency. Muscle tendon elasticity can be enhanced by resistance and plyometric training that engage the musculature causing an increase in stiffness (4).

Chronic training interventions, such as resistance training and plyometric training, performed over several weeks have been shown to improve RE (19). Acute methods such as warm-up routines and stimuli targeting a post-activation potentiation (PAP) effect are often utilized to enhance athletic performance. While general and specific warm-up protocols are commonly used to increase metabolic processes above resting levels, PAP is often utilized to “prime” the muscles to increase energy return and muscle efficiency (2). Though the effects of various PAP stimuli on power performance have been well studied, the effect of similar interventions on RE and endurance performance has been investigated much less (6).

Wei et. al. and Barnes et. al. both performed research focusing on the effects of acute PAP stimuli on RE (2,22). Of paramount consideration when determining the effect of PAP on performance is not only the potential benefit, but also the possible inverse effect of causing fatigue. Wei et al. investigated the effects of plyometric and resistance stimuli on RE in recreational athletes (22). The athletes performed a 10-min self-paced jog on a treadmill followed by either weighted or non-weighted strides with a 20% body weight vest for the control and resistance interventions. The plyometric intervention included squat, scissor, and double-leg bounds. The three interventions were followed by a 10-min resting period, jump test to determine leg stiffness, a 12-min running economy test and incremental running test. The Wei et al. study determined that leg stiffness increased 20% following the plyometric intervention (22). Though the results of Wei et al. study show an increased benefit from plyometric PAP, the subject criteria being non-runners detracts from the external validity (22). In the case of the Barnes et al. study, well trained endurance athletes were utilized, which results in more applicable data (2).

Barnes et al. compared the effects of a weighted vest at 20% body weight to non-weighted strides on endurance performance, but did not include a plyometric intervention (2). Each trial consisted of a 10-min warm-up followed by a 5-min sub-maximal run, intervention, 10-min recovery, jump test to determine leg stiffness, and a 5-min submaximal run concluding with an incremental running test (2). The weighted vest interventions resulted in a 20.4±4.2% in leg stiffness and a 6±1.6% in RE (2). These findings of increased leg stiffness and improved RE with weighted-vest strides contradict those of Wei who only showed improvements for the plyometric intervention. This may be due to the different training status of the participants and the effects of a given PAP stimulus on subsequent fatigue. Due to the promising findings in both studies, a comparison of plyometric and weighted-vest strides is warranted in trained populations.

Furthermore, these acute interventions targeting improvements in RE looked at RE over a fairly short time period. Sproule indicated that RE deteriorates over time in an accordance with intensity and duration (20). Additionally, there is evidence indicating that the effects of PAP deteriorate after 12 minutes (6), which calls into question whether acute PAP is beneficial for longer endurance sports beyond the timeframes investigated by Wei and Barnes. Thus, there is a gap in the literature both in solidifying the effects of various acute PAP interventions on RE and regarding the duration of such improvements over longer endurance events. Therefore, the purpose of this study was to determine the effects of two potentiating warm-up stimuli (weighted-vest strides and plyometrics) on running economy over short (5-10 minutes) and longer durations (30+ minutes) of exercise in trained distance runners. However, it is less clear if RE can be manipulated acutely through various warmup interventions.

REVIEW OF LITERATURE

Running Performance Factors

There are three primary factors that predict a runners potential running performance. The primary factors include the differentiation in VO_{2MAX}, lactate threshold (LT), and running economy (RE) (13). These three primary factors mentioned above, determine a majority of the performance capacity of long-distance running (13).

Firstly, VO_{2MAX} can be thought of as the maximal amount of oxygen that can be consumed by the body. Though athletes tend to try and increase VO_{2MAX}, it is inherently limited by the functionality of the cardiorespiratory systems (5). The result of having a high VO_{2MAX} is the increase in ability for aerobic adenosine triphosphate (ATP) formulation (3). There are many factors that manipulate VO_{2MAX}, including training, environment, genetics, and physiological factors, etc. There are some general physiological assumptions made when discussing VO_2. These include the fact that there is inherently an upper limit for O_2 uptake which limits performance factors, limiting endurance running performance. These factors can include physiological and genetic markers that limit adaptation (5). The first assumption is given that elite athletes experience a plateau in adaptation that causes a physiological maximum for VO_2. This plateau is experienced by all elite athletes and necessitates a diminishing returns effect (5).

These limitations are defined by the physiological limitations of the adaptations that elicit VO_2 performance. These include physiological characteristics including heart chamber size, heart wall thickness, plasma volume, etc. (13). The second understood assumption is that individuals, even elite athletes within the same sport are known to experience differing VO_{2MAX} levels. This in a large part is due to genetics and the physiological limitations mentioned above. Environmental factors such as where an individual was born also plays an important role in determining VO_{2MAX}. A high VO_{2MAX} is often a side-effect of distance running which gives these individuals higher VO_{2MAX} compared to novice athletes. There is a variety of factors at play that cause differing VO_2 and performance capability. The last assumption dictates that VO_{2MAX} is controlled by the rate at which oxygen can be delivered throughout the cardiorespiratory system (5).

The next performance factor is lactate threshold (LT) in which there is evidence supporting that LT is potentially a more effective determining factor amongst athletes of similar capability (9). It is important to performance because the LT dictates the point at which exercise intensity and blood lactate (bLa) becomes unsustainable if increased (9). This ability to continuously exercise is not without limits. Trained endurance athletes are able to maintain exercise intensities in which bLa is elevated for roughly 4 hour periods (9). OBLA is the point in which onset of blood lactate accumulation occurs and steady state ends (13). Most endurance runners aim to incorporate bouts of exercise at or above LT in the effort of increasing individual lactate threshold (13). The primary adaptations and the physiological significance that cause an increase in LT are enzymatic in nature. These enzyme adaptations occur with the primary function of removing lactate more efficiently and are facilitated by a decrease in PFK-1, increase in pyruvate, and increase in β-oxidation (13).

Though all running performance factors are important, they are not all made equal in determining performance. An over-reliance on VO_2 and LT is often seen in laymen's literature. As the understanding of running performance has increased, so has the understanding that among elite athletes, RE is the greatest defining factor given that RE varies roughly 30% amongst athletes of similar physiology (8).

