Analysis of Human Movement Patterns during Endurance Running

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ANALYSIS OF HUMAN MOVEMENT PATTERNS
DURING ENDURANCE RUNNING

By

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Bachelor of Science – Kinesiology Sciences
University of Nevada, Las Vegas
2011

Master of Science in Kinesiology
University of Nevada, Las Vegas
2014

A dissertation submitted in partial fulfillment
of the requirements for the

Doctor of Philosophy – Kinesiology

Department of Kinesiology and Nutrition Sciences
School of Allied Health Sciences
Division of Health Sciences
The Graduate College

University of Nevada, Las Vegas
August 2017
This dissertation prepared by

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entitled

Analysis of Human Movement Patterns during Endurance Running

is approved in partial fulfillment of the requirements for the degree of

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ABSTRACT

Endurance running and participation in racing events has flourished over the last decade. Recreational runners enter the training period for an upcoming race at differing levels of fitness and training. As individuals sign-up for the race, they typically follow the commitment with an increase in training load. The increases in training load are accomplished through a combination of increasing mileage, or duration of running, and running intensity through increase velocity. These increases are theoretically being applied in a progressive overload principle, where the musculoskeletal system has time to adapt to the breakdown provided from the previous training session. Progressive overload is based on applying a stimulus that pushes the threshold of the current structural limits of the system. The ability of the individual to withstand and adapt to the training overload is a key determinant in determination of performance success versus injury.

In applying a Dynamical Systems approach to endurance running analysis, coordination patterns and the variability were used in an attempt to identify the effects of approaching different performance thresholds. The method of coordination pattern calculations was continuous relative phase (CRP). This method uses a normalization process to eliminate amplitude and frequency differences between trials of the same variable. Following the normalization, phase angles for each variable are calculated from the angular position and velocity phase plots. CRP for each coupling, two variables that have a structural relationship, is calculated by subtracting the proximal phase angle from the distal phase angle. CRP variability (vCRP) was calculated as the standard deviation for each point of the cycle normalized data. CRP and vCRP were then calculated across different phases and couplings for each study to represent the motor pattern changes in response to the performance threshold intervention.
The purpose of this dissertation is to examine the effects of approaching performance thresholds on coordination patterns and coordination variability during treadmill running in healthy runners. To address this purpose, three individual studies were designed to challenge the current performance abilities of the participants. Each study addressed a different aspect of performance thresholds: (1) influence of increased running velocity, (2) increased oxygen consumption as percentage of peak consumption, and (3) perceived fatigue while running at multiple running velocities.

The purpose of study one was to investigate the effect of treadmill running velocity on the coordination patterns and variability of coordination of lower extremity couplings of healthy runners. A range of velocities relative to the participants preferred running velocity were chosen to identify the changes through a range of velocities. As this was the first study to investigate the effects of running velocity in healthy runners, the analysis was confined to the stance phase. The results of the first study identified changes in both CRP and vCRP due to changes in running velocity. Changes identified for CRP were seen in the Thigh IR/ER-Shank AB/AD coupling, the significant difference were measured in the propulsive phase for the right lower extremity and the loading phase for the left lower extremity. The Thigh FL/EX-Shank FL/EX coupling has the greatest vCRP significant findings across phases. The conclusion for study one was that running velocity increases did change CRP and vCRP variable during treadmill running.

The purpose for the second study was to investigate how the oxygen cost of running is related to coordination pattern couplings and coordination variability of healthy runners. 16 runners participated in this study, which was conducted over two sessions. During the first session, a graded exercise test was used to identify the peak oxygen consumption of the participant and to visually identify the ventilator threshold (VT). The oxygen consumption value
at VT was used to calculate the running velocity at VT. Runners performed two submaximal runs during session two in which steady-state oxygen consumption was collected. Participants were then grouped based on their difference in the percentage of peak VO\textsubscript{2} between two running velocities (VO\textsubscript{2} diff), preferred and 80% of speed at VT. The less economical group, VO\textsubscript{2} diff greater than 10%, reduced variability during mid-swing for Thigh AB/AD-Shank IR/ER, Shank IR/ER-Foot IN/EV, and Knee AB/AD-Shank IR/ER. Knee AB/AD-Foot IN/EV increased variability during propulsive and mid-swing phases. The more economical group was more in-phase during mid-swing of the 80% VT condition. Although there were differences between groups, the majority of the changes in coordination variability were in response to the increased running velocity regardless of relative cost to participant.

The purpose of the final study was to identify whether or not coordination patterns and coordination variability are influenced by perception of fatigue differently than runners who did not perceive fatigue. This study introduced a typical threshold training session in which intervals are used to provide short bursts of increased threshold training. Runners were grouped based on their perceived fatigue, which was reported by a questionnaire containing both analogue and Likert responses. The high-perceived fatigue group increased vCRP for the Torso FL/EX-Knee FL/EX coupling at the transition phases, toe-off and initial swing, for the left lower extremity. The majority of the differences between groups for vCRP were measured between the velocity differences. The low-perceive fatigued group reduced vCRP during the 10k race pace, but increased vCRP between the 2 minute and 4 minute collection at the 75% 10k pace. The results of this study supported the influence of running velocity on vCRP and CRP in both high and low-perceived fatigued runners.
ACKNOWLEDGEMENTS

I have had the privilege of having a mentor that reached beyond the walls of academia. Dr. John Mercer challenged my thoughts during each interaction, whether it was in person or via email. He continued to remind me to simplify my rambling and focus my efforts. He allowed me venture, sometimes on the edge, but would always be there to reign me back in. But what I have become most thankful in Dr. Mercer, was his constant reminder that life needs to be balanced and that family is first. Dr. Mercer, I thank you and challenge you to a game of foosball.

A special thank you to my committee for the hours of work you dedicated to my development and research.

Dr. Janet S. Dufek, Dr. Julia Freedman Silvernail, Dr. James Navalta, and Dr. Jennifer Kawi

There were a number of other collaborators and mentors that were instrumental along the way throughout my tenure at UNLV. I thank you all for your guidance and interesting conversations along the way.

Dr. Andrew Nordin, Dr. Kenji Masumoto, Dr. Szu-Ping Lee, and Dr. David Lee

A special thank you goes out to my fellow Graduate Students. We had some great conversations, good laughs and challenging debates. Whether they occurred in the office, laboratory, Naked City Pizza or at a Conference, I will cherish those times. A special shout out to Michael Soucy and Leland Barker, both for your assistance in data collections and late night pillow talk debates were instrumental in my daily routine.
The UNLV Graduate College and GPSA were instrumental in providing support for my research and travel to conferences. I thank you for all you have done for the UNLV graduate student body and myself.

Finally, I would like to thank a number of undergraduate and high school students that provided brilliant support during the collection of a large part of my dissertation work. I look forward to watching as you progress through school and decide on your own path.

Cheers!
DEDICATION

The old saying is true that ‘behind every good man there is a better woman’. I hit the jackpot when I met my wife, and beautiful mother of my two boys. Alexis Bailey was the strength and glue that kept our family working as a unit during the pursuit of multiple degrees, PhD and Masters. This achievement could not have been possible without her professional and personal sacrifices. She also continued to push be to follow my dreams and proclaim her belief in my knowledge and skill.

I dedicate not only this achievement to my wife and our wonderful children. Grayson and Daxton, I encourage you both to pursue YOUR dreams and follow your individual paths.
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CHAPTER 1
Overall Dissertation Introduction

By
Joshua Paul Bailey
Introduction

Endurance running has grown in popularity for recreational runners over the last few decades, with reports of over 17 million race finishers in the U.S. in 2015 (Running USA, 2016). Overuse injury rates have been reported to range between 20% and 79% (Bates & Osternig, 1977; Goss & Gross, 2012; Van Gent, Van Middelkoop, Van Os, Bierma-Zeinstra, & Koes, 2007). Common locations of injury are the knees, tibial stress fractures and other lower extremity structures designed to absorb the repetitive impacts (Bates & Osternig, 1977; Fredericson & Misra, 2007; Van Gent et al., 2007). Due to the repetitive nature of endurance running, traditional mechanical investigations have focused on lower extremity kinematics and kinetics associated with running.

Kinetic variables of interest have included impact force, loading rate, and peak vertical ground reaction force during the stance period of running (Goss & Gross, 2012; Mercer, Bezodis, Russell, Purdy, & DeLion, 2005), for example. The interest in these kinetic parameters is because they attempt to measure the mechanical demands placed on the structure that may lead to overuse injuries due to the repetitive nature of running. Lower extremity joint motion during stance, foot strike patterns, center of mass vertical oscillation (Farley & Ferris, 1998; Bailey, Mercer, & Dufek, 2016) and the relationship between stride frequency and stride length have drawn the interest from kinematic analyses.

An alternative approach to endurance running utilizes a Dynamical Systems approach to understand variability of movement patterns (Hamill, Palmer, & van Emmerick, 2012). A Dynamical Systems approach is based upon the theory that variability is inherent (and important) to the system and not noise. By engaging multiple movement patterns to achieve the same desired goal, it may be possible to avoid overuse injury by the reduction of repetitive patterns as
experienced with reduced pattern variability (Hamill, van Emmerik, Heidersheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008; van Emmerik, Rosenstein, McDemott, & Hamill, 2004). This view of variability in movement patterns representing a healthy state provides a differing perspective on the traditional view that variability is evident in the novice and unskilled pattern.

The current literature regarding the coordination patterns and the variability within these patterns is focused in the retrospective identification of differences between healthy runners and those diagnosed with an overuse pathology (Hamill et al., 1999; Miller et al., 2008). Reduced variability in movement patterns are associated with overuse running injuries, such as patellofemoral pain (PFP) and iliotibial band syndrome (ITBS) (Hamill et al., 1999; Miller et al., 2008). The literature is inconsistent on which of the coordination coupling patterns are significant between studies however, due to differences in phases of the running gait cycle and coupling investigated. There is also a gap in the literature on how healthy runners adjust their coordination patterns and variability in the coordination couplings following perturbations.

As the numbers suggest, not all recreational runners become injured during their training programs for an upcoming race, but overuse injuries are present. This is related to the increased training loads experienced during training. Race training programs typically last for approximately three months for a marathon race, with gradual increases in long run distance or time running. In addition to the increasing volume, training programs also increase running intensity, by incorporating track repeats and interval runs. Training programs are design to progressively overload the musculoskeletal system in a quick amount of time to prepare the runner for their race. The current training and fitness status of an individual runner provides a performance threshold in which the runner is comfortable. It is unknown however, how
coordination patterns and coordination variability differ between healthy runners during running intensities and distance that push their current fitness threshold.

The purpose of this dissertation is to examine the effects of approaching performance thresholds on coordination patterns and coordination variability during treadmill running in healthy runners. To address the purpose, protocols are designed to investigate the effects of approaching performance threshold measured as: 1) how runners respond to running velocity increases, 2) differences in intensity of runs between preferred running velocity and 90% of ventilator threshold, 3) the effect of perceived fatigue as a result of an hour interval run.
References:


CHAPTER 2
Effects of Treadmill Running Velocity on Lower Extremity Coordination
Variability in Healthy Runners

By
Joshua Paul Bailey

Co-authored by
Julia Freedman Silvernail, Janet S. Dufek, James Navalta, & John A. Mercer
Significance of the Chapter

To begin the investigation into the effects of approaching performance thresholds on coordination patterns and variability, the acute response to running velocity changes needed to be established. Performance literature has established a strong connection between the effects of increased running velocity on traditional kinematic variables (e.g. knee flexion angle, foot contact time and stride frequency). However, the focus of the coordination research has focused on a controlled velocity in order to calculate between participant differences between an injured population and a healthy population. Therefore, in order to relate any other changes due to approaching different performance thresholds, the effects of changing velocity need to be established. Understanding how an individual organizes their degrees of freedom to accomplish the increasing, or decreasing, running velocity in reference to their preferred pattern development is novel. It is also novel to investigate whether differences in running patterns can be measured in healthy runners during treadmill running.

The current study also focused on the stance period because a focus of overuse running related injury research focuses on the impact period with the ground. Understanding the differences during these periods is an essential component to understanding whether the coordination patterns are more affected by the loading response or the propulsive responses of running. Establishing a running velocity based analysis focused on acute changes was deemed essential based on the acute responses during a training protocol when the plan calls for an increase in running velocity.
Manuscript Note

This study has been written with the collaboration of the members of my Graduate Committee: Julia Freedman Silvernail, Janet S. Dufek, James Navalta, & John A. Mercer. The manuscript is currently under review with the journal of *Human Movement Sciences*. 
Abstract

The purpose of the current study was to investigate the effect of treadmill running velocity on the coordination patterns and variability of coordination of lower extremity couplings of healthy runners. Fourteen apparently healthy runners ran on a split-belt Bertec Force Instrumented Treadmill at five different velocities for two minutes per velocity. Lower extremity segmental angles for thigh, shank and foot of both left and right lower extremities separately were calculated. Stance phase was separated into three phases (loading, mid stance, and propulsion) identified by peak knee flexion. Continuous relative phase (CRP) was used to quantify coordination and variability between segmental couplings. Multiple one-way repeated measure ANOVAs were conducted to identify differences among velocity conditions at each phase and discrete events (foot contact, peak knee flexion during stance, and toe-off). Thigh internal/external rotation (IR/ER)-Shank abduction/adduction (AB/AD) coupling was different during the loading phase (p=0.016) for left and propulsive phase (p=0.02) for right lower extremities. Thigh flexion/extension-Shank flexion/extension showed the greatest differences in CRP variability across velocity conditions with differences occurring during loading phase, mid stance, propulsive phase, and peak flexion for both right and left lower extremities (p<0.05). Additionally, significant differences were seen in only one lower extremity for particular phases: Thigh FL/EX-Shank FL/EX (right toe-off, p=0.01), Thigh FL/EX-Foot inversion/eversion (IN/EV) (right to-off, p=0.032), Thigh IR/ER-Foot IN/EV (left propulsive, p=0.049 & toe-off, p=0.032), and Thigh IR/ER-Shank AD/AB (left peak knee flexion, p=0.046). The results illustrate a reduction in CRP variability as the treadmill velocity is increased.

Keywords
Dynamical Systems; Stride Frequency; Kinematics; Gait Patterns
Highlights

- Runners increased stride frequency as treadmill velocity increased.
- Stance phase coordination patterns unaffected by treadmill velocity.
- Healthy runners reduce CRP variability during stance phase as velocity increases.
- Unknown if reduced variability is within a ‘healthy’ range of variability.
Introduction

Endurance running popularity is evident by the 17 million finishers in U.S. sanctioned races in 2015 (Running USA, 2016). Running related injuries for recreational runners range from 20% to upwards of 79% (Goss & Gross, 2012; Van Gent, Van Middelkoop, Van Os, Bierma-Zeinstra, & Koes, 2007) and upwards of 90% for those training for a marathon (Fredericson & Misra, 2007). There is no clear understanding of what mechanical differences exist in runners who get injured during training and those that do not.

Endurance running involves the accumulation of repetitive foot-ground impacts during an extended run. Consequently, the lower extremity is required to absorb and distribute repetitive loads ranging from 1.5 to 3.5 times body weight (BW) (Goss & Gross, 2012; Hreljac, 2004) throughout the musculoskeletal structures. The most common locations of overuse injury related to the repetitive loads include the knee joint and tibial stress fractures (James, Dufek, & Bates, 2006; Van Gent, Van Middelkoop, Van Os, Bierma-Zeinstra, & Koes, 2007). From a performance perspective, understanding the organization of the lower extremity to utilize the stored energy during running may be valuable.

As running velocity increases, runners have the ability to manipulate stride frequency and/or stride length to achieve a desired running velocity (Dillman, 1975; Mercer, Mata, & Bailey, 2016). The influence of running velocity on kinetic and kinematic variables in healthy endurance runners has been investigated for decades. Kinetically, the impact force generally increases in response to increased running velocity have been shown to be related to an increased stride length (Mercer, Vance, Hreljac, & Hamill, 2002). It is important to recognize that a runner can select a gait pattern that could reduce the magnitude of impact force and/or increase the ability to attenuate impact force (Bates, 1989; Mercer, Vance, Hreljac, & Hamill, 2002; Mercer,
Bezodis, Russell, Purdy, & DeLion, 2005). Altering the stiffness, or compliance, of the lower extremity during stance and joint angle positions at foot contact (Dillman, 1975; Nigg, De Boer, & Fisher, 1995; Tsuji, Ishida, Oba, Ueki, & Fujihashi, 2015; Williams & Cavanagh, 1985; Farley & Ferris, 1998) are examples of mechanisms employed to affect the impact force and the subsequent attenuation.

Recent interest has focused on describing coordination patterns of lower extremity couplings and the variability of these patterns during running (Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016; Hamill, Palmer, & van Emmerick, 2012; Hamill, van Emmerik, Heidersheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008). Understanding coordination patterns and coordination variability is founded in the Dynamical Systems Theory which states that variability is inherent to a system vs. being considered movement errors. Specifically, it has been hypothesized that a certain degree of variability is inherent and a necessary component of a healthy state for a runner (Hamill, van Emmerik, Heidersheit, & Li, 1999). The presence of pattern variability, may engage the utilization of multiple patterns, reducing the risk of overuse injury (Hamill, van Emmerik, Heidersheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008; van Emmerik, Rosenstein, McDemott, & Hamill, 2004). It has been suggested that variability in itself does not provide a positive or negative role in injury prevention, but rather it may simply be a characteristic of healthy movement patterns (James R., 2004).

