Biomechanical Considerations for Uphill Running Performance

by

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DISSERTATION ABSTRACT

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Despite the growth in trail running participation over the past decade, there is limited research available to guide training for trail runners. Understanding the physiological and biomechanical influences on trail running performance would not only benefit elite trail runners, but also recreational runners who participate in the sport for its benefits to physical and mental health. The purpose of this dissertation was to identify biomechanical characteristics associated with running economy and speed increases across various grades, and evaluate the effect of heavy resistance training on uphill running economy and biomechanics.

Three projects were implemented to address the aims of this dissertation. The first project measured the joint kinetics of 12 recreational runners as they ran on level ground, 13% incline, and 13% decline grades at 3 different speeds. The results of this study indicated that increasing uphill running speed required greater increases in swing phase positive hip and negative knee work compared to level ground, while increasing downhill running speed required smaller increases in these variables. The second project measured the joint kinetics and gas exchange of 27 recreational runners as they performed submaximal running trials on level ground, 5% incline, and 10% incline grades. This study revealed a significant association between greater positive ankle plantar flexor work and better running economy during the 10% condition. For the third project, an 8-week heavy resistance training program was implemented to evaluate its effects on uphill running economy and biomechanics. Despite improved strength, the program did not result in significant changes to running economy, joint work or joint stiffness, suggesting

that other interventions to target uphill running economy need to be explored. Overall, this dissertation provides new insights into the biomechanics of uphill running performance. Perspectives relevant to runners, coaches, healthcare providers, and researchers are provided to help guide athlete training and future research directions in this area.

This dissertation includes unpublished co-authored material.

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CHAPTER I

INTRODUCTION

Background and Significance

Worldwide participation in trail running has grown substantially over the past 10 years, with over 2 million race participants in 2022.[1] The sport continues to grow as new events are established every year, ranging from 5ks to ultramarathons. Understanding the physiological mechanisms underlying trail racing performance and identifying effective training modalities is of upmost importance for professional trail runners and their coaches. Furthermore, running participation is associated with a 27% reduction in all-cause mortality risk, and has profound effects on anxiety, depression and psychological well-being.[2,3] The much larger population of recreational runners would greatly benefit from information about training and performance as they pursue what could be a lifelong mode of aerobic exercise.

Determinants of Trail Running Performance

Endurance running performance is modulated by an interaction of physiological, socioeconomic, psychosocial, genetic, and training factors.[4] The primary physiological contributors to endurance running performance have been previously identified as maximal oxygen uptake (VO_{2max}), lactate threshold, and running economy, each of which can be targeted with specific training parameters.[4,5,6] Running economy (RE) is the rate of metabolic energy consumed while running at a submaximal intensity.[7] Among runners with a similar VO_{2max}, RE can vary by 30% and those with better RE demonstrate better performance in distance running events.[4,5,8]

In contrast to flat road or track running, trail running requires athletes to cover uphill and downhill segments which range from short, steep sections to climbs that can last for several miles. These differences in terrain introduce physiological and biomechanical challenges that are unique from level ground running. While the classic predictors of endurance running performance still apply, lower extremity strength, muscle endurance, and uphill RE also appear to have significant influences on trail running performance.[9,10] Ehrström et al demonstrated that RE measured on a 10% incline and knee extensor muscle endurance were significantly correlated with 27 km trail race times.[9] Highlighting a relationship between these two factors, Lazzer et al. reported that runners with greater pre-race muscle power had smaller increases in metabolic cost from pre- to post-ultramarathon.[11] As the long duration and higher muscle contraction demands throughout these races leads to systemic and local fatigue, runners with better economy, muscle endurance, and strength may be better equipped to manage these stressors.

Mechanical and Physiological Differences Between Level Ground and Graded Running

The physiological and biomechanical differences between level ground, uphill, and downhill running have been well described. Compared to level ground, running uphill increases the metabolic cost of running by 1.8-2.7 times, with energy cost increasing linearly with steepness of grade.[12,13,14] This is due to the greater amount of positive work that must be performed by the musculoskeletal system to raise the center of mass to a higher position with each step via metabolic costly concentric contractions of the ankle plantar flexors and hip extensors.[15,16,17] Due to the incline, the foot meets the running surface earlier, resulting in a shorter step lengths and flight times and higher step frequencies.[18,19,20] The increase in step frequency leads to greater energy generation demands from the hip flexors and extensors during swing phase.[16]

In contrast, downhill running is less metabolically costly than level ground up to a -20% grade, when metabolic cost again begins to increase.[21] The reduction in metabolic cost during downhill running is due to the relative increase in energy dissipation over generation, which occurs via less costly eccentric contractions. While energy generation is still required up to a -10.5% grade, it is almost zero at a -15.6% grade.[22] The increased negative work during downhill running is performed primarily by the knee extensors.[21] Due to the position of the decline, flight times are longer than level ground despite similar contact times, resulting in lower step frequencies.[21]

Several studies have demonstrated strong correlations between RE on level ground, uphill and downhill grades in highly trained and elite runners.[8,12,23] However, in a more heterogeneous group of runners who ran between 1-5 times per week and were not all trail runners, RE on 5%, 10%, and 15% inclines were only moderately correlated with level ground RE.[24] While being a more economical level ground runner may contribute to better uphill RE, these data suggest there may be an influence of training on uphill RE, and that there may be different influences on uphill RE compared to that on level ground.

Biomechanical Influences on Running Economy

Running economy is influenced by metabolic, cardiovascular, biomechanical, anthropometric, and neuromuscular factors, and can be improved with training.[7] Due to the many factors at play, it is challenging to identify specific mechanisms underlying differences in RE between individuals. However, identifying the components of running that incur metabolic cost provides a framework from which to evaluate areas of potential cost savings. Through a series of experiments performed by Roger Kram and colleagues, the metabolic cost of running has been partitioned into four primary categories.[25] Three of these categories – body weight support/forward propulsion (80% of total cost), leg swing (7%), and lateral balance (2%) – are related to oxygen consumed by skeletal muscle for force production, and have potential to be influenced by biomechanical factors. The remaining category encompasses cost due to ventilation and cardiac work (11%).

In the first half of body weight support during level ground running, mechanical energy is absorbed by the muscle-tendon units via eccentric contractions. During this period of negative work, some of the absorbed mechanical energy is stored as strain energy in the elastic elements of the muscle-tendon unit. In the second half of stance, positive work is performed via the release of stored strain energy and generation of mechanical energy via concentric muscle contractions in order to propel the runner forward.[26] This use of strain energy allows for the efficiency of running to be 40-50% for slow speeds and up to 80% for fast speeds, which far exceeds the 25% efficiency of skeletal muscle alone.[27,28,29]

Any mechanical behavior that increases the contribution of strain energy to positive work or reduces the cost of concentric muscle contraction has the potential to improve RE. Strain energy storage and release can be increased via higher tendon stiffness, a characteristic that is observed in more economical runners.[30,31,32] The metabolic cost of concentric muscle contraction may be influenced by muscle strength or muscle-tendon dynamics. Muscle hypertrophy may improve RE by reducing the number of motor units required to produce force during running due to higher force production per muscle fiber.[33] Muscles with long tendons, such as the triceps surae, are able to contract at lower, more efficient velocities due to changes in tendon length rather than muscle fiber length throughout the gait cycle.[34] Increasing reliance on these more efficient muscle groups may be an effective strategy for improving RE.

Most studies that have investigated the relationship between level ground RE and biomechanics have focused primarily on spatiotemporal metrics rather than quantifying joint-level contributions to energy generation. A 2024 meta-analysis by Van Hooren et al. reported that higher step frequency, smaller vertical oscillation, and higher leg stiffness were associated with better RE.[35] While no joint kinetic variables were consistently associated with RE, 41 studies evaluated spatiotemporal variables and only 3 investigated the influence of joint stiffness, power, or work on RE.

Few studies have investigated the relationship between uphill RE and biomechanics. As with prior research on level ground RE, these studies have focused on spatiotemporal factors. Lemire et al. reported that more economical uphill runners adopt longer contact times, greater step lengths, and shorter aerial times compared to less economical runners.[36] These mechanical differences between economical and non-economical runners were not present in level ground or decline running, suggesting there may be different mechanisms for reducing metabolic cost between grade conditions. While spatiotemporal metrics can be used to provide a global overview of running mechanics, applying an inverse dynamics approach to investigate the joint-level kinetics related to uphill running efficiency would better guide the selection of training interventions for runners preparing for endurance events with uphill grades.

Training Interventions to Improve Running Economy

Heavy resistance training, high load isometrics, plyometrics, and hill interval training have all been shown to significantly improve RE.[37] Across runners of various training levels, 1-3 days per week of resistance training for 6-14 weeks has been shown to improve level ground RE by 2-8% in multiple studies.[38] Similar changes in RE have been demonstrated following plyometric exercise programs, while smaller changes have been shown in response to uphill interval training.[37,39] Improvements in RE in response to training interventions have been associated with increases in Achilles tendon stiffness, functional leg stiffness, and muscle strength. [33,40,41] These concomitant changes offer some insights into the mechanisms by which running economy improvements are achieved, and provide direction in training program design.

Thus far, it is unknown whether uphill RE can be improved and if so, by what mechanisms these improvements occur. Given the improvements in level ground RE associated with changes in muscle-tendon properties and lower extremity mechanics, it is reasonable to expect that uphill RE could also be improved with a targeted resistance training intervention. Due to the metabolic and mechanical differences between level ground and uphill running, the specific mechanisms by which improved uphill RE can be achieved may differ from level ground RE.

General and Specific Aims

The overall goal of this dissertation is to identify biomechanical factors that influence two major components of trail running performance: achieving faster running speeds and better running economy (RE) across various grades. This work will expand the current understanding of performance biomechanics for trail athletes, providing coaches, healthcare providers, and runners with tangible strategies to implement into training. This goal will be addressed via three specific aims.

Specific Aim 1: Describe mechanisms for increasing speed during uphill and downhill running

The overall goal of this aim is to inform coaches and trail athletes about the mechanical demands of making brief changes in speed across various grades. This becomes relevant during trail races when implementing “surges” to pass competitors. On level ground, submaximal running speed is increased by increasing stride length, swing and stance phase positive hip work, and stance phase positive ankle work.[42,43] To date, only one study has evaluated the mechanisms for increasing speed during uphill and downhill running.[44] The first study of this dissertation investigates the effect of grade and speed on lower extremity joint kinetics, and expands on the work that has been done previously by including swing phase joint kinetics. The purpose of this study is to determine whether mechanical strategies for increasing speed are different between level ground, uphill, and downhill running. Due to previous reports of greater changes in step frequency when increasing uphill speed compared to level ground, it is hypothesized that increasing uphill speed will be achieved by greater increases in swing phase positive hip and negative knee work compared to increasing speed on level ground. [18,45] Due to similar spatiotemporal changes across speed for level ground and downhill running, no differences in swing phase kinetic changes are expected between level ground and downhill running.

Specific Aim 2: Identify biomechanical factors associated with uphill running economy

The second study of this dissertation seeks to identify the biomechanical and lower extremity strength factors associated with uphill RE. The overall goal of this study is to inform athletes and coaches regarding the desirable biomechanics for reducing energy cost over long uphill grades. Compared to running on level ground, running uphill requires greater mechanical energy generation to raise the center of mass, which is achieved via concentric contractions of the hip extensors and ankle plantar flexors.[15,17,22,44] Due to differences in tendon structure, the ankle plantar flexors are regarded as a more efficient muscle group. As lower extremity resistance training has been shown to improve level ground running economy, it is likely that muscle strength may also play an important role in uphill RE.[33] Because of the recognized differences in muscle efficiency, it is hypothesized that greater stance phase positive ankle work, greater ankle joint stiffness, and lesser stance phase positive hip work will be associated with better uphill RE. Due to the greater mechanical energy generation demands on the hip and ankle extensors during uphill running, it is further hypothesized that greater hip extensor and ankle plantar flexor muscle strength will be associated with better uphill RE.

Specific Aim 3: Determine the effect of a resistance training program on uphill running economy and biomechanics

While improvements in level ground RE have been consistently achieved in response to specific training modalities, it is currently unknown if uphill RE can be improved. Unless runners are specifically targeting strength of the hip extensor and ankle plantar flexor muscle groups with resistance training, they are most likely underprepared for the demands of uphill running and may be less efficient due to strength limitations.[30] Greater strength of the hip extensor and ankle plantar flexor muscle groups may improve uphill RE by reducing the number of muscle fibers required to produce the force necessary for uphill running or by increasing tendon stiffness.[33,41] Resistance training may also influence the mechanical energy generation capacity of the lower extremity muscle groups, resulting in changes in running biomechanics.[46] The third study of this dissertation implements a heavy resistance training intervention for the hip extensors and ankle plantarflexors to improve uphill RE. The overall goal is to provide an evidence-based intervention to trail athletes and coaches to improve uphill running performance. It is hypothesized that level ground and uphill RE will improve in response to heavy resistance training, and this will be accompanied by increases in muscle strength and changes in joint kinetics.

Organization of Dissertation

This dissertation is written in a scientific manuscript format, where Chapters III-V have been or will be submitted to peer-reviewed journals. The following paragraph explains how these manuscripts fit together in a cohesive body of work. Bridge statements are included at the conclusion of Chapters III-IV to explain the relationship between studies.

The current chapter provides background information regarding the components of trail running performance, the mechanical and physiological differences between level ground and graded running, the influence of biomechanics on running economy, and training interventions aimed to improve running economy. Rationale for the research presented in this dissertation is provided in detail. Chapter II provides a summary of the study design, data collection, and data analysis methodologies for each study of this dissertation. Chapter III addresses Specific Aim 1, and describes the study that quantified the differences in mechanical strategies used to increase running speed across level ground, uphill, and downhill grades. Chapter IV addresses Specific Aim 2, detailing the study implemented to identify biomechanical characteristics associated with level ground and uphill running economy. Chapter V examines the effects of resistance training on level ground and uphill running economy, using the data from Chapter IV as a baseline measure to address Specific Aim 3. The final chapter summarizes the significant findings of the overall body of work, describing its implications in both research and practical applications. A discussion on the studies' limitations and suggestions for future directions is also included.

This dissertation includes co-authored work, some of which is currently under review in peer-reviewed journals. Chapter III is currently being reviewed by the journal *Scientific Reports*, and Chapters IV and V are in preparation for submission to appropriate journals. For all included manuscripts, Rachel M. Robinson was the primary investigator, responsible for data collection, analysis, interpretation, and dissemination. While Rachel M. Robinson designed the studies for Chapters IV and V, the Chapter III study was designed by Seth R. Donahue, a previous student in the Bowerman Sports Science Center at the University of Oregon. Aida Chebbi is also included as a co-author for Chapter III, as she was heavily involved in data collection and analysis. Michael E. Hahn, the co-author for all studies in this dissertation, served as the primary advisor for all included work.

CHAPTER II

GENERAL METHODOLOGY

Participants

Chapter III

Twelve healthy recreational runners were recruited to address Specific Aim 1 (Chapter III). Volunteers were enrolled if they were between 18-65 years old, ran a minimum of 5 miles per week, and were not currently experiencing a running related injury. Participant demographics are outlined in Table 2.1. All participants provided written informed consent prior to engaging in study activities, and all study protocols were approved by the University of Oregon Institutional Review Board (10062020.007).

Table 2.1 Specific Aim 1 participant demographics (mean ± SD)

	Age (y)	Mass (kg)	Height (cm)	Sex
Participants (n = 12)	24.4 ± 7.7	63.2 ± 10.0	171.00 ± 9.65	F: n = 7 M: n = 5

Chapter IV & V

An *a priori* power analysis was conducted using G*Power (version 3.1.9) to determine a sample size for Specific Aims 2 & 3 ($\alpha = 0.05$; power = 0.8). Based on this analysis using previously published data, a sample size of 13 would be required to detect a significant relationship between joint work and metabolic work (Specific Aim 2).[47] To detect a group-by-time interaction effect for submaximal oxygen consumption, a minimum of 24 participants would be required (Specific Aim 3).[41] Because the sample size for Aim 3 exceeded that of Aim 2, both aims were addressed within the same sample. Anticipating a 10% attrition rate, 28 participants were enrolled, with 14 allocated to the training group and 14 to the control group. Twenty-seven participants completed the study requirements for Specific Aim 2, and twenty-five participants (training group n = 14; control group n=11) completed the study requirements for Specific Aim 3.

Participants were eligible to enroll in this study if they were over 18 years old, ran an average of 10 miles per week for the past 12 weeks, and were currently able to run a 25:00 5k. Participants were excluded from the study if they had engaged in a lower extremity resistance training program ≥1x per week over the past 12 weeks, were a collegiate or national level runner, experienced a running related injury that caused stoppage of running for at least 7 days or 3 consecutive training sessions over the past 12 weeks, were diagnosed with a cardiovascular or neuromuscular condition, or were currently pregnant. Participants were recruited from local recreational running groups. Participant demographics for Specific Aim 2 and Specific Aim 3 are outlined in Table 2.2 and 2.3, respectively. All participants provided written informed consent prior to engaging in study activities and all study protocols were approved by the University of Oregon Institutional Review Board (STUDY00001264).

Table 2.2 Specific Aim 2 participant demographics (mean ± SD)

	Age (y)	**Mass (kg)**	**Height (cm)**	**Sex**
Participants (n = 27)	33.7 ± 12.8	70.2 ± 12.5	175.9 ± 9.1	F: n = 14 M: n = 13

Table 2.3 Specific Aim 3 participant demographics (mean ± SD)

	Age (y)	**Mass (kg)**	**Height (cm)**	**Sex**
Total (n = 25)	34.2 ± 13.2	70.4 ± 13.0	176.4 ± 9.2	F: n = 12 M: n = 13
Training (n = 14)	31.4 ± 10.4	66.4 ± 13.0	175.1 ± 9.6	F: n = 7 M: n = 7
Control (n = 11)	36.2 ± 14.9	74.2 ± 11.1	176.8 ± 8.9	F: n = 5 M: n = 6

Study Design and Experimental Protocol

Chapter III

A cross-sectional design was used to address Specific Aim 1. Participants completed 30s running trials on level ground (LG), 7.5° (13% grade) incline, and 7.5° (13% grade) decline at five different speeds determined by each participant's self-reported 5k race pace. Marker position (Motion Analysis Corp, Rohnert Park, CA) and ground reaction force (Bertec, Columbus, OH) data were recorded throughout each trial, and the middle 10 seconds were used for analysis. At least 30 seconds of rest were given between each trial. Participants wore their typical running shoes, none of which were carbon fiber plated.

Chapter IV & V

A randomized trial design was implemented to address Specific Aims 2 and 3. Repeated-measures testing for running economy, biomechanics, and muscle strength were completed for a resistance training and control group before and after an 8-week intervention period (Figure 2.1). The baseline running economy, biomechanics, and muscle strength measures were used to address Specific Aim 2, and a comparison of baseline to follow up measurements were used to address Specific Aim 3. Stratified randomization was used to assign participants to a training or control group, balancing each group for biological sex. Participants were randomized to each group according to order of enrollment, using an allocation list generated prior to the start of the study. The research team and participants were blinded to the group assignment until the conclusion of baseline testing.

Participants first completed a lactate threshold and $\dot{V}O_{2max}$ test, which was used to determine the test speeds for the subsequent running economy and biomechanics tests. The biomechanics and running economy tests were performed on an instrumented treadmill (Bertec, Columbus, OH) while marker position (Motion Analysis Corp, Rohnert Park, CA) and gas exchange (Parvo Medics TrueOne 2400, Parvo Medics, Sandy, UT) data were recorded. Participants ran for 10 minutes on level ground (0% grade) at 80% of speed at lactate turnpoint (sLTP), 5% grade at 2 km/h slower than the level ground speed, and 10% grade at 3.5 km/h slower than the level ground speed. Five minutes of rest were given between trials. Following the running trials, concentric strength of the right hip extensors, knee extensors, and ankle plantar flexors were tested at 60°/s using an isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY). The training group returned to the laboratory for a resistance training familiarization visit, 10 Repetition Maximum (10 RM) test, and twice-weekly resistance training sessions for 8 weeks prior to the post-test visit. For all data collection visits, footwear was standardized to the Brooks Launch 10 (Brooks Running, Seattle, WA).

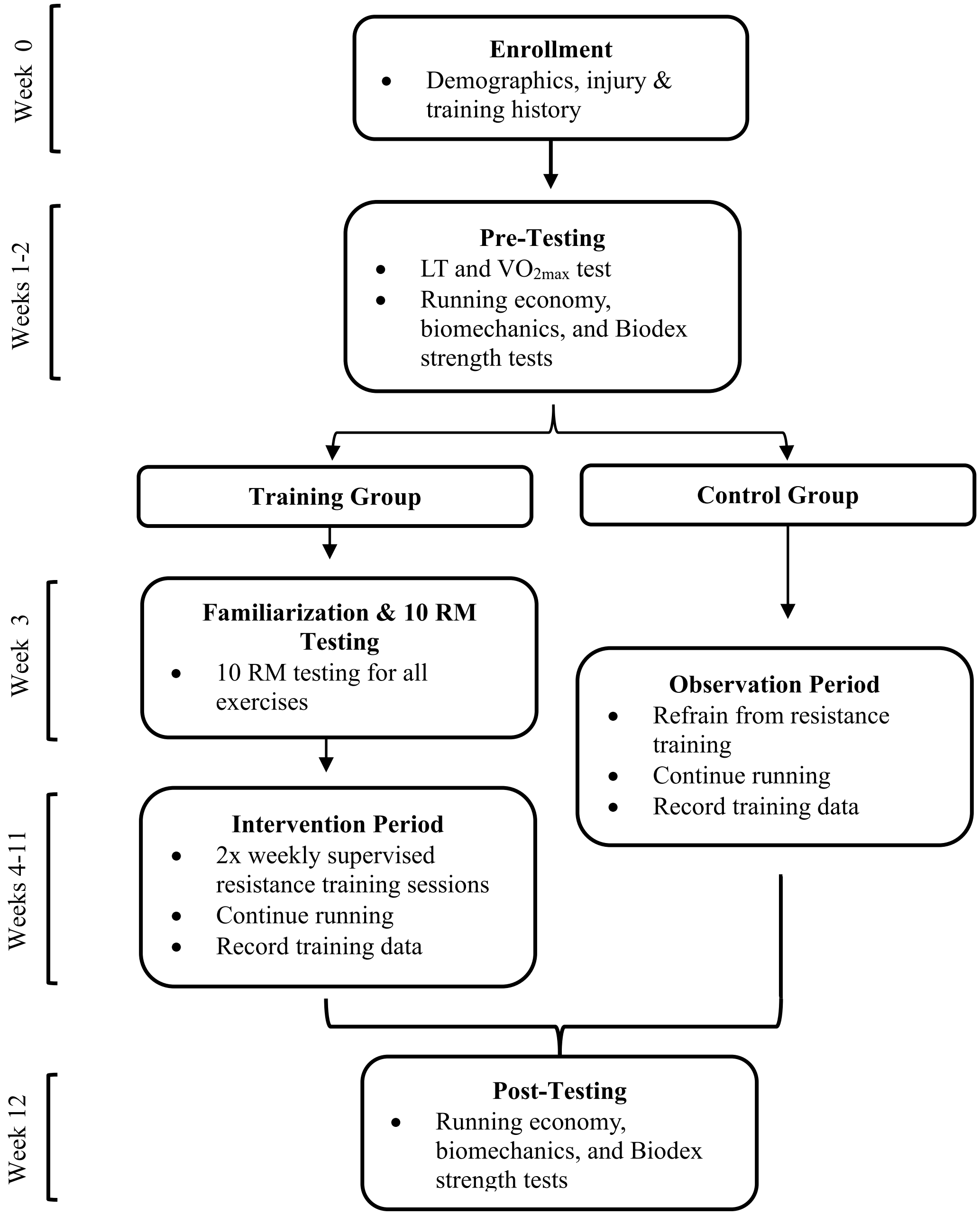

Figure 2.1 Study design and timeline for Chapters IV and V

Data Collection

Chapter III

Participants ran on an instrumented treadmill (Bertec, Columbus, OH) while wearing 45 retroreflective markers which were used to define the pelvis and bilateral thigh, shank, and foot segments. Three-dimensional marker data were collected at 200 Hz using an 8-camera motion capture system (Motion Analysis, Rohnert Park, CA) and ground reaction force data were collected at 1000 Hz (Bertec, Columbus, OH).