Running Economy Overview

RE can best be measured as the point at which steady state oxygen consumption occurs, given that running velocity remains constant (4). The primary factors that affect running economy are training, metabolic, cardiorespiratory, biomechanical, and neuromuscular efficiency (4). Training and its effect on biomechanical and neuromuscular efficiency is the primary concern of this review. The most common and in large part the primary adjustable determinant of running performance is an athlete's ability to adapt to training. "Training-induced stress imposed on a physiological process or structure is the stimulus for adaptation" (13). RE is a multi-faceted combination of both internal and external forces that act together to determine economy (14). These intrinsic factors can include the primary physiological systems (4), while extrinsic factors may include, an athletes training environment, training methods, footwear, etc. (14).

RE can be altered overtime with both acute as well as by chronic interventions via diet, strength straining, warm-up protocol, and kinematics (3). Multiple methodologies have been utilized to increase RE, including diet, warm-up, altitude training, and multiple strength training methodologies. As previously mentioned, both chronic and acute strategies have been utilized to increase RE. For the purposes of this paper, all training intervals repeated over the course of multiple days prior to testing will be considered chronic, training interventions.

Physiological and Biomechanical Determinants

As mentioned above, there are many physiological and biomechanical determining factors that limit and enhance performance. There is varying data available suggesting the efficacy of training methods and styles including the effect of hyperthermic exercise and exactly what its effect is on VO_2, RE, and mechanical efficiency (4). Muscle fiber type percentage and recruitment is another factor to be considered given evidence suggesting that athletes with a greater majority of Type I muscle fibers have greater oxidative capability (4). There are many biomechanical factors to be considered when examining an athletes RE, including spatiotemporal, kinematics, kinetics, and neuromuscular factors and the effects these categories have on capability

(14). There are certain anthropomorphic characteristics that should be considered prior to discussing factors capable of being altered. These characteristics are primarily due to genetics and as such are not malleable or important to an individual's personal adaptation. Body mass and mass distribution play a pivotal role in determining an individual's RE. As body mass increases, O_2 demand is disproportionately lower, indicating O_2 demand does not change proportionally along with body mass. (4).

Spatiotemporal factors are "an innate, subconscious fine-tuning of running biomechanics often referred to as self-optimization" (14). This innate functioning of the body to function economically is a direct function of natural biomechanical factors. Upper limb and trunk factors directly affect RE via kinematics biomechanical factors. Though there is conflicting data due to a limit in experimentation, there does seem to be an important role in the swinging motion of the arms and the forward leaning position of the body while running (14).

Lower limb determining factors are possibly more complex. Lower limb length is not considered a determining factor due to its lack of consistent effect on RE (4). The elastic energy storage found in the Achilles tendon reduces energy demand during running exercise (4). Other factors that affect RE are running style, gait patterns, stride, length/rate, vertical oscillation, and foot strike patterns. There is clear evidence that runners naturally will choose the running style and method including stride length and rate that is most efficient for the individual (4). Vertical oscillation, can increase RE when reduced, due to the fact that less energy is utilized to lift the foot above the ground (14). To date, the most efficient foot strike pattern has not been determined (4,14). Along with foot strike pattern is the interaction between the shoe or foot and the surface of the ground. It is unclear at this point whether there is clear interindividual data to support a thickness, weight, or taper of shoe without further analysis. There is evidence supporting the use of barefoot running and its positive effect on RE and elastic return, while greater cushioning will potentially increase the effect of mechanical efficiency (14). Ground force reaction (GRF) has also been shown to negatively affect RE (14). This being said, there is not a great correlation between GRF and RE (4).

Neuromuscular factors also greatly effect running economy via training and the positive adaptations that improve efficiency (4). Leg stiffness and the ability for the leg muscles to utilize elastic energy has been proposed to increase ballistic concentric acceleration during isometric contraction via adjusting tendon stiffness during deceleration phase (4). Elastic energy storage and the ability to increase musculotendinous stiffness has been proven to have a positive effect on RE though to what extent remains unclear.

Training Determinants

The main purpose of training is with the mindset to adapt the athlete’s body to be able to perform at a higher caliber. Thus far the primary focus has been the discussion of factors that are of little personal choice. On a physiological level, endurance training causes adaptations to morphological and functional factors (3). There is a direct correlation to the length of time an athlete has trained and the adaptation resulting (3). It is important when changing training methods to focus on a few adjustments at a time due to evidence that adapting too many physiological features may result in failure due to lack of specificity (14). There is evidence supporting that high-altitude natives naturally elicit lower VO_2 during submaximal exercise (3). This being said, training at high-altitudes as a sea-level native has proven inconclusive results on increasing VO_2 (3). There are also cardiorespiratory adaptations and changes in metabolic efficiency due to high-altitude training. Evidence supporting this shows that training at altitude provides positive adaptations to cardiorespiratory costs, metabolic substrate utilization and physiological adaptations.(3).

To date, there is currently no definitive evidence to suggest whether or not stretching prior to exercise positively or negatively effects RE (3). In the nutritional field there is evidence promoting increased dietary intake of nitric oxide (NO), which can be found in leafy green vegetables and is important to healthy muscle function and metabolic efficiency (3).

In this next section will be a discussion of High-Intensity Interval Training (HIT) and resistance training and the mechanisms of improvement involved. There are mixed results on the efficacy of HIT training to increase RE. Though there is evidence suggesting an increase in RE by 1-7% as a result of training above VO_{2MAX} (3). There is also evidence suggesting it is not as effective to utilize HIT as a method to increase RE for endurance athletes due to a lack of specificity and insufficient training volume (3).

Resistance training includes heavy or strength-endurance training and plyometric or explosive training. There is direct evidence supporting resistance training to aid in the increase in leg stiffness which results in increasing the transition from braking to the propulsive and elastic recoil phases of muscle tendon return (3). Plyometric and explosive training have become more popular due to the inherent specificity of movement that the activity provides (3). There is the potential for an increase in musculotendinous stiffness and elastic energy following plyometrics (3). Though positive findings suggest an improvement in RE is due to an improvement in neuromuscular function there is evidence supporting that resistance training is more effective than plyometric training for increasing RE performance (3).There is also evidence suggesting that running performance can be impaired the day following a bout of resistance training (3). This would be suggestive that it is important to structure resistance training to not inhibit running performance.