Coordination pattern variability characteristics have been used to identify possible differences in endurance running pathologies compared to healthy runners retrospectively (Hamill, van Emmerik, Heidersheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008; van Emmerik, Rosenstein, McDemott, & Hamill, 2004). However, there is limited understanding of
how healthy runners adjust coordination patterns and variability in response to running perturbations (Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016) and whether there is a prospective connection to run performance. Specifically, it is not clear how running velocity perturbations away from the preferred running velocity influences coordination patterns and/or variability. Therefore, the purpose of the current study was to investigate the effect of treadmill running velocity on the coordination patterns and variability of coordination of lower extremity couplings of healthy runners. The coordination patterns were analyzed using continuous relative phase and variability of continuous relative phase. It was hypothesized that treadmill running velocity would affect coupling coordination patterns and variability across different speeds.

**Methods**

**Participants**

Fourteen participants (9 men and 5 women; 24 ± 2 yrs; 75.2 ± 12.4 kg; 1.71 ± 0.10 m) completed treadmill running at five speeds. All participants arrived at the Sports Injury Research Center where the protocol was explained and they then signed a university-approved informed consent to participate. All participants were free from any lower extremity injury that may have interfered with their ability to run on a treadmill. Inclusion to participate in the study included comfort with treadmill running, indicated by previous history running and self-reporting during warm-up.

**Procedures**

All running trials were conducted on a split-belt Bertec Force Instrumented Treadmill (FIT, Bertec Corporation, Columbus, OH, USA). Treadmill speed was adjusted by a member of the research team at an acceleration of 1 m·s⁻¹·s⁻¹. Participants completed a five-minute minimum, self-selected velocity, warm-up period on the treadmill to ensure they were
comfortable. Following the warm-up period, participants identified a preferred comfortable running velocity on the treadmill, while blinded to the treadmill velocity display. Participants were instructed to identify a treadmill running speed that they felt they could comfortably maintain for 30 minutes. A researcher controlled the treadmill velocity and was instructed by the participant to increase or decrease the treadmill velocity until they identified the velocity representative of their 30-minute pace. The researcher then stopped the treadmill. This process was repeated three times with the average of three trials calculated and used to determine the speed settings for all five-velocity conditions.

Participants were then instrumented with a cluster marker set modeling the lower extremity and trunk during all trials. Rigid clusters were attached to the lateral aspects of the thigh and shank segments using elastic sporting wraps made of nylon and Lycra (SuperWrap Fabrifoam; Exton, PA, USA) and secured using duct tape. The pelvis, feet, and trunk were modeled using individual 14 mm reflective markers secured with double-sided tape and Cover Roll adhesive tape (BSN Medical, Luxembourg, Germany). Kinematic data were collected at 200 Hz using 12-infrared cameras (Bonita; Vicon Motion Systems Ltd., Oxford, UK). Kinetic data were collected at 2000 Hz from a single force platform of the FIT for all participants and trials.

The treadmill running protocol consisted of five running velocities, determined as a function of the self-identified running velocity. The five velocity conditions included: preferred running velocity (PRV), PRV - 0.25 m·s⁻¹ (PRV-0.25), PRV + 0.25 m·s⁻¹ (PRV+0.25), PRV + 0.5 m·s⁻¹ (PRV+0.5), and PRV + 1.0 m·s⁻¹ (PRV+1.0). Reported as a function of the runners preferred running velocity, PRV-0.25 was between 89-93% of PRV, PRV+0.25 between 107-111%, PRV+0.5 between 115-119% and PRV+1.0 was between 129-145% of PRV. All
conditions were randomly assigned for all participants to minimize order effects. Each velocity condition consisted of approximately two minutes of running on the treadmill, with the first minute used to allow achievement of a steady running pattern at that treadmill velocity. Following the first minute, two 20-second trials were collected with 10 s between trials. A minimum of one-minute rest was required between velocity conditions and up to five minutes if needed.

**Data Analysis**

Data for 15 consecutive strides were extracted from each 20 s data set. Label identification was conducted using Nexus 2.3 with frame-by-frame verification of proper labeling. Within Visual3D (C-Motion, Inc., Germantown, MD, USA) all kinematic marker trajectories were smoothed and filtered using a 4th order zero-lag Butterworth filter with a cut-off frequency of 8 Hz. Foot contact was identified when the vertical ground reaction force exceeded 50 N with the subsequent toe off occurring when the vertical ground reaction force fell below 50 N.

Segmental joint angles were identified for the thigh, shank, and foot, which were used in the continuous relative phase analysis. Stride frequency, center of mass vertical displacement during stance, knee sagittal joint angle, and foot segmental angles were calculated during stance bilaterally. All variables were normalized to 100% stance. Center of mass vertical displacement was divided into two phases: vertical position at foot contact to the lowest vertical position during stance (CM_drop) and the rise of the center of mass from the lowest vertical position to toe-off (CM_rise). Foot angles at contact were identified as well as segmental angles representing plantar/dorsiflexion and eversion/inversion angles. Knee angle was identified at foot contact, toe-off, and maximum flexion during stance.
**Continuous Relative Phase Calculations**

Thigh, shank and foot segmental angles were reconstructed using the cardan sequence transformation within Visual3D. Segmental angles were calculated from the right horizontal. Angular velocity was calculated using the first central difference method for each element of the segmental angle. All variables were exported as 100% stance as identified from foot strike to toe-off.

Angular positions \( \theta \); equation 1) and angular velocities \( \omega \); equation 2) for the each 15 stance periods per condition were normalized to eliminate frequency and amplitude differences among the individual stance periods (Miller, Meardon, Derrick, & Gillette, 2008). Normalization calculations were:

**Equation 1: Angular position normalization**

\[
\text{Angle} \ (\theta_i) = \frac{2 \times [\theta_i - \min(\theta_i)]}{\max(\theta_i) - \min(\theta_i)}
\]

**Equation 2: Angular velocity normalization**

\[
\text{Angular Velocity} \ (\omega_i) = \frac{\omega_i}{\max|\omega_i|}
\]

The minimum and maximum angle for the series of 15 strides per condition were used to normalize the angular position data. The angular velocity data were normalized to the maximal velocity within the 15 stance phases.

Phase angles (equation 3) were calculated as the angle defined by the right horizontal and the data point along the normalized stance phase (Miller, Meardon, Derrick, & Gillette, 2008).
Segmental phase angles were calculated for both right and left limbs independently from the 15 analyzed stance periods, using a custom Matlab script. Phase angles included thigh flexion/extension (FL/EX), thigh adduction/abduction (AB/AD), thigh internal/external rotation (IR/ER), shank flexion/extension (FL/EX), shank adduction/abduction (AB/AD), shank internal/external rotation (IR/ER), foot inversion/eversion (IN/EV), and foot plantar/dorsiflexion (PF/DF) (Hamill, van Emmerik, Heidersheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008; Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016)

Continuous relative phase (CRP) values were calculated for each element of the normalized stance phases by subtracting the distal segment from the proximal segment. CRP variability (vCRP) was calculated as the point-by-point the standard deviation of the normalized stance period across the 15 trials (stance periods) for each individual participant and each condition (Miller, Meardon, Derrick, & Gillette, 2008; Hamill, van Emmerik, Heidersheit, & Li, 1999). CRP and vCRP were calculated for seven segmental couplings of interest during the stance period: Thigh FL/EX-Shank FL/EX, Thigh AD/AB-Shank AD/AB, Thigh FL/EX-Foot PF/DF, Thigh IR/ER-Foot PF/DF, Thigh IR/ER-Shank AD/AB, Shank IR/ER-Foot IN/EV, and Shank AD/AB-Foot IN/EV. CRP and vCRP were averaged across three phases based on the occurrence of peak knee flexion during stance: loading, mid stance, and propulsive phases. Peak knee flexion was used to identify mid stance, with the phase including plus and minus 5% stance.
around peak flexion. Loading phase was defined as the time from ground contact to beginning of midstance. Propulsive phase was defined as the time starting at end of mid-stance and toe off.

**Statistical Analysis**

All dependent variables (Table 1) were analyzed for limbs separately, using multiple one-way repeated measure 1 x 5 (PRV, PRV± 0.25, PRV+0.5, PRV+1.0) analyses of variance (ANOVAs; \( \alpha = 0.05 \)). The assumption of sphericity was tested using Mauchly’s test, with huynh-Feldt corrections made for violations \( (p < 0.05) \). When appropriate, Sidak *post-hoc* tests were run to determine differences among conditions.

<table>
<thead>
<tr>
<th>Table 1: Dependent variable description for statistical analysis.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kinematic Variable</strong></td>
</tr>
<tr>
<td>Stride Frequency</td>
</tr>
<tr>
<td>CM_drop</td>
</tr>
<tr>
<td>CM_rise</td>
</tr>
<tr>
<td>FS to peak knee flexion</td>
</tr>
<tr>
<td>Peak knee flexion to TO</td>
</tr>
<tr>
<td><strong>Coordination Variable</strong></td>
</tr>
<tr>
<td>CPR_1 &amp; vCRP_1</td>
</tr>
<tr>
<td>Thigh FL/EX - Shank FL/EX</td>
</tr>
<tr>
<td>CRP_2 &amp; vCRP_2</td>
</tr>
<tr>
<td>Thigh AD/AB - Shank AD/AB</td>
</tr>
<tr>
<td>CRP_3 &amp; vCRP_3</td>
</tr>
<tr>
<td>Thigh FL/EX – Foot IN/EV</td>
</tr>
<tr>
<td>CRP_4 &amp; vCRP_4</td>
</tr>
<tr>
<td>Shank AD/AB – Foot IN/EV</td>
</tr>
<tr>
<td>CRP_5 &amp; vCRP_5</td>
</tr>
<tr>
<td>Thigh IR/ER – Foot PF/DF</td>
</tr>
<tr>
<td>CRP_6 &amp; vCRP_6</td>
</tr>
<tr>
<td>Thigh IR/ER – Shank AD/AB</td>
</tr>
<tr>
<td>CRP_7 &amp; vCRP_7</td>
</tr>
<tr>
<td>Shank IR/ER – Foot IN/EV</td>
</tr>
</tbody>
</table>

**Results**

As treadmill running velocity increased, there was a significant increase in stride frequency \( [F(4, 44) = 43.274, p <0.001, \eta^2 = 0.80] \). Pairwise significant differences are reported in Figure 1. CM_drop was significantly decreased across velocities for both right \( [F (4,44) = 20.60, p <0.001, \eta^2 =0.65] \) and left \( [F (1.82, 19.99) = 26.24, p<0.001, \eta^2 =0.71] \) limbs. Pairwise significant differences are shown in Figure 2. CM_rise was significantly different for
right limb \[ F (1.88,20.71 = 14.50, \ p <0.001, \ \eta^2 =0.57] \text{ and left limb } [F (1.87,20.53) = 15.16, \ p <0.001, \ \eta^2 =0.58].

Figure 1: Mean (±SE) for stride frequency across conditions

Conditions are oriented from slowest treadmill running velocity to the fastest (PRV-0.25m/s:PRV+1 m/s). # Significantly different from PRV+0.25m/s, PRV+0.50m/s and PRV+1.0/s conditions. $ Significantly different from PRV and PRV+1.0 m/s conditions.

Table 2: Mean and standard deviation (SD) for center of mass downward and upward motion.

<table>
<thead>
<tr>
<th>Variable</th>
<th>PRV - 0.25</th>
<th>PRV</th>
<th>PRV + 0.25</th>
<th>PRV + 0.5</th>
<th>PRV + 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LIMB</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>CM\text{rise} \ (m)</td>
<td>Right</td>
<td>0.082</td>
<td>0.006</td>
<td>0.080</td>
<td>0.003</td>
</tr>
<tr>
<td>CM\text{drop} \ (m)</td>
<td>Left</td>
<td>0.080</td>
<td>0.005</td>
<td>0.079</td>
<td>0.003</td>
</tr>
</tbody>
</table>

CM\text{rise}: center of mass upward; CM\text{drop}: center of mass downward
Conditions are oriented from slowest treadmill running velocity to the fastest (PRV-0.25m/s: PRV+1 m/s), with the dark gray bars representing the right leg. Pairwise comparisons showed PRV+1 m/s condition was significantly reduced over all other conditions (p < 0.05). PRV was significantly greater than all faster speed conditions, except right stance CM\text{rise}. 
Knee flexion/extension at foot contact was not different across velocities for right (p = 0.381) or left (p = 0.411) sides. Knee flexion/extension at toe-off was not different across velocities for right (p = 0.215) or left (p = 0.375) sides. Peak knee flexion during stance was not different across velocities for right (p = 0.395) or left (p = 0.360) limbs. Foot plantar/dorsiflexion was not different across velocities for right (p=0.292) or left (p=0.293) feet. Foot inversion/eversion was not different across velocities for right (p=0.286) or left (p=0.229) feet.

**Continuous Relative Phase**

Thigh IR/ER-shank AB/AD coupling during loading phase of the thigh was different for the right limb \[F(4,44) = 3.42, p = 0.016, \eta^2 = 0.24\] but not the left. Left limb propulsive phase of thigh IR/ER-shank AB/AD coupling was significantly different \[F(2.60,28.60) = 4.04, p = 0.02, \eta^2 = 0.30\] with a significant shift to more in-phase during PRV+1.0 versus PRV+0.25 conditions \((p = 0.013)\). There were no further CRP coupling differences across velocities \((p > 0.05)\).

**Continuous Relative Phase Variability**

Thigh FL/EX-Shank FL/EX vCRP was different across velocities for the loading phase for the left \([F(4,44)=6.78, p < 0.001, \eta^2 = 0.38]\) and right \([F(2.59,28.50)=5.86, p = 0.024, \eta^2 = 0.26]\) sides. The right limb coupling variability was significantly reduced during the fastest condition (PRV+1) versus the PRV \((p = 0.004)\) and the slowest running velocity (PRV-0.25, \(p = 0.043)\). Thigh FL/EX-Shank FL/EX vCRP was different across velocities during the propulsive phase for left \([F(4,40)=5.29 p = 0.001, \eta^2 = 0.33]\) and right \([F(4,40)=4.63, p = 0.003, \eta^2 = 0.30]\) limbs. Left limb vCRP was reduced from the slowest running velocity for each of the faster than preferred running conditions \((p > 0.05)\). Thigh FL/EX-shank FL/EX vCRP was significantly different only for the right limb couplings for mid stance \([F(4,44)=4.36, p = 0.005, \eta^2 = 0.28]\).
toe-off \([F(4,44)=3.3, \ p = 0.019, \ \eta^2 = 0.23]\), and during peak knee flexion \([F(4,44)=4.34, \ p = 0.005, \ \eta^2 = 0.28]\).

**Figure 2:** Variability CRP (SD) across velocities for each of the stance phases separated in left and right stance.

Conditions are oriented from slowest treadmill running velocity to the fastest (PRS-0.25m/s: PRS+1 m/s), with diamonds representing the loading phase, squares representing mid stance and the triangles representing propulsive phase. Left and right graphs correspond to left and right legs. Variability for all parameters decreased as speed increased (p < 0.05).

Thigh AB/AD-shank AB/AD vCRP was different at toe-off for the left limb \([F(4,44)=2.66, \ p = 0.045, \ \eta^2 = 0.30]\). Thigh FL/EX-foot PF/DF vCRP was significantly different for both right \([F(4,44)=5.49, \ p = 0.002, \ \eta^2 = 0.33]\) and left \([F(4,44)=4.62, \ p = 0.003,\)
\( \eta^2 = 0.30 \) limbs. The thigh FL/EX-foot PF/DF vCRP was significantly reduced for right limb only for the loading phase \( F(4,44)=3.57, p = 0.013, \eta^2 = 0.25 \), propulsive phase \( F(4,44)=3.67, p = 0.012, \eta^2 = 0.25 \), and during peak knee flexion \( F(4,44)=3.62, p = 0.012, \eta^2 = 0.248 \). The shank AB/AD-foot IN/EV vCRP was significantly different for the right limb during toe-off \( F(4,44)=3.61, p = 0.012, \eta^2 = 0.25 \). All other couplings were not different across velocities and comparisons (p > 0.05).

**Discussion**

The findings of the current study support the hypothesis that coordination patterns and coordination variability were influenced by increased treadmill velocity. Specifically, the thigh IR/ER-shank AB/AD coupling during loading phase for the right limb and propulsive phase for left limb became more in-phase with increases in velocity. Furthermore, where there were significant differences in vCRP, there was a reduction in variability in response to increased running velocity from the preferred running velocity.