Chapter IV & V

Participants ran on an instrumented treadmill (Bertec, Columbus, OH) while wearing 51 retroreflective markers which were used to define the trunk, pelvis, and bilateral thigh, shank, and foot segments. Three-dimensional marker data were collected at 200 Hz using an 8-camera motion capture system (Motion Analysis, Rohnert Park, CA), ground reaction force data were collected at 1000 Hz (Bertec, Columbus, OH), and gas exchange data were collected in 15s averages (Parvo Medics TrueOne 2400, Parvo Medics, Sandy, UT). Isokinetic strength data were collected at 100 Hz (Biodex Medical Systems, Inc., Shirley, NY). Running mileage, running time, elevation gain, and cross training time were recorded with participants' GPS watches and uploaded to Final Surge (Final Surge LLC, Raleigh, NC). The training group's 10 RM test results and resistance training session sets, repetitions, and weights were manually recorded.

Data and Statistical Analysis

Chapter III

Data analysis was completed in Visual 3D (HAS-Motion, Kingston, Ontario, CA). Raw marker trajectory and ground reaction force data were filtered using zero lag 4th-order low pass Butterworth filters with 6 and 15 Hz cutoff frequencies, respectively. Coordinate system definitions for each segment are outlined in Table 2.4. For all segments, a Cardan sequence of *x*-*y*-*z* was used for joint angle calculations, where *x* was the mediolateral axis, *y* was the anteroposterior axis, and *z* was the longitudinal axis. Gait events were defined using a 50N threshold, and used to calculate spatiotemporal metrics. Three-dimensional joint power for the right hip, knee, and ankle was calculated as the dot product of internal joint moment and joint angular velocity, and was normalized to body mass. Positive and negative joint work were calculated as the time integral of the positive and negative portions of the power-time curves, respectively. Stance and swing phase joint work were calculated separately.

Table 2.4: Anatomical coordinate systems for the pelvis, thigh, shank, and foot rigid-body segments

	Pelvis	**Thigh**	**Shank**	**Foot**
Origin	ASIS midpoint	Hip joint center	Knee joint center	Ankle joint center
Mediolateral (x) axis	Origin to R ASIS, pointing to the right	Cross product of the y-axis and z-axis, pointing to the right	Cross product of the y-axis and z-axis, pointing to the right	Cross product of the y-axis and z-axis, pointing to the right
Anteroposterior (y) axis	Cross product of the z-axis and x-axis, pointing anteriorly	Perpendicular to the plane passing through the epicondyles and hip joint center, pointing anteriorly	Perpendicular to the plane passing through the malleoli and knee joint center, pointing anteriorly	Ankle joint center to midpoint of the 1st and 5th metatarsal heads, pointing anteriorly
Longitudinal (z) axis	Perpendicular to the plane passing through the R and L ASIS markers and the PSIS midpoint, pointing superiorly	Knee joint center to hip joint center, pointing superiorly	Ankle joint center to knee joint center, pointing superiorly	Perpendicular to the plane passing through the 1st and 5th metatarsal heads, pointing superiorly

Two-way repeated measures ANOVAs (2 grades x 2 speed intervals) were performed in SPSS version 28 (IBM Corp., Armonk, NY) to test for the effect of grade on speed-induced changes in spatiotemporal and joint work variables. Separate tests were conducted to compare LG to UH and DH separately. When significant interactions were detected, the Bonferroni correction was applied to *post hoc* simple main effects. For significant main effects, the Bonferroni correction was applied to pairwise *post hoc* tests. Alpha levels were set to 0.05, and corrected *p*-values <0.05 were determined to be statistically significant.

Chapter IV

Biomechanics data analysis was performed in Visual 3D (HAS-Motion, Kingston, Ontario, CA) as described in Chapter III with a few minor differences. A trunk segment was added, with the origin at 50% of the distance between the ASIS midpoint and PSIS midpoint, the *z* axis from the origin to the acromia midpoint pointing superiorly, the *x* axis perpendicular to the plane passing through the origin, acromia midpoint, and sternum pointing to the right, and the *y* axis as the cross product of the *z* and *x* axes pointing anteriorly. The Visual 3D composite pelvis was used, which places the origin at 50% of the length between the ASIS midpoint and PSIS midpoint, closer to the center of mass. In addition to the spatiotemporal and joint work variables described in Chapter III, ankle and knee joint stiffness were calculated by dividing the change in joint moment by the change in joint angular displacement from initial contact to peak ankle dorsiflexion or knee flexion, respectively.[48]

Lactate threshold (LT) and lactate turnpoint (LTP) were calculated in RStudio (R version 4.2.2) using the lactater package (version 0.2.0) using the modified *D*max method.[49,50] For the running economy data, metabolic steady-state was defined as an observed plateau in $\dot{V}O_2$ time-series plots, a change in $\dot{V}O_2$ by <5% over the final 2 minutes of each trial, and a respiratory exchange ratio (RER) <1.0. The final 2 minutes of $\dot{V}O_2$, $\dot{V}CO_2$, and RER data were averaged and used for analysis. Running economy was expressed as gross energy cost (J/kg/km). Hip, knee, and ankle strength were defined as the highest peak torque generated over 3 dynamometry test trials, normalized to body mass (Nm/kg).

Linear regression analyses were conducted in SPSS version 28 (IBM Corp., Armonk, NY) for each biomechanical variable at each grade, with speed entered as a covariate. The Benjamini-Hochberg procedure was used to adjust *p* values for multiple comparisons, with an adjusted alpha level of $p < 0.05$.[51]

Chapter V

Biomechanics, lactate threshold and turnpoint, running economy, and dynamometry data were analyzed as described in Chapter IV. Mixed-model repeated measures ANOVAs (2 groups x 2 time points) were conducted in SPSS version 28 (IBM Corp. Armonk, NY) to test for the effect of resistance training on running economy, biomechanics, and strength variables. Separate tests were performed for the LG, 5% incline, and 10% incline conditions. When significant interactions were detected, the Bonferroni correction was applied to *post hoc* simple main effects. For significant main effects, the Bonferroni correction was applied to pairwise *post hoc* tests. Alpha levels were set to 0.05, and corrected p-values < 0.05 were defined as statistically significant.

CHAPTER III

BIOMECHANICAL STRATEGIES FOR INCREASING RUNNING SPEED ON LEVEL GROUND, UPHILL AND DOWNHILL GRADES

This chapter has been submitted for publication to Scientific Reports. Rachel M. Robinson collected and analyzed the data, and wrote the initial manuscript. Seth R. Donahue was responsible for study design and data collection. Aida Chebbi assisted in data collection and analysis. Michael E. Hahn provided mentorship and general oversight of the project, and finalized manuscript edits. All co-authors participated in editing and approving the final manuscript.

Introduction

The mechanical strategies for increasing running speed on level ground (LG) have been well described. At slow to moderate running speeds (2.0-5.02 m/s), increasing speed is driven by greater stance phase energy generation from the ankle plantar flexors, contributing to longer step lengths. [42,45,52,53] At faster speeds, stance phase positive ankle work plateaus and step length is limited. [45,52] Further increases in running speed must be achieved by increasing step frequency, requiring greater swing phase energy generation from the hip flexors to bring the leg forward and the hip extensors to return the leg toward the ground. [43,45,52,53] Fewer studies have evaluated the mechanisms for increasing speed when running uphill (UH) and downhill (DH). [18,44,54] As many road races and training routes include hilly terrain, understanding the combined effect of speed and grade on running biomechanics may be important for guiding athlete training and making informed decisions for return to running after injury.

Compared to running on LG, running UH requires greater stance phase energy generation to raise the center of mass (COM) to a higher vertical position with each step.[22,54] This is primarily achieved by increasing energy generation from the hip extensors during stance phase.[15,17,55] Despite lower ground reaction forces in UH running, a longer external moment arm at the hip facilitates this increase in stance phase energy generation.[15] In contrast, little to no changes in energy generation at the ankle and knee occur in UH running compared to LG, likely due to the lack of significant changes in the external moment arm at these joints. [15,44,55] Shorter step lengths and higher step frequencies are also characteristic of UH running.[18] Due to the incline, the foot meets the running surface earlier than it does in LG running, resulting in a shorter flight time and step length.[18,19,20] As a result, step frequency is higher in UH running compared to LG in order to maintain the same speed while taking shorter steps. [16,18] Similar to running fast on LG, the increased step frequency required for UH running also results in greater energy generation from the hip during swing phase.[16]

Fewer mechanical differences exist between LG and DH running. Spatiotemporal parameters including step frequency, stride length, flight time, and swing time are not significantly different between LG and DH running.[18,19,56] The primary mechanical difference between LG and DH running is increased energy absorption through the lower limb system during DH running, particularly by the knee extensors.[17,55,56] As the COM descends with each step, energy generation requirements throughout the entire gait cycle are reduced.[22,54]

Vernillo et al. have provided a rather comprehensive description of the combined effects of running speed and grade on spatiotemporal parameters, ground reaction forces, muscle activation, joint kinematics, and joint kinetics across 0°, ±5°, and ±10° grades at 2.50, 3.33 and 4.17 m/s. [18,44] In summary, increases in UH running speed were achieved by greater increases in step frequency and stance phase energy generation at the hip compared to increasing speed on LG. Increases in DH running speed were achieved by spatiotemporal changes similar to LG, with greater increases in the rate of stance phase energy absorption at the knee with faster DH speeds. While these results provide insight into the mechanical demands of various speed and grade combinations, swing phase joint kinetics were not examined. Given the individual effects of speed and grade on swing phase mechanics, quantifying their combined effect is warranted. By evaluating spatiotemporal variables and joint kinetics during stance and swing phases of running, the purpose of this study was to determine if the mechanical strategies for increasing steady-state speed during UH and DH running are different from those used on LG. Due to previous reports of greater changes in step frequency when increasing UH speed compared to LG, it was hypothesized that increasing UH speed would be achieved by greater increases in swing phase positive hip and negative knee work compared to increasing speed on LG. [18,45] Due to similar spatiotemporal changes across speed for LG and DH running, no differences in swing phase kinetic changes were expected between LG and DH running.

Methods

Participants

Twelve healthy recreational runners (7 female, age: 24.4 ± 7.7 yr., mass: 63.2 ± 10.0 kg, height: 171.0 ± 9.65 cm) provided written informed consent and volunteered to participate in this study. Participants were required to be between 18-65 years old to enroll in this study, though the age range of participants in this analysis was 18-41 years old which minimizes the effect of age on biomechanics.[57] Participants were not eligible to participate if they ran less than 5 miles per week or were currently experiencing a running related injury. All research protocols were approved by the University of Oregon Institutional Review Board (10062020.007).

Experimental Protocol

Participants completed a total of thirteen 30s running trials on a split-belt force-instrumented treadmill (Bertec, Columbus, OH) with an 8-camera motion capture system (Motion Analysis Corp., Rohnert Park, CA). Participants wore their typical training shoes, none of which were carbon fiber-plated. Running speed was based on each participant's self-reported current 5k race pace. Five 30s trials were performed on level ground (LG) in the following order: 1:30 min/mile slower than 5k pace, 1:00 min/mile slower than 5k pace, :30 min/mile slower than 5k pace, 5k pace, and :30 min/mile faster than 5k pace. Four 30s trials were performed on a 7.5° (13% grade) incline and decline in the following order: 1:30 min/mile, 1:00 min/mile, and :30 min/mile slower than 5k pace, and at 5k pace. The LG trials were completed first, followed by incline, then decline. Participants were given at least 30s of rest between each trial. Because several subjects were not comfortable completing the UH trial at 5k pace due to the fast speed and steep grade, only the speeds slower than 5k pace were considered for this analysis. As this analysis was part of a larger study, the 13% grade was selected to match the grade of an outdoor hill local to the laboratory.

Forty-five retroreflective markers were affixed to the pelvis and bilateral lower extremities, including the sacrum, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, clusters of 4 thigh markers and 4 shank markers each on a semi-rigid plate, medial and lateral epicondyles of the knee, medial and lateral malleoli, superior, inferior, and lateral aspects of the calcaneus, 1st and 5th metatarsal heads, dorsum of the foot, and the distal phalanx of the great toe. After a static trial was captured, the greater trochanter, epicondyle, and malleoli markers were removed. Five markers were placed on the corners of the treadmill surface to track the position of the treadmill and force platforms during the INC and DEC trials. Marker trajectory data were collected at a sampling frequency of 200 Hz and ground reaction force data were collected at a sampling frequency of 1000 Hz. The middle 10 seconds of each 30 second trial were used for analysis.

Data Analysis

Markers were labeled according to anatomical landmarks, and marker trajectory gaps were filled using a cubic spline function in Cortex software (Motion Analysis Corp., Rohnert Park, CA). The remainder of the analysis was performed in Visual 3D (HAS-Motion, Kingston, Ontario, CA). Static trials were used to define anatomic coordinate systems for the pelvis, thigh, shank, and foot, each modeled as a rigid body. Hip joint centers were estimated using inter-ASIS distance, based on the regression equations from Bell and Brand.[58] Knee and ankle joint centers were defined as the midpoint between the femoral epicondyles and malleoli, respectively. A Cardan rotational sequence (*x-y-z)* was used for angular calculations, where *x* was the mediolateral axis, *y* was the anteroposterior axis, and *z* was the vertical axis. Segment mass was estimated using mass proportions reported by Dempster and inertial properties for each segment were estimated based on segment mass and length.[59] The pelvis was modeled as a cylinder and all other segments were modeled as cones, with proximal and distal segment radii estimated as one-half the distance between medial and lateral joint markers. Segment center of mass and mass moments of inertia were estimated using segment mass and geometry.

Marker trajectories and ground reaction forces were filtered using 4^{th}-order low pass Butterworth filters with 6 and 15 Hz cutoff frequencies, respectively. Cutoff frequencies were selected based on residual analyses to minimize noise and maximize true signal passed by the filter.[60] Baseline analog signals from the force platforms were subtracted from each frame using the “FP Auto Baseline” function in Visual 3D. Initial contact and toe off were identified using the “Automatic Gait Events” function in Visual 3D, with a 50 N force threshold. Gait events were used to calculate step frequency, stance and swing time, and step length. Three-dimensional joint power for the right hip, knee, and ankle was calculated as the dot product of internal joint moment and joint angular velocity, and was normalized to body mass. Positive and negative joint work were calculated as the time integral of the positive and negative portions of the power-time curves, respectively. Stance and swing phase work were calculated separately to analyze the mechanical demands of each joint during these two phases of the running gait cycle. Because sagittal plane joint work accounts for 89% of total lower extremity work during running, only sagittal plane joint work was analyzed.[17]

Statistical Analysis

The average and standard deviation of each variable were calculated for the middle 10 seconds of each trial. Speed categories were defined as Speed 1 (1:30 min/mile slower than 5k pace), Speed 2 (1:00 min/mile slower than 5k pace), and Speed 3 (:30 min/mile slower than 5k pace). For each variable, the mean difference between Speed 1 and Speed 2 and between Speed 2 and Speed 3 were calculated within each grade. Approximate normality was assessed graphically by comparing histograms of mean differences for each variable to the normal distribution curve. Two-way repeated measures ANOVAs (2 grades x 2 speed intervals, n=12) were performed in SPSS (IBM Corp., Armonk, NY) with mean differences as the dependent variables. Separate tests were conducted to compare LG to UH and DH. Mauchly's test was used to assess sphericity, and Greenhouse-Geiser corrections were applied when the sphericity assumption was not met. When significant interactions were detected, the Bonferroni correction was applied to *post hoc* simple main effects. For significant main effects, the Bonferroni correction was applied to two-tailed pairwise *post hoc* tests. Alpha levels were set to 0.05, and corrected p-values < 0.05 were determined to be statistically significant.

Results

The average running speed for Speed 1, 2, and 3 were 3.23 ± 0.38, 3.44 ± 0.43, and 3.68 ± 0.49 m/s, respectively. Spatiotemporal averages for each grade and speed condition are displayed in Table 3.2 and Figure 3.1. Exemplar sagittal plane joint power curves for each grade and speed condition are displayed in Figure 3.2. Stance and swing phase joint work averages for each grade and speed condition are displayed in Tables 3.3 and 3.4, respectively, and Figure 3.3.

Level Ground vs. Uphill Running

Between the LG and UH conditions, no significant interaction effects were detected for change in spatiotemporal variables ($p > 0.05$). A significant main effect of grade was detected for change in step frequency ($p = 0.048$), step length ($p = 0.035$), swing time ($p = 0.029$), and flight time ($p = 0.028$). Increasing UH running speed was achieved by a greater increase in step frequency, lesser increase in step length and flight time, and greater decrease in swing time compared to LG. On average, step frequency increased by 2.5 steps/minute during LG and 5 steps/min during UH running with each :30 min/mile increase in speed ($p = 0.048$). Step length increased by 0.06 m on LG and 0.04 m on UH with each increase in speed ($p = 0.035$). Swing time reduced by 1 ms during LG running, and 9 ms during UH running with each increase in speed ($p = 0.029$). While flight time increased by 3 ms with each increase in speed on LG, it did not change with increasing UH speed ($p = 0.028$). Changes in contact time were not significantly influenced by grade or speed interval ($p > 0.05$). There were no significant main effects of speed interval for any spatiotemporal variable ($p > 0.05$).

No significant interaction effects nor main effects were detected for changes in stance phase joint work variables ($p > 0.05$). However, a significant main effect of grade was detected for change in swing phase negative hip work ($p = 0.025$), positive hip work ($p < 0.001$), and negative knee work ($p = 0.002$). On average, swing phase positive hip work increased by 0.064 J/kg during LG running and 0.118 J/kg during UH running with each :30 min/mile increase in speed. Swing phase negative hip work increased by 0.010 J/kg during LG running and 0.018 J/kg during UH running with each increase in speed. Swing phase negative knee work increased by 0.065 J/kg during LG running and 0.103 J/kg during UH running with each increase in speed.

Level Ground vs. Downhill Running

Between the LG and DH conditions, no significant interaction effects nor main effects of grade were detected for changes in spatiotemporal or stance phase joint work variables ($p > 0.05$). A main effect of speed interval was detected for change in step frequency only ($p = 0.028$), with a greater increase in step frequency from Speed 2 to 3 (4 steps/min) compared to Speed 1 to 2 (1 step/min). A significant main effect of grade was detected for swing phase positive hip work ($p = 0.008$) and swing phase negative knee work ($p = 0.027$). On average, swing phase positive hip work increased by 0.064 J/kg during LG running and 0.041 J/kg during DH running with each :30 min/mile increase in speed. Swing phase negative knee work increased by 0.065 J/kg during LG and 0.051 J/kg during DH running with each increase in speed. A significant main effect of speed interval was detected only for swing phase negative knee work ($p = 0.009$), with a greater increase from Speed 2 to 3 (0.070 J/kg) than from Speed 1 to 2 (0.045 J/kg). A significant grade-by-speed interval interaction effect was detected for swing phase negative ankle work ($p = 0.021$). However, it should be noted that the magnitude of swing phase negative ankle work across all conditions was near zero (Table 3.4).

Table 3.2 Spatiotemporal data for each grade and speed condition. Data are presented as mean ± standard deviation

	Level Ground	Uphill	Downhill
Step Frequency (steps/min) *†			
Speed 1	169 ± 11	177 ± 15	168 ± 16
Speed 2	171 ± 14	181 ± 15	168 ± 14
Speed 3	174 ± 14	187 ±17	173 ±18
Step Length (m) *			
Speed 1	1.15 ± 0.13	1.11 ± 0.12	1.17 ± 0.17
Speed 2	1.22 ± 0.15	1.15 ± 0.14	1.24 ± 0.17
Speed 3	1.28 ± 0.17	1.20 ± 0.14	1.29 ± 0.21
Contact Time (ms)			
Speed 1	226 ± 24	231 ± 25	221 ± 22
Speed 2	220 ± 24	223 ± 26	215 ± 22
Speed 3	210 ± 21	215 ± 26	207 ± 20
Swing Time (ms) *			
Speed 1	487 ± 27	452 ± 28	501 ± 59
Speed 2	484 ± 37	445 ± 29	506 ± 51
Speed 3	485 ± 36	434 ± 35	496 ± 58
Flight Time (ms) *			
Speed 1	131 ± 11	110 ± 7	141 ± 32
Speed 2	133 ± 12	110 ± 7	146 ± 27
Speed 3	137 ± 12	110 ± 9	145 ± 28

*: significant main effect of grade, UH v. LG ($p < 0.05$)
†: significant main effect of speed interval, DH v. LG ($p < 0.05$)

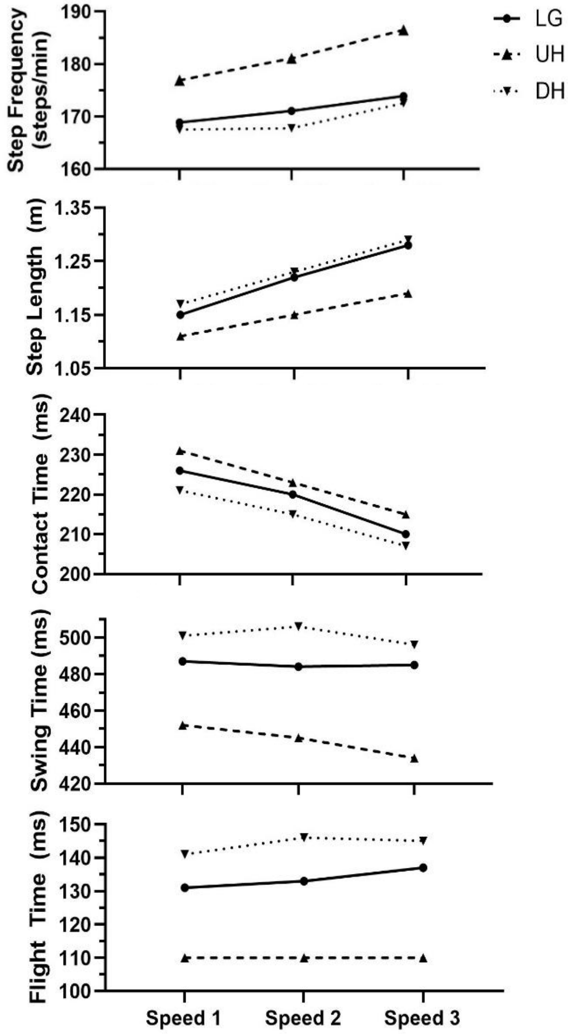

Figure 3.1 Effect of speed on mean spatiotemporal values for each grade condition. Error bars omitted for clarity.