Measuring Running Economy

The measuring of RE has become a common practice when determining the performance characteristics of endurance runners. The primary method of measuring RE is by measurement of oxygen consumption at a set treadmill speed below the lactate threshold after steady state has been reached, typically around 3-5 minutes (4). This process generally takes anywhere between 3-15 minutes depending on the subject and occurs below the LT ending once a respiratory exchange ratio (RER) is recorded (4). The measuring units is determinant on the data of interest. Most commonly the data is recorded in (ml/kg/min) to directly compare individuals based on mass at the same speed. Another measurement could read in either (ml/kg/km) or (kcal/kg/km), depending on whether or not the time to run a kilometer or caloric unit cost respectively were preferred (4). These methods also normalize for speed so comparisons can be made at different speeds. Though all performance factors are important to an athlete's overall capability, the utilization of RE is considered most effective when comparing athletes of similar aerobic and physical capabilities (7). Though RE is one of the primary determinants of endurance running performance, it is questionable at which point in a running bout, RE should be tested. According to (20), as the duration of exercise increases, there in a continued deterioration of RE throughout the bout of exercise.

Post-Activation Potentiation Overview

Post-Activation Potentiation (PAP) has been in the interest of athletes and sports practitioners for years. The act of potentiating the muscles prior to an exercise bout can be extremely useful when aiming to gain a competitive edge over athletes. There are potentially two benefits from PAP for endurance exercise. These are, the potential for PAP delaying the effect of fatigue during a bout of exercise, and increasing an athletes muscle elasticity which in turn could improve economy (10). PAP can be best defined as the pre-activation of muscle prior to the primary bout of exercise in which muscular performance is temporarily enhanced due to the prior contractile history(11). Though the evidence supporting PAP is clear, a potential side effect of PAP is neuromuscular fatigue (11). Thus, a primary consideration should also be to limit and balance fatigue with the potentiating effect of enhancing performance. Fatigue is a common byproduct of exercise that results in a decrease in skeletal muscle force (17). There are limitations that can potentially minimize the effectiveness of PAP, firstly being that the PAP effectiveness is limited by a 12 minute time period before having a null effect on exercise performance (6). PAP is utilized in a variety of sports ranging from power to endurance sports, though endurance generally receive less attention (6). To understand PAP, it is important to examine the physiological mechanisms that allow PAP to be effective.

In understanding the big picture of PAP, it is important to begin on the physiologic level to understand the underlying systems that make it possible. The function that makes muscle activation possible is the ability for muscle to contract, extend, or twitch. An important factor affecting PAP and its effectiveness is the fiber type that is being potentiated (10). Though Type II fibers generally show the greatest affinity towards PAP, Type I fibers can increase their maximum shortening velocity as a result of endurance training (10).

Two of the pathways to increased contraction, immediately following a maximal voluntary contraction and tetanic contraction (11). The primary mechanism of PAP has been suggested to be a metabolic process in which the myosin in skeletal muscle is phosphorylated which in turn would increase calcium sensitivity causing contraction (6). This process works most effectively when the skeletal muscle fascia calcium levels are low (11). Another measurement tool post tetanic potentiation, which is elicited via electrical muscular stimulation (11). There are multiple theories as to the physiological benefits of PAP, though one of the popular theories are that musculotendinous stiffness (MTS) is one of the primary beneficial adaptations (21). From previous studies, there is evidence supporting that as force production increases, so does MTS in proportion (17).

Determining the Presence of Potentiation

When determining the possible effectiveness of warm-up or PAP, it is important to verify that potentiation occurred. There is great benefit to including measures of neuromuscular output with performance measures to ensure potentiation occurred and to identify the underlying physiology involved (11). This can be tested for via multiple methodologies including muscle twitch verification, countermovement jumps (CMJ), depth jumps, 1 rep max (RM) (18). The three most common methods for determining the presence of PAP are peak torque, evoked twitch peak torque, and CMJ, and jump height (6). According to (15), two measures of PAP are the jump squat mean power and rate of force development. Yet on the other hand (16) determined that PAP is not associated with performance when measured via twitch contraction.

Activity Specific Potentiation

Due to interindividual variation in athletes, there are certain considerations to be made prior to training, including an individual's training status, age, anthropomorphism, gender, etc. (18). It is also important to acknowledge that PAP can be variable depending on the point in the season and the method to best adapt training to increase performance (6). There are many different methodologies for utilizing PAP to increase running performance. There is evidence supporting that utilizing strength training can improve lower limb muscle stiffness which results in a reduced ground contact time and increase performance (1). In a different research article, there is evidence supporting that plyometric training would result in improved RE (21). Supporting this determination is another research article that reported, following 9-weeks of plyometric training resulted in an improved RE (19).

Hill Repeats

One method of utilizing PAP for running events is uphill training. Uphill interval training which is a form of HIT has shown anecdotal evidence of success though more testing must be completed to confirm. Uphill interval HIT training has shown a positive effect on RE due to the specificity of movement which more closely coincides with running activities (3). There are various benefits from uphill interval running including physiological, biomechanical, and neuromuscular adaptations (12). During a 10km running race it was found that running and uphill walking are both successful activities to produce PAP (6). Barnes et al investigated the effects of uphill interval training on performance.(12). The purpose of the study was to compare multiple uphill interventions and the specific effect whether positive or negative, they had on performance (12). This study focused on twenty distance runners and the effect six weeks of 2 interval sessions per week and the effect the training sessions had on 5K running performance. One of the primary results of this study was that the groups that were training at the highest intensities showed the greatest improvement (12). Though this may not translate directly to the most beneficial training for acute trials, there is supporting evidence that acute neuromuscular adaptation is plausible.

There is a lack of information and research studies investigating the effects of inclined hill warm-ups on PAP and RE. Chronic adaptation and interventions have been thoroughly investigated concluding the benefits of hill intervals and its effect on running performance. The evidence gathered from the chronic adaptations could potentially validate the testing of acute interventions utilizing hills as a warm-up protocol. The physiological and biomechanical functions mentioned in the above research indicates leg stiffness as one of the primary adaptations.