An interesting finding of the current study, which supports previous findings (Mercer, Mata, & Bailey, 2016), was that runners adjusted stride frequency as running velocity increased. With the treadmill running velocities ranging from 2.2 m\( \cdot \)s\(^{-1} \) to 4.4 m\( \cdot \)s\(^{-1} \), the running velocities were below the intensity threshold when runners would typically begin to make adjustments in stride frequency (Dillman, 1975). Higher stride frequencies have been reported during treadmill running at the same velocities as overground (Riley, Dicharry, Franz, Della Croce, Wilder, & Kerrigan, 2008), with a possible lack of a plateau at higher velocities while running on a treadmill (Mercer, Mata, & Bailey, 2016). Increases in stride frequency may explain the lack of differences across treadmill running speeds in knee sagittal, foot sagittal, and foot frontal plane
motion during stance, especially during foot contact and toe-off. During treadmill running, runners lack the need to propel themselves forward, which may explain the use of increased stride frequency to maintain coordination patterns.

Although stride frequency changed in response to treadmill running velocities, runners did not adjust the majority of their lower extremity coordination patterns. The changes observed in thigh IR/ER-shank AB/AD couplings without changes in peak knee flexion angles, may be related to the averaging across a phase rather than identifying a discrete event. The relationship of stride frequency and running velocity in relation to development of skilled movement patterns are poorly understood. Coordination patterns and variability of some lower extremity couplings are affected by manipulating stride frequency while maintain running velocity (Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016). The current study used CRP to identify coordination patterns and divided the stance into slightly different phases than Hafer et al. (2016), which makes it more difficult to directly compare results from the two studies. The differences between studies was in regards to the periods of gait that parameters were averaged across; in the present study, parameters were analyzed in phases in order to report a more detailed image of the gait cycle.

The finding of reduced CRP variability in asymptomatic runners in response to an increased task demand (i.e., increased running velocity) provides new insight to the coordination during running. Healthy runners training for a road race typically include increases in velocity during a training program and/or within a training session; therefore, it would seem important to understand changes in velocity influence variability of coordination patterns. Reduced variability of coordination patterns have been associated with common endurance runner overuse pathologies when comparing the symptomatic runner to a healthy control (Hamill, van Emmerik,
Variability of coordination has been hypothesized to be an indicator of when a runner has an overuse injury related to endurance running (Hamill, van Emmerik, Heidersheit, & Li, 1999; Hamill, Palmer, & van Emmerick, 2012; Miller, Meardon, Derrick, & Gillette, 2008; van Emmerik, Rosenstein, McDemott, & Hamill, 2004). The connection, however, cannot be made between reduced coordination variability as the cause of overuse injuries. Further research conducting prospective studies including runners’ training volume and intensity periodization may lead to further insight into the pathology of these overuse injuries.

The reduction in CRP variability occurred to the greatest extent in the thigh FL/EX-shank FL/EX segmental coupling analysis. Thigh FL/EX-shank FL/EX was the only coupling that was observed to have reduced variability in the loading and mid stance phases of stance. This coupling was identified in this study due to the relationship of knee flexion to the center of mass change in position and therefore leg stiffness during stance. Thigh FL/EX-shank FL/EX coupling is not typically found in the clinically based coordination studies (Hamill, Palmer, & van Emmerick, 2012; Miller, Meardon, Derrick, & Gillette, 2008; van Emmerik, Rosenstein, McDemott, & Hamill, 2004). It was included in the current study as a possible focus of running form coaching and the concept of gliding along. The couplings of significance for the variability analyses were limited with velocity increases, dominated by the propulsive phase and toe-off instance of measure. The significant differences in the couplings other than thigh FL/EX-shank FL/EX were not shown to occur in both limbs. The differences in significant couplings and phases between right and left limbs, indicates a need for future studies to separate the left and right sides in the analysis looking at asymmetry. It is unknown however whether the magnitudes of reduced CRP variability in the healthy runners indicates a ‘too low’ or healthy range of
variability (Hamill, Palmer, & van Emmerick, 2012). It is possible that the runners were within a healthy range of variability even in the reduced state.

Runners who are training for a race, in which they are competitively involved, generally require speed training at velocities of performance thresholds as part of the overload principle. The results of this study indicate that exposure to higher running velocities may reduce the runner’s variability in lower extremity segmental coordination patterns without altering their coordination patterns. However, given the high standard deviations between runners in the coordination patterns for many of the couplings, future research may focus on the strategies of pattern development for individual runners.

Presently, it is unknown whether healthy runners that decrease CRP variability with increases in velocity have a greater susceptibility to overuse injuries during their training program. Prospective studies are needed to follow runners during training to see how patterns progress and whether injury happens when variability decreases or increases beyond some range.

There are limitations to the methodology used in determining the coordination patterns and variability of coordination. The normalization process of continuous relative phase calculations creates a higher order analysis, removing the ability to interpret the results to the original time series (Hamill, Palmer, & van Emmerick, 2012; Miller, Meardon, Derrick, & Gillette, 2008; Peters, Haddad, Heiderscheit, & Hamill, 2003). The method used during the normalization process is somewhat controversial and the methods chosen for this study were based on what is most commonly seen in the clinical gait literature. A major limitation of the study is the determination of phases and limiting the investigation in to the stance phase.
Conclusion

CRP variability was reduced in a number of specific couplings within certain phases of gait as treadmill velocity increased. It is important to note that limited CRP changes occurred during the increased treadmill velocity conditions. Specifically, the thigh IR/ER-shank AB/AD coupling became more in-phase with increases in velocity. It is unknown whether the reduced variability influences the risk of overuse injury for healthy runners or if they are within a healthy range of variability to achieve performance goals.
References:


CHAPTER 3

Effects of Cost of Running on Lower Extremity Coordination Patterns

By

Joshua Paul Bailey

Co-authored By

James Navalta, Robert Van Vliet, Julia Freedman Silvernail,

Janet S. Dufek, & John A. Mercer
Significance of the Chapter

The first study within the series found that runners adjusted their coordination patterns and coordination variability in response to increased running velocity. The design of study one was based on an absolute increase in velocity with respect to the runners preferred running velocity. However, it was not known how a runner responds relative to their peak aerobic capacity. Therefore, the second study in the series set out to identify how greater increases in the intensity of treadmill running change the coordination patterns and coordination variability in healthy runners. In this study, the second running velocity was set based upon the individual runner’s speed at ventilator threshold. The speed at ventilator threshold was achieved during a graded exercise test in which each runner’s individual peak aerobic capacity was determined. The current study used the change in percentage of oxygen consumption in relation to the their peak aerobic capacity as a representative of aerobic thresholds. This built upon study one because the running velocity changes were not absolute velocity changes, but rather a representation of individual aerobic capacity.

Manuscript Note

This study has been written with the collaboration of the members of my Graduate Committee (Julia Freedman Silvernail, Janet S. Dufek, James Navalta, & John A. Mercer) and an undergraduate researcher that worked with me through the Nevada INBRE Summer Research Program (Robert Van Vliet). The manuscript is currently under review with the Journal of Sport Sciences.
Abstract

The purpose of the current study was to investigate how the oxygen cost of running is related to coordination pattern couplings and coordination variability of healthy runners. Sixteen runners were divided into two groups based on the change in percentage of oxygen consumption relative to their peak oxygen consumption: ‘Low’ group (10 runners) less than 10%, ‘High’ group (6 runners) greater than 10%. Steady-state oxygen consumption was measured during two running velocities on a treadmill: preferred velocity ($V_{\text{pref}}$) and the velocity that would elicit 80% VO$_2$ of the ventilatory threshold ($V_{80\%VT}$). Ventilatory threshold (VT) was determined visually using the ventilatory equivalent method from graded exercise test during session one. Continuous relative phase calculations were used to identify coordination pattern and coordination variability differences between the two groups. Multiple 2x2 repeated measure ANOVAs were conducted to compare groups (Low, High) by (velocity: $V_{\text{pref}}, V_{80\%VT}$). The High group reduced variability during mid-swing and increased variability during propulsive and mid-swing phases. The Low group was more in-phase during mid-swing of the 80% VT condition. Although there were differences between groups, the majority of the changes were in response to the increased running velocity regardless of relative physiological cost to participants.

Key Words

Running Economy; Running Intensity; Kinematics; Treadmill; Coordination Variability
**Introduction**

Endurance athletes, both recreational and elite, follow training programs oriented around increasing training load of endurance running as they prepare for their race. The increase in training load is accomplished through a combination of increasing mileage and performing runs at a higher intensity, or running velocity. Increased running velocity introduces different loading patterns on the musculoskeletal system (Novacheck, 1998). Errors in training programs can reduce the success in races and have been proposed as a possible cause of overuse injury during periods of training for an endurance event (Fredericson & Misra , 2007; Goss & Gross, 2012; Van Gent, Van Middelkoop, Van Os, Bierma-Zeinstra, & Koes , 2007).

Associated with increases in running velocity, gait adjustments include decreased foot contact time (Mann & Hagy, 1980), increased stride length and stride frequency (Dugan & Bhat, 2005), and reduced vertical oscillation of the centre of mass of the runner (Dugan & Bhat, 2005; Novacheck, 1998). Following the introduction of an increased running velocity, the effect on the new training load can be determined by measuring the rise in the oxygen consumption during the run. The energetic cost associated with a running velocity is termed running economy (Saunders, Pyne, Telford, & Hawley, 2004), therefore runners who are more economical at a particular running velocity, consume less oxygen.

Running economy is influenced by different gait related factors. For example, as a runner changes stride frequency, running economy changes (Hunter & Smith, 2007). Changes in running mechanics that alter an individual’s economy at a given velocity depend upon a number of variables: centre of mass motion, shank angle at foot strike, maximum plantar flexion angle and angular velocity, peak knee flexion during stance and minimum knee velocity (Saunders, Pyne, Telford, & Hawley, 2004; Williams & Cavanagh, 1987). Running economy is considered
to be a better predictor of performance than maximal rate of oxygen consumption (VO$_{2\text{max}}$) (Saunders, Pyne, Telford, & Hawley, 2004; Williams, 2007).

The ability to structure an endurance-training program based off the identification of running intensities that cause a less economical pattern may be valuable. Unknown, however, is whether or not the oxygen cost of running is related to changes in coordination patterns or coordination variability in response to increasing velocity. Therefore, the purpose of the study was to investigate how the oxygen cost of running is related to coordination patterns and coordination variability of healthy runners. It was hypothesised that with increases in the oxygen cost of running, runners would adjust their coordination patterns and decrease their variability. A secondary hypothesis was that runners who were less economical at the higher running velocity would adjust their coordination patterns and decrease their variability to more than those that were more economical.

**Methods**

**Participants**

Sixteen runners (male 7 & female 9; 33.5 ± 5.7 yrs; 70.9 ±12.5 kg; 1.7 ± 0.1 m) from the university and local running and triathlon groups had volunteered to participate in a larger study. They were also evaluated for the current study. All participants fit within the ACSM Guidelines for low-risk during graded exercise testing and were less than 45 years of age (American College of Sports Medicine, 2013). Participants had experience running on treadmills; however, none of the runners used the treadmill as their main training mode of running.

All runners signed a University approved informed consent prior to any participation in the study. A Physical Activity Readiness Questionnaire was also used to screen participants for known cardiovascular challenges. A running history questionnaire was used to assess current
running history including training and racing experience. The average training volume was 23.3±14.2 miles per week and all runners had completed an endurance event of at least 5k within the past 6 months of data collection.

**Instrumentation**

Rate of oxygen consumption was measured using a Cosmed portable breath-by-breath metabolic gas analyser (K4b2; Cosmed USA Inc., California, USA). The K4b2 unit was calibrated prior to each participant each day using the both gas and volume calibration procedures defined by Cosmed. The portable data logger was secured to the anterior thoracic region level to the sternum via the custom Cosmed harness, with the wiring taped to reduce excessive movement noise. The real time signal was transmitted to a working laptop to enable the research team to monitor proper breath-by-breath collection and status within each of the testing procedures.

The graded exercise test was conducted on a Precor treadmill (Precor C966; Precor USA, Washington, USA). The submaximal running conditions were conducted on a split-belt Bertec force instrumented treadmill (Bertec FIT; Bertec Corporation, Ohio, USA). During the submaximal testing, three-dimensional kinematics were collected using a 12-camera motion capture system (Bonita; Vicon Motion Systems Ltd., Colorado, USA). Both motion capture and kinetic data from the Bertec FIT were synchronized and collected through Nexus 2.1 (Vicon Motion Systems Ltd., Colorado, USA).

**Procedures**

All participants completed two days of testing within one week of each other, but at least 24 hours apart. Participants began each testing day with a five-minute self-selected warm-up run.
on the treadmill they were using for that day. All participants reported they were comfortable running on the treadmill following the warm-ups.

During the first test day, runners completed a maximal effort graded exercise test to determine maximal oxygen consumption (VO2). Runners were instrumented with the Cosmed K4b2 and proceeded to conduct the maximal effort test. The graded exercise test began with the participant jogging at 2.24 m/s at 0% grade. The increments in increased intensity occurred every two minutes. Initial intensity increases occurred in treadmill velocity with increases of 0.45 m/s until the participant identified a comfortably challenging pace. The pace identified represented a perceived 10 k pace. The treadmill remained at the self-selected velocity for the remainder of the test. Further intensity increments were accomplished by increasing the incline of the treadmill by 3% every 2 minutes. The protocol was designed to elicit a maximal effort in within 15 minutes and all participants completed the test within 15 minutes. Participants were verbally encouraged to achieve maximal effort.

Test day two occurred within a week, but at least 24 hours later using the force-instrumented treadmill. Upon completion of the self-selected 5-minute warm-up, participants were instrumented with the metabolic system and a lower extremity reflective marker set. Rigid clusters were attached to the lateral aspects of the thigh and shank segments using elastic sporting wraps made of nylon and Lycra (SuperWrap Fabrifoam; Exton, PA, USA) and secured using duct tape. The pelvis and lower extremity were modeled using individual 14 mm reflective markers secured with double-sided tape and Cover Roll adhesive tape (BSN Medical, Luxembourg, Germany). Kinematic data were collected at 200 Hz using 12-infrared cameras (Bonita; Vicon Motion Systems Ltd., Oxford, UK). Kinetic data were collected at 2000 Hz from a single force platform of the FIT for all participants and trials.
The submaximal protocol consisted of running at two velocities: preferred velocity ($V_{\text{pref}}$) and the velocity that would elicit 80% of ventilatory threshold ($V_{80\%\text{VT}}$). Determination of ventilatory threshold was accomplished using the ventilatory equivalent method of visual identification (Gaskill, Ruby, Walker, Sanchez, Serfass, & Leon, 2011; Tartaruga, et al., 2012). To determine the velocity used for the 80% condition, the VO$_2$ at the VT was entered into the metabolic equation for running (American College of Sports Medicine, 2015) to determine the running velocity at a level grade (Equation 4).

**Equation 4: Speed at ventilatory threshold calculation**

\[
VO_2 = (0.2 \times S) + (0.9 \times S \times G) + 3.5
\]

$VO_2$: Gross oxygen consumption (ml/kg/min); $S$: speed (m/min); $G$: % grade

Two independent researchers were unable to determine ventilatory threshold of five participants. In these cases, it was determined that participants did achieve criteria for maximal effort test. Specifically, in these subjects, a plateau of VO$_2$ following increase in velocity or incline prior to stopping the test was not observed, and respiratory exchange ratio was not greater than 1.15, or heart rate did not reach age predicted maximum heart rate. (Tartaruga, et al., 2012). For these participants, the $V_{80\%\text{VT}}$ was a velocity greater than their $V_{\text{pref}}$ chosen to elicit a submaximal challenging effort. The submaximal effort was verified from the measured respiratory exchange ratio less than 1.0. Participants completed 8-10 minutes of running for each condition. VO$_2$ data were collected for three minutes after steady state VO$_2$ was reached. Steady state oxygen consumption was identified when the researcher visually identified a levelling off of the VO$_2$ – time graph for at least 20 seconds.
The breathing mask was removed between conditions and participants were encouraged to walk around, drink fluids, and recover for a minimum of five minutes. When the participant’s heart rate returned to within 15 beats of their initial heart rate upon entering the lab, at least five minutes, the mask was attached and the second condition was conducted.

The order of running velocity conditions was randomized across participants (5 runners began with the 80% VT velocity condition).

**Data Analysis**

For each running velocity condition, a 30 s motion capture trial was collected one minute after the acquisition of steady state. Each trial was then label identified using Nexus 2.3 with frame-by-frame verification of proper labelling. Each trial was then exported and further processed in Visual3D (C-Motion, Inc., Germantown, MD, USA) where all kinematic markers and force platform data were smoothed and filtered using 4th order zero-lag Butterworth filters. Kinematic markers were filtered with a cutoff frequency of 8 Hz, while force plate data were filtered using a 25 Hz cutoff frequency. Foot contact was identified when the vertical component of the ground reaction force reached 50 N.

Thigh, shank, and foot segmental angles were reconstructed using the cardan sequence transformation within Visual3D. Segmental angles were calculated from the right horizontal. Relative joint angles were calculated for the knee and ankle. Angular velocity was calculated using the first central difference method for each element of the segmental angle. Fifteen strides for the right side, lower extremity were extracted for analysis. Each stride was time-normalized so that an entire stride time was set to 100%.

Peak VO₂ (VO₂peak) was recorded as the greatest VO₂ during the graded exercise test.