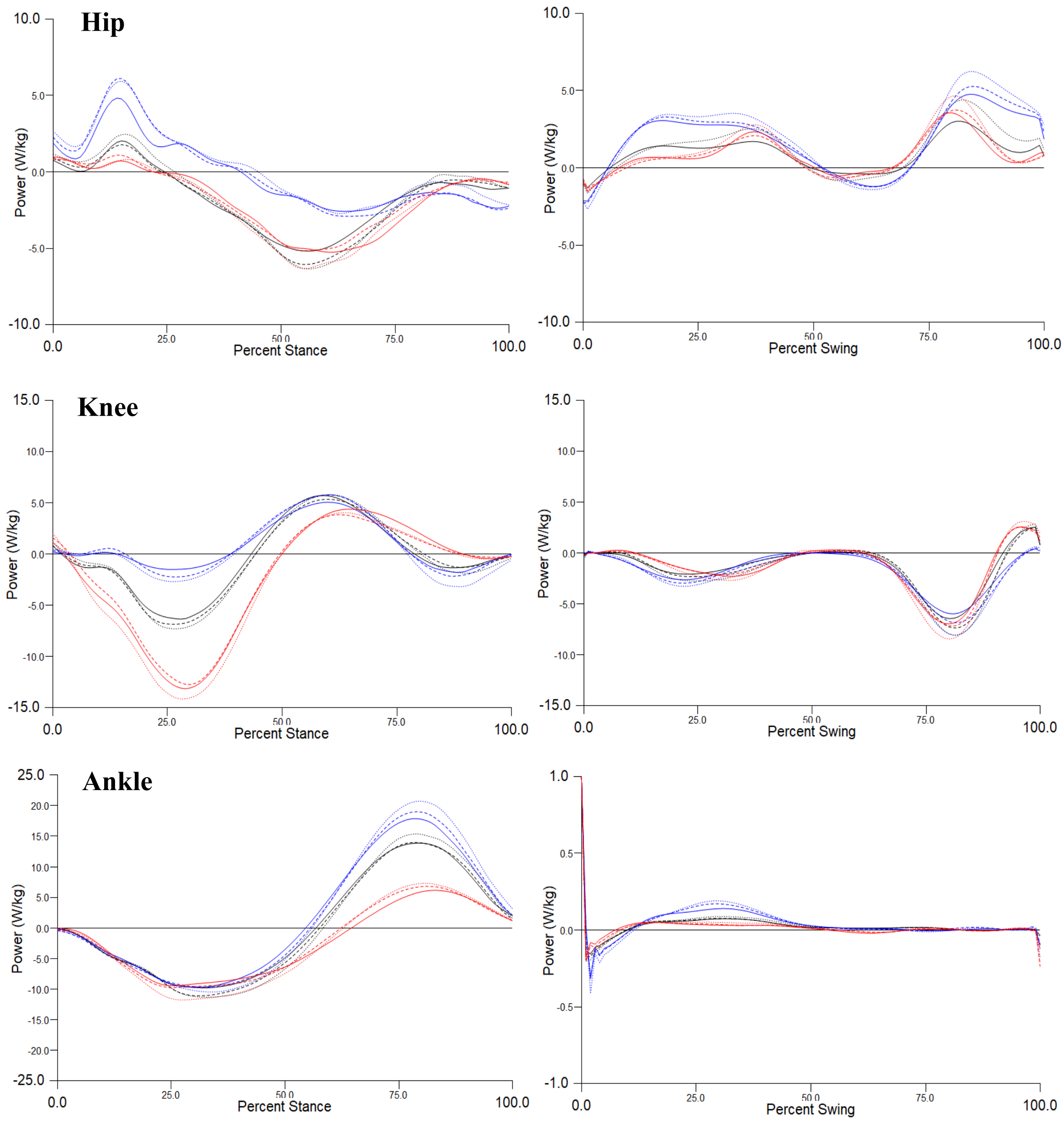

Figure 3.2 Exemplary sagittal plane power curves for the hip, knee, and ankle during stance and swing phase. LG is displayed in black, UH in blue, and DH in red. Speed 1 is displayed as a solid line, Speed 2 as dashed, and Speed 3 as dotted.

Table 3.3 Stance phase joint work data for each grade and speed condition. Data are presented as mean ± standard deviation

	Level Ground	Uphill	Downhill
Hip			
Stance Phase Negative Work (J/kg)			
Speed 1	.248 ± .171	.095 ± .092	.148 ± .121
Speed 2	.267 ± .176	.105 ± .106	.165 ± .122
Speed 3	.262 ± .161	.098 ± .085	.165 ± .130
Stance Phase Positive Work (J/kg)			
Speed 1	.062 ± .063	.365 ± .272	.037 ± .031
Speed 2	.070 ± .072	.410 ± .316	.042 ± .043
Speed 3	.084 ± .085	.425 ± .276	.050 ± .051
Knee			
Stance Phase Negative Work (J/kg)			
Speed 1	.412 ± .118	.206 ± .092	.622 ± .204
Speed 2	.407 ± .134	.203 ± .096	.606 ± .204
Speed 3	.414 ± .150	.219 ± .093	.629 ± .219
Stance Phase Positive Work (J/kg)			
Speed 1	.213 ± .073	.227 ± .058	.124 ± .070
Speed 2	.231 ± .094	.233 ± .060	.134 ± .062
Speed 3	.220 ± .073	.219 ± .066	.118 ± .058
Ankle			
Stance Phase Negative Work (J/kg)			
Speed 1	.470 ± .153	.515 ± .162	.511 ± .170
Speed 2	.500 ± .162	.542 ± .135	.525 ± .161
Speed 3	.542 ± .178	.548 ± .139	.542 ± .178
Stance Phase Positive Work (J/kg)			
Speed 1	.733 ± .090	1.05 ± .093	.410 ± .126
Speed 2	.732 ± .077	1.06 ± .121	.425 ± .113
Speed 3	.760 ± .102	1.08 ± .115	.437 ± .124

*: significant main effect of grade, UH v. LG ($p < 0.05$)
‡: significant main effect of grade, DH v. LG ($p < 0.05$)
†: significant main effect of speed interval, DH v. LG ($p < 0.05$)
§: significant grade-by-speed interval interaction effect, DH v. LG ($p < 0.05$)

Table 3.4 Swing phase joint work data for each grade and speed condition. Data are presented as mean ± standard deviation.

	Level Ground	Uphill	Downhill
Hip			
Swing Phase Negative Work (J/kg) *			
Speed 1	.065 ± .033	.089 ± .040	.057 ± .028
Speed 2	.076 ± .034	.102 ± .045	.078 ± .039
Speed 3	.086 ± .039	.125 ± .057	.090 ± .048
Swing Phase Positive Work (J/kg) *‡			
Speed 1	.515 ± .149	.808 ± .203	.347 ± .110
Speed 2	.575 ± .159	.926 ± .235	.372 ± .112
Speed 3	.643 ± .165	1.043 ± .269	.429 ± .137
Knee			
Swing Phase Negative Work (J/kg) *†‡			
Speed 1	.612 ± .126	.710 ± .143	.501 ± .145
Speed 2	.667 ± .146	.804 ± .164	.540 ± .152
Speed 3	.743 ± .159	.917 ± .212	.605 ± .181
Swing Phase Positive Work (J/kg)			
Speed 1	.038 ± .019	.010 ± .010	.053 ± .031
Speed 2	.041 ± .023	.013 ± .014	.053 ± .031
Speed 3	.044 ± .023	.018 ± .018	.059 ± .036
Ankle			
Stance Phase Negative Work (J/kg) §			
Speed 1	.004 ± .001	.005 ± .001	.005 ± .002
Speed 2	.004 ± .001	.006 ± .002	.005 ± .002
Speed 3	.005 ± .002	.006 ± .002	.006 ± .002
Swing Phase Positive Work (J/kg)			
Speed 1	.017 ± .003	.021 ± .004	.013 ± .003
Speed 2	.018 ± .004	.023 ± .005	.013 ± .002
Speed 3	.019 ± .005	.026 ± .005	.015 ± .003

*: significant main effect of grade, UH v. LG ($p < 0.05$)
‡: significant main effect of grade, DH v. LG ($p < 0.05$)
†: significant main effect of speed interval, DH v. LG ($p < 0.05$)
§: significant grade-by-speed interval interaction effect, DH v. LG ($p < 0.05$)

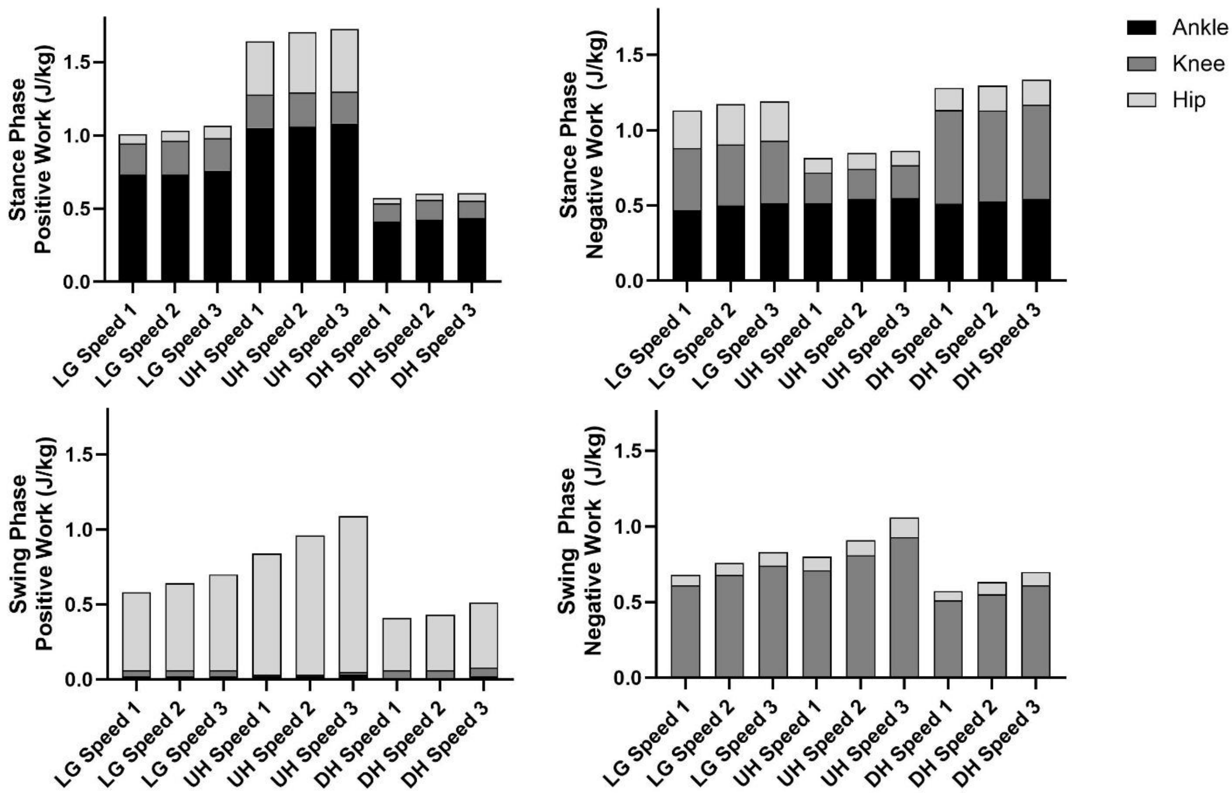

Figure 3.3 Average stance and swing phase joint work for each grade and speed condition. Error bars omitted for clarity.

Discussion

To determine whether the mechanical strategies for increasing speed on UH and DH are different from those utilized on LG, this study quantified spatiotemporal variables and joint work during stance and swing phase across a range of grades and submaximal running speeds. While stance phase joint work changed similarly across grades to increase speed, increasing UH and DH speed required significantly different changes in swing phase joint work compared to increasing LG speed. We accept our hypothesis that increasing UH speed is achieved by greater increases in swing phase positive hip and negative knee work compared to LG. We reject our hypothesis that no differences in swing phase joint kinetic changes exist between LG and DH running.

Increasing Uphill Running Speed

Consistent with previous studies, we found that increasing UH running speed is achieved by a greater increase in step frequency, and a smaller increase in step length and flight time compared to LG.[18,61] Additionally, swing time is reduced to a greater extent when increasing UH running speed compared to LG. On LG, increases in submaximal speeds are typically achieved by increasing step length to a greater extent than step frequency.[43] However, step length is limited during UH running due to earlier contact with the inclined surface, or to mitigate the greater amount of mechanical work that must be generated per step to raise the center of mass to a higher position.[17,18,19,61] Due to these step length constraints, more steps must be taken per minute to increase UH running speed. Since contact time is maintained across grades, this increase in step frequency must be achieved by swinging the leg forward more quickly to take the next step, resulting in a shorter swing time.[18,19,61] These mechanical changes mimic those of top-end sprinting on LG, where step length begins to plateau and step frequency increases at a higher rate. [43,45]

While a previous study identified a greater increase in stance phase positive hip work and lesser increase in stance phase positive ankle work to increase UH speed compared to LG, no effects of grade were found on stance phase joint work changes in the current study.[44] This difference in findings may be attributed to the smaller intervals between speeds in the current study (3.23, 3.44, and 3.68 m/s) compared to Khassetarash et al. (2.50, 3.33, 4.16 m/s).[44] In the current study, the primary differences between LG and UH joint kinetic changes occurred during swing phase. Increasing UH running speed required a greater increase in swing phase negative and positive hip work and negative knee work compared to LG. This is tied to the strategy of increasing step frequency to a greater extent than step length when increasing UH running speed.

As step frequency increases, more mechanical energy must be generated by the hip flexors to swing the leg forward, followed by the hip extensors in terminal swing to accelerate the leg toward the ground. In response to the increased energy generation over swing phase, more energy must be absorbed to decelerate the lower leg in terminal swing, resulting in a greater increase in negative knee work. While the importance of knee extensor, plantar flexor, and hip extensor strengthening is often recommended for uphill athletes, our examination of swing phase suggests that training hip and knee flexor strength may also be beneficial to prepare for the mechanical demands of UH running, particularly at faster speeds.[44]

Increasing Downhill Running Speed

Across all spatiotemporal variables, the magnitude of change in response to increased speed was not different between LG and DH conditions. However, a greater increase in step frequency from Speed 2 to 3 appeared to be driven by the DH condition (Figure 3.1, Table 3.2). Because running DH at faster speeds requires greater mechanical energy absorption at the knee, a greater increase in step frequency may be adopted to mitigate per-step negative knee work during stance.[44] Alternatively, this may be a result of being unaccustomed to running on a treadmill at a steep downhill grade. Visually, running DH on a treadmill is quite different than running on DH outside, as the surface just beyond the treadmill is flat. Rather than continuing to increase stride length at faster speeds, participants may elect to take shorter, quicker steps due to the visual interruption.

As with the LG vs. UH comparison, no effects of grade were identified for changes in stance phase joint work between LG and DH. Again, the primary differences between LG and DH kinetic changes occurred during swing phase, as faster DH speeds were achieved with smaller increases in swing phase positive hip and negative knee work. This is consistent with the overall reduction in energy generation requirements observed during DH running.[22,17] While swing phase negative ankle work increased slightly more during LG running compared to DH from Speed 1 to 2, negative ankle work is negligible during swing phase (Table 3.4) and this difference is not meaningful for practical applications.

Individual Strategies for Increasing Running Speed

Differences in mechanical strategies for increasing speed were observed across participants in the current study. Some participants demonstrated a step frequency-dominant strategy, while others demonstrated a step length-dominant strategy. Figure 3.5 depicts two participants who ran at 3.16 m/s for Speed 1, 3.35 m/s for Speed 2, and 3.58 m/s for Speed 3. Subject 1 (filled markers) demonstrated a step length-dominant strategy across all grades, increasing step length by 0.10-0.18m from Speed 1 to 3 with minimal changes in step frequency. Subject 2 (open markers) demonstrated a step frequency-dominant strategy, increasing step frequency by 9-14 steps/min from Speed 1 to 3 with minimal changes in step length. This illustration highlights that not all runners adhere to the commonly accepted mechanical strategies for increasing speed, and that runners may in fact switch strategies depending on the speed or grade. One possible influence on strategy selection is height of the runner; within our data set, Subject 1 was the tallest female participant (178 cm) and Subject 2 was the shortest female participant (157 cm). Other potential influences could be relative intensity, experience with treadmill running, or experience with hill running. Previous studies have demonstrated that runners tend to select step frequencies at or near the optimal oxygen cost, regardless of grade.[62] The difference in strategy selection may be due to participants choosing their most economical step frequency for the given speed and grade. However, this cannot be confirmed in the current study with the absence of metabolic data. While the most advantageous strategy cannot be confirmed by this study, coaches, trainers, and rehabilitation professionals should be aware that these different strategies exist when developing individualized training or rehabilitation programs.

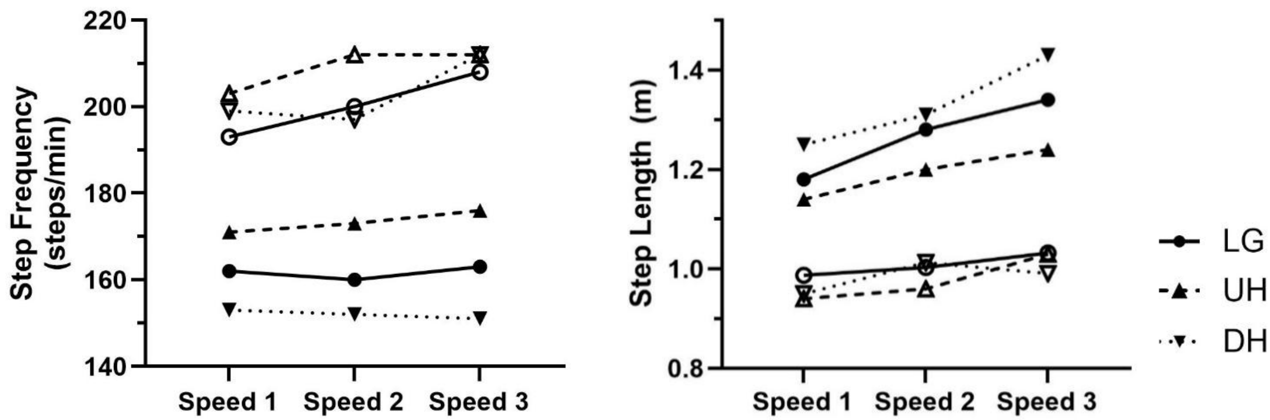

Figure 3.4 Individual mechanical strategies for increasing speed across LG, UH, and DH. Participant 1 is represented by filled markers and Participant 2 is represented by open markers.

Limitations

Some limitations should be considered when interpreting the results of this study. The order of trials was not randomized due to the time required to change the grade and to allow a gradual warm up to faster speeds. Therefore, it is not possible to rule out the effect of trial order on the observed mechanical changes. Because the running trials were only 30 seconds in length (total of 6.5 minutes of running) and participants were habitual runners, it is unlikely that our findings were influenced by fatigue. However, previous studies have suggested that longer trials are likely needed for running biomechanics to stabilize.[63] Due to the steep grade used for the uphill condition, maintaining the faster speeds for much longer than 30 seconds would not have been feasible. The results of this study are more likely to be applicable for understanding the short and frequent changes in running speed that occur when running on variable terrain. Rather than prescribing fixed test speeds for all participants, speeds were assigned based on each participant's self-reported current 5k race pace. The rationale for this strategy was to control for any mechanical differences that may be imposed by constraining participants to speeds that are faster or slower than their typical training paces. However, as current 5k pace was self-reported, it is possible that a uniform effort level was not maintained across participants. The small intervals between test speeds may minimize any potential differences in stance phase joint work changes. However, these speeds were selected to represent speeds that are most utilized by recreational runners during training. Because only one grade was analyzed, it is not clear at which grade mechanical strategies for increasing speed become different from LG.

Conclusion

In conclusion, this study demonstrates that different mechanical strategies are utilized to increase UH and DH speed compared to LG. Increasing UH speed is achieved by greater increases in step frequency and lesser increases in step length, requiring greater swing phase energy generation at the hip and energy absorption at the knee. Increasing DH speed requires a lesser increase in swing phase energy generation at the hip and energy absorption at the knee, with no differences in spatiotemporal parameters compared to LG. Different strategies for increasing speed are observed across participants, as some preferentially increased step frequency and others increased step length. Coaches, trainers, and rehabilitation professionals should be aware of the various strategies used to increase LG, UH and DH running speed in order to better individualize training, injury prevention, and rehabilitation programs for runners.

Funding Sources

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Bridge

The goal of Chapter III was to identify differences in the mechanical strategies for increasing speed across level ground, uphill, and downhill grades. This study demonstrated differences in how swing phase hip and knee joint kinetics change with speed between these three grades. While trail racing can require brief surges in speed, the majority of long trail races will be performed at submaximal intensities where metabolic energy conservation is key for performance. Chapters IV and V will explore biomechanical strategies for improving running economy, particularly on more metabolically costly uphill grades. Chapter IV first aims to identify biomechanical features associated with better uphill running economy. Chapter V follows with the implementation of a heavy resistance training program, to provide insights on how uphill running economy can be improved, and by what mechanisms this may occur.

CHAPTER IV

THE RELATIONSHIP BETWEEN LOWER EXTREMITY JOINT KINETICS AND UPHILL RUNNING ECONOMY

This chapter is in preparation for journal submission. Rachel M. Robinson was responsible for study design, data collection, data analysis, and writing the initial manuscript draft. Michael E. Hahn provided mentorship and aided in study design, general oversight, and editing the manuscript.

Introduction

Along with the maximal rate of oxygen consumption (VO_{2max}) and lactate threshold, running economy (RE) is one of the primary physiological predictors of endurance running performance.[4,5,6] RE can vary by up to 30% among runners with a similar VO_{2max}, and those with better RE tend to perform better in distance running events.[4,5,8] While this model of endurance performance has long been applied to the road and track, recent studies have demonstrated the importance of RE for trail running performance.[9,11,64] In contrast to the road or track, trail racing requires athletes to cover continuous uphill segments that can last for several miles. Running uphill increases the metabolic cost of running by 1.8-2.7 times that of level ground, increasing linearly with steepness of grade.[12,13,14] While this increase in metabolic cost is inevitable due to the mechanical demands of running uphill, runners who are able to minimize their metabolic cost during uphill running would be expected to perform better in events with long, sustained inclines.

Approximately 80% of the metabolic cost of running is attributed to body weight support and forward propulsion.[25] When running uphill, more positive work must be performed by the musculoskeletal system for forward propulsion compared to level ground.[17] Because negative work reduces and positive work increases with uphill running, the proportion of positive work provided by the release of elastic strain energy is reduced.[22,62,65] As a result, a greater proportion of positive work is performed by metabolically costly concentric contractions.[15,16] Muscles with long tendons, such as the triceps surae, are able to contract at slower, more efficient velocities due to changes in tendon length rather than muscle fiber length throughout the gait cycle.[34] Thus, the triceps surae muscle group is thought to be more efficient than the hip and knee extensor muscle groups which have shorter tendons relative to the muscle fascicles.[66] Increasing reliance on the more efficient ankle plantar flexors may serve as an effective mechanism for runners to reduce metabolic cost when running uphill.

Several previous studies have investigated the relationship between level ground RE and biomechanics. In a 2024 meta-analysis, Van Hooren et al. concluded that higher step frequency, smaller vertical oscillation, and higher leg stiffness were associated with better RE.[35] No other spatiotemporal, joint kinematic, or joint kinetic variables were consistently associated with RE. However, while 41 studies evaluated spatiotemporal variables, only 3 of the studies investigated the influence of joint stiffness, power, or work on RE. Similarly, the few studies that have examined the effect of biomechanics on uphill RE have focused primarily on spatiotemporal metrics, reporting that more economical uphill runners adopt a longer contact time, greater step length, and shorter aerial time compared to less economical runners.[36] These mechanical differences between economical and non-economical runners differ from those observed during level ground or downhill running, suggesting there may be different mechanisms for reducing metabolic cost between grade conditions.[36] While spatiotemporal metrics can be used to provide a global overview of running mechanics, applying an inverse dynamics approach to investigate the joint-level kinetics related to uphill RE would better explain the relationship between metabolic energy consumption and mechanical energy generation during running across different grades. This information would help guide the selection of training interventions for runners preparing for long endurance events with variable terrain.

