THE EFFECTS OF A 30-MINTUE RUN ON HIP ABDUCTOR STRENGTH AND HIP RUNNING KINEMATICS: A DYNAMICAL SYSTEMS APPROACH

by

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Li-Shan Chou

Existing literature has identified several risk factors for the development of lower limb injuries and musculoskeletal disorders in recreational runners, including hip abductor muscle strength deficits as well as abnormal patterns in hip running kinematics. Studies have indicated that hip abductor muscles play a role in stabilizing the hip during running and that hip abductor strength deficits are associated with the development of overuse injuries as well as abnormal hip kinematics while performing tasks upright. However, the relationship between hip abductor strength deficits and abnormal pelvic kinematics while running remains unclear.

This study intends to clarify the relationship between hip abductor muscle fatigue and associated hip kinematic changes in healthy runners by implementing a novel 30-minute approximately lactate threshold treadmill run as a fatigue protocol while investigating hip kinematic changes at 7 equidistant time points over the course of the protocol. In terms of analyzing hip kinematics, this study implements a dynamical systems approach, analyzing the variability of Trunk-Pelvis (Tr-P) and Pelvis-Thigh (P-T) segment couplings in the 3 anatomical planes, as well as a conventional analysis of individual hip kinematic variables, specifically pelvic drop, trunk lean, and hip adduction.

Twenty-three subjects between the ages of 18 – 40, who have not sustained major running related injuries, and regularly run at least 20 miles a week participated in this study. Participants performed a triplet of hip abductor muscle maximal voluntary contractions (MVCs) to establish a baseline and a post-fatigue strength assessment before and after a 30-minute run, during which kinematic changes were assessed through the use a 3-D motion capture system and 39 reflective markers placed on key anatomical landmarks.

Using a significance threshold of 0.05, it was found that hip abductor strength decreased significantly following the 30-minute protocol ($p < 0.0001$) while pelvic drop significantly increased ($p < 0.001$). Statistical analysis of the continuous relative phase variability data from Tr-P and P-T segment couplings in the three anatomical planes indicated that there was no significant within-subject effect of time. However, a two-way repeated ANOVA a significant between-subject effect of sex was found in the Tr-P segment coupling in the transverse plane ($p < 0.05$). Additionally, statistically significant interaction effects of sex and time were found in the sagittal and frontal plans of the P-T and Tr-P segment couplings ($p < 0.05$), respectively.

The findings of this study improve the current understanding of the relationship between hip abductor fatigue and hip kinematics in both healthy male and female runners, which may have implications for the development of effective injury prevention strategies and useful investigations in the future.

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I must begin by expressing how incredibly grateful to have been a member of the University of Oregon's Motion Analysis Laboratory. I want to give my sincere thanks to Professor Li-Shan Chou and my doctoral student mentor JJ Hannigan. Without their support, mentorship, and guidance, this project would not have been possible. They have been instrumental in facilitating my growth as a researcher and have helped me develop a strong appreciation for research and respect for the scientific process. I must also thank my lab partner Colin Lipps, who I've had the pleasure of working with for the past two years, and Theresa Chen, who provided consistent and enthusiastic assistance with software and hardware issues during the final few months of data collection. This thesis is a testament to the amazing people I've had the opportunity to work and I dedicate this body of work to the Motion Analysis Laboratory.

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And finally, Mom, Dad, and Eugene, I love you all so much. Thank you for the 22+ years (or 17+ years for you, Eugene) of love. I could write a 1000+ page piece about how much I love you all but my hands still hurt from finishing this thesis.

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Introduction

Running is one of the most popular recreational sports in the United States. A survey performed in 2016 indicated that the number of individuals participating in competitive running has tripled to 17.1 million in the past two decades[1]. It is worth noting that the number 17.1 million only encompasses the population of runners that participate competitively and that it does not come close to reflecting the total number of Americans that partake in the sport in either a competitive or noncompetitive capacity. As an activity, running is popular for its beneficial health outcomes including, but not limited to, increased aerobic capacity, lower blood pressure, cholesterol levels and better immune function.[2,3,4] Moreover, running is a highly accessible form of exercise that does not require significant financial investment prior to participating and can be performed in almost any setting.