**Continuous Relative Phase**
Angular positions and angular velocities for the 15 strides per condition were normalized to eliminate frequency and amplitude differences among the individual strides (Miller, Meardon, Derrick, & Gillette, 2008). Phase plots were created for each parameter by graphing the normalized angular position on the x-axis and velocity signals on the y-axis. Phase angles were then calculated as the angle defined by the right horizontal and the data point along the normalized stance phase (Miller, Meardon, Derrick, & Gillette, 2008).

Continuous relative phase (CRP) values were calculated for each element of the normalized strides by subtracting the distal segment from the proximal segment. CRP variability (vCRP) was calculated as the point-by-point standard deviation of the normalized 15 trials for each individual participant and each condition (Miller, Meardon, Derrick, & Gillette, 2008; Hamill, van Emmerik, Heidersheit, & Li, 1999). CRP and vCRP were calculated for ten separate couplings (Table 3) and five phases (Table 4) of the stride cycle (Hamill, van Emmerik, Heidersheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008; Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016).

**Subject grouping**

Participants were stratified based on their difference in oxygen consumption between the two velocity conditions. Average VO₂ was calculated for each condition with the percent difference between conditions then calculated. Group 1 consisted of ten participants that had less than 10% (5.6 ± 2.0%) difference between oxygen consumption (Low) and Group 2 were six participants who recorded a greater than 10% (14.8 ± 3.4%) difference (High).
Table 3: Couplings for continuous relative phase analysis.

<table>
<thead>
<tr>
<th>Coupling Name</th>
<th>Proximal component</th>
<th>Distal component</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRP_1</td>
<td>Thigh FL/EX</td>
<td>Shank FL/EX</td>
</tr>
<tr>
<td>CRP_2</td>
<td>Thigh AB/AD</td>
<td>Shank IR/ER</td>
</tr>
<tr>
<td>CRP_3</td>
<td>Thigh AB/AD</td>
<td>Foot IN/EV</td>
</tr>
<tr>
<td>CRP_4</td>
<td>Thigh IR/ER</td>
<td>Shank IR/ER</td>
</tr>
<tr>
<td>CRP_5</td>
<td>Shank IR/ER</td>
<td>Foot IN/EV</td>
</tr>
<tr>
<td>CRP_6</td>
<td>Knee FL/EX</td>
<td>Shank IR/ER</td>
</tr>
<tr>
<td>CRP_7</td>
<td>Knee FL/EX</td>
<td>Foot AB/AD</td>
</tr>
<tr>
<td>CRP_8</td>
<td>Knee FL/EX</td>
<td>Ankle PF/DF</td>
</tr>
<tr>
<td>CRP_9</td>
<td>Knee AB/AD</td>
<td>Shank IR/ER</td>
</tr>
<tr>
<td>CRP_10</td>
<td>Knee AB/AD</td>
<td>Foot IN/EV</td>
</tr>
</tbody>
</table>

Abbreviations: FL – flexion; EX – extension; AB – abduction; AD – adduction; IR – internal rotation; ER – external rotation; PL – plantar flexion; DR – dorsiflexion

Table 4: CRP phase separation definitions

<table>
<thead>
<tr>
<th>Phases</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1: Loading Stance</td>
<td>First half of stance phase (0%-15% stride)</td>
</tr>
<tr>
<td>Phase 2: Propulsive Stance</td>
<td>Second half of stance (15-30% stride)</td>
</tr>
<tr>
<td>Phase 3: Early Swing</td>
<td>30% of swing phase (31-51% stride)</td>
</tr>
<tr>
<td>Phase 4: Mid Swing</td>
<td>40% of swing phase (52-82% stride)</td>
</tr>
<tr>
<td>Phase 5: Terminal Swing</td>
<td>30% of swing phase (83-101% stride)</td>
</tr>
</tbody>
</table>

Statistical Analysis

Independent t-tests compared groups for age, mass, height, peak VO₂, and velocities for the two submaximal run conditions. All CRP and vCRP couplings were analysed using multiple 2 (VO₂ diff: Low, High) x 2 (velocity: Vₚₑₙ, Vₘₜₐₓ) mixed model repeated measure analyses of variance (ANOVAs). Group was the between group factor, with velocity condition the within group factor (α = 0.05). The assumption of sphericity was tested using Mauchy’s test, with Huynh-Feldt corrections made for violations (α = 0.05). When appropriate, Sidak post-hoc tests were run to determine differences among group.
When interactions were present ($\alpha = 0.05$), multiple one way repeated measure analyses (ANOVAs) with Sidak pairwise comparisons for time for each ‘VO$_2$ diff’ group ($\alpha = 0.05$). Independent t-tests were run to compare group differences at each velocity level ($\alpha = 0.025$).

Results

There was no difference between groups for VO$_2$peak, V$_{\text{pref}}$ and V$_{80\%\text{VT}}$ ($p > 0.05$; Table 5). There was a significant Group*Velocity condition VO$_2$ ($F = 28.028, p < 0.001$). Simple main effects analysis was conducted to assess the nature of the interaction. There were no differences across group for oxygen consumption at each of the velocity conditions ($p > 0.025$). Low group had a significant mean difference between conditions (2.92 mL/kg/min; $F_{[1,9]} = 48.757, p < 0.001, \eta^2 = 0.844$), while High group had a significant mean difference between conditions (6.80 mL/kg/min; $F_{[1,5]} = 113.40, p < 0.001, \eta^2 = 0.958$).

Table 5: Group characteristics.

<table>
<thead>
<tr>
<th>Group</th>
<th>Variable</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>t-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Age (yrs)</td>
<td>31.8</td>
<td>4.7</td>
<td>-1.632</td>
<td>0.125</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>36.3</td>
<td>6.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Mass (kg)</td>
<td>67.0</td>
<td>11.0</td>
<td>-1.714</td>
<td>0.109</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>77.3</td>
<td>13.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Ht (m)</td>
<td>1.7</td>
<td>0.1</td>
<td>-0.621</td>
<td>0.544</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>1.7</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>VO$_2$ peak (ml/kg/min)</td>
<td>52.6</td>
<td>6.5</td>
<td>1.918</td>
<td>0.076</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>46.8</td>
<td>4.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>C1 velocity (m/s)</td>
<td>2.9</td>
<td>0.46</td>
<td>1.481</td>
<td>0.161</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2.6</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>C2 velocity (m/s)</td>
<td>3.4</td>
<td>0.55</td>
<td>1.680</td>
<td>0.119</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>3.1</td>
<td>0.19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
There was a significant Group*Velocity interaction \((F = 4.962, p = 0.043)\) during mid-swing for Thigh AB/AD-Shank IR/ER. Simple main effects analysis was conducted to assess the nature of the interaction. There were no differences between groups at each of the velocity conditions \((p > 0.05)\). Low group was significantly more in-phase during the higher intensity \(V_{80\%VT}\) condition \((F[1,9] = 6.276, p = 0.034, \eta^2 = 0.411)\), while High group was not significantly different \((p = 0.422)\). 

Additionally, continuous relative phase analysis revealed a number of significant main effects between intensity conditions. Thigh FL/EX-Shank FL/EX was significantly more in-phase during the faster \(V_{80\%VT}\) condition during the loading phase \((F[1,14] = 14.474, p = 0.002, \eta^2 = 0.508)\), mid-swing phase \((F[1,14] = 10.786, p = 0.005, \eta^2 = 0.438)\) and terminal swing mid-swing phase \((F[1,14] = 4.794, p = 0.046, \eta^2 = 0.255)\). Knee FL/EX-Ankle PL/DR was more in-phase during the faster \(V_{80\%VT}\) condition \((F[1,14] = 5.960, p = 0.029, \eta^2 = 0.622)\) during the propulsive phase of stance.

There were significant Group*Velocity interactions in vCRP for Thigh AB/AD-Shank IR/ER \((F = 7.709, p = 0.015)\), Shank IR/ER-Foot IN/EV \((F = 4.864, p = 0.045)\) and Knee AB/AD-Shank IR/ER \((F = 13.221, p = 0.003)\) during mid-swing (Figure 1). There were no differences across Group at each of the velocity conditions \((p > 0.025)\). For all vCRP interactions, High group reduced variability during the faster \(V_{80\%VT}\) condition: Thigh AB/AD-Shank IR/ER \((F[1,5] = 7.668, p = 0.039, \eta^2 = 0.605)\), Shank IR/ER-Foot IN/EV \((F[1,5] = 17.396, p = 0.009, \eta^2 = 0.910)\) and Knee AB/AD-Shank IR/ER \((F[1,5] = 12.269, p = 0.017, \eta^2 = 0.710)\) during mid-swing (Figure 3). The Low group was not significantly different across velocities for any coupling \((p > 0.05)\).
Main effects analyses showed a significant reduction in vCRP for the High group during the 80% VT velocity for each coupling. There was no difference between conditions for the Low group.

Thigh FL/EX-Shank FL/EX variability was significantly reduced during the faster $V_{80\%VT}$ condition during early swing ($F[1,14] = 8.535, p = 0.011, \eta^2 = 0.379$) and mid-swing ($F[1,14] = 15.147, p = 0.002, \eta^2 = 0.520$). Knee AB/AD-Foot IN/EV was significantly different at each phase of analysis, but in different directions. vCRP was reduced during loading ($F[1,14] = 5.891, p = 0.029, \eta^2 = 0.206$), early swing ($F[1,14] = 14.489, p = 0.002, \eta^2 = 0.509$), and terminal swing ($F[1,14] = 19.531, p = 0.001, \eta^2 = 0.560$). During the propulsive phase ($F[1,14] = 17.994, p = 0.001, \eta^2 = 0.562$) and mid-swing phase ($F[1,14] = 26.199, p < 0.001, \eta^2 = 0.652$) there was an increase in the vCRP from Knee AB/AD-Foot IN/EV.

**Discussion**

Based on the group classification of oxygen consumption difference between running conditions, runners adjusted their coupling patterns and vCRP differently in response to the increased running velocity. In accordance with previous coordination research with injured (Hamill, van Emmerik, Heidersheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008; van
Emmerik, Rosenstein, McDemott, & Hamill, 2004) and healthy (Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016) runners, the changes were not universal across couplings and phases. Differences existed in coordination variability during mid-swing between the groups based on the change in oxygen consumption between treadmill velocity conditions. The findings provide evidence that changes in the pattern of movement and variability may be related to cost of velocity increases rather than the magnitude of velocity increase. Understanding this relationship between the magnitude of velocity increase and the cost of that increase may provide valuable insight into how to increase training intensity during race training.

Dividing the groups based on change in oxygen consumption relative to an individual’s peak oxygen consumption was used to show how similar relative velocity increases affect individuals differently. The results indicate that runners adjust vCRP differently based on the relative intensity increases with respect to their peak oxygen capacity. Less economical runners may respond to the higher running velocities as novice, or unskilled, individuals do. As dynamical systems theory accepts a healthy level of variability in human movement patterns (Stergiou & Decker, 2011) a reduction in variability is often proposed to be representative of unhealthy (Hamill, van Emmerik, Heidersheit, & Li, 1999; Heiderscheit, Hamill, & Van Emmerik, 2002) or less skilled individuals. The current study adds to the knowledge of healthy runners reducing their coordination variability during non-preferred running task, such as increasing stride frequency (Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016).

The differences between groups observed provide support of current literature identifying the differences in mechanics due to running economy (Saunders, Pyne, Telford, & Hawley, 2004; Williams & Cavanagh, 1987). The current study did not examine each runner at the same velocities, but rather as velocities that represented relative increases with respect to their
measured aerobic capacity. Therefore the use of running economy to describe the differences between groups is based on their relative running velocities, rather than comparing absolute velocity magnitude increases between groups. Running economy has been defined as the ‘energy demand for a given velocity at submaximal running’ (Saunders, Pyne, Telford, & Hawley, 2004). Grouping for the current investigation used the relative intensities of the participants compared to their peak oxygen consumption value, creating an economy value representative of their relative intensity for comparison (Fletcher, Esau, & MacIntosh, 2009). The less economical participants reduced their coordination variability during mid swing on a number of couplings, which may indicate a more intense run caused a reduction in the number of degrees of freedom used. Interestingly, the only change in coordination pattern was a transition to more in-phase for the more economical group during the propulsive phase of thigh AB/AD-shank IR/ER coupling during the 80% VT condition.

Coordination pattern changes during stance phase occurred in couplings that may be components of lower extremity stiffness, regardless of grouping based on change in oxygen consumption. Increased running velocity has been shown to produce changes in both kinematics (Dugan & Bhat, 2005; Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011) and kinetics during stance (Simpson & Bates, 1989). Transition to a more in-phase coordination of thigh FL/EX-shank FL/EX at the more intense running velocity, may represent the motor program designed to generate a stiffer leg during stance. The more economical runners may possess an enhanced ability to utilize stored energy resulting in stiffness with more in-phase thigh AB/AD-shank IR/ER during propulsion. It is recognized that center of mass vertical oscillation was not measured during the current study, limiting the ability to make a direct connection to lower extremity stiffness.
Changes in coordination patterns and variability were more evident during swing phase versus stance, possibly as a result of running on a treadmill. It is proposed that due to the reliance on the movement of the treadmill belt to move the stance limb, limited differences are experienced as velocity increases. Kinematic differences have been reported between treadmill and overground (Nelson, Dillman, Lagasse, & Bickett, 1972; Nigg, De Boer, & Fisher, 1995; Sinclair, Richards, Taylor, Edmundson, Brooks, & Hobbs, 2013) leading to the possibility that coordination pattern adjustments between the two modes of running may be different. Given the current challenges of capturing three-dimensional motion capture and oxygen consumption during continuous overground running, future investigations into possible differences are important.

Running is a complex activity with the individualised ability to coordinate structures through numerous degrees of freedom. Incorporating a dynamical systems perspective, grounded in Berstein’s theories, coordination patterns and variability have been used to identify differences in injured runners and non-injured runners (Hamill, van Emmerik, Heidersheit, & Li, 1999; Miller, Meardon, Derrick, & Gillette, 2008; van Emmerik, Rosenstein, McDemott, & Hamill, 2004). Utilising a dynamical systems perspective following endurance running perturbations has been limited, but has shown the possibility in identifying differences in runners following stride rate manipulations (Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016). It is currently unknown whether the difference in patterns between groups is enough to produce a difference in performance. Building off the current findings, it is proposed that by measuring vCRP may provide a suggestive relative intensity increase for the next mesocycle of a training program.

Limitations of the current study are recognized. The current study used two groups representing differences in running economy, rather than using the same participants running at
multiple intensities. Measuring the same runners at multiple submaximal conditions may provide
a more detailed example of the influence of running intensity on coordination patterns and
variability. The possible difference in treadmill running and overground trials limit the
application of the findings to treadmill running, increasing the need to repeat a similar study
overground.

The selection of couplings and phases of the current analysis may have masked some
differences during strides. The couplings and phases were selected with the best representation
based on the current literature, but were also expanded on based on proposed couplings
important for endurance running performance. A number of couplings included a mixture of
relative and segmental joints for comparison. These couplings were chosen because they were
determined to be of interest in pattern development. The inclusion of a segmental component
into a coupling with the proximal relative joint angle to which it is a component was done only
for different planes of motion. Although it is understood that the distal segment contributes to the
measured motion of the proximal joint angle, it was accepted that the contribution was reduced
based on the different planes coupled. Future studies should combine coordination analyses with
traditional kinematics to draw a more comprehensive and practical conclusion.

Conclusion

The majority of adjustments in coordination patterns and variability of patterns were
experienced as a result of the increased running velocity regardless of the relative physiological
cost of the participant. However, the less economical group of runners reduced coordination
patterns during mid-swing, while more economical runners became more in-phase during the
propulsive phase.
References


CHAPTER 4
Effect of Perceived Fatigue on Coordination Patterns and Variability
During an Interval Treadmill Run

By
Joshua Paul Bailey

Co-authored By
Janet S. Dufek, Julia Freedman Silvernail,
James Navalta, & John A. Mercer
Significance of the Chapter

The first two studies support the hypothesis that coordination patterns and coordination variability are affected by increasing running velocity. There is also support that the individual relative intensity of these changes affects the couplings and direction of these changes. Both of the first two studies were conducted when the runners were in a non-fatigued state and with acute responses to the intervention. During endurance running, especially during races or long training sessions, runners will often continue running while in a fatigued state. Additionally, a common training session used to prepare runners for race day is an interval run. Intervals are a series of stacked periods of a recovery velocity followed by a short period of higher velocity running. The purpose of these sessions is to train the musculoskeletal system to run faster in a progressive overload, in preparation for the intensity of race performance. In addition to the interval runs, training programs require a gradual increase in mileage, or duration, of the long runs to achieve the desired distance of the upcoming race. Because of the demand each of these overload stimuli place on the system, it is important to identify changes in the organization of running patterns. Therefore, the final study in the series, attempts to identify difference between groups of runners that perceive fatigue and those that do not perceive fatigue.