Plyometric Training

Plyometric training is an explosive type of training that instead of using heavy weights uses quick movements to elicit an explosive muscular response. Plyometric training is utilized to enhance the stretch shortening cycle (19). Saunders (19) determined that 9 weeks of plyometric training increased average power, shorter time to maximal dynamic strength, and a lower VO_2 slope. One of the main adaptations that occurs from plyometric warm-up protocol is leg stiffness.

In Wei's research study, a comparison between the effects of a plyometric and resistance intervention were analyzed. The purpose of this research was to determine if RE could be increased via acute plyometric and resistance protocols (22). The results of this study indicated there was a 20% increase in leg stiffness following the plyometric protocol (22). The interventions included a control, plyometric, and resistance warm-up protocol. The subject group for this intervention included twelve healthy university students. All individuals in the study were purported to be of good health and free from injury. The subjects were not trained endurance athletes, exercising less than 5 hours per week. In the control interventions, a 10-min self-paced jog on a treadmill was followed by six, 10-s strides with or without extra load with 1 min recovery between each. For the resistance group, the subjects performed the strides while wearing a weighted vest equal to 20% body mass (22). Following the warm-up, "a 10-min recovery followed by five maximal continuous straight-leg jumps were performed to illustrate leg stiffness" (22). As mentioned above, increases in musculotendinous stiffness result in an increase in RE and thus performance. The plyometric warm-up intervention was performed via 2x8 squat jumps, 2x8 scissor jumps, and 2x8 double leg bounds with 60-s recovery between sets (22). This was then followed by the plyometric jump test to determine the presence and extent of leg stiffness. Following the warm-up and leg-stiffness assessment, an incremental running test to exhaustion was performed on a treadmill.

The results of this study indicated that there were no statistically significant changes in VO_2, RE or leg stiffness following resistance and plyometric procedures (22). There was significant correlation between RE and leg stiffness indicated following the plyometric warm-up when running at 8km/h. The primary limitation to this study was that trained endurance athletes were not utilized. This could potentially change the results of future studies.

Weighted Vest Strides

Weighted vest warm-up protocols are another potential PAP providing procedure to increase running performance via RE. According to one study testing the effects of weighted vest warm-up procedure on RE, there was determined to be a positive effect between this procedure and leg stiffness. Leg stiffness as previously mentioned has a positive effect on RE via an increase in elastic energy return. In (22), a comparison between resistance with a weighted vest and plyometric intervention was compared. The weighted vest intervention included a “10-min self-paced jog on a treadmill was followed by six, 10-s strides with or without extra load with 1 min recovery using a weighted vest equal to 20% body mass” (22).

K.R. Barnes’ study “Warm-up with a weighted vest improves running performance via leg stiffness and running economy” illustrates the benefits of resistance loading prior to an endurance activity (2). The result of a weighted vest study and its effect on RE showed an increase of 6% RE following the intervention (2). The purpose of the study was to determine if athletes would show an increase in performance following strides with a weighted vest (2). The subject group in this study included eleven trained distance runners. A primary visitation for the purposes of familiarization was performed to inform the participants of how the trials would be performed. Each trial was "preceded by a 10-min jog followed by a 5-min bout of submaximal running at 14km/h" (2). Metabolic measurements were taken including VO_2, CO_2, minute ventilation, and respiratory exchange ratio (RER). RPE, RE, RER, and minute ventilation were all measured for steady state activities. The two trials consisted of a control and an intervention trial consisting of 6x10-s strides with a 60-s walking recovery and strides with a weighted vest equal to 20% body mass, respectively. Following the warm-up, a 10-min recovery was utilized prior to the incremental treadmill test. Physiological neuromuscular adaptations were measured following the incremental test via multiple jump tests performed on an AccuPower force plate.

This study focused on the effects of warm-up with a weighted vest and resulted in an increase in performance. There was a significant increase in peak speed measured as 2.9% increase. There was no resulting effect on VO_{2MAX}. There was an increase in leg stiffness that resulted post weighted vest strides which measured at 20.4% ±4.2%. Possibly the most significant adaptation that occurred was a 6% ± 1.6% increase in running economy (2). The results of this study indicate the effect of weighted vest warm-up having a positive effect on "mental performance and race readiness, peak speed, and leg stiffness as well as increases in RE and performance" (2).

The study mentioned above showed the positive effect of strides with a weighted vest on running speed (2). It was concluded from this study that, RE is positively effected as a result of the priming effect of leg stiffness via weighted vest strides (2).

The information provided above illustrates how it is possible to increase running performance factors via PAP. Acute changes to RE and performance can be performed by multiple methods. The primary method discussed in this paper is the effect that leg stiffness has on RE. Though anecdotal evidence is abundant, there is a need for continued research into the effects that potentiating exercises have on performance.

METHODS

General Design

The study employed a randomized, crossover design comparing the potentiating effects of three warm-up trials (control, plyometric, and weighted strides) on running economy over short (~5 minutes) and longer (~45 minutes) durations. All trials were separated by a 48-hour period so as to allow necessary recovery.

Subjects

Eleven trained, recreational runners were recruited for this study. However, due to voluntary attrition, only 5 subjects completed all the procedures. Subject inclusion criteria required participants to have been participating in regular running for the previous six weeks for a minimum of three days of running per week while remaining injury free over that time period. All subjects were capable of running a minimum of 6 mph (10:00/mile) for approximately one-hour to participate in this study. Exclusion factors included presences of cardiorespiratory disease and musculoskeletal injuries. IRB ethics approval were received prior to implementation and recruitment of subjects. All subjects provided informed consent prior to being included in the study and were informed that they would not receive compensation for time involved in the study besides access to personal physiological and metabolic data upon completion.