While the benefits of running as a form of recreational exercise are well documented and commonly touted, running does come with risks. It is not uncommon for runners to experience a variety of injuries that generally arise from overuse of muscle groups and repeated impact. A review carried out in 2007 by Gent et al. indicated that the average injury rate among runners can vary widely from percentages as low as 19.4% to as high as 92.4% per year.[5] With average injury rates potentially approaching percentages as high as 92.4%, runners put themselves at risk of developing chronic musculoskeletal pathologies which can potentially compromise their physical well-being. Considering the sheer number of individuals that participate in running, it is prudent to investigate potential markers for injury to develop appropriate preventative and rehabilitative interventions. In doing so, it may be possible to mitigate the

morbidity of running related musculoskeletal pathologies within both injured and healthy running populations.

The research undertaken within the Department of Human Physiology's Motion Analysis Laboratory seeks to develop a reliable method to identify individuals at risk of developing an overuse running injury. Past studies conducted in the Motion Analysis Laboratory have examined the relationship between hip abductor muscle strength changes and resultant changes in abnormal running kinematics associated with running related overuse injuries.[19,20] These studies have largely employed pre-post study designs to determine if kinematics change in response to hip abductor fatigue interventions. However, the use of pre-post study designs does not permit the assessment of hip kinematics in response to graded degrees of muscle fatigue, necessitating a fatigue protocol that allows for the assessment of temporal kinematic changes.

This study hopes to bolster the current biomechanics literature's understanding of the relationship between hip abductor muscle strength and abnormal hip running kinematics. A 30-minute estimated lactate threshold run was implemented as a fatigue protocol. Throughout the protocol, individual hip kinematic data and continuous relative phase variability data of Trunk-Pelvis and Pelvis-Thigh coupled segments were collected at seven equidistant time intervals, allowing for temporal and between-sex analysis of kinematic changes in response to fatigue.

Background

Hip Abductor Muscles as a Focal Point of Investigative Inquiry

The hip abductor muscle group is composed of the gluteus medius, the gluteus minimus, the tensor fasciae latae, the sartorius, and the piriformis. Upon review of the literature, the hip abductor muscle group were identified as a focal area of investigative interest due to their suspected association with the development of chronic lower extremity injuries and pathologies associated with running. In a study performed by Niemuth et al. 2005, it was found that injured recreational runners with ipsilateral lower extremity injuries demonstrated significant deficits in hip abduction strength on the side of their injuries, indicating the existence of a potential relationship between hip abductor muscle group strength and chronic lower extremity injuries. [17]

Multiple studies have been conducted to investigate the relationship between hip abductor muscle strength and lower extremity injuries and pathologies. Past research has since identified excess pelvic drop, trunk lean[6,7], and hip adduction as potential kinematic markers[8] typical of individuals with chronic lower extremity pathologies. Additionally, individuals with chronic lower extremity pathologies have also been found to exhibit significantly weaker hip abduction strength compared to healthy controls, indicating that lower extremity musculoskeletal abnormalities are linked to deficits in hip abductor muscle strength as well.[8,15,16,17] While it is tempting to employ deductive reasoning and conclude that weak hip abductors are associated with abnormal kinematic markers that indicate a presence of lower extremity pathologies, the literature offers conflicting results regarding the potential relationship between hip abductor muscle strength and hip kinematics.

Studies that have explored the potential relationship between hip abductor strength and abnormal hip kinematics in healthy subjects have yielded conflicting results. In a study by Heinert et al. 2008 with 30 healthy subjects split equally into two subgroups, one subgroup consisted of subjects with high hip abductor strength while the other subgroup of subjects consisted of subjects with low hip abductor strength. It was found that there were no significant differences in hip kinematics between the two subgroups, suggesting that weakened hip abductors may not necessarily be linked to abnormal hip kinematics.[18] However, other studies involving the comparative analysis of subgroups of healthy subjects with differing hip abductor strengths have shown a moderate correlation between strength deficits and excess hip adduction and trunk lean, two potential kinematic markers of lower extremity pathologies.[20,21]

Investigations into the potential relationship between hip abductor strength and hip kinematics in runners with chronic lower extremity pathologies have also generated unclear results. Hip abductor strength deficits are well documented in runners with patellofemoral pain syndrome and rehabilitation protocols involving hip abductor strengthening regimen have been found to be effective in improving hip abductor strength and mitigating pain associated with overuse injuries.[19,20] Initially, it seems plausible that hip kinematics would also improve with increased hip abductor strength, however there is evidence that conflicts with this expectation. In a study by Esculier et al. 2015, comparing the hip kinematics of runners with PFPS to runners without PFPS, no significant between group differences were found in the kinematic variables associated with lower extremity overuse pathologies mentioned above or gluteus

medius muscle strength[21], refuting the association of hip abductor strength deficits with lower extremity pathologies.