Manuscript Note

This study has been written with the collaboration of the members of my Graduate Committee: Julia Freedman Silvernail, Janet S. Dufek, James Navalta, & John A. Mercer. The manuscript is currently under review with the journal of Sports Biomechanics.
Abstract

During the course of a training program, runners will typically increase running velocity and volume possibly encountering fatigue during a run, which is characterized as a feeling of general tiredness. The purpose of the current study was to identify whether or not level of perceived fatigue affects coordination patterns and coordination variability in runners. Twenty endurance runners completed a 1-hour run that included running velocity intervals at 75% of estimated 10k race pace (5 minutes) and estimated 10k race pace (1 minute). After each run, subjects completed a fatigue questionnaire and were grouped based on their post-run perceived fatigue. 3D motion capture data were collected during the run and analysed to generate coordination pattern and variability of the pattern as dependent variables. Multiple mixed model ANOVAs were conducted to test for differences between perceived fatigue groups. Coordination variability was greater for high-perceived fatigue group during the 75% 10k pace velocity over time. The low-perceived fatigue group reduced variability in a number of couplings during the 10k race pace running velocity. It was concluded that perception of fatigue was related to the way coordination patterns varied during a 1-hour interval run.

Key Words

treadmill running; kinematics; continuous relative phase; submaximal running
Introduction

Endurance running is an individualised sport often focused on achieving a performance time goal, which is typically based on previous racing experiences. Endurance athletes traditionally incorporate a combination of steady-velocity submaximal and high intensity interval training activities (Laursen & Jenkins, 2002). High-intensity interval training has been adopted by numerous training programs based on the effective stress placed upon aerobic energy systems to provide rapid improvements (Sloth, Sloth, Overgaard, & Dalgas, 2013). High-intensity training involves periods of high-intensity or velocity bouts followed by periods of recovery (Laursen & Jenkins, 2002). The aerobic benefits have been shown to occur in both recreational and elite endurance athletes (Laursen & Jenkins, 2002).

The major difference between steady-state and interval training sessions is the inclusion of multiple velocities during the high-intensity training. Introduction to the demands of the faster velocity to the body is essential, as it is well established that there are gait and kinematic differences based on running velocity (Dugan & Bhat, 2005; Mann & Hagy, 1980; Novacheck, 1998). Performance of repeated maximum effort sprints resulted in maximal force production reduction, however, failed to adjust submaximal running mechanics (Morin & Samozino, 2016). During training, programs typically do not require athletes to repeat sprints until fatigued, or volitional exhaustion, rather a desired number of intervals are targeted to achieve maximal benefit. Time and intensity of intervals are often the desired training load parameter created for a training program. The duration of the training run that is required to produce the desired aerobic and mechanical stress is an important component in training program development.

The importance of understanding the changes of running mechanics over the duration of a run are essential to assess the athletes’ response to the imposed stressor. Often connected as an
effect of running duration is fatigue, which is often measured either as a decrease in a performance variable or time to volitional exhaustion (Enoka & Duchateau, 2016). Fatigue is a complex variable to assess and to interpret for practical use due to the vagueness of its definition. Jones and Hanson (as cited by Bates, Osternig, & James, 1977) proposed that running pattern changes due to fatigue have been associated with the changes in the organisation of the neuromuscular pattern development. Furthermore, a major challenge in relating the measured differences resulting from fatigue to the practical application of a training program, stem from the differences in research protocols and endurance training protocols. Therefore, a more practical application of the results of a high-intensity interval run may be to incorporate the perceived fatigability of a runners which incorporates the psychosocial state of the runner in response to the imposed demands (Enoka & Duchateau, 2016).

It is unknown whether or not a runners’ perceived fatigue affects their ability to maintain coordination patterns and variability of patterns during an endurance run. The ability of a runner to manipulate degrees of freedom to produce the desired pattern development of endurance running is considered a key component of a healthy functioning neuromuscular pattern. A connection can be drawn between the perception of fatigue and the Dynamical Systems coordination patterns based on the proposed neuromuscular pattern development of both. However, there is a paucity of literature on the link between perceived fatigue and coordination patterns and variability. Therefore, the purpose of the current study was to identify whether or not level of perceive fatigue affects coordination patterns and coordination variability in runners. It was hypothesised that runners experiencing self-reported perceived fatigue would exhibit a greater change in continuous relative phase variability during an hour run at two running velocities.
Methods

Participants

A convenience sample of the local running, triathlon and university communities was recruited via social media. Twenty runners (eleven male, nine female; 31.2 ± 11 years, 1.73 ± 0.1 m, 74.0 ± 11.7 kg) participated in the university-approved study and gave their written consent upon arrival prior to session one. Inclusion criteria for participation in the study required an average of at least 10 km running weekly and reported comfort running on a treadmill for an hour.

Instrumentation

The distance and time to complete the 1-mile run was recorded using a Garmin Forerunner 910xt (Garmin International, Inc., Olathe, KS, USA) watch with a heart rate monitor was used to record the time and distance for a one-mile max effort run out doors. The data recording on the device was switched out of the proprietary ‘smart recording’ to sampling at 1 Hz. The data were uploaded to Garmin Connect, where the one-mile time was exported for each participant’s trial.

A twelve-camera, 200-Hz Vicon motion capture system (Bonita, Vicon Motion Systems, Centennial, CO, USA) was used to collect three-dimensional motion while participants ran on a split-belt force instrumented treadmill (Bertec FIT, Bertec Corporation, Columbus, OH, USA).

Data Collection

The study was conducted in two testing sessions, which were held on separate days completed within one week and at least 24-hours between sessions. During session one, participants completed a one-mile maximum effort run on a rectangular 800-m path on campus outside of the laboratory.
The path was designed with the long straight sections being 150 m long and the width 25 m on each side. The runners were able to round the corners, enabling them to maintain speed around the corners. A self-selected warm-up of at least five minutes was required for each participant prior to completion of the one-mile maximum effort run. The participants performed a warm-up run around the path to familiarise themselves with the path on campus. An 800-m path was measured using a distance wheel prior to the study. Each participant’s path was recorded using a Garmin 910xt GPS watch with the instruction to complete the loop twice. The time it took to complete the one-mile maximum effort run was used to estimate the runner’s 10 k race time and race pace using Runnersworld.com (Race Time Predictor). The range of speeds for the study was broad with the fastest runner completing the one-mile run in 5 minutes 25 seconds and the slowest runner completing the run in 9 minutes 49 seconds.

During session two, participants were instrumented with a full-body retro reflective marker set. Rigid clusters were attached to the thighs and shanks using elastic sporting wraps made of nylon and Lycra (SuperWrap Fabrifoom; Exton, PA, USA) and secured for the hour run with duct tape. Pelvis was modelled using individual reflective markers on left and right anterior iliac crest, posterior iliac crest and suprailiac crest. Torso was modelled using xiphoid process, sternocleido mastoid, right and left acromion processes, C7 and T12 vertebral processes. Left and right feet were modelled using markers on 1st and 5th metatarsals, based on second toe, and a triangle representing the heel. A static calibration trial was collected prior to the start of the one-hour run with the reflective markers added to the knee (medial and lateral knee joint lines) and ankle (medial and lateral malleoli). The calibration trials were removed following the calibration trial.
Since the instrumented treadmill has a split-belt system, participants were instructed to run on one of the treadmill belts for the entire one-hour run. The one-hour treadmill run incorporated an interval style run with two running speeds as a function of the participant’s estimated 10 km race pace. In total, there were ten intervals, each consisting of five minutes running at 75% of their 10 km race pace (10K\textsubscript{75%}) followed by one minute at 10 km race pace (10K\textsubscript{race}). The participants remained on the treadmill while velocity was changed. Prior to changing speed, the researcher informed the participant of the increasing, or decreasing, of speed three seconds prior to initiation of the speed adjustment. The treadmill belt acceleration was set for a gradual adjustment at 0.5 m/s/s. Prior to the application of the retro reflective markers, participants warmed up on the treadmill for five minutes, during which time they experienced the speed increase from the slow to fast speeds at the four minute mark.

Motion capture data were collected for a total of 30 trials across the 1-hour run. Each trial consisted of a 30 s data collection. For each 10K\textsubscript{75%} interval, data were collected twice (at the two (10K\textsubscript{2min}) and four (10K\textsubscript{4min}) minute mark of each 5-min interval). For each 10K\textsubscript{race}, data were collected once per interval at the 20 s mark of each interval. Therefore, the 30 trials consisted of 20 while running at 10K\textsubscript{75%} and 10 while running at 10K\textsubscript{race}.

The participants were blinded to when each data collection was conducted. Participants were encouraged to complete the entire hour run, but two participants did not complete the hour. One participant informed the researcher that he needed to stop after completing seven of the intervals. A second participant completed eight intervals prior to the researcher stopping the study due to their inability to match the treadmill belt speed. Both of the participants self-reported fatigue present when they stopped the interval run short of the hour.
To assess level of fatigue during the 1-hour run, a self-generated fatigue questionnaire was administered twice during session two. The questionnaire contained a combination of an analogue scale and a series of likert-type word association measures (Figure 4) (Enoka & Duchateau, 2016). Participants were asked to identify how they identified upon arrival to the research facility prior to warm-up and then again following the completion of the one-hour treadmill run. The initial rating by each participant was to ensure there was a lack of perceived fatigue upon arrival.

**Figure 4: Perceived Fatigue Questionnaire**

![Running Fatigue Questionnaire](image)

1. Please locate where you stand on the following line by placing an ‘x’ on the line that represents how you feel.

<table>
<thead>
<tr>
<th>Fatigue absent</th>
<th>Most fatigue ever</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Please provide the answer that is most representative to how the term describes how you are feeling now.

   a. **Worn out**
   0 = Not at all  1 = A little  2 = Moderately  3 = Quite a bit  4 = Extremely

   b. **Fatigued**
   0 = Not at all  1 = A little  2 = Moderately  3 = Quite a bit  4 = Extremely

   c. **Exhausted**
   0 = Not at all  1 = A little  2 = Moderately  3 = Quite a bit  4 = Extremely

   d. **Sluggish**
   0 = Not at all  1 = A little  2 = Moderately  3 = Quite a bit  4 = Extremely

   e. **Weary**
   0 = Not at all  1 = A little  2 = Moderately  3 = Quite a bit  4 = Extremely

**Data Analysis**

For each interval completed, there were three 30 s trials collected. The hour run was subdivided into four periods of interest for analysis: beginning of the run (start), one-third of the
run, two-thirds of the run, and the last data collection (end). Table 6 identifies which time points, intervals, were used for analysis dependent upon the number of intervals completed during the run.

Table 6: Middle interval defined per intervals completed.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Seven</td>
<td>Start</td>
<td>X</td>
<td>1/3rd</td>
<td>X</td>
<td>2/3rd</td>
<td>X</td>
<td>End</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Eight</td>
<td>Start</td>
<td>X</td>
<td>1/3rd</td>
<td>X</td>
<td>X</td>
<td>2/3rd</td>
<td>X</td>
<td>End</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ten</td>
<td>Start</td>
<td>X</td>
<td>X</td>
<td>1/3rd</td>
<td>X</td>
<td>X</td>
<td>2/3rd</td>
<td>X</td>
<td>X</td>
<td>End</td>
</tr>
</tbody>
</table>

Intervals completed: represents the total number out of ten intervals achieved during run. Start: First collection analysed; 1/3rd: Second collection time point analysed; 2/3rd: Third collection time point analysed; End: Final collection time point analysed.

Each trial was processed by first extracting 15 strides per limb. Nexus 2.3 (Vicon Motion Systems Ltd., Oxford, UK) was used for label identification and trial trimming to include the 15 strides. A custom Visual3D (C-Motion, Inc., Germantown, MD, USA) pipeline was constructed to smooth and filter all kinematic marker trajectories using a 4th order zero-lag Butterworth filter with a cut-off frequency of 8 Hz. Treadmill vertical ground reaction force data were smoothed and filtered using a 4th order zero-lag Butterworth filter with a cut-off frequency of 25 Hz.

Treadmill vertical ground reaction force experienced drift during the hour treadmill run. A custom Matlab script was used to demean the drift and adjust the zero offset for each of the 30 s collections. To accomplish this, ten aerial phases across the 30 s trial were identified and used to calculate the mean zero offset across all strides. The adjusted ground reaction force data were then parsed to identify foot contact using a 50 N threshold of the vertical ground reaction force.
Each of the variables was then separated into the 15 strides per limb and normalised to 100% of stride (101 data points).

Stride frequency was calculated as the mean stride frequency for the series of strides independently for each time point. Centre of mass vertical displacement was subdivided into the downward phase during stance (CM\textsubscript{down}) and the upward vertical displacement from the lowest during stance and the peak during the subsequent aerial phase (CM\textsubscript{up}). Relative angles of the knee were calculated at foot contact (FC) and at the peak flexion angle during stance and swing. Torso inclination was calculated at foot contact.

Participants were grouped based on their self-perceived ratings of fatigue: high-perceived fatigue and low-perceived fatigue. The combined scores were used to assess the perceived state of fatigue resulting from the one-hour interval treadmill run (Enoka & Duchateau, 2016). Participants were classified as high-perceived fatigue (High-PF) if they self-reported more than 50% rating for both the Likert response and the analogue scale. A 50% rating for the Likert response portion was achieving a score at least 10 out of a possible 20 points. The 50% for the analogue scale was marking the line to the right of the halfway point, which was at the 7 cm mark of a 14 cm line. A low-perceived fatigue (Low-PF) rating was reported for all participants who did not reach the 50% rating on the both the Likert response and analogue scale.

**Continuous Relative Phase**

Angular positions and angular velocities were calculated in Visual3D and normalised to stride. Removal of amplitude and frequency differences of angular position and velocity data was accomplished through normalisation within a condition (Miller, Meardon, Derrick, & Gillette, 2008). Angular position was normalised according to the minimum and maximum angle for the
series of 15 strides (Equation 1; p. 14). Angular velocity was normalised to the maximal velocity within the series of 15 strides per trial and condition (Equation 2; p. 15).

Phase angles were calculated for every point of the phase plot created by normalised angular position and velocity data. Phase angles (Equation 3, p.15) were calculated as the angle defined by the right horizontal and the data point along the phase plot (Miller, Meardon, Derrick, & Gillette, 2008). Phase angles were calculated for all segmental and relative angles of interest for the coupling relationships. Coupling patterns of interest (Table 7) were identified based on the previous lower extremity running pathology literature (Hamill, van Emmerik, Heidersheit, & Li, 1999; Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016; Miller, Meardon, Derrick, & Gillette, 2008) and proposed couplings important for performance. Due to the limited literature focused on performance and healthy runners, performance couplings were identified to represent changes in skeletal muscle fatigue.

Continuous relative phase (CRP) was calculated as the difference in the phase angle of the proximal variable from the distal variable point-by-point for each of the 15 strides per condition. The CRP variability (vCRP) was calculated as the point-by-point standard deviation of the normalised 15 strides. CRP phase calculations were based on percentages of a gait cycle and discrete events, with CRP and vCRP representative of the mean through that phase of the stride (Table 8).
Table 7: CRP couplings defined

<table>
<thead>
<tr>
<th>Proximal phase angle</th>
<th>Distal phase angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh FL/EX</td>
<td>Shank FL/EX</td>
</tr>
<tr>
<td>Thigh FL/EX</td>
<td>Shank IR/ER</td>
</tr>
<tr>
<td>Thigh IR/ER</td>
<td>Shank IR/ER</td>
</tr>
<tr>
<td>Thigh AB/AD</td>
<td>Shank IR/ER</td>
</tr>
<tr>
<td>Thigh IR/ER</td>
<td>Foot IN/EV</td>
</tr>
<tr>
<td>Thigh AB/AD</td>
<td>Foot IN/EV</td>
</tr>
<tr>
<td>Torso FL/EX</td>
<td>Knee FL/EX</td>
</tr>
<tr>
<td>Knee FL/EX</td>
<td>Foot FL/EX</td>
</tr>
<tr>
<td>Knee FL/EX</td>
<td>Foot IN/EV</td>
</tr>
</tbody>
</table>

FL: Flexion; EX: Extension; IR: Internal rotation; ER: External rotation; IN: Inversion; EV: Eversion; AB: Abduction; AD: Adduction

Table 8: Coupling phase divisions defined.

<table>
<thead>
<tr>
<th>Phase:</th>
<th>Definition:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial swing</td>
<td>First 33% of swing phase</td>
</tr>
<tr>
<td>Mid Swing</td>
<td>Middle 33% of swing phase</td>
</tr>
<tr>
<td>Terminal swing</td>
<td>Final 33% of swing phase</td>
</tr>
<tr>
<td>Early stance</td>
<td>First 33% of stance</td>
</tr>
<tr>
<td>Mid stance</td>
<td>Middle 33% of stance</td>
</tr>
<tr>
<td>Late stance</td>
<td>Final 33% of stance</td>
</tr>
<tr>
<td>Foot contact</td>
<td>Frame of foot contact</td>
</tr>
<tr>
<td>Toe-off</td>
<td>Frame of toe-off</td>
</tr>
</tbody>
</table>

Statistical Analysis

Left and right limbs were analysed separately for all analyses. They were not compared to measure for asymmetry during the current study. The mean and coefficient of variation was calculated for all traditional dependent variables. All dependent variables were analysed between the two running velocities using multiple 2 (group: High-PF, Low-PF) x 4 (interval: start, one-third, two-thirds, end) x 2 (velocity: 10K_{2min}, 10K_{race}) mixed model repeated measure analyses of variance (ANOVAs). Additionally, all dependent variables were analysed between the two time points for the 10K_{75%} velocity using multiple 2 (group: High-PF, Low-PF) x 4 (interval: start,
one-third, two-thirds, end) x 2 (velocity: 10K_{2min}, 10K_{4min}) mixed model repeated measure analyses of variance (ANOVAs). Fatigue group was used as the between group factor, with interval and velocity conditions as the within participant factor ($\alpha = 0.05$). The assumption of sphericity was tested using Mauchy’s test, with Huynh-Feldt corrections made for violations ($\alpha = 0.05$). When appropriate, Sidak post-hoc tests were run to determine differences among group.