Several studies have also demonstrated improved RE in response to resistance training, suggesting that lower extremity muscle strength plays an important role in RE.[30,31,32,33,41] It has been suggested that individuals with greater muscle strength will need to recruit a relatively lower proportion of motor units to run at a submaximal velocity compared to runners with lesser strength. [38,67] With less motor units performing mechanical work, metabolic cost may be minimized. Due to the greater force-generating demands with uphill running, lower extremity muscle strength may play an even more crucial role in uphill RE.

The purpose of this study was to determine the influence of lower extremity joint kinetics and concentric muscle strength on RE over level ground, 5% and 10% grades. Due to the recognized differences in muscle efficiency, it was hypothesized that greater stance phase positive ankle work, greater ankle joint stiffness, and lesser stance phase positive hip work would be associated with better uphill RE. Due to the greater mechanical energy generation demands on the hip and ankle extensors during uphill running, it was further hypothesized that greater hip extensor and ankle plantar flexor muscle strength would be associated with better uphill RE.

Methods

Participants

Based on an *a priori* power analysis (G*Power version 3.1.9) using previously published data, a minimum of 13 participants were required to detect a significant relationship between joint work and metabolic work (power = 0.8; $\alpha = 0.05$).[47] Twenty-eight recreational runners provided written informed consent per the requirements of the University of Oregon Institutional

Review Board (STUDY00001264). One participant withdrew after the first visit due to a running-related injury not associated with study activities. Participants were eligible to enroll if they were over 18 years old, ran an average of 10 miles per week for the past 12 weeks, and were currently able to run a 25:00 5k. Participants were excluded from the study if they had engaged in a heavy lower extremity resistance training program ≥1x per week over the past 12 weeks, were a collegiate or national level runner, experienced a running related injury that caused stoppage of running for at least 7 days or 3 consecutive training sessions over the past 12 weeks, were diagnosed with a cardiovascular or neuromuscular condition, or were currently pregnant. Participants provided self-reported demographic and training characteristics upon enrollment, which are outlined in Table 4.1 and Figure 4.1.

Table 4.1 Participant demographics and training characteristics. Data are presented as mean ± standard deviation.

	Total (n = 27)	**Female (n = 14)**	**Male (n = 13)**
Age *(y)*	33.7 ± 12.8	25.4 ± 5.3	42.8 ± 12.4
Mass *(kg)*	70.2 ± 12.5	61.4 ± 7.7	79.6 ± 9.4
Height *(cm)*	175.9 ± 9.1	169.3 ± 4.0	183.0 ± 7.6
Years of Running Experience *(y)*	14.0 ± 11.2	9.9 ± 4.1	18.7 ± 14.8
Average Weekly Mileage *(mi/wk)*	27.0 ± 12.5	21.0 ± 8.8	33.5 ± 12.9
Current 10k Pace *(min/mi)*	7:22 ± 0:51	7:42 ± 0:34	7:01 ± 0:59

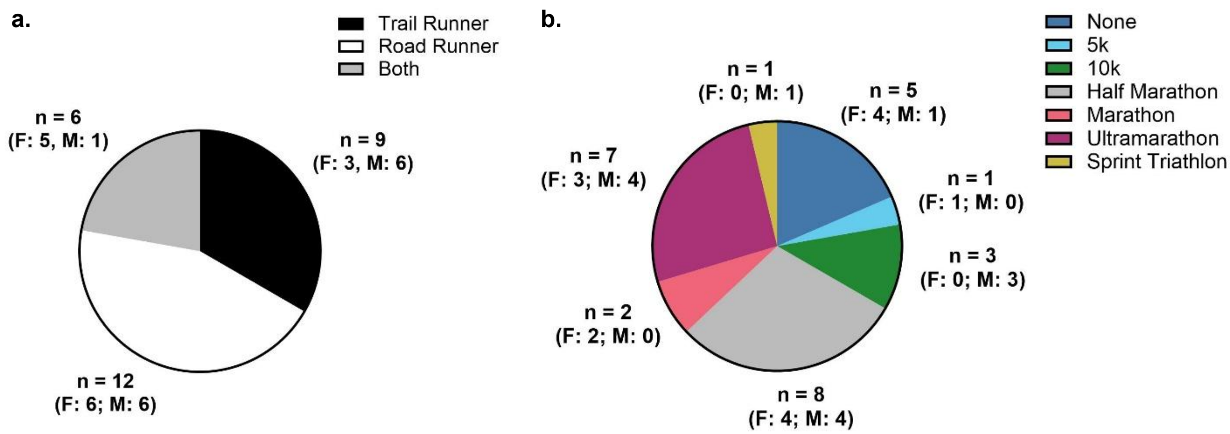

Figure 4.1 Distribution of a) runner type and b) current training focus (%)

Experimental Protocol

Visit 1: Lactate Threshold and $\dot{V}O_{2max}$ Test

On the first study visit, participants completed a lactate threshold (LT) and maximal oxygen consumption ($\dot{V}O_{2max}$) test. Participants were asked to refrain from food or drink other than water 3 hours prior to the visit, caffeine 6 hours prior, alcohol or recreational drugs 12 hours prior, and hard workouts or races 24 hours prior. For all data collection visits, footwear was standardized, using the Brooks Launch 10 (Brooks Running, Seattle, WA) to control the effects of shoe weight and material properties on RE. Gas exchange was measured via indirect calorimetry using a Parvo Medics TrueOne 2400 system (Parvo Medics, Sandy, UT). The metabolic cart was turned on at least 1 hour prior to collection to allow for sufficient warming of the pneumotach and was calibrated before each session using a calibration gas mixture (16% O_2 and 4% CO_2) and 3L calibration syringe. Baseline gas exchange, heartrate (Polar H10, Polar Electro, Kempele, Finland) and fingertip blood lactate concentration (Lactate Plus, Nova Biomedical, Waltham, MA) were collected during a 3-minute standing baseline period. The LT test was completed on a high-speed treadmill (Woodway, Waukesha, WI) at 0% grade, and gas exchange data were collected in 15s averages. While many studies perform LT tests on a 1% grade, 0% was selected in this study to maintain consistency with subsequent biomechanics and running economy trials. The initial speed was set to 5 km/h slower than each participant's estimated 10k pace, and increased by 1 km/h every 3 minutes until volitional fatigue. Participants straddled the treadmill belt for 30 seconds after each stage to collect 2 fingertip blood lactate samples, which were averaged for analysis. Following completion of the LT test, participants rested for 10 minutes. For the $\dot{V}O_{2max}$ confirmation test, participants ran 2 km/h slower than the final stage of the lactate threshold test beginning at 1% grade. Grade was increased by 1% every minute until volitional fatigue.

Visit 2: Running Economy, Biomechanics, and Strength Test

The second visit was scheduled between 2-14 days after Visit 1, within 2 hours of the same start time. Participants were asked to adhere to the same pre-test instructions as Visit 1. Retroreflective markers were adhered to the sternum, C7 spinous process, bilateral acromia, lateral epicondyles, radial styloid processes, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), sacrum, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, heads of the 1st and 5th metatarsals, distal 1st phalange, and superior, inferior, and lateral aspects of the calcaneus. Clusters of 4 markers were placed on the posterolateral aspect of each thigh and shank. Five markers were placed on the corners of the treadmill surface to track the position of the treadmill and force platforms. Following a static marker capture and 3 minutes of standing baseline gas exchange collection, the greater trochanter, femoral epicondyle, and malleoli markers were removed.

After a 5-minute warm up run at :30 min/mile slower than the LG test speed, participants completed three 10-minute running trials on an instrumented treadmill (Bertec, Columbus, OH) on LG, 5% incline (2.9°), and 10% incline (5.7°). These grades were selected because they are common grades included in trail races that typically would not require participants to walk. The speed at lactate turn point (sLTP) determined at Visit 1 was used to calculate the speeds for each trial to control for the effect of relative intensity on substrate utilization and metabolic cost.[68] The LG trial was performed at 80% of sLTP. To ensure participants remained below the LTP during the 5% and 10% incline trials, data from Margaria et al. were used to adjust the incline trial speeds to match the estimated energy cost of the LG trial.[69] Based on these data, the 5% and 10% incline trials were performed at 0.56 m/s and 0.97 m/s slower than the LG trial, respectively. Trial order was randomized, and participants were given 5 minutes of rest between trials. Gas exchange was recorded in 15s averages throughout each trial using the Parvo Medics TrueOne 2400 system (Parvo Medics, Sandy, UT). Steady state was defined as a visual plateau in $\dot{V}O_2$, a $<5\%$ change in $\dot{V}O_2$ and RER between the final 2 minutes of each trial, and RER <1.0. If minute-to-minute changes in $\dot{V}O_2$ and RER exceeded 5% between minutes 9 and 10, an additional minute was added to the trial until these criteria were met. A maximum of 2 minutes were added to the trials. Marker trajectory data were collected at a sampling frequency of 200 Hz (Motion Analysis Corp., Rohnert Park, CA) and ground reaction force data were collected at a sampling frequency of 1000 Hz. Marker and force data were collected for 30 seconds at the 1:00, 5:00 and 8:00 time points. The middle 10 seconds of the 8:00 capture were used for analysis. If key markers fell off prior to the 8:00 time point, the 5:00 capture was used for analysis. This occurred in 2 total trials throughout the study. The average heart rate over the final minute of each trial was recorded. Participants were asked to report their Borg Rating of Perceived exertion following each trial, using a visual chart with numerical and written descriptions.

Following the running trials, isokinetic dynamometry testing was completed using a System 4 Pro Biodex Isokinetic Dynamometer (Biodex Medical Systems, Inc., Shirley, NY). The right knee extensors, ankle plantar flexors, and hip extensors were tested concentrically at 60°/s. The knee extensors and ankle plantar flexors were tested in sitting and the hip extensors were tested in supine, with straps secured to minimize motion of other joints. For the ankle plantar flexor test, the knee was fixed in 30° flexion. For each muscle group, participants performed 5 submaximal practice trials, followed by 3 maximal effort trials with 1 minute of rest between each trial. The peak torque produced over the 3 test trials was normalized to body weight and used for analysis.

Data Analysis

Lactate Threshold and $\dot{V}O_{2max}$ Data

The $\dot{V}O_{2peak}$ was calculated as the greatest 30-second rolling average of $\dot{V}O_2$ during the final stage of the lactate threshold test. The $\dot{V}O_{2max}$ was calculated as the greatest 30-second rolling average of $\dot{V}O_2$ during the $\dot{V}O_{2max}$ confirmation test. All $\dot{V}O_2$ measures were normalized to body mass. Maximum heart rate (HR) was calculated as the greatest 30-second rolling average during the final stage of the lactate threshold or $\dot{V}O_{2max}$ confirmation test, whichever was higher. Lactate threshold (LT) and lactate turn point (LTP) were calculated in RStudio (R version 4.2.2) using the lactater package (version 0.2.0). The LT was defined as the speed prior to the first point-to-point rise in blood lactate (BLa) >0.4 mM. The LTP was calculated using the modified *D*max method, which fits a third-order polynomial function to the measured lactate values.[49] The point that is the maximal perpendicular distance between the fitted curve and a straight line connecting the LT and the final lactate point is the LTP.[50]

Running Economy Data

The final 2 minutes of $\dot{V}O_2$ and $\dot{V}CO_2$ data were averaged and used for analysis. Running economy was expressed as relative gross energy cost of transport (ECOT) to control for the variation in test speeds and substrate utilization across participants.[25,68,70] The Péronnet and Massicotte equation was used to calculate metabolic power (W) from $\dot{V}O_2$ and $\dot{V}CO_2$ as described by Kipp et al.[71] To convert to units of ECOT (J/kg/km), metabolic power (W) was divided by speed (m/s) and multiplied by 1000. The mass recorded prior to the start of each trial was used to normalize ECOT, oxygen cost of transport (OCOT), and submaximal $\dot{V}O_2$ to body mass.

Biomechanics Data

A cubic spline function was applied to fill marker trajectory gaps using Cortex (Motion Analysis Corp., Rohnert Park, CA). The remainder of the analysis was performed using Visual 3D (HAS-Motion, Kingston, Ontario, CA). Anatomic coordinate systems for the trunk, pelvis, thigh, shank, and foot were defined using the static capture, with each segment modeled as a rigid body. The pelvis segment was defined according to the Visual 3D composite pelvis, which places the origin of the pelvis segment at the midpoint between the mid-ASIS and mid-PSIS to align the pelvis origin close to the center of mass. Hip joint centers were estimated using inter-ASIS distance, based on the regression equations from Bell and Brand.[58] Knee and ankle joint centers were defined as the midpoint between the femoral epicondyles and malleoli, respectively. Tracking coordinate systems were defined for each segment, using the sternum, C7 spinous process, and acromia for the trunk, left and right ASIS and PSIS for the pelvis, a cluster of four markers for the thigh, a cluster of four markers for the shank, and the distal heel, 1st metatarsal head, 5th metatarsal head, and toe markers for the foot.

Mass proportions reported by Dempster were used to estimate segment mass, and inertial properties were calculated by Visual 3D for each segment using segment mass and length.[59] The pelvis was modeled as a cylinder and all other segments were modeled as truncated cones, with proximal and distal segment radii estimated as one-half the distance between medial and lateral joint markers. Mass moments of inertia were estimated by Visual 3D using segment mass and geometry, and segment center of mass location was estimated using segment geometry and length.[72,73]

Marker trajectories and ground reaction forces were filtered using 4th-order zero lag low pass Butterworth filters with 6 and 15 Hz cutoff frequencies, respectively. The "FP Auto Baseline" function in Visual 3D was used to subtract baseline analog signals from the force platforms from each frame.[74] Gait events were identified using the "Automatic Gait Events" function in Visual 3D, with a 50 N force threshold.[75] Three-dimensional joint power for the right hip, knee, and ankle was calculated as the dot product of internal joint moment and joint angular velocity, and was normalized to body mass. Positive and negative joint work were calculated as the time integral of the positive and negative portions of the power-time curves, respectively. Because sagittal plane joint work accounts for 89% of total lower extremity work during running, only sagittal plane joint work was analyzed.[17] Because body weight support and forward propulsion account for 80% of the metabolic cost of running, only stance phase joint work was analyzed for this study.[25] Ankle and knee joint stiffness were calculated by dividing the change in body-mass normalized joint moment by the change in joint angular displacement from initial contact to peak ankle dorsiflexion or knee flexion, respectively.[48]

Statistical Analysis

Separate linear regression analyses were conducted in SPSS version 28 (IBM Corp., Armonk, NY) to determine the effect of each demographic (age, mass, height, years of running experience, weekly mileage), biomechanical (stance phase positive hip, knee and ankle work, ankle and knee stiffness) and strength variable (peak hip extensor, knee extensor, and ankle plantar flexor torque) on ECOT (J/kg/km) at each grade (LG, 5% grade, 10% grade). Speed was included as a covariate when assessing the biomechanical variables. For all tests, the multicollinearity, autocorrelation, and homoscedasticity assumptions were met. Multicollinearity was assessed using the variance inflation factor (VIF) and autocorrelation was assessed using the Durbin-Watson statistic. Histograms of standardized residuals and Normal P-P plots were used to test for approximate normality. One-way ANOVAs were used to test for differences in ECOT between sexes, runner types, and runners with different training focuses. In the case of a significant ANOVA ($p < 0.05$), post-hoc independent samples t-tests were performed with unequal variances assumed. For all statistical tests, Benjamini-Hochberg procedure was used to adjust p values for multiple comparisons using the p.adjust function (version 3.6.2) in R, with an adjusted alpha level of $p < 0.05$ (R version 4.2.2).[51]

Results

Physiological Data

Participants completed an average of 7.81 ± 0.79 stages of the lactate threshold test, reaching a maximum speed of 4.34 ± 0.43 m/s. The average speed at LTP was 3.79 ± 0.39 m/s. A summary of the lactate threshold and $\dot{V}O_{2max}$ test results is presented in Table 4.2.

Table 4.2 $\dot{V}O_2$, speed, BLa, and HR data from the lactate threshold and $\dot{V}O_{2max}$ tests. Data are presented as mean ± standard deviation.

	Total (n = 27)	**Females (n = 14)**	**Males (n = 13)**
$\dot{V}$O2 Max *(ml/kg/min)*	55.44 ± 6.75	52.43 ± 4.10	58.34 ± 7.33
$\dot{V}$O2 Peak *(ml/kg/min)*	53.96 ± 6.60	51.38 ± 4.63	56.23 ± 7.09
$\dot{V}$O2 at LTP *(ml/kg/min)*	46.17 ± 5.20	44.97 ± 3.57	48.68 ± 6.00
$\dot{V}$O2 at LT *(ml/kg/min)*	38.80 ± 5.02	36.77 ± 3.56	41.18 ± 5.56
Speed at $\dot{V}$O2 Peak *(m/s)*	4.34 ± 0.43	4.09 ± 0.25	4.61 ± 0.43
Speed at LTP *(m/s)*	3.79 ± 0.39	3.58 ± 0.25	4.00 ± 0.39
Speed at LT *(m/s)*	3.17 ± 0.39	3.00 ± 0.29	3.35 ± 0.40
BLa at LTP *(mmol/L)*	3.12 ± 0.80	2.84 ± 0.82	3.42 ± 0.68
BLa at LT *(mmol/L)*	1.31 ± 0.42	1.17 ± 0.39	1.46 ± 0.41
HR Max *(bpm)*	183.52 ± 10.42	186.00 ± 10.19	180.85 ± 10.38
HR at LTP *(bpm)*	168.11 ± 10.02	171.36 ± 10.85	164.62 ± 8.05
HR at LT *(bpm)*	150.48 ± 10.23	153.36 ± 11.47	147.38 ± 8.03

On average, the running economy trials were performed at 3.03 ± 0.31 m/s for the LG condition, 2.47 ± 0.31 m/s for the 5% grade condition, and 2.06 ± 0.31 m/s for the 10% grade condition. For all running economy trials, $\dot{V}O_2$ and RER changed <5% over the final 2 minutes and RER remained <1.0, meeting the steady-state criteria established prior to the start of the study. On average, $\dot{V}O_2$ changed ±1.41%, ±1.28%, and ±1.07% over the final 2 minutes of the level ground, 5% grade, and 10% grade trials, respectively. The group average $\dot{V}O_2$ during the LG, 5% grade, and 10% grade trials remained below the average $\dot{V}O_2$ at LTP (Figure 4.2). While all participants remained below their $\dot{V}O_2$ at LTP for the LG and 5% incline trials, $\dot{V}O_2$ during the 10% grade trial was at or above the $\dot{V}O_2$ at LTP for 7 participants (100-106% of $\dot{V}O_2$ at LTP). Similarly, the average BLa following the LG (1.55 ± 0.88) and 5% grade (2.23 ± 1.03) trials remained below BLa at LTP (3.12 ± 0.80), but the BLa following the 10% grade (4.11 ± 2.21) trial did not. Because the RER remained <1.0, all trials were completed using primarily aerobic metabolism and were deemed appropriate to include in the analysis. A summary of gas exchange, BLa, HR, and RER data for each grade is presented in Table 4.3.

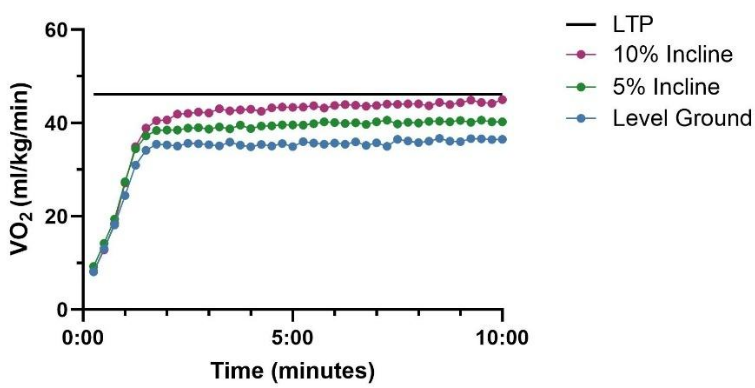

Figure 4.2 Group mean time series plots for $\dot{V}O_2$ across each grade condition. The group mean $\dot{V}O_2$ at LTP is included as a reference.

Table 4.3 Running economy test data presented as mean ± standard deviation.

	LG	5% Grade	10% Grade
Speed *(m/s)*	3.03 ± 0.31	2.47 ± 0.31	2.06 ± 0.31
$\dot{V}O_2$ *(ml/kg/min)*	36.32 ± 4.50	40.32 ± 5.24	44.31 ± 6.53
Percent $\dot{V}O_2$ at LTP *(%)*	78 ± 4	86 ± 4	95 ± 7
OCOT *(ml/kg/km)*	199.77 ± 12.23	272.16 ± 14.96	359.88 ± 20.49
ECOT *(J/kg/km)*	4188.96 ± 256.16	5726.23 ± 296.28	7626.17 ± 420.82
BLa *(mmol)*	1.55 ± 0.88	2.23 ± 1.03	4.11 ± 2.21
RER	0.84 ± 0.03	0.86 ± 0.03	0.89 ± 0.04
HR *(bpm)*	151.39 ± 12.67	157.85 ± 11.81	165.44 ± 11.94
RPE	10.44 ± 1.12	12.11 ± 1.72	13.93 ± 1.82

Effect of Biomechanics and Strength on Energy Cost of Transport

Spatiotemporal and joint stiffness data are summarized in Table 4.4, and stance phase joint work data are displayed in Figure 4.3. Results of the linear regression analyses for ECOT across each grade are displayed in Tables 4.5-4.7 and Figure 4.4. Across all grade conditions, the only biomechanical variable significantly associated with ECOT when controlling for speed was positive ankle work during the 10% grade condition ($\beta = -3054.56$; $p = 0.013$). This relationship was not maintained over the LG ($\beta = 667.53$; $p = 0.698$) or 5% grade ($\beta = -428.99$; $p = 0.761$) conditions. Positive hip work, positive knee work, ankle stiffness, and knee stiffness were not significantly associated with ECOT for any grade condition. The normalized peak torque for the right ankle plantar flexors, knee extensors, and hip extensors assessed via isokinetic dynamometry were 1.00 ± 0.24 Nm/kg, 2.12 ± 0.41 Nm/kg, and 2.93 ± 0.75 Nm/kg, respectively. Ankle plantar flexor, knee extensor, and hip extensor strength were not significantly associated with ECOT for any grade condition (Tables 4.5-4.7).

Table 4.4 Spatiotemporal and joint stiffness data presented as mean ± standard deviation.