Considering the contradictory results offered by past studies, the relationship between hip abductor strength and pelvic running kinematics, if there is one, has yet to be clarified, making the hip abductor muscles a worthwhile area of investigation. Due to the conflicting findings in the literature which suggest that the abnormal hip kinematics associated with injury are not reliably induced by fatigue, it is necessary to both validate existing and employ different kinematic assessments that can potentially serve as more reliable markers of kinematic changes resulting from strength alterations, and transitively, lower extremity overuse injuries. To accomplish the latter and former, this study used a dynamical approach towards hip kinematics, assessing the intersegment coordination between trunk-pelvis and pelvis thigh segment couplings in response to hip abductor strength deficits while also assessing change in pelvic drop, trunk lean, and hip adduction changes in response to fatigue as well.

Intersegment Coordination: A Dynamical Systems Approach to Hip Kinematics

While past studies have investigated individual hip running kinematic variables in response to fatigue. No studies to date have implemented a dynamical systems approach and investigated the interaction between anatomical segments proximal to the pelvis and the pelvis itself in response to fatigue.

In 1998, Hamill et al. proposed a method of identifying the presence of chronic overuse injuries using dynamical systems theory[22], investigating the coordinated coupling of proximal segments or joints rather than individual injury factors such as

pelvic drop, trunk lean, and hip adduction. Dynamical system theory evaluates the interaction of multiple injury factors by determining the variability of a system through an approach called continuous relative phase, abbreviated to CRP, which combines spatial and temporal information into a singular coordinative measure that can then be used to determine the variability of a system.[22,23]

Analyzing coordinative variability is a critical to the dynamical systems approach as it quantitatively describes how moving joints or segments interact to control movement. Literature has implicated excessively low coordinative variability as an indication of increased risk of overuse injury. Lower variability indicates that there is a narrower range of repeatable motions for given joints and segments which has been speculated to cause stress on connective tissues.[22] Runners that possess chronic overuse injuries and pathologies tend to display lower continuous relative phase variability between proximally coupled lower extremity segments.[22,23,24] For example, this has been demonstrated in the literature that runners with PFPS display lower CRP between thigh-shank and shank-foot segment couplings compared to healthy runners.[22]

Few studies have investigated the coupling of the pelvis segment to proximal thigh and trunk segments but no study to date has assessed coordinate variability changes within the latter and former segment couplings in response to fatigue.[25] By analyzing the continuous relative phase variability of Trunk-Pelvis and Pelvis-Thigh segment couplings, it may be possible to identify an alternative and more reliable means of identifying lower extremity injury development.

Use of a Lactate Threshold Run as a Fatigue Protocol

To investigate the kinematic changes associated with skeletal muscle fatigue, studies have employed a wide range of fatigue protocols to induce strength reduction in skeletal muscles, ranging from isometric contractions of specific muscle groups to exhaustive runs depending on the intended study design. Given the variety in investigative aims and logistical limitations, an established consensus has yet to be reached in identifying an ideal fatigue protocol.

However, a systematic review by Santamaria et al. in 2010, which investigated discrepancies between the various fatigue protocols and means of evaluating fatigue employed within the literature, called for the implementation of fatigue protocols that induce generalized fatigue and study designs that permit the assessment of temporal kinematic changes in response to graded degrees of fatigue. The review found that fatigue protocols that induce generalized fatigue rather than fatigue in specific muscle groups were found to be favorable as they better simulated the demands experienced by subjects in their respective active environments. Study designs that allow for temporal assessments of fatigue or markers of fatigue were proposed to be advantageous as identifying the timing of fatigue effects could prove valuable in injury prevention[26].

Employment of fatigue protocols aimed at inducing generalized fatigue is well represented in past investigations into the effects of fatigue on running kinematics. In a 2011 study by Abt et al., subjects partook in a fatiguing run at an identified ventilatory heart rate threshold as a fatigue protocol.[27] Similar protocols was used by Dierks et al. 2010 and Derrick et al. 2002 in which subjects were fatigued by running on a treadmill at a self-selected training pace and completing a run at their most recent 3200m pace at

maximal intensity, respectively.[28,29] In all of these studies, kinematic variables of interest were measured prior to and after the fatigue intervention. However, only Derrick et al. 2002 has attempted to assess temporal kinematic changes associated with increasing time to fatigue by measuring kinematic variables in the middle of the fatigue protocol.