Experimental Protocol

A summary of the experimental protocol is provided in Figure 1. Each trial began with a 10-min warm-up self-paced submaximal jog, followed immediately by baseline leg-stiffness/power index test using the Just Jump Mat (Power Systems, Knoxville, TN) 5-jump test. A 5-min submaximal run performed at the individual's estimated 1-hour race pace was then completed immediately prior to the experimental warm-up interventions. Estimated paces were calculated from a recent race performance utilizing the online McMillian Running Calculator. During each 5-min submaximal run, a metabolic cart (ParvoMedics TrueOne 2400, Salt Lake City, USA) was utilized to measure VO_2, RER, CO_2, and minute ventilation. This data was then utilized to calculate RE throughout the duration of the trials. Metabolic measurements were recorded during the last two minutes of each 5-min run. Rating of perceived exertion and heart rate were also recorded throughout the trials.

Following the first 5-min submaximal run, subjects completed one of the 3 experimental conditions. The control intervention consisted of performing 6 x 10-s strides overground (60s total) with 1-minute (60-sec) of recovery between strides without load at a self-selected pace equivalent to perceived 1-mile race pace. The weighted-vest resistance intervention was performed in the same manner as the control intervention, with the exception of subjects utilizing a weighted-vest measuring 20% body weight. The plyometric intervention consisted of performing a series of body weight countermovement jumps (2 x 8 squat jumps, 2 x 8 scissor jumps, and 2 x 8 double leg bounds with 1-minute (60-sec) between sets. All subjects were informed on how to correctly perform movements prior to the intervention.

A 10-min resting period occurred immediately following the conclusion of each intervention to replicate the common waiting time prior to the beginning of a running event. A second leg-stiffness test was performed following the rest period using the 5-jump test. A second 5-min submaximal run was then again performed at the same testing speed as prior to the intervention to determine the short-term effects of the intervention on RE. Immediately following the 5-minute RE test, subjects completed a 30-min submaximal run at a pace 30 seconds per mile slower than the RE testing speed. Following the 30-minute bout, a third 5-min submaximal run was performed at the previously tested RE speed. Lastly, a final leg-stiffness test was performed at the conclusion of the last RE test.

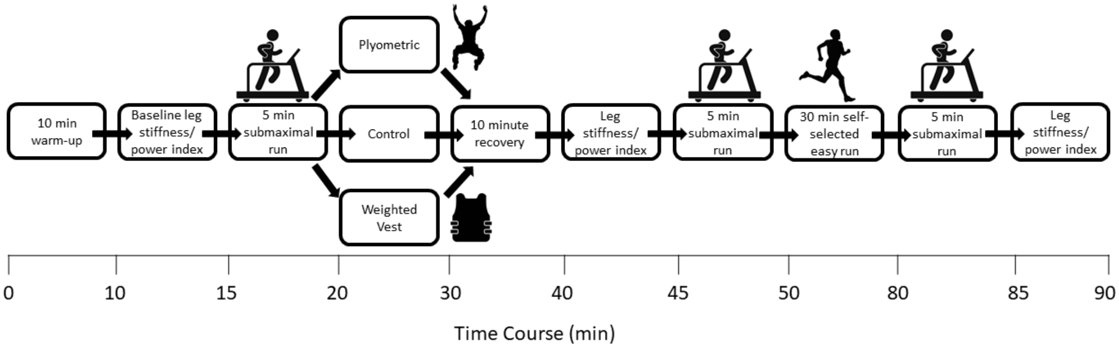

Figure 1. Experimental Protocol

Statistical Analysis

A two-way (condition x time) repeated measures ANOVA was utilized to determine the differences in running economy and leg stiffness.

RESULTS

Subject demographic data as well as estimated 1-hour race paces that were used for the 5-minute running economy trials are displayed in Table 1. Running economy normalized to speed (ml/kg/km) is represented in Fig 1. There was no main effect for condition (p=0.535) or condition by time interaction (0.238). There was a main effect for time (p=0.012), with follow-up pairwise comparisons showing significant differences at the post intervention time point to the post 30-min run. These data are also expressed as relative VO2 (ml/kg/min) in Figure 2. The HR (Figure 3) and RPE (Figure 4) responses are also provided.

The power factor measured via the Just Jump Mat is represented in Fig 5. There was a trend towards a significant condition effect (p=0.061) which appeared to be driven by higher values for the weighted vest condition. There was no effect for time ($p=0.1467$) or condition by time interaction($p=0.46$)

During the 30-min running intervals, HR data was recorded. Average speed was the same for each runner between each intervention. Averages between intervention trials were recorded and indicated that the weighted vest, plyometric, and control protocol heart rates were 166.8±12.24, 165±7.11, and 163.4±8.96 BPM respectively.

DISCUSSION

The purpose of this study was to determine the effects of warm-up on running economy in trained distance runners. The warm-up protocols involved a series of plyometric movements, weighted-strides with a weighted-vest equal to 20% body mass, and a control strides protocol. The primary findings of this study are that the warm-up protocols had a statistically insignificant effect on running economy. Further, the data did not support a statistically significant change in leg stiffness as a result of the warm-up protocols.

The lack of effect on running economy contradicts some previous studies (2,22) which showed that either the plyometric or weighted-vest protocols had a positive effect on running economy. In Barnes et. al, the results indicated that strides with a weighted-vest elicited an increase in leg-stiffness which in turn increased running economy via measured peak running speed (2). Peak running speed was utilized in determining changes in performance in Barnes et al (2) and submaximal running speeds were performed at 14 km/h for all subjects. In this study, submaximal running paces were performed at a relative pace that was equal to the estimated 1-hour race pace for each subject (7.2 ± 0.96 mph).

Methodology for this research was designed with the intention of combining aspects from Barnes et. al. and Wei et. al. research (2,22). Barnes et. al. utilized well-trained distance runners that were described as having run 105.6 ± 30.9 km per week for the previous 6-weeks (2). The subjects in this study were considered to be more trained than Wei et al. but average distance per week was not measured in this study (2,22). While screening participants for this study it was a requirement that runners be well trained by participating in regular exercise uninterrupted by injury for the previous 6-weeks while also being capable of running at a minimum pace of 10 min/mile for 60 minutes. Recreationally-trained runners were utilized in an attempt to reduce the potential for untrained increases in performance that would be seen on untrained individuals. This aspect differed from Wei et al. in which untrained recreationally active subjects were utilized as subjects for the study. The subject criteria for Wei et al. may have been a contributing factor for the degree of improvement that was witnessed as a result of the plyometric protocol.