	LG	5% Grade	10% Grade
Speed *(m/s)*	3.03 ± 0.31	2.47 ± 0.31	2.06 ± 0.31
Step Frequency *(steps/min)*	172 ± 9	168 ± 7	165 ± 6
Step Length (*m)*	1.06 ± 0.11	0.88 ± 0.12	0.75 ± 0.12
Contact Time *(ms)*	254 ± 24	284 ± 22	307 ± 26
Swing Time *(ms)*	444 ± 24	431 ± 28	421 ± 21
Flight Time (*ms)*	96 ± 20	75 ± 20	59 ± 19
Ankle Stiffness *(Nm/kg/deg)*	0.15 ± 0.04	0.14 ± 0.02	0.13 ± 0.02
Knee Stiffness *(Nm/kg/deg)*	0.08 ± 0.02	0.09 ± 0.02	0.12 ± 0.04

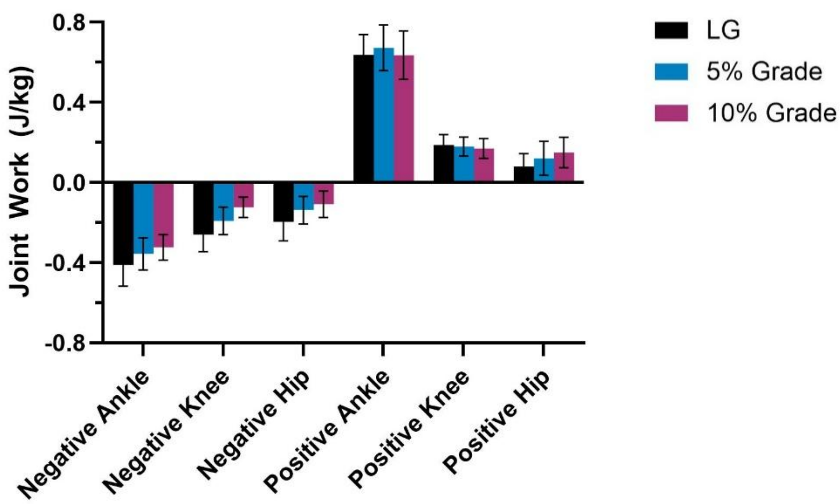

Figure 4.3 Group mean stance phase negative and positive joint work for each grade condition. Standard deviation is represented by error bars

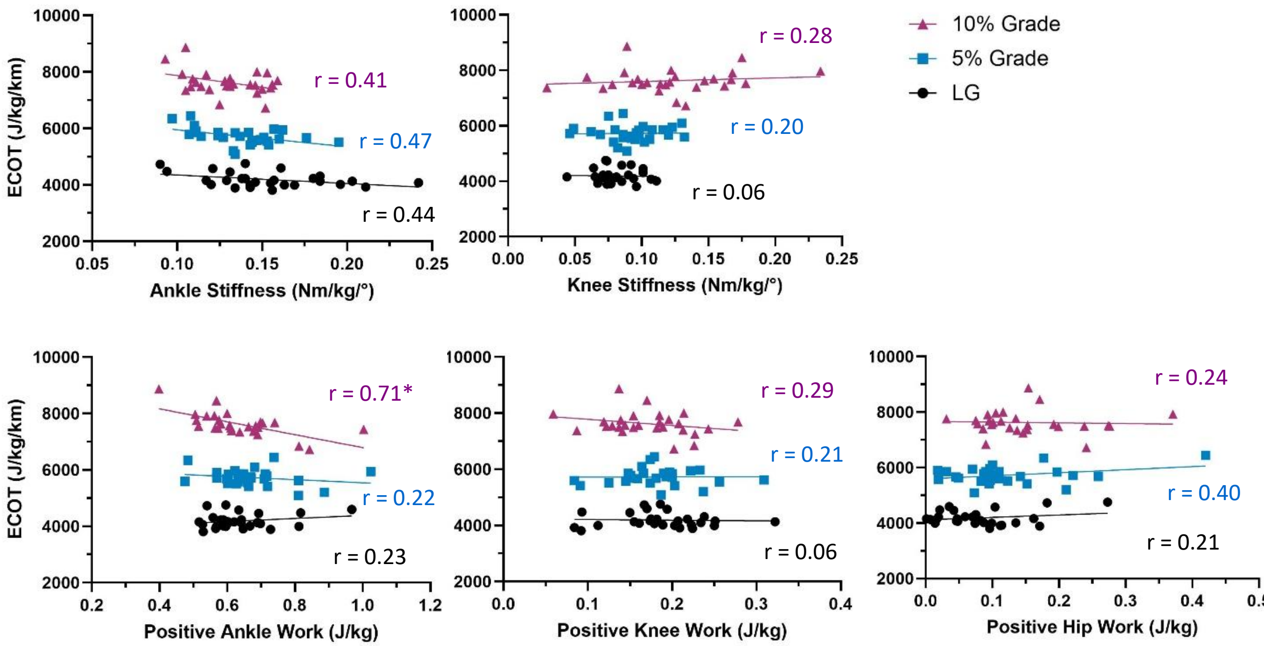

Figure 4.4 Relationship between joint kinetics and energy cost of transport (ECOT) across grade conditions. Plots display bivariate relationships, but variables were evaluated with speed as a covariate. The model correlation coefficient (r) for each variable is displayed per condition. *Significant association ($p < 0.05$) between β (stiffness or joint work) and ECOT.

Effect of Demographics on Energy Cost of Transport

Mass, height, age, years of running experience, and weekly mileage were not significantly associated with ECOT for any grade condition (Tables 4.5-4.7). A significant difference in ECOT was detected across runner type for the 10% grade condition only (p = 0.017). Road runners (n=12) demonstrated a significantly higher ECOT (7873.88 ± 419.10 J/kg/km) compared to trail runners (n = 9; 7410.27 ± 314.71 J/kg/km; p = 0.015) and runners who performed both trail and road running (n = 6; 7475.59 ± 330.88 J/kg/km; p = 0.029). In a follow-up analysis, trail runners demonstrated significantly greater positive ankle work (0.691 ± 0.147 J/kg) than road runners (0.591 ± 0.089 J/kg) during the 10% grade (equal variances not assumed, one-sided p = 0.048). While a significant difference in 10% grade ECOT was detected across runners with different training focuses (p = 0.032), post-hoc tests were not significant.

There was not a significant difference in ECOT between sexes for any grade condition.

Table 4.5 Results of the linear regression analyses evaluating the effect of biomechanical, strength, and demographic factors on LG ECOT.

	Model r	Model Sig.	β	Lower 95% CI	Upper 95% CI	β Sig.
Biomechanics						
Positive Ankle Work *(J/kg)*	0.23	0.845	667.53	-519.07	1854.77	0.698
Positive Knee Work *(J/kg)*	0.06	0.965	-258.25	-2304.82	1788.32	0.902
Positive Hip Work *(J/kg)*	0.21	0.845	863.05	-817.49	2543.58	0.698
Ankle Stiffness *(Nm/kg/°)*	0.44	0.845	-3346.45	-6247.33	-445.58	0.338
Knee Stiffness *(Nm/kg/°)*	0.06	0.965	-797.14	-8511.25	6916.97	0.902
Strength						
Ankle Plantar Flexor Torque *(Nm/kg)*	0.18	0.845	189.07	-235.23	613.38	0.698
Knee Extensor Torque *(Nm/kg)*	0.08	0.888	51.74	-205.80	309.29	0.888
Hip Extensor Torque *(Nm/kg)*	0.18	0.845	60.71	-77.90	199.31	0.698
Demographics						
Mass *(kg)*	0.23	0.845	-4.78	-12.96	3.40	0.698
Height *(cm)*	0.11	0.845	-3.09	-14.59	8.41	0.845
Age *(y)*	0.16	0.845	-3.13	-11.32	5.06	0.712
Running Experience *(y)*	0.25	0.845	5.68	-3.76	15.12	0.698
Weekly Mileage *(mi/wk)*	0.01	0.965	-0.23	-8.70	8.24	0.955

Table 4.6 Results of the linear regression analyses evaluating the effect of biomechanical, strength, and demographic factors on 5% Grade ECOT.

	Model r	Model Sig.	β	Lower 95% CI	Upper 95% CI	β Sig.
Biomechanics						
Positive Ankle Work *(J/kg)*	0.22	0.679	-428.99	-1783.89	925.92	0.761
Positive Knee Work *(J/kg)*	0.21	0.679	644.29	-2195.54	3484.12	0.761
Positive Hip Work *(J/kg)*	0.40	0.462	1241.41	-118.02	2600.84	0.442
Ankle Stiffness *(Nm/kg/°)*	0.47	0.462	-5809.19	-10755.44	-862.94	0.299
Knee Stiffness *(Nm/kg/°)*	0.20	0.679	1055.25	-4782.13	6892.63	0.771
Strength						
Ankle Plantar Flexor Torque *(Nm/kg)*	0.10	0.679	118.63	-377.93	615.18	0.761
Knee Extensor Torque *(Nm/kg)*	0.10	0.679	72.39	-225.01	369.80	0.761
Hip Extensor Torque *(Nm/kg)*	0.29	0.462	114.70	-41.21	270.60	0.462
Demographics						
Mass *(kg)*	0.18	0.679	-4.24	-13.81	5.34	0.761
Height *(cm)*	0.16	0.679	-5.22	-18.43	7.99	0.761
Age *(y)*	0.03	0.865	-0.80	-10.38	8.78	0.865
Running Experience *(y)*	0.11	0.679	3.07	-8.23	14.37	0.761
Weekly Mileage *(mi/wk)*	0.32	0.462	-7.65	-16.93	1.62	0.442

Table 4.7 Results of the linear regression analyses evaluating the effect of biomechanical, strength, and demographic factors on 10% Grade ECOT.

	Model r	Model Sig.	β	Lower 95% CI	Upper 95% CI	β Sig.
Biomechanics						
Positive Ankle Work *(J/kg)*	0.71	0.013*	-3054.56	-4431.39	-1677.73	0.013*
Positive Knee Work *(J/kg)*	0.29	0.719	-1562.77	-5535.10	2409.55	0.854
Positive Hip Work *(J/kg)*	0.24	0.777	164.89	-2210.12	2539.91	0.985
Ankle Stiffness *(Nm/kg/°)*	0.41	0.498	-7353.86	-16051.40	1343.86	0.463
Knee Stiffness *(Nm/kg/°)*	0.28	0.719	1436.45	-2515.45	5388.35	0.854
Strength						
Ankle Plantar Flexor Torque *(Nm/kg)*	0.03	0.985	55.26	-653.05	763.58	0.985
Knee Extensor Torque *(Nm/kg)*	0.02	0.985	19.76	-404.70	444.21	0.985
Hip Extensor Torque *(Nm/kg)*	0.17	0.719	97.38	-130.49	325.26	0.854
Demographics						
Mass *(kg)*	0.03	0.985	1.13	-12.69	14.94	0.985
Height *(cm)*	0.20	0.719	-9.13	-27.76	9.50	0.854
Age *(y)*	0.00	0.985	0.12	-13.49	13.74	0.985
Running Experience *(y)*	0.02	0.985	-0.86	-16.98	15.26	0.985
Weekly Mileage *(mi/wk)*	0.32	0.498	-10.70	-23.89	2.50	0.463

Discussion

The aim of this study was to identify biomechanical characteristics that are favorable for reducing energy cost when running uphill, with the overarching goal of improving performance for trail endurance athletes. Joint work and stiffness variables were specifically investigated due to their representation of muscle work and neuromuscular control, which have well-described theoretical influences on energy cost.[7] In a sample of male and female recreational runners encompassing a range of ages and training backgrounds, greater mechanical energy generation by the ankle plantar flexors was associated with lower energy cost when running on a 10% incline. This association was not maintained on a LG or 5% grade, and no other joint work, stiffness, or strength factors were significantly associated with RE in this study. Therefore, our hypothesis was partially supported.

Effect of Biomechanics on Energy Cost of Transport

Previous studies that have investigated the influence of biomechanics on uphill RE have focused solely on spatiotemporal metrics and global kinematics and kinetics such as vertical stiffness and whole-body external work.[12,24,36,76] Most of these studies included small groups of highly trained endurance runners, with potentially insufficient variability to detect significant influences of biomechanics on RE.[12,76] In a larger, heterogeneous group, Lemire et al. reported that longer contact time, shorter aerial time, and lower whole-body external work were associated with lower energy cost on a 10% incline.[36] The current study expands on this work by investigating mechanical energy contributions from the lower extremity muscle groups that are primarily involved in uphill running. The average energy cost for the LG and 10% grade condition in the current study are comparable to previous studies, considering our use of gross energy cost and the Peronnet and Massicotte equation which has been shown to produce slightly higher energy cost values compared to other equations.[36,71] Of the investigated biomechanical variables, the only one to demonstrate a significant association with RE when speed was controlled was positive ankle work during the 10% incline condition. Previous studies have demonstrated significant increases in positive hip work during uphill running compared to LG, with smaller, more speed-dependent increases in positive ankle work, and slight reductions in positive knee work.[15,44] As shown in Figure 4.3, similar patterns were observed in the current study. Despite the overall increase in positive hip work, there does appear to be a cost-savings benefit to maximizing energy generation by the ankle plantar flexors. As noted previously, this is in alignment with previous studies that have suggested the ankle plantar flexors are better suited for efficiency due to their morphology.[66] The lack of relationship between ankle plantar flexor work and RE on the LG and 5% incline demonstrates a grade-dependent influence of biomechanics on RE. Perhaps small differences in joint work distribution have a greater influence on the 10% grade due to the much higher energy cost of running on steeper grades.

On level ground, greater vertical and leg-spring stiffness have been associated with better RE.[35,77] Joint stiffness calculations apply a torsional spring model to explain the stiffness characteristics of each lower extremity joint, reflecting both tendon stiffness and neuromuscular activation patterns.[77] Knee joint stiffness appears to have a greater influence on vertical and leg-spring stiffness than ankle joint stiffness does, suggesting that knee joint stiffness may have greater implications in RE.[78] Tam et al. is one of few studies that has investigated the effect of joint stiffness on RE, showing that greater knee stiffness and lesser ankle stiffness are associated with better LG RE.[79] The current study demonstrated no relationship between knee stiffness and RE at any grade. Though not statistically significant, a moderate association was observed between ankle stiffness and RE across all three grade conditions (Figure 4.4). Specifically, more economical runners tended to demonstrate greater ankle joint stiffness, in contrast to Tam et al.'s findings. A notable difference between the two studies is that while biomechanics and gas exchange were measured synchronously in the current study, Tam et al. measured gas exchange on a treadmill and biomechanics overground. As there are known differences between treadmill and overground biomechanics, the methodology of the current study may be more appropriate for investigating these relationships.

Effect of Strength and Training History on Energy Cost of Transport

Running biomechanics are frequently targeted by coaches and runners in hopes of improving performance. While the current study did not investigate the effect of training on positive ankle work when running on steep inclines, identifying it as a desirable biomechanical target is an important step. As there was not a significant relationship between plantar flexor strength and energy cost, it appears that generating greater energy from the ankle plantar flexors during running is not simply a product of having stronger plantar flexors. Rather, our results suggest that participating in trail running may lead to this adaptation, as runners who self-identified as trail runners demonstrated significantly lower energy cost and greater plantar flexor work when running on the 10% incline. Changes in RE and biomechanics with participation in running have been documented previously. Moore et al. demonstrated that after a 10-week running program, beginner runners demonstrated improvements in RE and changes in kinematics that explained 94% of the variance in change in RE.[80] At the beginning of the current study, participants were asked to report whether they considered themselves a trail runner, road runner, or participated in both equally. Due to the self-report nature of this question and cross-sectional design of the study, we cannot assume that a causal relationship exists. However, these data suggest that trail running may result in specific physiological and biomechanical adaptations that should be explored in future studies.

Limitations

While this study presents novel relationships between biomechanics and uphill RE, some limitations should be considered when interpreting the results. The overall goal of this work is to inform coaches and athletes seeking to improve trail running performance. The 10-minute trials below LTP reflect a steady state condition but are much shorter than many uphill bouts encountered on outdoor trails. Increasing reliance on the ankle plantar flexors on steep inclines may be beneficial in the short term, but it is unknown how muscle fatigue may influence this over longer distances. Trail running also introduces variable surfaces, which are not accounted for when running on a treadmill; differences in biomechanics and metabolic cost may exist between treadmill and trail conditions. Because only two incline grades were included in this study, it is unknown at what specific grade generating greater ankle plantar flexor work becomes beneficial, and whether it continues to provide benefit on grades steeper than 10%. Furthermore, while RE is a component of endurance performance, the current study did not include a direct measure of performance. Future studies in this space should consider including a performance measure, such as an uphill race performance or time trial, to determine if the same biomechanical variables related to better RE also result in better trail endurance performance. Finally, because this study included a variety of recreational runners, the results cannot be directly applied to elite endurance runners. Future studies may expand on this work by investigating the relationship of biomechanics and RE in a fatigued state, across various populations of runners, across a greater variety of grades, or in the context of a performance measure. Additionally, future intervention studies should investigate the mechanisms by which uphill RE can be improved.

Conclusion

In a heterogeneous group of recreational runners, greater positive ankle plantar flexor work was associated with lower ECOT (better RE) when running on a 10% grade. While not significantly influenced by plantar flexor strength, significantly lower ECOT and greater positive ankle work were observed in runners who reported participating in trail running. These findings suggest that addressing the energy generation capacity of the plantar flexors may be a worthwhile target for improving uphill running performance, and that this could be achieved by engaging in hill running. Future studies should investigate the effect of training interventions on uphill RE, and whether these improvements are accompanied by changes in lower extremity joint work.

Funding Sources

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Bridge

The goal of Chapter IV was to identify biomechanical characteristics associated with better uphill running economy. Greater energy generation by the ankle plantar flexors was identified as a significant predictor of better running economy on a steep uphill grade. Trail runners presented both with greater ankle plantar flexor work and better running economy on the steep uphill. These data suggest that there are biomechanical features that are preferential for long, uphill efforts, and that specific training may promote development of these features. Chapter V investigates the effect of a heavy resistance training program on uphill running economy and biomechanics, using data from Chapter IV as a baseline measure. The study presented in this chapter implements a program similar to those that have resulted in improved level ground running economy, with focus on the most important muscle groups for uphill running. This study also seeks to identify the mechanisms by which running economy improves in response to a resistance training program by investigating changes in biomechanics and lower extremity muscle strength.

CHAPTER V

THE EFFECT OF RESISTANCE TRAINING ON UPHILL RUNNING ECONOMY AND BIOMECHANICS

This chapter is in preparation for journal submission. Rachel M. Robinson was responsible for study design, data collection, data analysis, and writing the initial manuscript draft. Michael E. Hahn provided mentorship and aided in study design, general oversight, and editing the manuscript.

Introduction

As trail running and ultra-endurance racing have grown in popularity, researchers have sought to identify predictors of trail running performance.[9,10,64,81,82] In the classic model of endurance running performance, VO_{2max}, lactate threshold, and running economy (RE) are significant predictors of road and track race times.[4,5,6] While VO_{2max} and velocity at VO_{2max} remain important in trail running, lower extremity strength and uphill RE also appear to have a significant influence on performance.[9,10] While some studies report that uphill RE (7.5-12% grade) is highly correlated with level ground RE, these studies have included small groups of highly trained or elite runners who perform significant volumes of training on both terrains.[8,12] Due to the notable differences in biomechanics and metabolic demand between level ground and uphill running, it is possible the two modalities are distinct, trainable skills.[18]

Compared to level ground, uphill running incurs a significantly greater metabolic cost due to greater mechanical energy generation requirements.[21] Most of the additional energy generation during uphill running is performed by the hip extensors, though ankle plantar flexor work also increases at steeper grades.[17,21] In order to meet the mechanical demands of uphill running, greater hip extensor and ankle plantar flexor strength may be beneficial. While its effects on uphill RE have yet to be investigated, one of the most commonly studied and practically implemented strategies to improve level ground RE is resistance training. In moderately-trained, well-trained, and elite endurance runners, 1-3 days per week of resistance training for 6-14 weeks has been shown to improve level ground RE by 2-8% in multiple studies.[38] The majority of studies have employed a heavy resistance training (HRT) approach (2-6 sets of 3-10 repetitions at >70% of 1 repetition maximum), improving maximal strength without increases in body mass.[38]

The theorized mechanisms for improved RE in response to HRT include increased tendon stiffness, increased muscle strength, and changes in running biomechanics. During the negative work phase of the gait cycle, strain energy is stored in the elastic elements of the muscle-tendon units, then subsequently released to contribute to positive work.[26] Stiffer muscle-tendon units are capable of storing and releasing more strain energy, reducing the amount of work that needs to be produced by metabolically costly concentric contractions. Focusing on Achilles tendon contributions, Albracht et al demonstrated a 16% increase in medial gastrocnemius tendon-aponeurosis stiffness and 7% increase in plantar flexor strength in response to an isometric plantarflexion program, with a concomitant 4% improvement in RE.[41] Along with increased tendon stiffness, a similar program has also been shown to reduce concentric contraction velocity of the soleus fascicles.[83] Per the force-velocity relationship, muscle fibers contracting at slower velocities are able to produce greater force.[84] This may allow for a reduction in motor unit recruitment during running, reducing the amount of metabolic energy required to produce a given force. While several studies hypothesize that resistance training may improve RE via improvements in running biomechanics, there is limited evidence demonstrating biomechanical changes in response to resistance training, especially in relation to changes in RE.[46,85] Most of these studies limit biomechanical analyses to spatiotemporal metrics.[46] Investigating joint kinetics may provide insight into how resistance training-elicited changes in musculotendinous properties translate to the force-generating function of the lower extremity during running.

Therefore, the purpose of this study was to determine the effect of an 8-week HRT program on level ground and uphill RE in recreational runners and determine whether changes in RE were associated with changes in running biomechanics and lower extremity muscle strength. It was hypothesized that RE across all grades would improve in response to HRT and this would be accompanied by increases in muscle strength and changes in joint kinetics.

Methods

Participants

Participants were eligible to enroll in this study if they were >18 years old, were not a collegiate or national level runner, were able to run a 25:00 5k, were not diagnosed with a cardiovascular or neuromuscular condition, and were not currently pregnant. Over the past 12 weeks, participants must have run an average of at least 10 miles/week, not participated in a lower extremity resistance training program ≥1x per week, and not experienced a running related injury that caused stoppage of running for at least 7 days or 3 consecutive training sessions. Participants provided self-reported demographic and training characteristics upon enrollment, which are outlined in Table 5.1. All participants provided written informed consent per the requirements of the University of Oregon Institutional Review Board (STUDY00001264).

Table 5.1 Participant demographics and training characteristics. Data are presented as mean ± standard deviation.

	Total (n = 25)	**Training (n = 14)**	**Control (n = 11)**	***p*-value**
Age *(y)*	34.2 ± 13.2	31.4 ± 10.4	36.2 ± 14.9	0.235
Mass *(kg)*	70.4 ± 13.0	66.4 ± 13.0	74.2 ± 11.1	0.086
Height *(cm)*	176.4 ± 9.2	175.1 ± 9.6	176.8 ± 8.9	0.409
Sex	F: n = 12 M: n = 13	F: n = 7 M: n = 7	F: n = 5 M: n = 6	0.830
Years of Running Experience *(y)*	14.3 ± 11.6	15.5 ± 13.6	12.2 ± 7.7	0.571
Average Weekly Mileage *(mi/wk)*	27.9 ± 12.6	27.5 ± 11.1	26.5 ± 14.2	0.889
Current 10k Pace *(min/mi)*	7:21 ± 0:53	7:12 ± 1:05	7:33 ± 0:29	0.378

An *a priori* power analysis (G*Power version 3.1.9) indicated that 12 participants per group would be required to detect a group-by-time interaction effect for submaximal oxygen consumption (power = 0.8; $\alpha = 0.05$).[41] Anticipating a 10% attrition rate, 28 participants were enrolled, with 14 randomly allocated to a training group and 14 to a control group. Stratified randomization was used for group assignment, balancing each group for biological sex. Participants were randomized according to order of enrollment, using an allocation list generated prior to the start of the study. The research team and participants were blinded to the group assignment until the conclusion of baseline testing. One male participant withdrew from the study after the first visit due to a running-related injury not associated with study activities. Two female participants withdrew prior to the final study visit; one due to pregnancy and one due to a running-related injury not associated with study activities. All 3 of the participants who withdrew had been pre-assigned to the control group. Among the training group, 28% identified as trail runners, 36% identified as road runners, and 36% reported participating in both equally. Among the control group, 36% identified as trail runners, 55% identified as road runners, and 9% reported participating in both equally. Most participants reported currently training for a half marathon (training group: 29%; control group: 27%) or ultramarathon (training group: 29%; control group: 27%), while 21% of the training group and 18% of the control group reported no current training goal.