Sex-Related Kinematic Differences

While the salient aim of this project was to investigate existing and potentially improve means of identifying lower extremity overuse injury risk for all runners, it is important to understand that there are well documented sex differences in regard to lower extremity overuse injury morbidity as well as hip abductor strength deficits and abnormal running kinematics.

It has been found that there is a higher incidence of PFPS in females. While PFPS may not be completely representative of all lower extremity overuse injuries that afflict females, the fact that it is common and occurs more frequently among females has warranted substantial investigations into potential contributing risk factors to PFPS development in females. A systematic review by Prins et al. 2009 [30] indicated that females with patellofemoral pain syndrome exhibit significantly decreased abduction strength compared with healthy controls. Additionally, multiple other studies that have found that females at risk of or suffering from lower extremity injuries tend to demonstrate greater deficits in muscle strength, including that of the hip abductors, compared to healthy female and male counterparts. [6,31] The literature provides convincing evidence that significant differences in hip abduction strength exist between males and females.

Regarding individual hip joint kinematic markers of injury, the literature provides evidence of hip kinematics differences existing between sexes. In a study conducted by Weeks et al. 2015, hip adduction range in males was found to be significantly less than that of females.[32] Additionally, a 2012 study by Nakagawa et al. observed significant between sex differences in pelvic drop, trunk lean, and hip adduction. However, the assessment of individual hip kinematic variables do not seem to reliably demonstrate that there are sex-dependent differences in the way hip kinematics change in response to muscle fatigue.[33,34]

It should be noted that no study to date has used continuous relative phase variability as means to identify and distinguish sex influenced kinematic changes in response to fatigue. Implementation of a dynamical approach to assess variability changes between segment couplings could prove to be useful in distinguishing characteristics of fatigue induced, sex-related differences in hip kinematic changes.

It is necessary to understand the role of sex in influencing kinematic changes in response to fatigue; understanding the effects and interaction of sex could prove useful in fine tuning existing injury detection and rehabilitation methods. This study will employ two-way repeated measures ANOVAs to detect the presence of a significant between-subjects effect of sex as well as potential interactions between sex and time for both individual hip kinematics and CRP variability.

Investigative Aims and Hypothesis

Understanding that weakened hip abductor muscles are typical of individuals suffering from overuse injuries or pathologies, and that excess pelvic drop, trunk lean, hip adduction, and lower coordinate variability are potential markers for increased risk of overuse injuries, this study intends to assess the response of individual hip kinematic variables and CRP variability of trunk-pelvis and pelvis-thigh segment couplings in response to hip abductor muscle changes over the course of a 30-minute lactate threshold running protocol. Additionally, this study also intends to assess if males and females exhibit different changes in their individual hip kinematic variables and CRP variability in response to hip abductor strength changes.

Regarding the kinematics associated with the individual hip joint, based on the findings of Nakagawa et al. 2012 and Noehren et al. 2013 [6,7], it was hypothesized that pelvic drop, trunk lean, and hip adduction would increase in response to the protocol and a significant main effect of time would be detected for each variable. However, for the individual hip joint kinematic variables, no between-subjects effect of time was expected to be observed. Regarding the variability data generated by Trunk-Pelvis and Pelvis-Thigh segment couplings, it was hypothesized that CRP Deviation Phase variability for both couplings in all anatomical planes would decrease over the course of the protocol upon reviewing the findings of Miller et al. 2008.[9] Additionally, it was anticipated that CRP Deviation Phase variability data would demonstrate a within-subjects effect of time and a between-subjects effect of sex for both couplings in all anatomical planes.

Methods

The IRB approval of this study was granted in 2016 and data collection began during the Fall of 2016. All subjects were provided documents detailing the study and signed an informed consent form approved by the University of Oregon.

Subject Qualification Criteria and Recruitment

To qualify as a participant, prospective subjects were required to be between 18 to 45 years old, maintain an average weekly running mileage of at least 20 miles per week over the past month, and report no major injuries in the six months preceding their testing date.

In total, 23 qualified subjects were recruited for this study. Of the original pool of 23, 20 subjects completed the entire experimental protocol and had their resulting strength and kinematic data used for statistical analysis. The three subjects that were not factored into statistical analysis yielded poor kinematic data that could not be processed effectively. This group of 20 subjects consisted of 11 females and 9 males.