When three-way interactions were present ($\alpha = 0.05$), multiple two-way repeated measure analyses of variance (ANOVAs). When two-way interactions were present ($\alpha = 0.05$), multiple one way repeated measure ANOVAs with Sidak pairwise comparisons of interval for each fatigue group ($\alpha = 0.05$). Independent t-tests were run to compare fatigue levels at each of the 4 levels of interval per velocity condition ($\alpha = 0.05$).

**Results**

Group separation based on the rating of perceived fatigue resulted in nine participants in the High-PF group (6 male & 3 female; 28.1 ± 10.7 years, 1.74 ± 0.08 m; 73.4 ±12.5 kg) and eleven in the Low-PF group (5 male & 6 female; 33.7 ± 11.1 years, 1.72 ± 0.10 m; 74.6 ±11.5 kg). All runners except for two completed the hour run. Both participants who did not complete the hour run were classified into the fatigue group based on the perceived fatigue scale response. Stride frequency was not different between groups, but was significantly greater during the 10K_{race} treadmill velocity [$F(1,18)=5.767, \ p = 0.027, \ \eta^2 = 0.243$].

Mean and standard deviations for all kinematic variables are presented in Table 9. CM_{up} had a significant Fatigue*Interval interaction ($p < 0.05$) for the left limb during both velocity analyses. There were no between group differences at any time point. The vertical displacement of the CM_{up} was significantly reduced during the 10K_{2min} condition [$F(3,24)=6.697, \ p = 0.002, \ \eta^2 = 0.456$] with a pairwise difference between start and two-thirds intervals ($p = 0.046$).
<table>
<thead>
<tr>
<th></th>
<th>RIGHT:</th>
<th></th>
<th></th>
<th></th>
<th>LEFT:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fatigue group</td>
<td>T1</td>
<td>T2</td>
<td>T3</td>
<td>T4</td>
<td>Fatigue group</td>
<td>T1</td>
<td>T2</td>
</tr>
<tr>
<td></td>
<td>Mean:</td>
<td>SD:</td>
<td>Mean:</td>
<td>SD:</td>
<td>Mean:</td>
<td>SD:</td>
<td>Mean:</td>
<td>SD:</td>
</tr>
<tr>
<td>Knee Angle @ Foot Contact (deg)</td>
<td>LPF V1</td>
<td>20.0</td>
<td>3.5</td>
<td>21.0</td>
<td>3.3</td>
<td>21.5</td>
<td>3.2</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td>HPF V1</td>
<td>23.7</td>
<td>3.2</td>
<td>24.4</td>
<td>3.6</td>
<td>25.1</td>
<td>3.0</td>
<td>25.4</td>
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<tr>
<td></td>
<td>LPF V2</td>
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<td>3.4</td>
<td>21.3</td>
<td>3.2</td>
<td>21.5</td>
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<td>21.7</td>
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<td></td>
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<td>3.4</td>
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<td>25.2</td>
<td>3.0</td>
<td>25.7</td>
</tr>
<tr>
<td></td>
<td>LPF V3</td>
<td>21.6</td>
<td>3.1</td>
<td>22.2</td>
<td>3.1</td>
<td>22.5</td>
<td>2.8</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td>HPF V3</td>
<td>26.1</td>
<td>3.4</td>
<td>26.6</td>
<td>4.6</td>
<td>26.9</td>
<td>3.4</td>
<td>28.2</td>
</tr>
<tr>
<td>Torso Inclination @ Foot Contact (deg)</td>
<td>LPF V1</td>
<td>-10.6</td>
<td>6.1</td>
<td>-11.6</td>
<td>6.9</td>
<td>-12.3</td>
<td>7.3</td>
<td>-13.2</td>
</tr>
<tr>
<td></td>
<td>HPF V1</td>
<td>-9.0</td>
<td>7.1</td>
<td>-8.9</td>
<td>7.0</td>
<td>-9.7</td>
<td>6.4</td>
<td>-9.7</td>
</tr>
<tr>
<td></td>
<td>LPF V2</td>
<td>-10.8</td>
<td>6.8</td>
<td>-11.7</td>
<td>7.1</td>
<td>-13.0</td>
<td>7.4</td>
<td>-13.6</td>
</tr>
<tr>
<td></td>
<td>HPF V2</td>
<td>-8.4</td>
<td>7.0</td>
<td>-8.7</td>
<td>6.7</td>
<td>-10.0</td>
<td>6.9</td>
<td>-9.7</td>
</tr>
<tr>
<td></td>
<td>LPF V3</td>
<td>-10.5</td>
<td>7.5</td>
<td>-12.6</td>
<td>7.2</td>
<td>-13.1</td>
<td>7.8</td>
<td>-13.3</td>
</tr>
<tr>
<td></td>
<td>HPF V3</td>
<td>-9.1</td>
<td>7.3</td>
<td>-9.4</td>
<td>7.8</td>
<td>-9.7</td>
<td>7.6</td>
<td>-9.6</td>
</tr>
<tr>
<td>Peak Knee Flexion Stance (deg)</td>
<td>LPF V1</td>
<td>42.2</td>
<td>4.2</td>
<td>43.3</td>
<td>3.9</td>
<td>43.5</td>
<td>3.6</td>
<td>44.0</td>
</tr>
<tr>
<td></td>
<td>HPF V1</td>
<td>44.5</td>
<td>3.4</td>
<td>45.4</td>
<td>3.7</td>
<td>45.7</td>
<td>3.5</td>
<td>46.0</td>
</tr>
<tr>
<td></td>
<td>LPF V2</td>
<td>41.9</td>
<td>4.0</td>
<td>43.7</td>
<td>3.8</td>
<td>43.6</td>
<td>3.2</td>
<td>43.8</td>
</tr>
<tr>
<td></td>
<td>HPF V2</td>
<td>44.1</td>
<td>3.6</td>
<td>45.5</td>
<td>4.1</td>
<td>46.2</td>
<td>3.4</td>
<td>46.1</td>
</tr>
<tr>
<td></td>
<td>LPF V3</td>
<td>43.0</td>
<td>4.1</td>
<td>44.0</td>
<td>4.2</td>
<td>44.8</td>
<td>4.3</td>
<td>44.7</td>
</tr>
<tr>
<td></td>
<td>HPF V3</td>
<td>45.5</td>
<td>3.5</td>
<td>47.2</td>
<td>4.6</td>
<td>46.8</td>
<td>2.9</td>
<td>47.1</td>
</tr>
<tr>
<td>Peak Knee Flexion Stride (deg)</td>
<td>LPF V1</td>
<td>85.9</td>
<td>4.6</td>
<td>88.5</td>
<td>5.2</td>
<td>88.4</td>
<td>5.5</td>
<td>88.5</td>
</tr>
<tr>
<td></td>
<td>HPF V1</td>
<td>96.2</td>
<td>11.2</td>
<td>95.4</td>
<td>10.1</td>
<td>94.9</td>
<td>9.5</td>
<td>94.2</td>
</tr>
<tr>
<td></td>
<td>LPF V2</td>
<td>87.2</td>
<td>5.6</td>
<td>88.7</td>
<td>5.2</td>
<td>89.1</td>
<td>5.8</td>
<td>88.4</td>
</tr>
<tr>
<td></td>
<td>HPF V2</td>
<td>95.9</td>
<td>11.5</td>
<td>94.7</td>
<td>9.3</td>
<td>93.3</td>
<td>8.0</td>
<td>95.0</td>
</tr>
<tr>
<td></td>
<td>LPF V3</td>
<td>101.5</td>
<td>12.6</td>
<td>100.6</td>
<td>9.6</td>
<td>103.9</td>
<td>11.5</td>
<td>107.5</td>
</tr>
<tr>
<td></td>
<td>HPF V3</td>
<td>111.2</td>
<td>13.3</td>
<td>112.1</td>
<td>14.7</td>
<td>112.0</td>
<td>14.6</td>
<td>112.8</td>
</tr>
</tbody>
</table>

**Abbreviations:**
- LPF = Low-Perceived Fatigue
- HPF = High-Perceived Fatigue
- V1 = 10K @ 2 min
- V2 = 10K @ 4 min
- V3 = 10K_race
- T1 = interval at start
- T2 = interval at 1/3rd of run
- T3 = interval at 2/3rds of run
- T4 = interval at end of run
Left knee angle at foot contact had a significant Fatigue*Velocity interaction

\[ F(1,18)=10.708, \ p = 0.004, \ \eta^2 = 0.373 \] for the 10K_{2min} and 10K_{race} conditions. Group differences found decreased knee flexion for the Low-PF group at all interval analyses \((p < 0.05)\). The Low-PF group contacted the ground with greater knee flexion at start interval during 10K_{race} \((t = -4.730, \ p = 0.001)\). The High-PF group increased knee flexion during 10K_{race} for each interval \((p < 0.05)\). Right peak knee flexion during swing had a significant Fatigue*Interval interaction \([F(3,54) = 3.403, \ p = 0.040, \ \eta^2 = 0.109]\). The Low-PF group ran with less peak knee flexion during swing at the start of 10K_{2min} \((t = 2.601, \ p = 0.026)\). The Low-PF group was significantly different during the run \([F(3,30) = 6.038, \ p = 0.002, \ \eta^2 = 0.376]\], with increased peak knee flexion during the one-third \((p = 0.014)\) and two-third \((p = 0.005)\) intervals compared to the start interval. Torso inclination during left foot contact had a significant Fatigue*Velocity interaction \([F(1,18)=5.673, \ p = 0.028, \ \eta^2 = 0.240]\). No simple main effect differences were reported between groups nor within groups \((p>0.05)\). There were no other differences between fatigue groups for gait characteristics and kinematics.

**Continuous Relative Phase**

The significant couplings and variables are reported as the simple main effects across significant interactions. There were a number of differences in the coordination patterns between groups, as measured by the interactions in the mixed model repeated measure ANOVAs \((p < 0.05)\). All significant interactions for CRP yielded simple main effect differences. The significant main effects are divided by limb. Table 10 reports the simple main effects for the 3-way (Fatigue*Velocity*Interval) interactions. Appendix 1 reports the simple main effects of the Fatigue*Velocity interactions and Table 11 reports the Fatigue*Interval interactions.
There were a number of significant interactions for variability CRP ($p < 0.05$). Table 12 presents the significant simple main effect analyses, while Table 13 reports the significant interactions that did not yield simple main effect differences.
Table 10: Simple main effect results of couplings with a significant 3-way (Fatigue*Velocity*Interval) interaction.

**LEFT:**

<table>
<thead>
<tr>
<th>Coupling</th>
<th>VC:</th>
<th>Phase:</th>
<th>Sig Int:</th>
<th>Int Stats:</th>
<th>Between:</th>
<th>Interval:</th>
<th>Velocity:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh FL/EX-Shank FL/EX</td>
<td>C1:C3</td>
<td>Terminal Swing</td>
<td>FTS</td>
<td>F = 4.003, p = 0.012</td>
<td>NONE</td>
<td>LPF: more in-phase (p=0.002)</td>
<td>HPF: more in-phase C3 (p = 0.045)</td>
</tr>
<tr>
<td>Thigh IR/ER-Foot IN/EV</td>
<td>C1:C3</td>
<td>Terminal swing</td>
<td>FTS</td>
<td>F = 3.578, p = 0.02</td>
<td>NONE</td>
<td>LPF: more in phase C3 F(3,30)=5.618, p=0.004, η² = 0.360</td>
<td>HPF: more in-phase T2 (t = 2.372, p = 0.045)</td>
</tr>
<tr>
<td>Torso FL/EX-Knee FL/EX</td>
<td>C1:C2</td>
<td>Toe-off</td>
<td>FTS</td>
<td>F = 3.848, p = 0.014</td>
<td>NONE</td>
<td>C1 F(3,24) = 4.703, p = 0.01 &amp; T2_T3 (p = 0.021) &amp; T2_T3 (p = 0.041)</td>
<td>NONE</td>
</tr>
<tr>
<td>Knee FL/EX-Foot IN/EV</td>
<td>C1:C3</td>
<td>Early Stance</td>
<td>FTS</td>
<td>F = 3.314, p = 0.027</td>
<td>NONE</td>
<td>LPF: more in-phase C1 F(3,30) = 3.191, p = 0.038, η² = 0.242</td>
<td>LPF: more in-phase T1 (t = 3.001, p = 0.013) &amp; T4 (t = -5.643, p &lt; 0.001)</td>
</tr>
<tr>
<td>Knee FL/EX-Foot IN/EV</td>
<td>C1:C3</td>
<td>Foot Contact</td>
<td>FTS</td>
<td>F = 3.841, p = 0.014</td>
<td>NONE</td>
<td>HPF: more in-phase C3 F(3,30) = 3.028, p = 0.049, η² = 0.275</td>
<td>HPF: more in-phase T2 (t = 2.353, p = 0.033)</td>
</tr>
<tr>
<td>Knee FL/EX-Foot IN/EV</td>
<td>C1:C2</td>
<td>Late Stance</td>
<td>FTS</td>
<td>F = 3.017, p = 0.038</td>
<td>NONE</td>
<td>LPF: more out phase T1 (t = -2.474, p = 0.033) &amp; T4 (t = -3.145, p = 0.010)</td>
<td>NONE</td>
</tr>
</tbody>
</table>

**RIGHT:**

<table>
<thead>
<tr>
<th>Coupling</th>
<th>VC:</th>
<th>Phase:</th>
<th>Sig Int:</th>
<th>Int Stats:</th>
<th>Between:</th>
<th>Interval:</th>
<th>Velocity:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh FL/EX-Shank IR/ER</td>
<td>C1:C2</td>
<td>Terminal Swing</td>
<td>FTS</td>
<td>F = 3.638, p = 0.018</td>
<td>NONE</td>
<td>LPF: more out-phase T2 (t = 2.966, p = 0.014) &amp; T4 (t = -5.643, p &lt; 0.001)</td>
<td>HPF: more out-phase T2 (t = 2.966, p = 0.014) &amp; T4 (t = -5.643, p &lt; 0.001)</td>
</tr>
<tr>
<td>Thigh FL/EX-Shank IR/ER</td>
<td>C1:C2</td>
<td>Initial Stance</td>
<td>FTS</td>
<td>F = 3.949, p = 0.022</td>
<td>NONE</td>
<td>HPF: Trend for group during C1</td>
<td>LPF: more out-phase T4 (t = 3.269, p = 0.008)</td>
</tr>
<tr>
<td>Thigh AB/AD - Foot IN/EV</td>
<td>C1:C2</td>
<td>Terminal Swing</td>
<td>FTS</td>
<td>F = 3.638, p = 0.018</td>
<td>NONE</td>
<td>LPF: more out-phase T2 (t = 2.966, p = 0.014) &amp; T4 (t = 2.272, p = 0.046)</td>
<td>HPF: more out-phase T4 (t = 3.269, p = 0.008)</td>
</tr>
<tr>
<td>Thigh AB/AD - Foot IN/EV</td>
<td>C1:C2</td>
<td>Early Stance</td>
<td>FTS</td>
<td>F = 3.492, p = 0.022</td>
<td>NONE</td>
<td>HPF: trend to more out-phase C1 (p=0.051)</td>
<td>HPF: more out-phase T4 (t = 3.269, p = 0.008)</td>
</tr>
<tr>
<td>Torso FL/EX-Knee FL/EX</td>
<td>C1:C2</td>
<td>Toe-off</td>
<td>FTS</td>
<td>F = 3.486, p = 0.022</td>
<td>LPF: more in-phase C1T3 (t = 2.393, p = 0.28)</td>
<td>HPF: more out-phase T2 (t = 3.469, p = 0.008) &amp; more in-phase T3 (t = 2.567, p = 0.033) &amp; more in-phase T4 (t = 2.397, p = 0.038)</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: Phase: significant phase; Sig Int = Significant interaction; Int Stats = reported statistics for interaction; Between = Independent t-test result between fatigue groups; Time = Repeated measure ANOVA results within fatigue groups; Velocity = paired t-test results between fatigue groups. Groups: LPF = Low-Perceived Fatigue & HPF = High-Perceived Fatigue; Velocity condition (VC): C1 = 10k 75% @ 2min; C2 = 10k 75% @ 4 min; C3 = 10k race; Interval Condition: T1 = Interval at start of run; T2 = Interval one-third of run; T3 = Interval two-thirds of run; T4 = Interval at end of run Statistical Interactions: FTS = 3-way interaction (Fatigue*Interval*Velocity); FT = 2-way interaction (Fatigue*Interval); FS = 2-way interaction (Fatigue*Velocity)
Table 11: Simple main effect results of coupling with a significant Fatigue*Intervals interaction.