Experimental Protocol

An overview of the study protocol and timeline is outlined in Figure 5.1. On the first study visit, participants performed a lactate threshold (LT) and maximal oxygen consumption ($\dot{V}O_{2max}$) test. Within the next 2 weeks, participants performed a RE, biomechanics, and dynamometry assessment. Participants in the training group returned to the laboratory for an 8-week HRT program, and both groups were asked to continue their planned running training and record all exercise activities with a GPS watch. At the end of the study period, the RE, biomechanics, and dynamometry assessment was repeated.

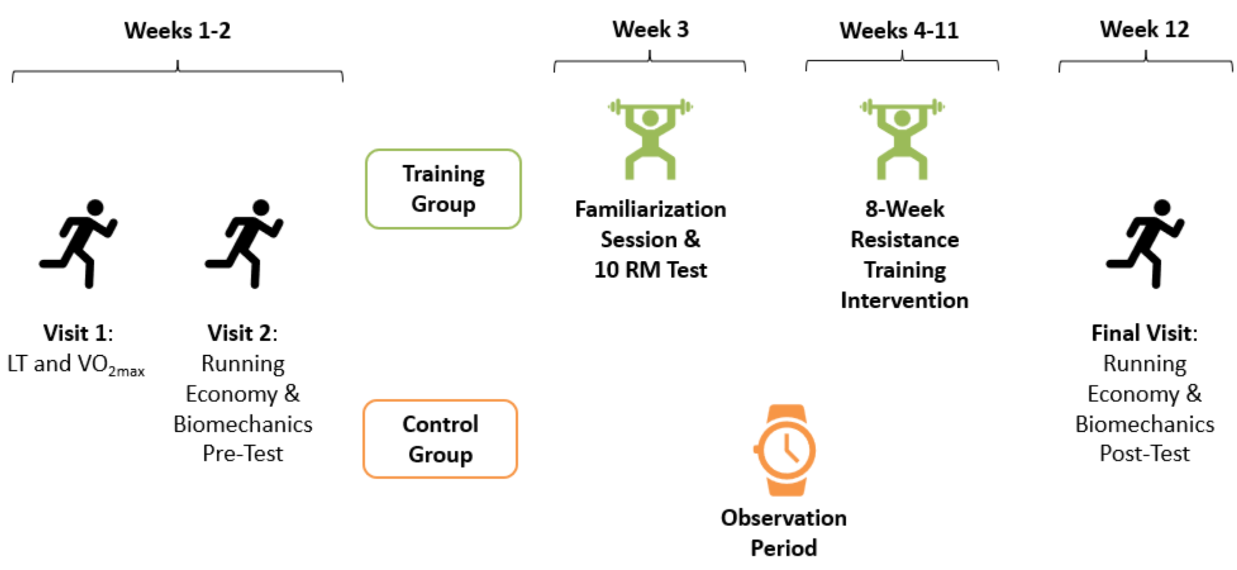

Figure 5.1 Study protocol and timeline

Visit 1: Lactate Threshold and $\dot{V}O_{2max}$ Test

Prior to the LT and $\dot{V}O_{2max}$ test, participants were asked to refrain from food or drink other than water within 3 hours of the visit, caffeine within 6 hours, alcohol or recreational drugs within 12 hours, and hard workouts or races within 24 hours. Footwear was standardized, using the Brooks Launch 10 (Brooks Running, Seattle, WA) for all study visits to control the effects of shoe weight and material properties on RE. Gas exchange was measured in 15s averages via indirect calorimetry, using a Parvo Medics TrueOne 2400 system (Parvo Medics, Sandy, UT). The metabolic cart was turned on at least 1 hour prior to collection and was calibrated before each session using a calibration gas mixture and 3L calibration syringe. Participants stood for 3 minutes while baseline gas exchange, heart rate (Polar H10, Polar Electro, Kempele, Finland) and fingertip blood lactate (Lactate Plus, Nova Biomedical, Waltham, MA) were collected. The LT test was completed on a high-speed treadmill (Woodway, Waukesha, WI) at 0% grade. While many studies perform LT tests on a 1% grade, 0% was selected for this study because subsequent running economy and biomechanics tests would be performed at a 0% grade. Participants began the test at 5 km/h slower than their self-reported 10k pace and increased by 1 km/h every 3 minutes until volitional fatigue. Participants straddled the treadmill belt for 30 seconds after each stage to collect 2 fingertip blood lactate samples, which were averaged for analysis. Participants rested for 10 minutes following completion of the LT test. For the $\dot{V}O_{2max}$ confirmation test, participants ran 2 km/h slower than the final stage of the lactate threshold test beginning at 1% grade. Grade was increased by 1% every minute until volitional fatigue.

Visit 2: Running Economy, Biomechanics, and Dynamometry Test

The second visit was scheduled within 2-14 days of Visit 1, and included RE, biomechanics, and dynamometry testing. Participants were asked to adhere to the same pre-test instructions as Visit 1, and the start time was scheduled within 2 hours of the Visit 1 start time. Fifty-one retroreflective markers were placed on the trunk, pelvis, bilateral lower extremities, and bilateral upper extremities to define the trunk, pelvis, thigh, shank, and foot segments. Five markers were placed on the corners of the treadmill surface to track the position of the treadmill and force platforms. Static marker position and baseline gas exchange data were collected during 3 minutes of standing.

Participants completed a 5-minute running warm up at :30 min/mile slower than the level ground test speed to accommodate to the instrumented treadmill (Bertec, Columbus, OH). Three 10-minute running trials were completed on the instrumented treadmill on level ground, 5% incline (2.9°), and 10% incline (5.7°) in a randomized order. Prior to each trial, participant mass was recorded while wearing the markers and footwear. The level ground trial was performed at 80% of speed at lactate turn point (sLTP) which was determined using data from Visit 1. For the 5% and 10% incline trials, data from Margaria et al. were used to adjust the incline trial speeds to match the estimated energy cost of the level ground trial.[69] The 5% and 10% incline trials were performed at 0.56 m/s and 0.97 m/s slower than the level ground trial, respectively. Participants were given 5 minutes of rest between trials. The Parvo Medics TrueOne 2400 system (Parvo Medics, Sandy, UT) was used to record gas exchange data in 15s averages throughout each trial. A metabolic steady state was defined as a $<5\%$ change in $\dot{V}O_2$ and RER between the final 2 minutes of each trial, and RER <1.0. If the change in $\dot{V}O_2$ and RER exceeded 5% between minutes 9 and 10, an additional minute was added to the trial until these criteria were met. A maximum of 2 minutes were added to the trials. Marker trajectory data were collected at a sampling frequency of 200 Hz (Motion Analysis Corp., Rohnert Park, CA) and ground reaction force data were collected at a sampling frequency of 1000 Hz. Marker and force data were collected for 30 seconds at the 1:00, 5:00 and 8:00 time points, and the middle 10 seconds of the 8:00 capture were used for analysis. In the event key markers fell off a participant before the 8:00 time point, the 5:00 capture was used for analysis. This occurred for 4 total trials throughout the study. The average heart rate over the final minute of each trial was recorded. A visual chart of the Borg Rating of Perceived Exertion (RPE) scale with numerical and written descriptions was provided, and participants were asked to report their rating after each trial.

Isokinetic dynamometry testing was completed using a System 4 Pro Biodex Isokinetic Dynamometer (Biodex Medical Systems, Inc., Shirley, NY). The right knee extensors, ankle plantar flexors, and hip extensors were tested concentrically at 60 °/s. The knee extensors and ankle plantar flexors were tested in a seated position and the hip extensors were tested in supine. The knee was fixed in 30 degrees of flexion for the ankle plantar flexor test. Participants performed 5 submaximal practice trials for each muscle group, followed by 3 maximal effort test trials separated by 1 minute of rest. The peak torque produced over the 3 test trials was normalized to body mass and used for analysis.

At the conclusion of Visit 2, participants received their group assignment. Participants in the control group were asked to refrain from resistance training throughout the study period. Participants in the training group returned to the laboratory for a familiarization visit, 10 repetition maximum (10 RM) test, and an 8-week resistance training program.

Resistance Training Exercise Descriptions

The resistance training program consisted of a seated double leg calf raise, body weight squat, and standing single leg calf raise (Figure 5.2). The seated calf raise was performed on a seated calf raise machine (Titan Fitness, Memphis, TN). Participants were instructed to maintain an upright trunk and move through their full ankle range of motion. A metronome was set to 30 bpm, and participants were instructed to match the upper and lower portions of the movement to each beat. The box squat was performed using a squat rack and 18-inch box (Rogue Fitness, Columbus, OH). Participants were instructed to place their feet slightly wider than shoulder width, place the barbell on their shoulders, and sit on the box. From this position, they were instructed to stand up. For each subsequent repetition, they were instructed to contact the box with their hips without fully sitting. The single leg calf raise was performed by holding a kettlebell on the ipsilateral side and maintaining a light touch on a barbell positioned at chest height with the contralateral hand to assist with balance. A metronome was set to 40 bpm, and participants were instructed to match the upper and lower portions of the movement to each beat. The single leg calf raise was performed without shoes to reduce range of motion limitations due to footwear.

Figure 5.2 Set up for each exercise used in the resistance training program.

<u>Familiarization Session</u>

During the familiarization visit, participants were instructed in a 5-minute dynamic warm up which included a knee to chest stretch, quadricep stretch, body weight squat, reverse lunge with overhead reach, and toe walking for 1 minute each. Following the warm up, participants completed 3 sets of 10 repetitions of seated calf raises, box squats, and single leg standing calf raises. The first set was completed with body weight only. For the second set, the seated calf raise was performed with 5-10kg of weighted plates, the box squat was performed with a 15 or 20 kg barbell, and the single leg calf raise was performed with a 10 lb. kettlebell. For the third set, the participant chose to either use the same resistance as the second set or slightly increase the resistance. They were instructed by the research team to select a weight that easily allowed 10 repetitions. Sixty seconds of rest were given between each set. During this session, the research team provided demonstrations, verbal instruction, and feedback to ensure safe and correct performance of each exercise.

10 Repetition Maximum Test

The 10 RM test was completed 2-7 days after the familiarization session. The purpose of the 10 RM test was to estimate each participant's 1 RM and assign individualized resistance for each exercise at the start of the resistance training program. The protocol is outlined in Figure 5.3.[86] Spotting was provided by the research team to ensure participant safety.

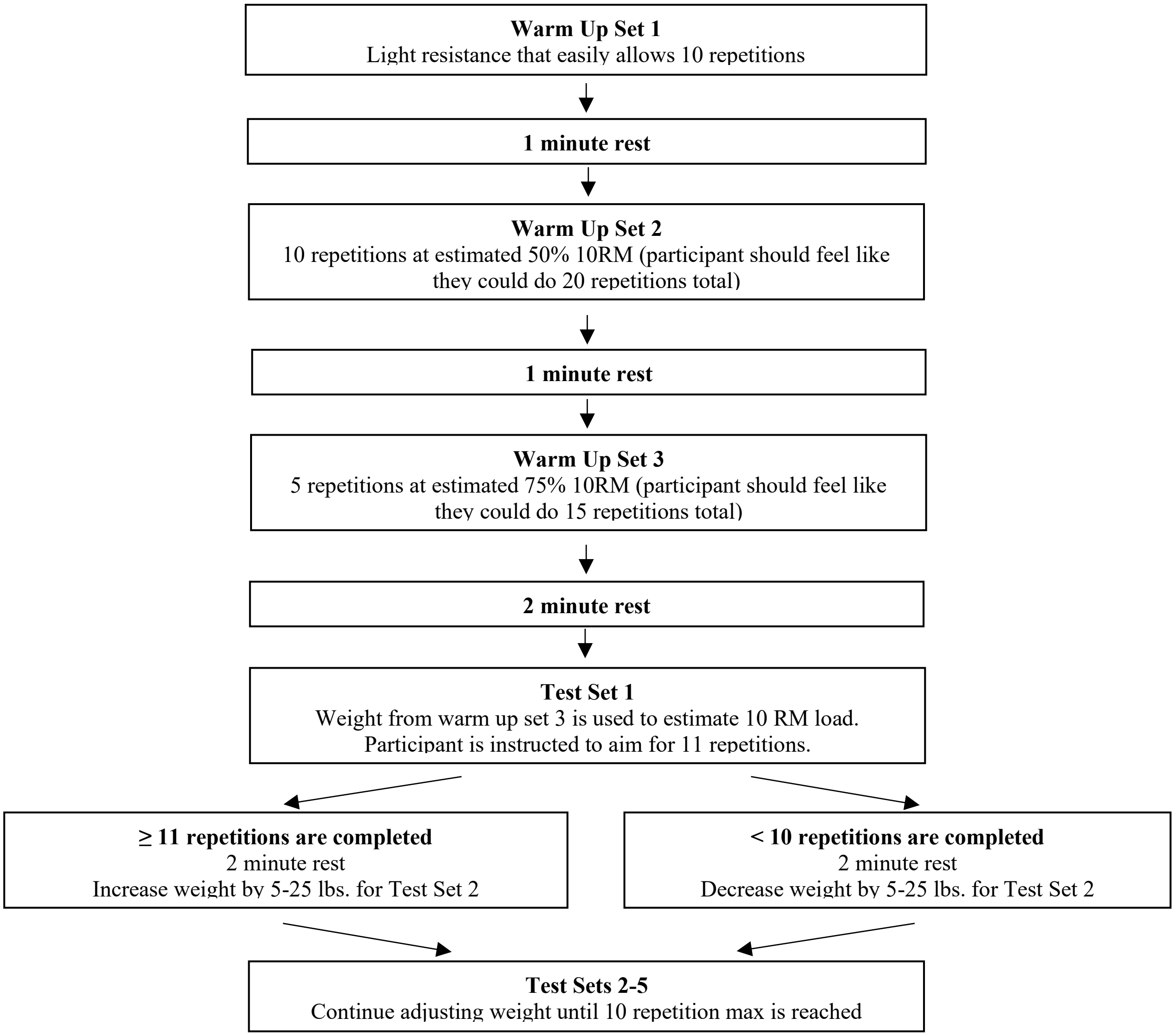

Figure 5.3 10-repetition maximum test protocol

Resistance Training Program

Beginning at least 2 days after the 10 RM test, training group participants presented to the laboratory twice weekly for 8 weeks to complete the resistance training program. Sessions were separated by a minimum of 48 hours. The 5-minute warm up used during the familiarization session was completed at the beginning of each resistance training session. The sets, repetitions, and intensity prescribed throughout the program are outlined in Table 5.2. Participants completed one warm up set of 10 repetitions for each exercise at 50% of the prescribed resistance for the session. One minute of rest was provided after the warm up set, and 2 minutes of rest were provided after all other sets. To adjust for changes in 1 RM estimates throughout the program, participants were instructed to perform as many repetitions as possible during the third set of each exercise on Week 3 Day 2, Week 5 Day 2, and Week 7 Day 2. If a participant was able to perform more repetitions than the number assigned to the session, the number of completed repetitions was used to re-calculate the estimated 1 RM for the following session.[86] This procedure was also completed during the final resistance training session to estimate the final 1 RM. Sessions were supervised by the research team to improve program adherence, ensure safe and correct exercise performance, and assess readiness for progression. Spotting was provided by the research team to ensure participant safety. In the event a participant was unable to come to the laboratory for a session, they were provided with the session dosage and asked to complete the exercises on their own.

Table 5.2 Progression of sets, repetitions, and intensity throughout the 8-week resistance training program.

Training Week	Sets	Repetitions	Intensity
1	3	10	70% 1RM (11 RM)
2	3	8	Session 1: 75% 1 RM (10 RM) Session 2: 80% 1RM (8 RM)
3-4	3	6	85% 1 RM (6 RM)
5-6	4	6	85% 1 RM (6 RM)
7-8	3	4	90% 1 RM (4 RM)

Training Tracking

To track weekly training volume and intensity throughout the study, all participants registered with Final Surge (Final Surge LLC, Raleigh, NC) and linked their existing Strava, Garmin Connect, or Coros account. Participants were asked to continue their planned training and record any activities they would consider exercise. In the event a participant did not use a GPS watch, a Garmin Forerunner GPS watch (Garmin, Olathe, KS) was issued for the study period. Weekly running mileage, running time, average pace, elevation gain, and total activity time (sum of running and cross training time) were recorded for all participants.

Post-Test Visit

At the conclusion of the study period, all participants repeated the RE, biomechanics, and dynamometry assessment. The methods for the Post-Test Visit were identical to Visit 2. The running speeds and order of running trials were maintained between Visit 2 and the Post-Test Visit. The post-test was scheduled 10 weeks after Visit 2 for the control group, and between 2-7 days after the final resistance training session for the training group. The Post-Test visit time was scheduled within 2 hours of the Visit 2 time.

Data Analysis

Lactate Threshold and $\dot{V}O_{2max}$ Data

The $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$ were calculated as the greatest 30-second rolling average of relative $\dot{V}O_2$ during the final stage of the lactate threshold test and $\dot{V}O_{2max}$ confirmation test, respectively. Maximum heart rate (HR) was calculated as the greatest 30-second rolling average during the last stage of the lactate threshold or $\dot{V}O_{2max}$ confirmation test, whichever was higher. Lactate threshold (LT) and lactate turnpoint (LTP) were calculated using the lactater package (version 0.2.0) in RStudio (R version 4.2.2). The LT was defined as the speed prior to the first point-to-point rise in blood lactate (BLa) >0.4 mM. The modified *D*max method, which fits a third-order polynomial function to the measured lactate values, was used to calculate LTP.[49] The point lying at the maximal perpendicular distance between the fitted curve and a straight line connecting the LT and the final lactate point was defined as the LTP.[50]

Running Economy Data

The $\dot{V}O_2$ time series plots were examined to confirm a plateau had been reached by the final 2 minutes of the running economy tests. Steady state was defined as a change in $\dot{V}O_2$ by <5% over the last 2 minutes of each trial, and RER <1.0. The final 2 minutes of $\dot{V}O_2$, $\dot{V}CO_2$, and RER data were averaged and used for analysis. Because within-subjects changes were assessed, RE was expressed as relative $\dot{V}O_2$ (ml/kg/min). Oxygen cost of transport (OCOT; ml/kg/km) and energy cost of transport (ECOT; J/kg/km) data are also provided. For ECOT calculations, the Péronnet and Massicotte equation was used to calculate metabolic power (W) from $\dot{V}O_2$ and $\dot{V}CO_2$ as described by Kipp et al.[71] To convert to J/kg/km, metabolic power (W) was divided by speed (m/s) and multiplied by 1000. The mass recorded prior to the start of each trial was used to normalize submaximal $\dot{V}O_2$, OCOT, and ECOT.

Biomechanics Data

Marker trajectory gaps were filled using a cubic spline function in Cortex (Motion Analysis Corp., Rohnert Park, CA). The remainder of the analysis was performed using Visual 3D (HAS-Motion, Kingston, Ontario, CA). The trunk, pelvis, thigh, shank, and foot were modeled as rigid bodies. The pelvis segment was defined according to the Visual 3D composite pelvis. The regression equations from Bell and Brand were used to estimate hip joint center location from inter-anterior superior iliac spine (ASIS) distance.[58] The midpoint between the femoral epicondyles and malleoli were used to estimate the knee and hip joint centers, respectively. Tracking coordinate systems were defined for each segment, using the sternum, C7 spinous process, and acromia for the trunk, left and right ASIS and posterior superior iliac spine (PSIS) for the pelvis, a cluster of four markers for the thigh, a cluster of four markers for the shank, and the distal heel, 1st metatarsal head, 5th metatarsal head, and toe markers for the foot.

Segment mass was estimated using Dempster's mass proportions, and inertial properties were calculated using segment mass and length.[59] The pelvis was modeled as a cylinder and all other segments were modeled as cones, with proximal and distal segment radii estimated as one-half the distance between medial and lateral joint markers. Mass moments of inertia were estimated using segment mass and geometry, and segment center of mass location was estimated using segment geometry and length.[72,73]

Fourth-order zero lag low pass Butterworth filters with 6 and 15 Hz cutoff frequencies were used to filter marker trajectory and ground reaction force data, respectively. Baseline analog signals were subtracted from the force platforms from each frame using the "FP Auto Baseline" function in Visual 3D.[74] Initial contact and toe off were identified using the "Automatic Gait Events" function, with a 50 N force threshold.[75] Sagittal plane body-mass normalized joint power was calculated as the dot product of internal joint moment and joint angular velocity for the hip, knee and ankle. Positive and negative joint work were calculated as the time integral of the positive and negative portions of the power-time curves, respectively. As previous studies have determined that body weight support and forward propulsion account for 80% of the metabolic cost of running, only stance phase joint work was analyzed.[25] Ankle and knee joint stiffness were estimated by dividing the change in joint moment by the change in joint angular displacement from initial contact to peak ankle dorsiflexion or knee flexion, respectively.[48]

Statistical Analysis

For all variables, approximate normality was assessed graphically by comparing histograms for each variable to the normal distribution curve and evaluating Normal QQ plots. Independent samples t-tests were performed to test for differences in baseline demographic, training, and physiological variables between the training and control groups (SPSS, IBM Corp. Armonk, NY). Equal variances were assumed, and a significant difference was defined as two-tailed $p < 0.05$.

Mixed-model repeated measures ANOVAs (2 groups x 2 time points) were conducted to test for the effect of resistance training on running economy, biomechanics, and strength variables. Separate tests were performed for the level ground, 5% incline, and 10% incline conditions. Mauchly's test was used to assess sphericity, and Greenhouse-Geiser corrections were applied when the sphericity assumption was not met. When significant interactions were detected, the Bonferroni correction was applied to *post hoc* simple main effects. For significant main effects, the Bonferroni correction was applied to pairwise *post hoc* tests. Alpha levels were set to 0.05, and corrected *p*-values < 0.05 were determined to be statistically significant.

Bivariate correlation analyses were performed to evaluate relationships between pre- to post-test changes in RE, biomechanics, and strength variables across the entire sample. The Benjamini-Hochberg procedure was used to adjust *p* values for multiple comparisons using the p.adjust function (version 3.6.2) in R, with an adjusted alpha level of $p < 0.05$ (R version 4.2.2).[51]

Results

Lactate Threshold and $\dot{V}O_{2max}$ Test

Participants completed an average of 7.80 ± 0.82 stages of the LT test reaching a maximum speed of 4.35 ± 0.45 m/s. The average speed at LTP was 3.79 ± 0.40 m/s. There were no significant differences in LT or $\dot{V}O_{2max}$ test results between the training and control groups (Table 5.3).

Table 5.3 $\dot{V}O_2$, speed, BLa, and HR data from the lactate threshold and $\dot{V}O_{2max}$ tests. Data are presented as mean ± standard deviation.