Additional aspects from both Barnes and Wei were changed as well in an attempt to increase reliability of data. To increase the reliability of the data and to decrease the effects of day-to-day variation in potentiation, baseline power data was collected immediately after the warm-up and prior to the potentiation intervention. In the study performed by Wei et al. jump and VO_2 data was only recorded after the warmup interventions and thus could only be compared between interventions. In Barnes et al. the data is represented as there being a positive effect on running economy of 6% ± 1.6% as a result of the weighted-vest warm-up intervention (2). The results are taken by only utilizing the post-intervention data points and comparing them between control and weighted-vest trials. While analyzing our results for statistical significance we also included an examination of specifically the post-intervention results but failed to see statistical significance in changes to running economy.

The 30-min treadmill run was added to the intervention protocol in an attempt to simulate an endurance event and determine if the benefits of the warmup intervention on running economy, if any, extended beyond the initial minutes of an exercise bout. This aspect was not included in previous research (2,22). As a result of there being no acute effect of the warm-up protocols effect on running economy, it is not likely that the warm-up condition would have a positive effect on running economy over longer durations. A trend that was perceived as a result of this study was that individuals running economy decreased overtime in accordance with duration of exercise. This trend affected all individuals within all trials indicating that the warm-up protocols did not prevent a decrease in running economy.

Certain limitations were experienced in this study that potentially effected the statistical significance and outcomes of the study. 11 subjects were recruited to participate in this study and for a variety of reasons only 5 subjects were able to complete and be included in the results of this study. The dropout rate for this study was high and was due to multiple mitigating circumstances including 2 for time commitment, 2 for injury related to outside activities unrelated to this study, and 2 for other unforeseen circumstances. A third limitation to this study is that the control of subjects outside activities could not be better controlled due to the fact that all were currently in training for races that called for specific training. A fourth limitation to this study was correctly estimating individuals pacing for the five- and thirty-minute intervals. Pacing was estimated utilizing a recent run equal to or longer than a 5K in which the subject estimated was close to their race pace for the duration. These times and paces were utilized to calculate the estimated race paces. The limitation arose because some individuals overestimated their running pace capabilities which resulted in a higher than required exertion. It is possible that due to an overestimation of individuals abilities, subjects were subjected to higher intensity bouts of exercise that could potentially skew HR, RPE, and VO_2 data. The results of this being that individuals would also become potentially more exhausted than anticipated and would elicit less change in power output as a result. It is important in future research to ensure that the estimated running paces for individuals correspond with what the subjects are currently able to perform at.

The results of this study indicate that though there was no statistically significant effect of warmup intervention on running economy, running economy did get worse following a 30-minute endurance run. This indicates that warmup protocols prior to an endurance race may have less of an impact on running economy than previously thought.

Future studies should examine the change in running economy in endurance athletes over different durations in time. The effects of specific warm-up protocol should also be expanded upon to include methods that are more realistic so as to practices that would potentially be utilized by an athlete prerace.

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Tables and Figures

Table 1. Demographic, BMI, 1-Hour Estimated Race Pace

Variables	Total (n = 5)
Age (years)	34 ± 12.75
Gender	Male
Weight (kg)	184.4 ± 20.44
Height (in)	179 ± 6.78
BMI (%)	25.96 ± 2.41
1-Hour Estimated Race Pace (mph)	7.2 ± 0.96

All values represent mean ± SD.