<table>
<thead>
<tr>
<th>LEFT: Coupling:</th>
<th>VC:</th>
<th>Phase:</th>
<th>Sig Int:</th>
<th>Int Stats:</th>
<th>Between:</th>
<th>Interval:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh AB/AD - Foot IN/EV</td>
<td>C1:C2</td>
<td>Initial Swing</td>
<td>FT</td>
<td>$F = 3.036, p = 0.037$</td>
<td>NONE</td>
<td>LPF: more in-phase</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F(3,30) = 6.155, $p = 0.002$, $\eta^2 = 0.381$</td>
<td>T1T4 ($p = 0.008$)</td>
<td></td>
</tr>
<tr>
<td>RIGHT: Coupling:</td>
<td>VC:</td>
<td>Phase:</td>
<td>Sig Int:</td>
<td>Int Stats:</td>
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<td>-----------</td>
</tr>
<tr>
<td>Thigh FL/EX-Shank FL/EX</td>
<td>C1:C3</td>
<td>Late Stance</td>
<td>FT</td>
<td>$F = 3.026, p = 0.037$</td>
<td>NONE</td>
<td>LPF: more in-phase</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T2_T3 ($p = 0.032$)</td>
<td></td>
</tr>
<tr>
<td>Thigh IR/ER-Foot IN/EV</td>
<td>C1:C3</td>
<td>Foot Contact</td>
<td>FT</td>
<td>$F = 3.008, p = 0.038$</td>
<td>NONE</td>
<td>HPF: more in-phase</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F(1.63,16.31) = 4.142, $p = 0.042$, $\eta^2 = 0.293$.</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: Phase: significant phase; Sig Int = Significant interaction; Int Stats = reported statistics for interaction; Between = Independent t-test result between fatigue groups; Time = Repeated measure ANOVA results within fatigue groups; Velocity = paired t-test results between fatigue groups.

Groups: LPF = Low-Perceived Fatigue & HPF = High-Perceived Fatigue; Velocity condition (VC): C1 = 10k 75% @ 2min; C2 = 10k 75% @ 4 min; C3 = 10k race; Interval Condition: T1 = Interval at start of run; T2 = Interval one-third of run; T3 = Interval two-thirds of run; T4 = Interval at end of run

Statistical Interactions: FTS = 3-way interaction (Fatigue*Interval*Velocity); FT = 2-way interaction (Fatigue*Interval); FS = 2-way interaction (Fatigue*Velocity)
**Table 12: Simple main effect results of vCRP couplings with a significant interaction.**

**LEFT:**

<table>
<thead>
<tr>
<th>Coupling:</th>
<th>VC:</th>
<th>Phase:</th>
<th>Sig Int:</th>
<th>Int Stats:</th>
<th>Between:</th>
<th>Interval:</th>
<th>Velocity:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh FL/EX-Shank FL/EX</td>
<td>C1:C2</td>
<td>Late</td>
<td>FS</td>
<td>F = 4.582, p = 0.046</td>
<td>HPF: less variable</td>
<td>NA</td>
<td>NONE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stance</td>
<td></td>
<td></td>
<td>C1T1 (t = -2.247, p = 0.037)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C2T1 (t = -2.207, p = 0.041)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C3T3 (t = -2.436, p = 0.025)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thigh FL/EX-Shank IR/ER</td>
<td>C1:C3</td>
<td>Early</td>
<td>FS</td>
<td>F = 5.652, p = 0.029</td>
<td>NA</td>
<td>NONE</td>
<td>LPF: reduced variability T2 (t = 3.903, p = 0.003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thigh AB/AD - Foot IN/EV</td>
<td>C1:C3</td>
<td>Early</td>
<td>FS</td>
<td>F = 13.525, p = 0.002</td>
<td>NONE</td>
<td>NONE</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torso FL/EX- Knee FL/EX</td>
<td>C1:C2</td>
<td>Initial</td>
<td>FTS</td>
<td>F = 4.396, p = 0.008</td>
<td>LPF: less variable</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Swing</td>
<td></td>
<td></td>
<td>C1T3 (t = 2.825, p = 0.011)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&amp; C1T4 (t = 2.834, p = 0.011)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HPF: increased variability</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C1 F(3,30) = 4.435, p = 0.013, ( \eta^2 = 0.357 )</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T2_T4 (p = 0.040)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torso FL/EX- Knee FL/EX</td>
<td>C1:C2</td>
<td>Toe-Off</td>
<td>FTS</td>
<td>F = 2.917, p = 0.042</td>
<td>HPF: increased variability</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C1 F(3,30) = 3.523, p = 0.030, ( \eta^2 = 0.306 )</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T2_T4 (p = 0.016)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee FL/EX- Foot PF/DF</td>
<td>C1:C3</td>
<td>Initial</td>
<td>FS</td>
<td>F = 5.074, p = 0.037</td>
<td>NONE</td>
<td>NA</td>
<td>LPF: reduced variability T2 (t = 5.877, p &lt; 0.001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Swing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee FL/EX- Foot IN/EV</td>
<td>C1:C2</td>
<td>Toe-Off</td>
<td>FT</td>
<td>F = 2.806, p = 0.048</td>
<td>HPF: increased variability</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C1 F(3,30) = 4.623, p = 0.011, ( \eta^2 = 0.366 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T2_T4 (p = 0.012)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee FL/EX- Foot IN/EV</td>
<td>C1:C2</td>
<td>Foot</td>
<td>FTS</td>
<td>F = 3.098, p = 0.034</td>
<td>HPF: greater variability</td>
<td>NONE</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact</td>
<td></td>
<td></td>
<td>C2T1 (t = -2.344, p =0.031)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HPF: Reduced variability</td>
<td>T2 (t = 2.293, p = 0.045)</td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviations:** Sig Int = Significant interaction; Int Stats = reported statistics for interaction; Velocity = paired t-test results between fatigue groups. Groups: LPF = Low-Perceived Fatigue & HPF = High-Perceived Fatigue; Velocity condition (VC): C1 = 10k 75% @ 2min; C2 = 10k 75% @ 4 min; C3 = 10k race; Interval Condition: T1 = Interval at start of run; T2 = Interval one-third of run; T3 = Interval two-thirds of run; T4 = Interval at end of run Statistical Interactions: FTS = 3-way interaction (Fatigue*Interval*Velocity); FT = 2-way interaction (Fatigue*Interval); FS = 2-way interaction (Fatigue*Velocity)

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Table 13: Significant interaction for vCRP, which lack simple main effect differences.

<table>
<thead>
<tr>
<th>Coupling:</th>
<th>VC:</th>
<th>Phase:</th>
<th>Sig Int:</th>
<th>Int Stats:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh IR/ER-Shank IR/ER</td>
<td>C1:C2</td>
<td>Toe-Off</td>
<td>FT</td>
<td>F = 3.344, p = 0.026</td>
</tr>
<tr>
<td>Thigh IR/ER-Foot IN/EV</td>
<td>C1:C2</td>
<td>Late Stance</td>
<td>FS</td>
<td>F = 4.582, p = 0.046</td>
</tr>
<tr>
<td>Knee FL/EX-Foot PF/DF</td>
<td>C1:C2</td>
<td>Terminal Swing</td>
<td>FTS</td>
<td>F = 2.833, p = 0.047</td>
</tr>
<tr>
<td>Knee FL/EX-Foot IN/EV</td>
<td>C1:C2</td>
<td>Foot Contact</td>
<td>FTS</td>
<td>F = 2.735, p = 0.038</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coupling:</th>
<th>VC:</th>
<th>Phase:</th>
<th>Sig Int:</th>
<th>Int Stats:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh FL/EX-Shank IR/ER</td>
<td>C1:C3</td>
<td>Mid swing</td>
<td>FT</td>
<td>F = 3.114, p = 0.034</td>
</tr>
<tr>
<td>Thigh FL/EX-Shank IR/ER</td>
<td>C1:C3</td>
<td>Late stance</td>
<td>FTS</td>
<td>F = 3.419, p = 0.024</td>
</tr>
<tr>
<td>Thigh AB/AD-Shank IR/ER</td>
<td>C1:C2</td>
<td>Early Stance</td>
<td>FS</td>
<td>F = 5.108, p = 0.036</td>
</tr>
<tr>
<td>Thigh AB/AD-Foot IN/EV</td>
<td>C1:C3</td>
<td>Late Stance</td>
<td>FTS</td>
<td>F = 3.419, p = 0.024</td>
</tr>
<tr>
<td>Thigh AB/AD-Foot IN/EV</td>
<td>C1:C2</td>
<td>Toe-Off</td>
<td>FS</td>
<td>F = 4.586, p = 0.046</td>
</tr>
<tr>
<td>Torso FL/EX-Knee FL/EX</td>
<td>C1:C2</td>
<td>Early Stance</td>
<td>FS</td>
<td>F = 5.108, p = 0.036</td>
</tr>
<tr>
<td>Knee FL/EX-Foot IN/EV</td>
<td>C1:C3</td>
<td>Terminal Swing</td>
<td>FTS</td>
<td>F = 3.345, p = 0.026</td>
</tr>
<tr>
<td>Knee FL/EX-Foot IN/EV</td>
<td>C1:C3</td>
<td>Foot Contact</td>
<td>FTS</td>
<td>F = 3.119, p = 0.033</td>
</tr>
</tbody>
</table>

Abbreviations: Phase: significant phase; Sig Int = Significant interaction; Int Stats = reported statistics for interaction; Velocity condition (VC): C1 = 10k 75% @ 2min; C2 = 10k 75% @ 4 min; C3 = 10k race; Statistical Interactions: FTS = 3-way interaction (Fatigue*Interval*Velocity); FT = 2-way interaction (Fatigue*Interval); FS = 2-way interaction (Fatigue*Velocity)

Discussion and Implications

CRP and vCRP changed differently within perceived fatigue groups, Low-PF and High-PF. There were a number of similar adjustments made for both groups, but the focus of this discussion is how the groups performed differently. The High-PF group was the only group that increased variability between intervals, with the adjustments occurring during transitions from stance to swing in toe-off and initial swing phase. An interesting finding was the differences in reduction of vCRP for the Low-PF group in response to increased running velocity for a number of couplings. Also, the changes in kinematics and coordination patterns were experienced in both the Low-PF and High-PF group, but did not follow the same distinctive pattern differences based on group.
A novel finding in the current study was the difference in adjustment seen during the recovery intervals (i.e., 10K_{2min}) toward the end of the run in the High-PF group. The High-PF group increased vCRP during the 10K_{2min} collection session (Table 8), which was the period of collection following the higher velocity interval. The difference here may be an indication that there was a delayed ability to recover during the 10K_{2min} condition following the 10K_{race} interval. Previously, it has been reported that a state of fatigue, measured decreases in performance variable, did not yield changes in submaximal running mechanics (Jean Benoit Morin, Tomazin, Samozino, Edouard, & Millet, 2012). The differences between the methodologies used in this study vs. Morin et al. (2012) were the time to and type of recovery between velocity intervals, as well as the intensity of the high velocity interval. Analysis of the current results seem to illustrate an ability to expand the coordination of multiple degrees of freedom during a recovery period, in a group of runners experiencing perceived fatigue. What is unknown, however, is whether or not this was a protective strategy in preparation for the final higher velocity run, or a result of the perceived fatigue. Miller et al. (2008) reported both an increased and decrease variability in runners with a history of iliotibial band syndrome following an exhaustive run. The current study did not find the same significant coupling differences, which was expected based in the differences in collapsing across phases of the current study.

It is important to note that although a number of differences based on perceived fatigue were measured, the vast majority of the differences were reduced variability due to the increase in running velocity. In response to increased running velocity, variability decreased in the Low-PF group only (Table 8). The runners that self-reported Low-PF may have utilised strategies that handle the changes in running velocity. This is supported by the significant differences occurring during the middle two intervals. Interestingly, when comparing 10K_{2min} and 10K_{4min}, variability
increased in the Low-PF group for two couplings. The High-PF group reduced variability in the initial swing phase during Torso FL/EX-Knee FL/EX during the 10K75% analysis. High-PF in the current study produced increased and reduced variability for a number of couplings for each group. Variability fluctuating between increased and decreased for differing couplings has been shown in the iliotibial band syndrome population (Miller, Meardon, Derrick, & Gillette, 2008), but not in healthy runners.

Similar to the variability of coordination, shifts of continuous relative phase between perceived fatigue groups were observed with running velocity changes. There was no particular pattern for which couplings shifted (i.e. to a more in-phase versus anti-phase coupling). Furthermore, given the differences in the peak knee flexion at foot contact, it was anticipated that there would be group differences in the couplings that comprise knee flexion. There were not differences, however, in the Thigh FL/EX-Shank FL/EX between groups. It is proposed that in order to produce a more practical application of CRP analyses, connecting these changes in variability and coordination patterns to traditional kinematics and lower extremity stiffness is essential. It is acknowledged that due to the higher order processing of CRP, the application is limited (Hamill, Emmerik, Heiderscheit, & Li, 1999). There also needs to be a greater effort to identify useful couplings for a performance-based analysis, which may lead to better structure of a training program and injury prevention strategy.

There are a number of limitations that are recognized for the current study. A perceived fatigue questionnaire was used due to the connection between the mind and pattern development. The general body of literature uses either performance measurements or a simple run to volitional exhaustion. Treadmill running may have limited, or changed, the movement patterns and variability adjustments differently than if the study was conducted overground. The current
study did not collapse across limbs, nor did it choose to focus on the dominant limb. The authors believe suggest future studies identifying the dominant limb as an identifier of which limb to analyse. Finally, the selection of the interval speeds may have limited the level of fatigue within the participants. Future studies may benefit from identifying fatigue level as a continuum, rather than an absolute grouping.

Conclusion

Changes in vCRP were measured during the interval run, but the changes were difference among the perceived fatigue groups. Variability for the Low-PF group changed to the greatest extent during the increase to 10k_race running velocity. The High-PF group responded with an increased variability during the 10K_2min condition across intervals. During the development of a training program, measuring when a runner responds as the Low-PF group versus the High-PF group may provide a valuable metric for when to increase running velocity. When a runner does not increase their vCRP following the high velocity intervals, they may be ready to increase their running velocity.
References


CHAPTER 5

Overall Dissertation Conclusion

By

Joshua Paul Bailey
Conclusion

The overarching purpose of this dissertation was to examine the effects of approaching performance thresholds on coordination patterns and coordination variability during treadmill running in healthy runners. To address this purpose, three individual studies were designed to challenge the current performance abilities of the participants while measuring coordination patterns. Each study addressed a different aspect of performance thresholds: (1) influence of increased running velocity, (2) increased oxygen consumption as percentage of peak consumption, and (3) perceived fatigue while running at multiple running velocities.

A Dynamical Systems approach was utilised to identify possible changes in running pattern development and the variability of the patterns. The theory is oriented around the ability to organize a numerous degrees of freedom in a way that yields a movement pattern that achieves a particular task. The vast amount of research utilising coordination patterns and coordination variability is focused on understanding mechanisms of overuse injuries. Therefore, there are numerous gaps in performance research that need to be identified prior to the usage as a training tool.

Based upon the experiments conducted as part of this dissertation, it is concluded that the response to increased running velocity during treadmill running was a decrease in coordination variability for a number of segmental couplings. This decrease in variability at the higher running velocities suggests that runners become more constrained in the ability to utilise multiple degrees of freedom. The risk of reduced variability is the repetitive loading in the same pattern through a joint has been identified as a possible cause of overuse injury. From a performance perspective, the decrease in variability may indicate a task that is challenging the current fitness or athletic capabilities if the runner. However, not all coordination variability differences were
observed to exist in both limbs. Further investigation should look into the bilateral differences related to muscular endurance of the lower extremity.

The second analysis focused more on the individual physiological response to an increase in running velocity through measuring the change in oxygen consumption relative to peak aerobic capacity. This study produced two distinctively different groups separated by the difference in oxygen consumption represented as a percentage of their peak consumption. Experimentally, runners were required to run at an objectively set velocity based upon their ventilatory threshold. The other velocity that was used was their self-identified preferred running velocity. The difference in VO2 during these conditions was used to group runners. The runners who had the greater increase in percentage of peak aerobic capacity between runs reduced coordination variability in a number of couplings during mid-swing and propulsive phases. This increase in constrained pattern development through these phases indicates a possible increase in oxygen consumption to reduce the degrees of freedom. Decreasing degrees of freedom requires skeletal muscle contraction, possibly leading to a greater increase in the oxygen cost of locomotion.

A major observation made from the second study, however, was the lack of differences in coordination variability and coordination patterns between groups. The majority of the differences measured were due to increasing running velocity regardless of grouping based on percentage of peak oxygen consumption. The second velocity was based on the individual runners’ speed at ventilatory threshold. Therefore, the higher velocity approached their individual aerobic threshold. What is unknown is the experience of the runners at the higher running velocities. It is possible that some of the runners in each of the groups were more comfortable at the higher intensity, so during the duration of the steady-state run, the velocity did
not cause them to increase their oxygen consumption as great. This brings into the question of whether not experience exercising close to your performance thresholds has a training effect in coordination variability.