	Total (n = 25)	**Training (n = 14)**	**Control (n = 11)**	***p*-value**
$\dot{V}$O2 Max *(ml/kg/min)*	55.16 ± 6.68	56.17 ± 7.88	53.74 ± 4.55	0.392
$\dot{V}$O2 Peak *(ml/kg/min)*	53.43 ± 6.51	54.11 ± 7.41	52.44 ± 4.55	0.566
$\dot{V}$O2 at LTP *(ml/kg/min)*	46.10 ± 5.41	46.30 ± 6.17	45.58 ± 4.09	0.753
$\dot{V}$O2 at LT *(ml/kg/min)*	38.70 ± 5.19	39.34 ± 5.73	37.81 ± 4.46	0.487
Speed at $\dot{V}$O2 Peak *(m/s)*	4.35 ± 0.45	4.38 ± 0.54	4.32 ± 0.32	0.734
Speed at LTP *(m/s)*	3.79 ± 0.40	3.82 ± 0.47	3.77 ± 0.30	0.766
Speed at LT *(m/s)*	3.17 ± 0.40	3.20 ± 0.43	3.13 ± 0.37	0.705
BLa at LTP *(mmol/L)*	3.11 ± 0.81	3.09 ± 0.86	3.14 ± 0.77	0.880
BLa at LT *(mmol/L)*	1.32 ± 0.43	1.28 ± 0.46	1.37 ± 0.40	0.609
HR Max *(bpm)*	183 ± 10	183 ± 11	183 ± 10	0.904
HR at LTP *(bpm)*	167 ± 9	168 ± 9	166 ± 9	0.758
HR at LT *(bpm)*	149 ± 9	149 ± 10	149 ± 8	0.928

Running Economy Test

On average, the RE trials were performed at 3.00 ± 0.39 m/s for the level ground condition, 2.50 ± 0.33 m/s for the 5% grade condition, and 2.10 ± 0.36 m/s for the 10% grade condition. For all trials, $\dot{V}O_2$ and RER changed <5% over the final 2 minutes and RER remained <1.0, meeting the steady-state criteria established prior to the start of the study. On average, $\dot{V}O_2$ changed ±1.40%, ±1.51%, and ±1.16% over the final 2 minutes of the level ground, 5% grade, and 10% grade trials, respectively. The group average $\dot{V}O_2$ during the level ground, 5% grade, and 10% grade trials remained below the average $\dot{V}O_2$ at LTP. While all participants remained below their $\dot{V}O_2$ at LTP for the level ground and 5% incline trials, $\dot{V}O_2$ during the 10% grade trial was at or above the $\dot{V}O_2$ at LTP (100-107% of $\dot{V}O_2$ at LTP) for 7 participants (2 training group; 5 control group) during the pre-test and 5 participants (2 training group; 3 control group) during the post-test. Similarly, the average BLa following the level ground (pre: 1.59 ± 0.90; post: 1.60 ± 0.83) and 5% grade (pre: 2.21 ± 1.06; post: 2.05 ± 0.92) trials remained below BLa at LTP (3.11 ± 0.81), but the BLa following the 10% grade (pre: 4.17 ± 2.28; post: 3.78 ± 2.22) trial did not. Because the RER remained <1.0, all trials were completed using primarily aerobic metabolism and were appropriate to include in the analysis.

Effect of Resistance Training on Physiological Outcomes

Across all grade conditions, no significant interaction nor main effects were detected for submaximal $\dot{V}O_2$ during the RE test (Figure 5.4). Likewise, there were no significant interaction or main effects when RE was expressed as either OCOT or ECOT (Table 5.4). On average, level ground $\dot{V}O_2$ increased by 0.11% for the training group and decreased by 2.49% for the control group from the pre- to post-test (Table 5.4). The 5% grade $\dot{V}O_2$ increased by 0.09% for the training group and decreased by 2.04% for the control group. The 10% grade $\dot{V}O_2$ increased by

0.62% for the training group and decreased by 2.43% for the control group. Changes in RE ranged from an 11% increase to a 7% decrease in the training group, and from an 8% increase to a 12% decrease in the control group. Five participants in the training group improved RE by ≥3% over at least one grade condition and four worsened by ≥3%. Five participants in the control group improved RE by ≥3% over at least one grade condition and one worsened by ≥3%. No significant interaction effects nor main effects were detected for mass, RER, blood lactate concentration, or heart rate (Table 5.4). A significant main effect of group was detected for RPE for the 10% condition only, with the control group reporting a higher RPE than the training group (p = 0.037).

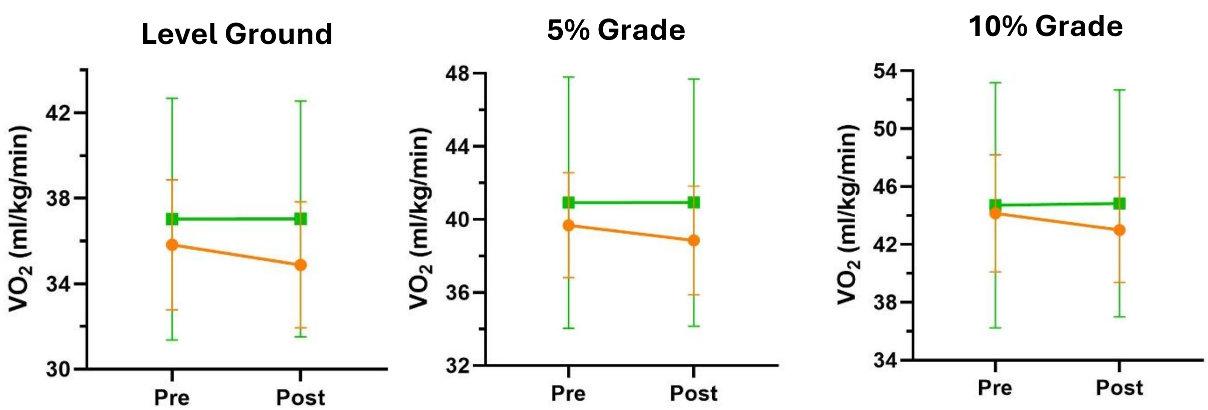

Figure 5.4 Mean pre- and post- intervention RE (submaximal $\dot{V}O_2$) for the training and control groups. Standard deviation is represented by error bars.

Table 5.4 Pre- and post-intervention physiological outcomes for the training and control groups. Data are presented as mean ± standard deviation.

	Training Group (n = 14)		**Control Group (n = 11)**		**Group-by-Time**
	Pre	**Post**	**Pre**	**Post**	***p*-value**
Level Ground					
Speed *(m/s)*	3.05 ± 0.38		3.01 ± 0.24		
Mass *(kg)*	66.39 ± 13.05	67.24 ± 13.24	75.36 ± 11.54	75.67 ± 10.80	0.368
$\dot{V}O2$ *(ml/kg/min)*	37.02 ± 5.66	37.06 ± 5.47	35.82 ± 3.04	34.88 ± 2.95	0.126
OCOT *(ml/kg/km)*	201.55 ± 11.37	201.90 ± 10.96	198.41 ± 14.07	193.18 ± 13.03	0.116
ECOT *(J/kg/m)*	4.24 ± 0.25	4.24 ± 0.24	4.15 ± 0.28	4.04 ± 0.28	0.118
RER	0.84 ± 0.04	0.85 ± 0.05	0.83 ± 0.03	0.83 ± 0.02	0.543
BLa *(mmol/L)*	1.48 ± 0.85	1.53 ± 0.74	1.73 ± 0.98	1.68 ± 0.97	0.833
HR *(bpm)*	149.69 ± 12.58	148.62 ± 14.81	154.10 ± 14.48	152.30 ± 13.38	0.709
RPE	10.29 ± 1.27	10.64 ± 1.22	10.45 ± 0.93	10.64 ± 1.36	0.727
5% Grade					
Speed *(m/s)*	2.50 ± 0.38		2.46 ± 0.24		
Mass *(kg)*	66.37 ± 13.07	67.19 ± 13.24	75.39 ± 11.49	75.65 ± 10.75	0.339
$\dot{V}O2$ *(ml/kg/min)*	40.91 ± 6.88	40.92 ± 6.76	39.68 ± 2.88	38.84 ± 2.97	0.211
OCOT *(ml/kg/km)*	272.96 ± 15.78	272.98 ± 14.38	269.95 ± 15.60	264.12 ± 14.52	0.189
ECOT *(J/kg/m)*	5.74 ± 0.31	5.76 ± 0.31	5.68 ± 0.31	5.56 ± 0.30	0.139
RER	0.86 ± 0.03	0.87 ± 0.04	0.86 ± 0.03	0.86 ± 0.02	0.615
BLa *(mmol/L)*	2.15 ± 0.97	2.11 ± 1.05	2.30 ± 1.20	1.97 ± 0.76	0.516

HR *(bpm)*	156.21 ± 11.65	156.21 ± 12.39	157.36 ± 11.63	155.27 ± 11.01	0.289
RPE	11.71 ± 1.54	11.71 ± 0.99	12.00 ± 1.41	11.71 ± 1.42	0.246
10% Grade					
Speed *(m/s)*	2.09 ± 0.38		2.04 ± 0.24		
Mass *(kg)*	66.40 ± 13.04	67.24 ± 13.24	75.32 ± 11.48	75.65 ± 10.81	0.379
V̇O2 *(ml/kg/min)*	44.70 ± 8.47	44.83 ± 7.84	44.15 ± 4.05	43.00 ± 3.64	0.154
OCOT *(ml/kg/km)*	357.68 ± 13.70	359.78 ± 19.16	362.30 ± 28.52	352.78 ± 23.99	0.127
ECOT *(J/kg/m)*	7.57 ± 0.28	7.65 ± 0.44	7.68 ± 0.58	7.49 ± 0.49	0.106
RER	0.88 ± 0.04	0.90 ± 0.06	0.89 ± 0.03	0.90 ± 0.03	0.376
BLa *(mmol/L)*	3.55 ± 1.87	3.55 ± 2.26	4.95 ± 2.59	4.07 ± 2.23	0.152
HR *(bpm)*	161.71 ± 11.98	161.93 ± 13.03	168.27 ± 11.12	165.27 ± 11.43	0.059
RPE	13.29 ± 1.49	13.36 ± 1.69	14.55 ± 1.92	15.00 ± 2.24	0.567

Effect of Resistance Training on Biomechanical Outcomes

Descriptive spatiotemporal data are displayed in Table 5.5. Across all grade conditions, no significant interaction effects were detected for joint work or stiffness variables (Table 5.6). A significant main effect of time was detected for knee stiffness during the 5% condition only, with knee stiffness increasing from pre- to post-test ($p = 0.009$).

Table 5.5 Spatiotemporal data presented as mean ± standard deviation

	Training Group (n = 14)		**Control Group (n = 11)**	
	Pre	**Post**	**Pre**	**Post**
Level Ground				
Step Frequency *(steps/min)*	172 ± 7	172 ± 7	172 ± 7	173 ± 8
Step Length *(m)*	1.07 ± 0.13	1.07 ± 0.14	1.05 ± 0.10	1.05 ± 0.11
Contact Time *(ms)*	251 ± 27	253 ± 25	258 ± 22	257 ± 21
Swing Time *(ms)*	447 ± 21	448 ± 31	440 ± 27	440 ± 33
Flight Time *(ms)*	99 ± 22	100 ± 27	91 ± 20	90 ± 21
5% Incline				
Step Frequency *(steps/min)*	169 ± 8	168 ± 7	168 ± 8	169 ± 8
Step Length *(m)*	0.89 ± 0.14	0.90 ± 0.14	0.88 ± 0.11	0.87 ± 0.11
Contact Time *(ms)*	278 ± 27	282 ± 27	290 ± 15	291 ± 18
Swing Time *(ms)*	435 ± 28	435 ± 31	428 ± 26	420 ± 29
Flight Time *(ms)*	80 ± 23	78 ± 25	70 ± 16	65 ± 20
10% Incline				
Step Frequency *(steps/min)*	165 ± 8	165 ± 8	165 ± 5	166 ± 7
Step Length *(m)*	0.76 ± 0.14	0.76 ± 0.13	0.74 ± 0.10	0.74 ± 0.10
Contact Time *(ms)*	301 ± 33	304 ± 29	312 ± 16	314 ± 16
Swing Time *(ms)*	428 ± 19	425 ± 24	414 ± 21	410 ± 26
Flight Time *(ms)*	66 ± 22	62 ± 21	53 ± 14	50 ± 16

Table 5.6 Pre- and post-intervention biomechanical outcomes for the training and control groups. Data are presented as mean ± standard deviation (*$p < 0.05$)

	Training Group (n = 14)		**Control Group (n = 11)**		**Group-by-Time**
	Pre	**Post**	**Pre**	**Post**	***p*-value**
Level Ground					
Positive Ankle Work *(J/kg)*	0.642 ± 0.094	0.641 ± 0.097	0.637 ± 0.094	0.619 ± 0.135	0.470
Positive Knee Work *(J/kg)*	0.195 ± 0.053	0.201 ± 0.055	0.171 ± 0.057	0.169 ± 0.043	0.583
Positive Hip Work *(J/kg)*	0.075 ± 0.072	0.071 ± 0.080	0.087 ± 0.057	0.071 ± 0.033	0.465
Ankle Stiffness *(Nm/kg/°)*	0.16 ± 0.04	0.18 ± 0.05	0.14 ± 0.03	0.14 ± 0.03	0.428
Knee Stiffness *(Nm/kg/°)*	0.08 ± 0.02	0.08 ± 0.02	0.08 ± 0.01	0.09 ± 0.02	0.782
5% Grade					
Positive Ankle Work *(J/kg)*	0.702 ± 0.118	0.671 ± 0.121	0.645 ± 0.116	0.623 ± 0.134	0.704
Positive Knee Work *(J/kg)*	0.187 ± 0.049	0.203 ± 0.057	0.171 ± 0.050	0.177 ± 0.046	0.509
Positive Hip Work *(J/kg)*	0.117 ± 0.106	0.118 ± 0.083	0.122 ± 0.059	0.104 ± 0.023	0.354
Ankle Stiffness *(Nm/kg/°)*	0.14 ± 0.03	0.14 ± 0.03	0.13 ± 0.02	0.13 ± 0.02	0.620
Knee Stiffness *(Nm/kg/°)*	0.09 ± 0.02	0.09 ± 0.02	0.09 ± 0.03	0.11 ± 0.03	0.032*
10% Grade					
Positive Ankle Work *(J/kg)*	0.662 ± 0.132	0.654 ± 0.124	0.617 ± 0.114	0.598 ± 0.117	0.558
Positive Knee Work *(J/kg)*	0.181 ± 0.053	0.178 ± 0.053	0.157 ± 0.047	0.162 ± 0.043	0.547
Positive Hip Work *(J/kg)*	0.135 ± 0.085	0.140 ± 0.068	0.170 ± 0.066	0.154 ± 0.046	0.222
Ankle Stiffness *(Nm/kg/°)*	0.13 ± 0.02	0.14 ± 0.02	0.13 ± 0.02	0.13 ± 0.02	0.263
Knee Stiffness *(Nm/kg/°)*	0.11 ± 0.04	0.11 ± 0.03	0.13 ± 0.04	0.15 ± 0.06	0.287

Effect of Resistance Training on Strength Outcomes

All participants performed 16 total resistance training sessions, with the exception of two female participants who completed 15 sessions due to missing the final session. Of all completed sessions, 93% were supervised in the lab. All participants demonstrated improvements in estimated 1RM for all exercises except for one female participant who demonstrated no change for the box squat. On average, estimated 1RM improved by 56% for the seated calf raise, 43% for the squat, and 47% for the standing single leg calf raise from the 10 RM test to the final resistance training session (Figure 5.5).

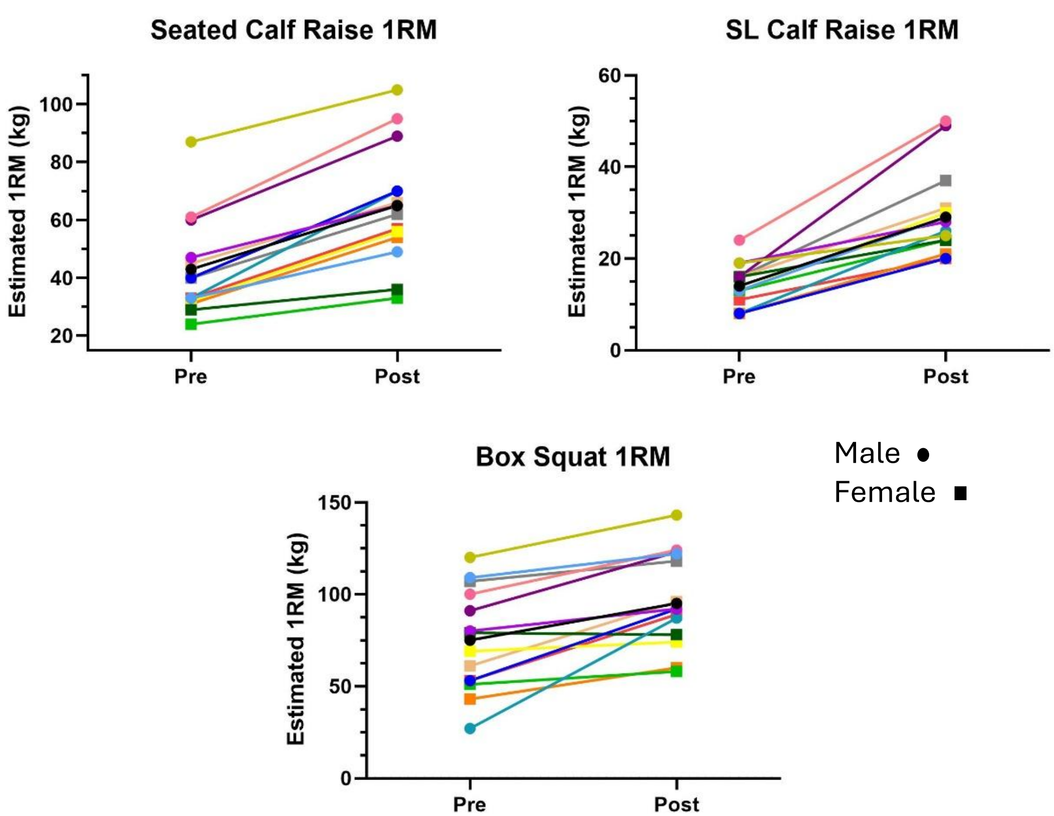

Figure 5.5 Changes in estimated 1RM from pre-intervention (10 RM test) to post intervention (final resistance training session). Individuals are represented by color. Sample mean is represented in black.

A significant group-by-time interaction effect was detected for peak ankle plantar flexor torque measured via dynamometry (Figure 5.6, Table 5.7). The training and control group were not significantly different at baseline (*p* = 0.393), but the training group demonstrated significantly greater peak ankle torque compared to the control group following the intervention period (*p* = 0.002). The training group demonstrated a 23% improvement in peak ankle plantar flexor torque (*p* = 0.004), while the control group did not change (2% decrease; *p* = 0.763). The interaction effect (*p* = 0.113), main effect of time (*p* = 0.812), and main effect of group (*p* = 0.069) were not significant for peak knee extensor torque, though the training group trended toward greater peak torque pre- and post-intervention (Table 5.7). Likewise, the interaction effect (*p* = 0.155), main effect of time (*p* = 0.972), and main effect of group (*p* = 0.059) were not significant for peak hip extensor torque, though the training group trended toward greater peak torque pre- and post-intervention (Table 5.7).

Table 5.7 Pre- and post-intervention dynamometry outcomes for the training and control groups. Data are presented as mean ± standard deviation (*$p < 0.05$)

	Training Group (n = 14)		**Control Group (n = 11)**		**Group-by-Time**
	Pre	**Post**	**Pre**	**Post**	***p*-value**
Peak Ankle Plantar Flexor Torque *(Nm/kg)*	1.02 ± 0.25	1.25 ± 0.24	0.93 ± 0.25	0.91 ± 0.24	0.026*
Peak Knee Extensor Torque *(Nm/kg)*	2.24 ± 0.51	2.34 ± 0.48	2.01 ± 0.24	1.94 ± 0.37	0.113
Peak Hip Extensor Torque *(Nm/kg)*	3.10 ± 0.84	3.25 ± 0.87	2.70 ± 0.63	2.54 ± 0.54	0.155

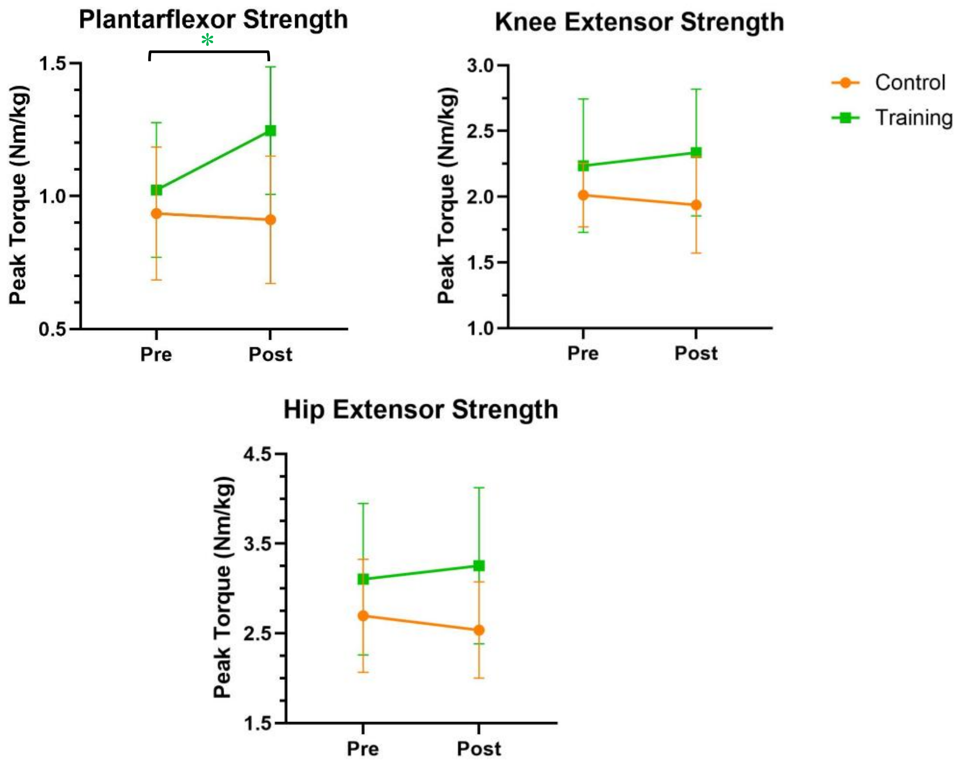

Figure 5.6 Mean pre- and post-intervention dynamometry outcomes for the training and control groups. Error bars represent standard deviation. (*significant main effect, $p < 0.05$)

Activity Tracking Data

Activity tracking data were obtained from Final Surge for 23 of the 25 participants. On average, participants recorded 25.10 ± 13.40 miles per week throughout the study period (training group: 26.10 ± 13.79 mi/wk; control group 23.82 ± 13.50 mi/wk). Descriptive statistics are provided for average weekly mileage, pace, weekly elevation gain, and weekly activity time in Table 5.8. Pre-enrollment data were only obtained from 8 participants. For these participants, average weekly mileage remained consistent between the month prior to Visit 1 and the first month of the enrollment period (pre-study: 25.48 ± 8.92 mi/wk; first month: 24.51 ± 9.80 mi/wk).

Table 5.8 Summary of training data from the first and final months of study enrollment. Data are presented as mean ± standard deviation.