Figure 1. VO_2 ml/kg/km measured during 5-minute intervals

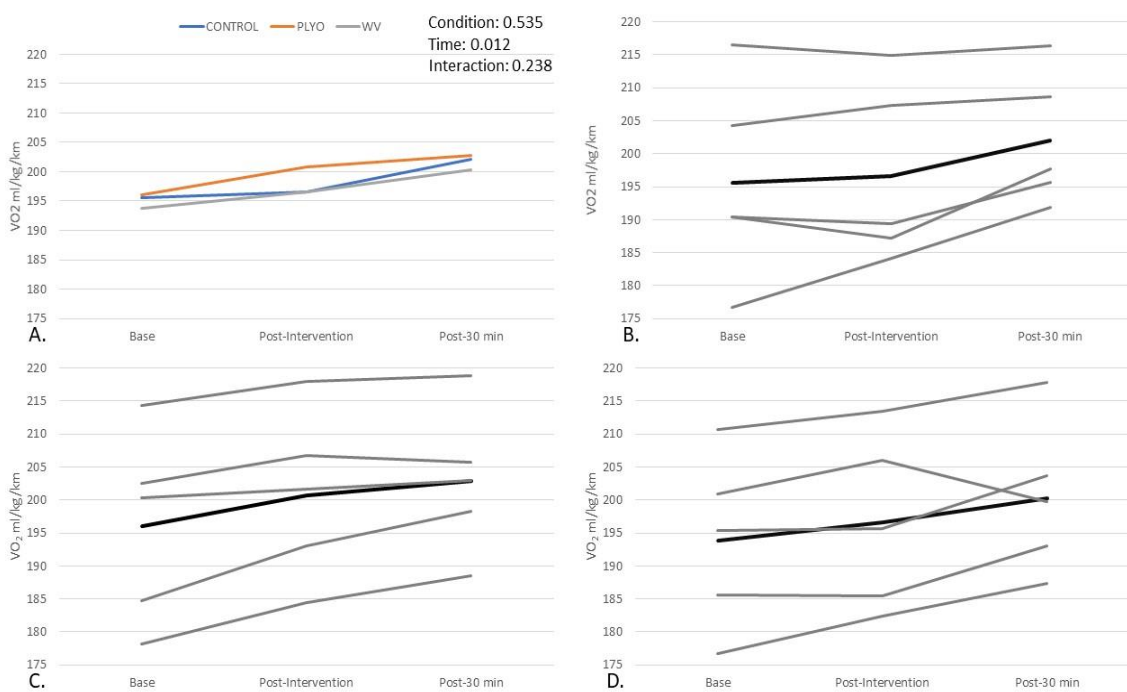

Figure 2. VO_2 ml/kg/min measured during 5-minute intervals

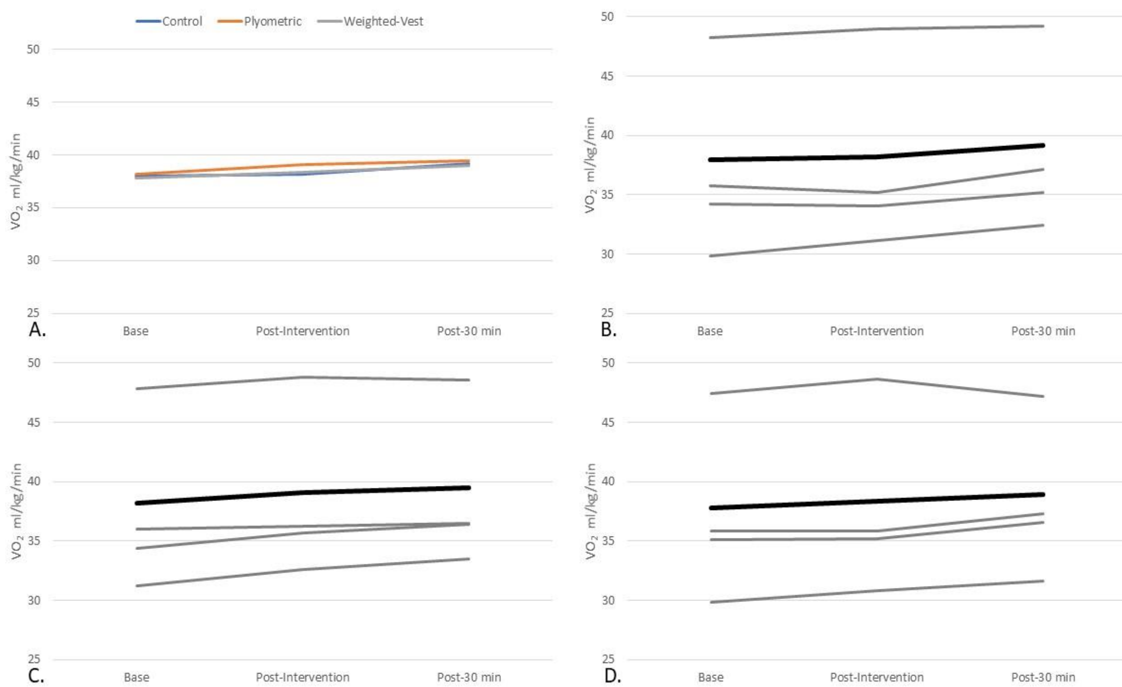

Figure 3. Heart Rate Data for 5-minute Intervals

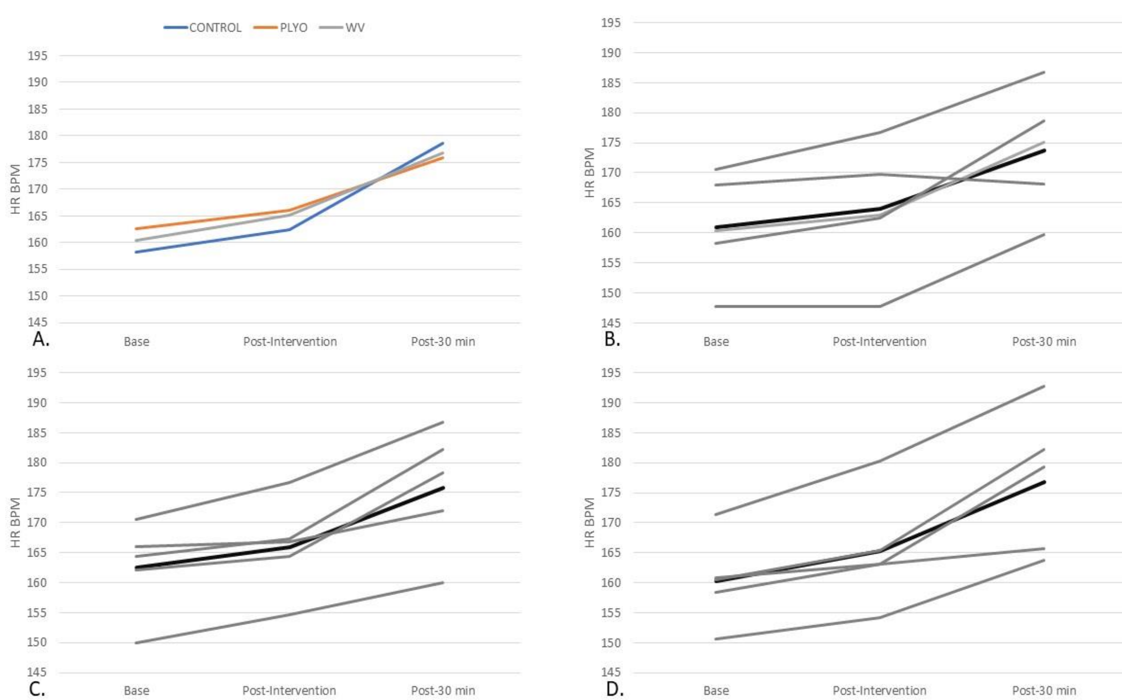

Figure 4. Rate of Perceived Exertion following 5-minute intervals

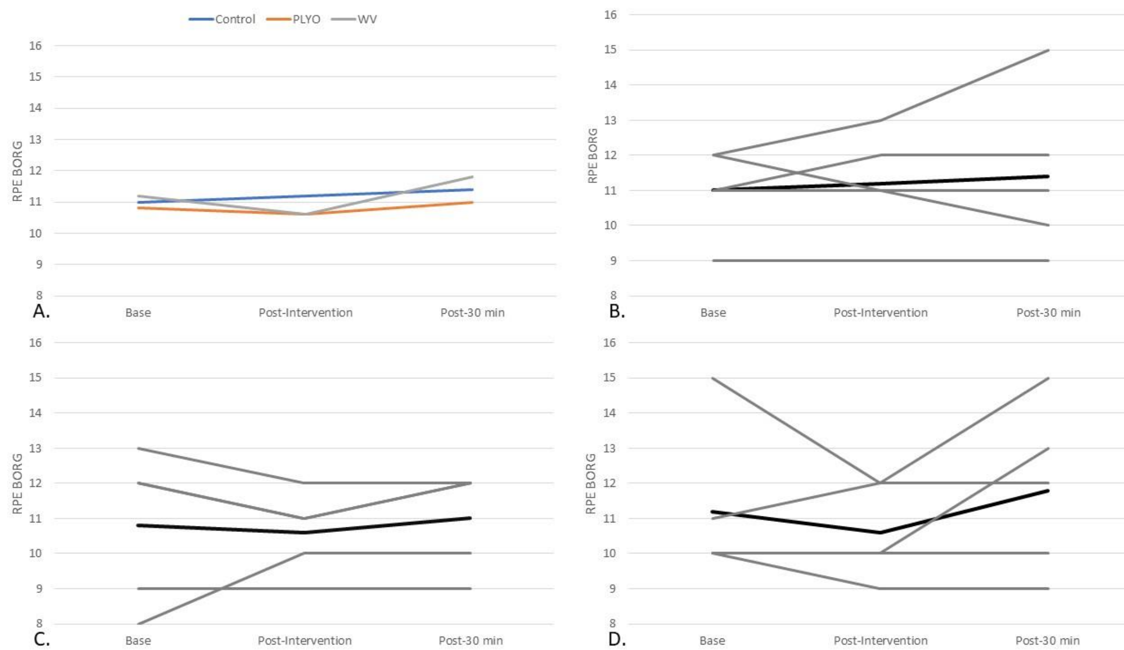

Figure 5. Power Factor measured via "Just Jump Mat"

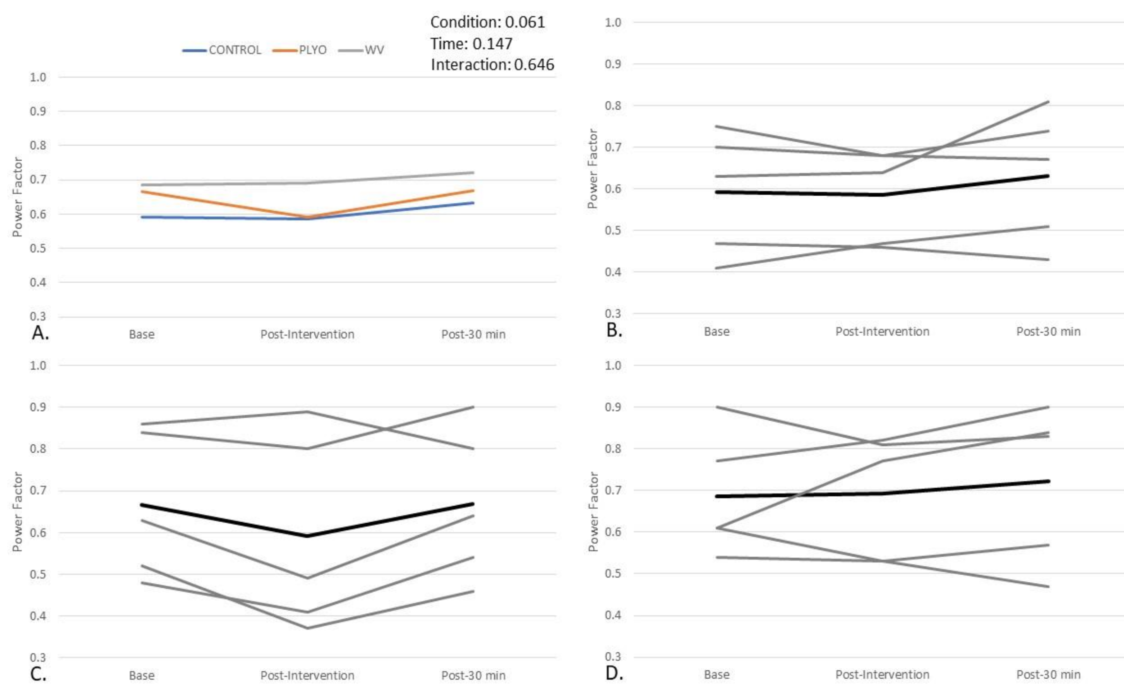

Figure 1. Running economy expressed relative to body mass and running speed (ml/kg/km) during 5-minute intervals at baseline, pre-intervention, and post 30-min. (A) Average group response across all conditions and time points. Individual responses (light grey lines) and mean responses (dark grey lines) across timepoints for control condition (B), plyometric condition (C), and weighted-vest condition (D).

Figure 2. Oxygen consumption expressed relative to body mass (ml/kg/min) during 5-minute intervals at baseline, pre-intervention, and post 30-min run. (A) Average group response across all conditions and time points. Individual responses (light grey lines) and mean responses (dark grey lines) across timepoints for control condition (B), plyometric condition (C), and weighted-vest condition (D).

Figure 3. Average heart rate during 5-minute intervals at baseline, pre-intervention, and post 30-min run. (A) Average group response across all conditions and time points. Individual responses (light grey lines) and mean responses (dark grey lines) across timepoints for control condition (B), plyometric condition (C), and weighted-vest condition (D).

Figure 4. Rating of perceived exertion during 5-minute intervals at baseline, pre-intervention, and post 30-min run. (A) Average group response across all conditions and time points. Individual responses (light grey lines) and mean responses (dark grey lines) across timepoints for control condition (B), plyometric condition (C), and weighted-vest condition (D).

Figure 5. Average jump power factor at baseline, pre-intervention, and post 30-min run. (A) Average group response across all conditions and time points. Individual responses (light grey lines) and mean responses (dark grey lines) across timepoints for control condition (B), plyometric condition (C), and weighted-vest condition (D).

VITA

Connor Bigenho, graduated from Shelton High School in 2015 and continued his Education by enrolling at Stephen F. Austin State University in Fall of 2015. He received his Bachelor of Science in Biology in Fall 2019 with an emphasis in Evolution and Ecology and a minor in Photography. In Spring of 2020 he enrolled in Graduate School and Stephen F. Austin State University. In Fall 2021 he received his Master's degree from the Kinesiology and Health Science Department.

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Style Designation: *International Journal of Exercise Science*

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