The final study in the dissertation was to investigate whether or not the perception of fatigue during an interval treadmill run would be related to coordination patterns. The previous observations provided evidence that increasing running velocity affected coordination variability and coordination. What remained unknown was whether or not coordination patterns and variability were affected differently over time as a result of the perception of fatigue. Experimentally, a one-hour run was divided into an interval run incorporating the known influence of running velocity. Interestingly, the main difference between the high-perceived fatigue group and the low-perceived fatigue group over time was an increase in variability at the submaximal running velocity for the high-perceived fatigue group. The increase was measured after returning to the slower running velocity following the higher velocity interval. The increase observed in the Torso FL/EX-Knee FL/EX during left lower extremity stride at toe-off and initial swing maybe related to an increased difficulty recovering quicker. Future studies should include heart rate, or another metric, to measure duration of recovery.

In connection with the previous two studies, the majority of the differences between the variability of the two groups were measured due to differences in running velocity. The reduced variability as a result of increasing running velocity estimated 10k race pace was measured in the low-perceived fatigue group. The reduction was measured in a number of couplings during the middle two data collection periods of the run. It is theorized that the low-perceived fatigue group may have utilised the reduced variability to conserve energy while achieving the higher running velocity. There were varied responses between the two data collection per interval cycle at the
lower running velocity, as both the low-perceived fatigue and high-perceived fatigue groups adjusted their variability. Coordination pattern differences between groups were due to the changes in running velocity rather than do to the duration of the run.

The series of studies supports the hypothesis that endurance runners adjust their coordination patterns and variability when measured using continuous relative phase. The current focus was on increases in running intensity through increases in running velocity in a treadmill. Increases in intensity yield different pattern development and the variability of the coordination patterns regardless of oxygen consumption and perception of fatigue. However, the perception of fatigue has a marked effect on variability changes over the course of a run. What is unknown, however, is whether or not the measured changes in variability is beneficial or detrimental during the training adaptation period for race performance. Additionally, it is unknown whether or not shifting a coordination pattern to a more in-phase or anti-phase pattern is beneficial.
### APPENDIX 1: SIMPLE MAIN EFFECT RESULTS OF COUPLINGS WITH A SIGNIFICANT FATIGUE*VELOCITY INTERACTION.

#### LEFT:

<table>
<thead>
<tr>
<th>Coupling:</th>
<th>VC:</th>
<th>Phase:</th>
<th>Sig Int:</th>
<th>Int Stats:</th>
<th>Between:</th>
<th>Velocity:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh FL/EX-Shank FL/EX</td>
<td>C1:C2</td>
<td>Mid Swing</td>
<td>FS</td>
<td>F = 5.788, p = 0.027</td>
<td>NONE</td>
<td>LPF: more out-phase during T3 (t = 2.243, p=0.049) &amp; HPF: more in-phase during T4 (t=2.347, p=0.047)</td>
</tr>
<tr>
<td>Thigh FL/EX-Shank FL/EX</td>
<td>C1:C2</td>
<td>Mid Stance</td>
<td>FS</td>
<td>F = 6.484, p = 0.020</td>
<td>NONE</td>
<td>LPF: trend group T2</td>
</tr>
<tr>
<td>Thigh IR/ER-Foot IN/EV</td>
<td>C1:C2</td>
<td>Early Stance</td>
<td>FS</td>
<td>F = 6.061, p = 0.024</td>
<td>NONE</td>
<td>HPF: more in-phase during T2 (t = 2.372, p = 0.045)</td>
</tr>
<tr>
<td>Thigh IR/ER-Foot IN/EV</td>
<td>C1:C2</td>
<td>Mid Stance</td>
<td>FT</td>
<td>F = 3.000, p = 0.038</td>
<td>NONE</td>
<td>LPF: More out-phase T1 (t = 3.055, p=0.012) &amp; T2 (t = 3.332, p = 0.008) &amp; T3 (t = 3.172, p = 0.010) &amp; T4 (t = 2.656, p = 0.024)</td>
</tr>
<tr>
<td>Thigh AB/AD - Foot IN/EV</td>
<td>C1:C3</td>
<td>Initial Swing</td>
<td>FS</td>
<td>F = 4.61, p = 0.046</td>
<td>NONE</td>
<td>LPF: more out-phase T2 (t = 2.867, p = 0.012) &amp; T4 (t = 2.701, p = 0.022)</td>
</tr>
<tr>
<td>Torso FL/EX-Knee FL/EX</td>
<td>C1:C2</td>
<td>Mid Swing</td>
<td>FS</td>
<td>F = 7.806, p = 0.012</td>
<td>LPF: more in-phase T1 (t = 2.835, p = 0.11) &amp; LPF: more out-phase T4 (t = 3.021, p = 0.013)</td>
<td></td>
</tr>
<tr>
<td>Knee FL/EX-Foot PF/DF</td>
<td>C1:C3</td>
<td>Terminal swing</td>
<td>FS</td>
<td>F = 8.135, p = 0.011</td>
<td>NONE</td>
<td>HPF: more out-phase T4 (t = 2.715, p = 0.026)</td>
</tr>
<tr>
<td>Knee FL/EX-Foot PF/DF</td>
<td>C1:C2</td>
<td>Late Stance</td>
<td>FS</td>
<td>F = 9.775, p = 0.006</td>
<td>NONE</td>
<td>LPF: more in-phase T1 (t = 2.705, p = 0.022)</td>
</tr>
<tr>
<td>Knee FL/EX-Foot PF/DF</td>
<td>C1:C2</td>
<td>Toe-off</td>
<td>FS</td>
<td>F = 4.872, p = 0.041</td>
<td>NONE</td>
<td>LPF: more in-phase T1 (t = 4.195, p = 0.002) &amp; HPF: more out-phase T3 (t = -2.782, p = 0.024)</td>
</tr>
</tbody>
</table>

#### RIGHT:

<table>
<thead>
<tr>
<th>Coupling:</th>
<th>VC:</th>
<th>Phase:</th>
<th>Sig Int:</th>
<th>Int Stats:</th>
<th>Between:</th>
<th>Velocity:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh FL/EX-Shank IR/ER</td>
<td>C1:C3</td>
<td>Initial Swing</td>
<td>FS</td>
<td>F = 8.095, p = 0.011</td>
<td>NONE</td>
<td>LPF: more out-phase T1 (t = -3.615, p &lt; 0.005) &amp; T3 (t = -5.633, p &lt; 0.001) &amp; HPF: more out-phase T3 (t = -4.119, p = 0.003)</td>
</tr>
<tr>
<td>Thigh IR/ER-Shank IR/ER</td>
<td>C1:C3</td>
<td>Foot Contact</td>
<td>FS</td>
<td>F = 9.611, p = 0.006</td>
<td>NONE</td>
<td>HPF: more in-phase T3 (t = 2.854, p = 0.021)</td>
</tr>
<tr>
<td>Thigh IR/ER-Shank IR/ER</td>
<td>C1:C2</td>
<td>Foot contact</td>
<td>FS</td>
<td>F = 4.799, p = 0.042</td>
<td>NONE</td>
<td>HPF: trend toward more out-phase T4 (p = 0.089)</td>
</tr>
<tr>
<td>Thigh AB/AD-Shank IR/ER</td>
<td>C1:C3</td>
<td>Initial Swing</td>
<td>FS</td>
<td>F = 7.044, p = 0.016</td>
<td>NONE</td>
<td>HPF: more out-phase T3 (t = 2.442, p = 0.040)</td>
</tr>
<tr>
<td>Thigh AB/AD-Shank IR/ER</td>
<td>C1:C2</td>
<td>Foot Contact</td>
<td>FS</td>
<td>F = 6.496, p = 0.02</td>
<td>NONE</td>
<td>LPF: more in-phase T4 (t = 2.788, p = 0.019)</td>
</tr>
<tr>
<td>Thigh AB/AD - Foot IN/EV</td>
<td>C1:C3</td>
<td>Toe-off</td>
<td>FS</td>
<td>F = 12.683, p = 0.002</td>
<td>LPF: more in-phase</td>
<td>LPF: more out-phase</td>
</tr>
<tr>
<td>Muscle Group</td>
<td>Stage</td>
<td>Phase</td>
<td>Significant Phase</td>
<td>Interaction</td>
<td>Significance</td>
<td></td>
</tr>
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</tr>
<tr>
<td>Torso FL/EX-Knee FL/EX</td>
<td>C1:C3</td>
<td>Mid-swing</td>
<td>FS</td>
<td>F = 6.532, p = 0.02</td>
<td>NONE</td>
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<tr>
<td>Torso FL/EX-Knee FL/EX</td>
<td>C1:C2</td>
<td>Mid Swing</td>
<td>FS</td>
<td>F = 4.537, p = 0.047</td>
<td>LPF: more in-phase</td>
<td></td>
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<tr>
<td>Torso FL/EX-Knee FL/EX</td>
<td>C1:C2</td>
<td>Foot Contact</td>
<td>FS</td>
<td>F = 6.496, p = 0.02</td>
<td>NONE</td>
<td></td>
</tr>
<tr>
<td>Knee FL/EX-Foot PF/DF</td>
<td>C1:C3</td>
<td>Terminal swing</td>
<td>FS</td>
<td>F = 7.176, p = 0.015</td>
<td>NONE</td>
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<tr>
<td>Knee FL/EX-Foot PF/DF</td>
<td>C1:C3</td>
<td>Mid stance</td>
<td>FS</td>
<td>F = 4.984, p = 0.039</td>
<td>NONE</td>
<td></td>
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<tr>
<td>Knee FL/EX-Foot PF/DF</td>
<td>C1:C3</td>
<td>Late Stance</td>
<td>FS</td>
<td>F = 6.902, p = 0.017</td>
<td>LPF: more out-phase</td>
<td></td>
</tr>
<tr>
<td>Knee FL/EX-Foot PF/DF</td>
<td>C1:C2</td>
<td>Late Stance</td>
<td>FS</td>
<td>F = 6.958, p = 0.017</td>
<td>NONE</td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviations:**
- Phase: significant phase
- Sig Int = Significant interaction
- Int Stats = reported statistics for interaction
- Between = Independent t-test result between fatigue groups
- Time = Repeated measure ANOVA results within fatigue groups
- Velocity = paired t-test results between fatigue groups
- Groups: LPF = Low-Perceived Fatigue & HPF = High-Perceived Fatigue
- Velocity condition (VC): C1 = 10k 75% @ 2min; C2 = 10k 75% @ 4 min; C3 = 10k race
- Interval Condition: T1 = Interval at start of run; T2 = Interval one-third of run; T3 = Interval two-thirds of run; T4 = Interval at end of run
- Statistical Interactions: FTS = 3-way interaction (Fatigue*Interval*Velocity); FT = 2-way interaction (Fatigue*Interval); FS = 2-way interaction (Fatigue*Velocity)
Appendix 2: Chapter 2 Article Copyright

The article comprising Chapter 2 titled “Effects of treadmill running velocity on lower extremity coordination variability in healthy runners” has been submitted for publication in Human Movement Science. The publisher for Human Movement Science, Elsevier, allows pre-print manuscripts to be included in theses and dissertations (https://www.elsevier.com/__data/assets/pdf_file/0007/55654/AuthorUserRights.pdf). Therefore, no copyright approval was required for this manuscript.
APPENDIX 3: CHAPTER 3 ARTICLE COPYRIGHT

The article comprising Chapter 3 titled ‘Effects of cost of running on lower extremity coordination patterns’ is an Author’s Original Manuscript of an article submitted for consideration in Journal of Sports Sciences [copyright Taylor & Francis/society]; Journal of Sports Sciences is available at:

http://www.tandfonline.com/loi/rjsp20
The article comprising Chapter 4 titled ‘Effect of perceived fatigue on coordination patterns and variability following an interval treadmill run’ is an Author’s Original Manuscript of an article submitted for consideration in *Sports Biomechanics* [copyright Taylor & Francis/society]; *Sports Biomechanics* is available at:

http://www.tandfonline.com/toc/rspb20/current
CURRICULUM VITAE

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Education:
Ph.D. University of Nevada, Las Vegas (Projected) Summer 2017
Kinesiology, Biomechanics (Emphasis)
Dissertation theme: ‘Investigation into the possible effects performance thresholds have on coordination patterns and variability during endurance running’
Mentor: John A. Mercer

M.S. University of Nevada, Las Vegas Summer 2014
Kinesiology, Biomechanics (Emphasis)
Thesis title: ‘An evaluation of kinematic variables during stance phase of a training endurance run’
Mentor: Janet S. Dufek

B.S. University of Nevada, Las Vegas Fall 2011
Kinesiology

Academic Experience:
Graduate Assistantship University of Nevada, Las Vegas
Teaching Assistant – Kinesiology
Biomechanics of Endurance Performance (undergraduate/graduate) Spring 2017
Endurance Physiology (undergraduate/graduate) Fall 2015 & 2016
Biomechanics (undergraduate) Spring 2016
Research Assistant – Kinesiology 2014-2017
Laboratory Manager
Laboratory space scheduling
Laboratory organization
Ordering supplies
Equipment Integration & training
Vicon Motion Capture, Delsys Trigno EMG, Exeter Shoe Impact Tester, Noraxon EMG & Cosmed K4b2 Metabolic Testing unit
Data Acquisition and Analysis Mentor
Matlab & Visual3D
Research Assistant – Physical Therapy 2013-2014
Equipment Integration
Vicon (Bonita) Motion Capture, Delsys Trigno & Bertec FIT
Research Liaison for DPT students
Data Acquisition and Analysis Mentor

Teaching Assistant
Undergraduate Biomechanics Lab (KIN 346)
SIRC Laboratory Calendar Manager
Fitness Trainer Instructor

Professional Fitness Institute
Las Vegas, NV

2012-2013

2007-2008

Certificates & Programs:

Graduate College Mentorship Certificate Program
University of Nevada, Las Vegas
Spring 2017

Graduate College Research Certificate Program
University of Nevada, Las Vegas
Spring 2017

IRONMAN Certified Coach
Dec 2016

National Strength & Conditioning – Certified Personal Trainer
2007- Present

Courses Taught:

KIN 456/656 Biomechanics of Endurance Performance
Spring 2017

KIN 346 Biomechanics
Spring 2016

40 Undergraduate students
Introduction to Biomechanics

KIN 457/657 Physiology of Endurance Performance
Fall 2015 & 2016

Average 25 students (Undergraduate & Masters)
Exercise physiology topics as they relate to the endurance athletes, both from a performance and recovery perspective.

KIN 346 Biomechanics Lab Sections
Fall 2012-Spring 2013

KIN 743 Research Techniques of Biomechanics, TA
Spring 2015

Graduate course practical application laboratory experience
Demonstration of all equipment for students in the class

Research:

Grants:


Bailey, J.P. (2016) Graduate & Professional Student (GPSA) Travel Grant, University of Nevada, Las Vegas, USA $475


Bailey, J.P. (2015) Graduate & Professional Student (GPSA) Research Grant, University of Nevada, Las Vegas, USA $775

Bailey, J.P. and Dufek, J.S. (2012) INBRE (Institutional Development Award Network of Biomedical Research Excellence) Undergraduate Research Opportunity Program, University of Nevada, Las Vegas, USA $4000

Awards:

Publications:
Peer-reviewed Papers:


Refereed technical paper or conference proceedings:

Refereed poster presentations:


Bailey, J.P., Nordin, A.D., & Dufek, J.S. (Thematic Poster) Effects of stride length perturbations on anterior-posterior components during the stance phase of walking. American College of Sports Medicine (ACSM) 61st Annual Meeting, 5th World Congress on Exercise is Medicine and World Congress on the Role of Inflammation in Exercise, Health and Disease, Orlando, USA, May 2014.

Bailey, J.P., Nordin, A.D., & Dufek, J.S. Step length perturbations alter variations in center of mass horizontal velocity. 2013 Meeting of the American Society of Biomechanics, Omaha, USA, September 2013.


Non-refereed poster presentations:


Non-refereed podium presentations:


Invited Guest Lectures:


Service:

Committees:
Grant Review Committee, Graduate and Professional Student Association. Fall 2015-Spring 2016.
Mentorships:
Gaden, B. (Fall 2016). Undergraduate independent study – Data collection & processing.
Santos, I. (Fall 2016). Undergraduate Independent study – Data collection & processing.
Flores, L. (Summer 2016). INBRE (Institutional Development Award Network of Biomedical Research Excellence) Undergraduate Research Opportunity Program.

Laboratory tours:
Dawson Elementary Student Outreach (2015), Laboratory activity tours UNLV prospective students. (Vicon, Biodex, Alter-G, Shoe testing & Force plate demonstrations).
James Dexter, P.T., M.A. University of New Mexico, Director, Center for Gait and Motion Analysis, UNM Health Sciences Center, Division of Physical Therapy. Vicon-Delsys Trigno: integration and analysis demonstration.

Professional Memberships:
National Strength & Conditioning Association (NSCA-CPT) 2006-Present
American College of Sports Medicine (SW chapter & National) 2012-Present
American Society of Biomechanics (Student Member)