	Training Group (n = 13)		Control Group (n = 10)	
	First Month	**Final Month**	**First Month**	**Final Month**
Average Weekly Mileage *(mi/wk)*	26.77 ± 14.34	26.75 ± 14.81	22.41 ± 15.42	24.16 ± 13.65
Average Pace *(min/mi)*	9:29 ± 1:56	9:28 ± 1:50	9:35 ± 1:29	9:48 ± 0:54
Average Weekly Elevation Gain *(ft)*	1500 ± 1552	1453 ± 1593	1371 ± 2291	1352 ± 1451
Average Weekly Activity Time *(hh:mm)*	5:45 ± 3:54	6:53 ± 5:52	4:49 ± 4:16	5:18 ± 4:03

Correlation of RE, Biomechanics, and Strength Changes

Across the entire sample, change in RE was not significantly correlated with change in running biomechanics or strength for any grade condition (Table 5.9). While the correlation between 10% grade RE and ankle stiffness approached significance, it was not significant following the correction for multiple comparisons.

Table 5.9 Correlation coefficients between changes in RE and joint work, stiffness, and strength at each grade. Correlation coefficients and 95% confidence intervals are presented.

	LG RE	5% Grade RE	10% Grade RE
Ankle Work	-0.10 (-0.48, 0.30)	-0.23 (-0.57, 0.19)	0.02 (-0.37, 0.42)
Knee Work	0.09 (-0.31, 0.47)	0.10 (-0.30, 0.48)	0.31 (-0.10, 0.63)
Hip Work	0.05 (-0.35, 0.44)	0.04 (-0.36, 0.43)	0.11 (-0.30, 0.49)
Ankle Stiffness	-0.13 (-.50, 0.28)	-0.18 (-0.54, 0.23)	-0.36 (-0.66, 0.04)
Knee Stiffness	0.26 (-0.15, 0.59)	0.29 (-0.12, 0.61)	0.29 (-0.11, 0.62)
Ankle Strength	0.27 (-0.14, 0.60)	0.16 (-0.25, 0.52)	0.15 (-0.26, 0.52)
Knee Strength	0.30 (-0.11, 0.62)	0.17 (-0.25, 0.53)	0.32 (-0.09, 0.63)
Hip Strength	0.17 (-0.25, 0.53)	0.13 (-0.28, 0.50)	0.13 (-0.28, 0.50)

Discussion

The purpose of this study was to determine if an 8-week HRT program improved uphill RE, and to identify changes in lower extremity strength and biomechanics that may explain changes in RE. The HRT program targeted the ankle plantar flexors and hip extensors, the primary muscle groups responsible for energy generation during uphill running. Despite increases in ankle plantar flexor strength and estimated 1RM for each of the prescribed exercises, RE was not significantly affected by the HRT program. Likewise, there were no significant changes in the evaluated running biomechanics, and changes in RE were not significantly correlated with changes in running biomechanics or muscle strength. Therefore, our hypotheses were not supported.

Effect of Resistance Training on Running Economy

This study implemented a HRT program similar in duration, intensity, and exercise type compared to a number of previous studies that reported improvements in level ground RE.[33,87,88,89] Like the current study, others have implemented similar programs without demonstrating RE improvements.[38,90] There are not clear differences in study population or exercise dosage between studies that did or did not report changes in RE, suggesting that runners' responses to resistance training can be variable and there may be underlying factors influencing this response.[38] We observed individual RE improvements above the indirect calorimetry measurement error and smallest worthwhile change (>2.75%) in both the training and control groups.[91] Improvements occurred in both male and female runners, trail and road runners, and across a range of ages (20-52 yrs.) and years of running experience (3-45 yrs.). While running dosage was not controlled in this study, there were no observed differences in training volume or intensity between participants who demonstrated improved RE and those who did not. Because running dosage was not controlled, participants likely entered the study period at different points in their training cycles. It is possible that some of these changes in RE were due to training factors external to the study. Additionally, while time of day was controlled between tests and participants were asked to adhere to pre-test fasting and exercise instructions, specific nutritional and fatigue-level factors were not evaluated and their influence on each test cannot be assessed.

Despite previously reported benefits of HRT for level ground RE, our results suggest that HRT does not appear to have a significant influence on uphill RE for recreational runners. Plyometric training, which has demonstrated mixed but overall positive effects on level ground RE may be worthwhile for future intervention studies to explore.[38,40] The elastic energy storage potential is reduced during uphill running, but is still likely to play a role in minimizing metabolic cost by reducing concentric contraction demands.[22] While HRT may result in greater tendon stiffness and muscle strength, plyometric training may be more specific for tuning the mechanisms of the stretch-shortening cycle relevant for energy transfer during uphill running. Another method worth exploring is uphill running training, either in the form of intervals or sustained, uphill runs. Uphill running interval training protocols have been shown by one study to have inconsistent effects on level ground RE, but their effect on uphill RE has not been evaluated.[39] As runners train on uphill grades, perhaps they adopt changes in their mechanics or muscle-tendon dynamics that lead to reduced metabolic cost over time, similar to the adaptations of new runners training on level ground.[80] While the long term effects of hill running were not evaluated in the current study, we did observe that the control group reported a significantly higher RPE during the 10% condition. As there was a smaller percentage of self-identified trail runners in the control group, this suggests that trail runners may be better accustomed to the effort of running up a 10% grade. While differences in physiological measures at the 10% grade were not observed, this provides some rationale for future studies to evaluate the effect of specific hill training on uphill RE and performance.

Relationship Between Resistance Training, Running Economy, and Biomechanics

While some studies propose that resistance training may improve RE via changes in running biomechanics, there is very limited evidence to support this claim. Most studies evaluating the effect of resistance training on RE do not include a detailed biomechanical analysis, and many that do measure biomechanics only investigate spatiotemporal factors.[46] Analyses that include joint kinetics provide a more detailed explanation of the metabolic-to-mechanical energy transfer that occurs during running. The current study investigated the effect of HRT on sagittal plane joint work and stiffness, and assessed whether changes in these variables were associated with changes in RE. These variables were selected because the mechanical energy produced by the hip extensors, knee extensors, and ankle plantar flexors account for most of the metabolic cost of running.[17,25] Contrary to our hypothesis, changes in muscle strength did not translate to changes in joint work or stiffness during level ground or uphill running. While some individuals in the study did demonstrate meaningful changes in RE, these were not associated with significant changes in biomechanics.

A recent meta-analysis identified that higher step frequency, lower vertical oscillation, and higher leg stiffness are associated with better level ground RE.[35] While this may encourage runners or coaches to change these mechanical features, there is no evidence to suggest that this will result in improved RE. In fact, previous studies demonstrate that runners tend to naturally choose a step frequency near what is metabolically optimal, suggesting that altering biomechanics may have detrimental effects on RE.[92,93] However, these studies evaluate short-term effects, and it is possible that long term adaptation to biomechanical changes may result in different outcomes.[94] If it is desirable to change running biomechanics, our results and those of previous studies suggest that resistance training alone is unlikely to achieve these changes.[46] Rather, gait retraining strategies that have been shown to result in meaningful biomechanical changes, such as visual and audio feedback, are more likely to be successful.[95] To determine whether runners should aim to change biomechanics for RE improvement, it will be necessary to implement gait retraining programs targeting specific biomechanical features, and assess long-term changes in RE. This holds true for both level ground and uphill running.

Benefits of Resistance Training for Endurance Runners

Despite the lack of significant level ground or uphill RE and biomechanical changes in the current study, there are several reasons that endurance runners may benefit from resistance training. As mentioned previously, several studies have shown significant level ground RE improvements in response to resistance training in multiple populations.[38] Others have demonstrated specific performance benefits such as faster time trials and longer time to exhaustion. [38,85] While evidence for the effect of resistance training on injury risk is limited, a recent study by Desai et al. found that runners who were 90% compliant with a twice-weekly resistance training program were 85% less likely to experience a running related injury compared to a control group.[96,97] As a whole, there is substantial evidence to support the inclusion of resistance training programming for endurance runners. Although uphill RE was not significantly affected by resistance training in the current study, future studies should evaluate the effect of resistance training on performance outcomes specific to the trail runners, such as uphill time trials, time to exhaustion during uphill exercise tests, or trail race performance.

Limitations

There were several strengths regarding the methodology of this study. While many previous resistance training studies have included only male participants, an equal number of male and female participants were included and balanced between training and control groups. Running economy was measured at a relative intensity below each participant's lactate turnpoint rather than an absolute velocity, which has been recommended by previous authors due to the effects of relative intensity on substrate utilization.[38,68] While many studies limit RE trials to 3 minutes, we elected to use 10-minute trials to confirm that steady-state had been reached. This was particularly important for the 5% and 10% inclines, where speed was adjusted using Margaria et al.'s data rather than the direct measure of 80% of speed at LTP that could be used for the level ground condition.[69] Control footwear was used for all study visits, minimizing the effect of footwear design and materiality on RE measures. Supervision of resistance training sessions led to high compliance and allowed for control of the exercise performance quality and appropriate dosage.

Given these strengths, this study also presents with limitations that should be considered when interpreting the results. Recreational runners were recruited for this study, which resulted in a heterogenous sample. Participant age ranged from 19-66 yrs., with 1-45 years of running experience, a variety of current training goals, and a variety of trail running experience. While both male and female participants were included, the study was not sufficiently powered to evaluate sex differences in the resistance training response. Running programming was not controlled, and participants were enrolled at various points in their training cycles. Thus, it is possible that individual variation in running volume, frequency, intensity, and terrain could have influenced the response to resistance training. Weekly mileage, elevation gain, and total activity time were tracked via GPS, and substantial changes in these metrics were not observed between groups or throughout the study. Experimental control of these demographic and training variables would have provided greater confidence that they did not influence the resistance training outcomes.

While most resistance training sessions (93%) were completed in the lab, participants did not always have access to the same equipment or spotting support when sessions were completed outside of the lab. As a result, some modifications were made during out-of-lab sessions such as using a lighter weight or different equipment (i.e. seated barbell calf raise instead of seated calf raise machine) which may not have provided an equivalent load. This may have influenced resistance training adaptations for the few participants that did perform out-of-lab sessions. The box squat exercise was selected to target the hip and knee extensors. Because the same 18 inch box was used for all participants, squat depth was influenced by participant height, which would influence hip and knee extensor recruitment.[98,99] Participants were not cued to achieve a specific trunk angle during the squat, and variations in trunk flexion would also influence hip and knee extensor recruitment.[100] This may explain the lack of significant changes in hip and knee extensor dynamometry for the training group. Future studies implementing a squat intervention should consider controlling for these factors, particularly if knee and hip extensor strength outcomes are separately evaluated.

Conclusion

In a group of recreational endurance runners, an 8-week HRT program did not significantly influence RE, joint work, or joint stiffness on a level ground, 5%, or 10% grade. Across the sample, changes in RE were not associated with changes in lower extremity strength or joint kinetics. While previous studies have demonstrated improved level ground RE in response to HRT, future studies should evaluate the effectiveness of alternative training modalities for improving uphill RE, such as plyometrics or hill training. Based on the current evidence, healthcare providers and coaches should not expect HRT to influence level ground or uphill running biomechanics, and should not aim to change running biomechanics in order to improve RE.

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CHAPTER VI

CONCLUSION

Summary of Findings

During long trail races, runners must transition between level ground, uphill, and downhill segments of varying lengths, always attempting to find a balance between speed and sustainability. There are times during which minimizing metabolic cost is the priority, such as on long, uphill climbs. There are also situations that call for short surges in speed, such as obtaining a more favorable position as a trail narrows. Each of these contexts elicit unique biomechanical and physiological demands. While previous research has described the biomechanics of increasing running speed and minimizing metabolic on level ground, few studies have examined these factors for uphill running. This dissertation sought to address these gaps by implementing two distinct studies. The first study focused on describing the mechanisms for increasing speed on level ground, uphill and downhill grades. The second identified biomechanical factors associated with uphill running economy and evaluated the effect of heavy resistance training on uphill running economy and biomechanics. The aim of this dissertation as a whole was to equip athletes, their coaches, and healthcare providers with information that can be directly applied to training program design specifically for trail runners.

Chapter III described spatiotemporal factors and joint kinetics across three different speeds and grades, demonstrating a difference in mechanical strategies for increasing uphill and downhill running speed compared to level ground. Increasing uphill running speed required a greater increase in step frequency and lesser increase in step length compared to level ground, leading to greater swing phase energy generation by the hip flexors and extensors and energy absorption by the knee extensors. Increases in downhill running speed were achieved with similar spatiotemporal changes compared to level ground, but with lesser swing phase energy generation by the hip flexors and extensors and lesser energy absorption by the knee flexors. As previous studies of similar design have focused solely on stance phase joint kinetics, the current study expanded on what was previously known by including swing phase kinetics.[44] The results of this chapter suggest that runners preparing for uphill events may benefit from specific concentric training of the hip flexors and extensors and eccentric training of the knee flexors in order to meet the muscular demands of fast uphill running. This information is also useful for runners who are returning to trail running after experiencing an injury to one of these muscle groups. Along with specific resistance training, practicing speed increases on downhill grades may be an effective strategy to reintroduce running-specific load to the hip flexors, hip extensors, and knee flexors. It may be advantageous to delay faster uphill running to later phases of rehabilitation.

Chapter IV examined biomechanical, muscle strength, and demographic factors that were associated with uphill running economy. While joint kinetics did not significantly affect running economy on level ground or 5% grades, runners who demonstrated greater positive ankle plantar flexor work on a 10% grade were more economical. These results were in alignment with previous comparative biomechanics studies that suggested the ankle plantar flexors to be more efficient than the hip extensors.[66] Although mechanical energy generation demands are higher on steeper grades, runners who relied on the ankle plantar flexors were able to generate mechanical energy at a lower metabolic cost. This is a novel finding, as previous studies have not investigated joint kinetics in relation to uphill running economy.[36] In order to apply these findings, it will be necessary to identify effective training mechanisms to increase the positive work contribution of the ankle plantar flexors on steep grades. Results from the current study suggest that plantar flexor strength alone will not translate to this biomechanical technique. Rather, participating in trail running may be a more worthwhile training mechanism, as trail runners demonstrated both better running economy and greater ankle plantar flexor work on the 10% grade compared to road runners.

Utilizing data collected from Chapter IV as a baseline measure, Chapter V sought to investigate the effect of a heavy resistance training program on uphill running economy and biomechanics. While completing 8 weeks of heavy resistance training did result in significant improvements in ankle plantar flexor strength, this did not translate to changes in running economy or biomechanics on level ground, 5%, or 10% grades. These findings contrast with previous studies that have demonstrated improved level ground running economy in response to similar resistance training interventions.[38] The lack of effect in the current study may have been due to the heterogenous group of participants or lack of control for training cycle timing. While athletes, coaches, and healthcare providers may choose to implement heavy resistance training for other performance and injury prevention benefits, the findings presented in this chapter warrant exploration of alternative training modalities to improve uphill running economy or change biomechanics.

The results of this dissertation as a whole provide new insights on the biomechanics of uphill running performance and how they should be considered in training. Chapters III and IV highlight the increased mechanical demands of uphill running, demonstrating that the mechanisms for faster and more economical running differ from those observed on level ground. Specifically, runners should expect greater hip flexor, hip extensor, and knee flexor work when running fast on uphill grades, and should consider the cost-savings benefit of greater reliance on the ankle plantarflexors on steep uphill grades. Chapters IV and V indicate that while runners may benefit from resistance training for other reasons that have been previously published, it does not appear to be an effective means to improve uphill running economy or change running biomechanics. These chapters do suggest, however, that simply participating in trail running may result in positive impacts on running economy and perceived exertion on steep inclines. While the studies of this dissertation did not evaluate trail running as an intervention, the observed differences in biomechanical and physiological factors between trail and road runners warrants further investigation. In the context of this dissertation and previous studies, trail runners are encouraged to engage in resistance training as a component of their preparation for the mechanical demands of graded running. Athletes and coaches should also be aware that positive biomechanical and physiological adaptations may occur without outside intervention as runners gain more experience and exposure to trail running. To elucidate the timing, dosage, population-specific considerations, and mechanisms behind these changes will require ongoing research.

Limitations

Researchers, coaches, healthcare providers, and athletes should consider the limitations of this dissertation when interpreting its results. These limitations include those inherent to commonly accepted biomechanical and physiological data collection techniques, as well as study-specific limitations in ecological validity, generalizability, and study design.

All studies of this dissertation applied an inverse dynamics approach to estimate joint kinetics. While this approach is standard in the field of biomechanics, it does present with known limitations. Inverse dynamics uses measured kinematics and force data to calculate the net moments produced by the muscles around a joint. In measuring kinematics, it is assumed that 3-D marker positions are consistent with body segment positions. Motion of the skin or clothing that retroreflective markers are adhered to introduces error to body segment position estimates, though surface markers are far more reasonable than bone pins for running biomechanics studies. Given the population of runners recruited for this study, skin motion artifact was likely minimized, though some of the larger participants may have been subject to more artifact. Participants also wore tight-fitting clothing, self-adhesive wraps, and tape to minimize marker motion. While marker position was monitored throughout each data collection, it is possible that marker clusters secured around the thigh and shank segments could have slid inferiorly, especially over the 10 minute trials of Chapters IV and V. Even a few millimeters of motion may significantly influence joint angle calculations. Kinematic measurements also rely on consistent placement of static markers to define segment endpoints, and even small placement errors can lead to significant variations in joint angle measurement.[101,102] While two separate researchers applied static markers for the Chapter III study which may have introduced more error, only one researcher applied static markers for the Chapters IV and V study. The largest concern for accuracy of marker placement is for those used to define the hip joint center, as the posterior superior iliac spines are difficult to palpate in some individuals, particularly if more soft tissue is present. In contrast to the Bell and Brand regression equation used to estimate hip joint center in this dissertation, functional techniques in which the hip joint center is defined as the center of rotation from individual participant motion trials have demonstrated greater accuracy.[103] The hip work calculations reported in this dissertation are therefore subject to a level of error that could have been minimized had a different approach been applied.

As with biomechanical measurements, there are limitations inherent to the use of indirect calorimetry for estimating the rate of gas exchange during exercise. This measurement technique assumes that all expired air is measured by the gas sensors and flow meters within the device. The mouthpieces utilized for the Chapters IV and V study could allow for escape of air outside of the system if participants were not consciously focusing on maintaining a tight seal around their lips. Gas exchange levels were monitored for any unexpected drops, and participants were reminded to keep their lips sealed if drops were observed. The steady-state criteria were met for all participants, indicating that there were not large changes in gas exchange over the last 2 minutes of each trial. However, escape of gases around the mouthpiece cannot be entirely ruled out.

While the overall goal of this dissertation was to provide guidance for trail runners, all data collections were laboratory-based and performed on a treadmill. There are clear differences in terrain variability, surface firmness, and obstacle presence between trails and treadmills which are likely to influence biomechanical and physiological measures. However, joint kinetics cannot currently be accurately measured outside of the lab, rendering the laboratory-based measurements necessary for the goals of these studies. Additionally, a limited number of grades was assessed across the studies and the results may not be generalizable to grades outside of those investigated in this dissertation.

Specific to Chapter III, one of the primary limitations was the short trial duration of 30 seconds, which is below the recommended duration to achieve stable biomechanical measures. While the short duration was necessary due to the steep grade and faster speeds used in this study, this may have influenced the observed effects of speed and grade on biomechanics. Additionally, the order of trials was not randomized, and it is therefore not possible to rule out the effect of trial order on the observed mechanical changes. Finally, participant speeds were based on self-reported 5k pace, and there was no way to determine whether participants were accurate in reporting this. If a participant had not been a runner for very long, it is possible that they may have over- or underestimated their pace, leading to differences in relative intensity between participants. In turn, this may have influenced the magnitude of joint kinetic and spatiotemporal changes across speeds.

While Chapters IV and V implemented longer running trials than most running economy studies, these bouts were much shorter than those performed by trail runners in the real world. In longer events where fatigue begins to play a role, the relationship between biomechanics and running economy may be different than those reported in these chapters. Additionally, the estimated running speed adjustments for the 5% and 10% grades were based on data from two male middle-distance runners from a study published in 1963.[69] These adjustments did not apply perfectly to the current sample of recreational runners, demonstrated by the greater oxygen and energy costs reported for the uphill conditions compared to level ground. The data still met our criteria for metabolic steady state, but future work may be necessary to define equivalent grade-based metabolic cost estimations that take training level and sex into account. Finally, while the heterogeneous sample was desirable for the goals of Chapter IV, this was not ideal for the goals of Chapter V. The variance in participant age, training experience, and current training practices may have influenced the sample-level response to heavy resistance training. While trends between these differences and intervention response were not observed, experimental control of these factors would be preferrable.

Recommendations for Future Work

Research on uphill and trail running performance is relatively limited, but considering the increasing popularity of trail running there is motivation to continue exploring this area. This dissertation provides new perspectives on the biomechanics of uphill running performance and opens opportunities for future work in this space. The included studies focused on biomechanical factors associated with running economy and speed changes, which have important influences on performance. However, neither study included a performance-specific outcome. Future studies should investigate the relationship between the factors investigated in this work with a performance measure, such as an outdoor uphill time trial. This would provide a stronger link between lab-based measures and real world outcomes.

Future research that describes the mechanisms underlying the effects of resistance training on running economy is also called for, as many explanations are largely theoretical. Currently, there is some evidence that resistance training results in increased Achilles tendon stiffness with concomitant improvements in level ground running economy.[41] However, most studies in this area do not include measures of running biomechanics, muscle activation and recruitment patterns, or tendon stiffness. Including electromyography and tendon stiffness measures before and after an intervention would provide greater clarity regarding the neuromuscular and mechanical adaptations that may explain changes in running economy.

In order to best guide training for uphill athletes, interventions to improve uphill running economy should be further investigated. Chapter V demonstrated that 8 weeks of heavy resistance training did not significantly affect running economy. Implementing a study with a similar program but using a more homogenous group and tighter control of training-related factors would provide stronger evidence regarding the effect of resistance training on uphill running economy. The results of Chapters IV and V suggest that performing uphill running may lead to uphill running economy improvements. In order to confirm this, an uphill running intervention could be applied to runners who habitually run on level ground. The specific dosage and timeline required to detect significant effects of such a program is currently unknown.

APPENDIX: DEMOGRAHPICS FORM

These following questions were presented to Chapters IV and V participants upon enrollment in a Google Forms format.

1. Please enter your participant ID number provided by the researcher

2. What is your age?

3. What is your biological sex (sex assigned at birth)?

    a. Female

    b. Male

    c. Intersex

4. What is your shoe size?

    a. Women's 7

    b. Women's 7.5

    c. Women's 8

    d. Women's 8.5

    e. Women's 9

    f. Women's 9.5

    g. Women's 10

    h. Men's 9

    i. Men's 9.5

    j. Men's 10

    k. Men's 10.5

    l. Men's 11

    m. Men's 11.5

n. Men's 12

o. Other

5. How many years of running experience do you have?

6. How many miles per week have you run on average over the past 3 months?

7. Do you currently use a GPS watch to record your runs or cross training activities?

a. Yes

b. No

8. Which running events do you typically train for?

a. Shorter than 5k

b. 5k

c. 10k

d. Half Marathon

e. Marathon

f. Ultramarathon

g. I do not train for specific running events

h. Other

9. Which type of running event are you currently training for?

a. Shorter than 5k

b. 5k

c. 10k

d. Half Marathon

e. Marathon

f. Ultramarathon

g. I am not currently training for a running event

h. Other

10. Do you consider yourself a “road runner” or “trail runner”?

a. Road Runner

b. Trail Runner

c. I participate in road and trail running equally

11. Please list any running related injuries you have experienced in the past, including which side was affected (i.e. right Achilles tendinitis)

12. At what pace do you think you can CURRENTLY run a 10k? (i.e. 8:00 min/mile, 7.5 miles per hour)

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