Anthropometric Data:

Subjects' anthropometric data were recorded to calculate running kinematics. Anthropometric measurements recorded include:

- Height (cm)
- Weight (kg)
- ASIS width (cm)
- Thigh Length (cm)
- Thigh Circumference (cm)
- Calf Length (cm)
- Calf Circumference (cm)
- Knee diameter (mm)
- Malleoli Height (cm)
- Malleoli Width (mm)
- Foot Length (cm)
- Foot Width (cm

ASIS width was defined as the distance between the bilateral anterior superior iliac spines, bony projections of the pelvis' iliac bones. Thigh Length was measured from the greater trochanter of the femur to the lateral epicondyle of tibia. Calf length was defined as the distance between the lateral epicondyle and the lateral malleolus. Thigh circumference measurements were taken at the halfway mark between the greater trochanter and lateral epicondyle. Calf circumference measurements were taken at the widest point of the calf.

Protocol Overview

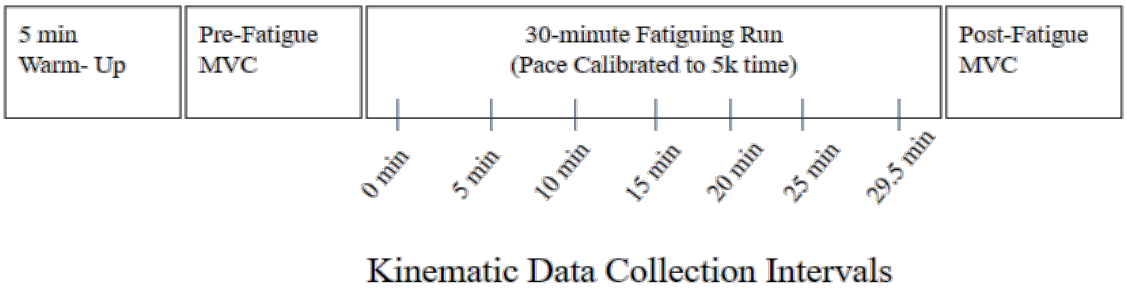


Figure 1: Outline of the experimental protocol performed by each subject.

Participants began by performing a 5-minute warm up run on a treadmill at a self-selected pace. Following this warm up run, subjects' anthropometric measurements were collected prior to the initial round of strength testing. Using a Biodex 3 Dynamometer system, a preliminary strength assessment was obtained. Participants were instructed to perform three maximal voluntary contractions with their dominant limb, as defined by the preferred leg to use when kicking a soccer ball, while assuming a hip side-lying position to facilitate isolated contractions of the hip abductor muscles. Each maximal voluntary contraction was followed by a fifteen second rest period.

Verbal encouragement and visual feedback was provided to subjects during the strength assessment.

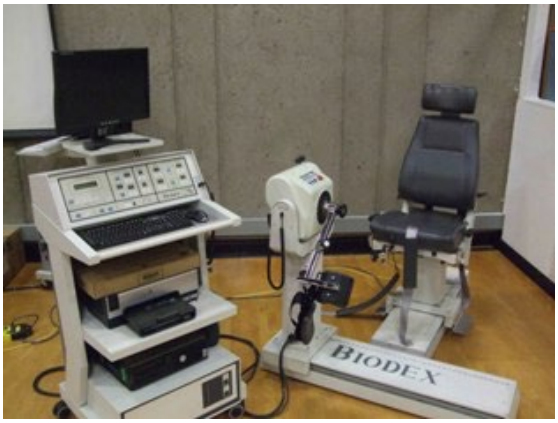


Figure 2: Biodex 3 dynamometer used to assess hip abductor strength

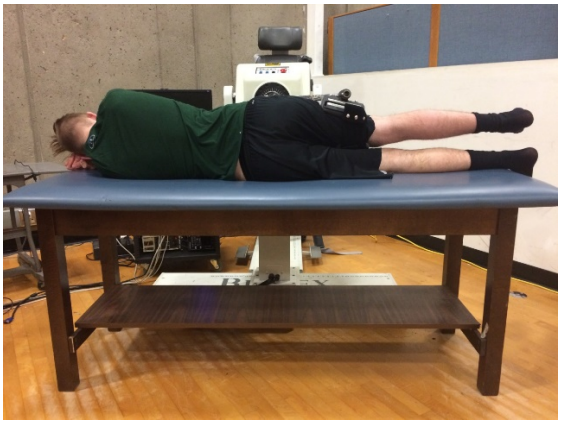


Figure 3: The hip side-lying position is shown above.

Afterwards, a 12-camera motion capture system (Motion Analysis Crop., Santa Rosa, CA) sampling at 200 Hz was used to record three-dimensional reflective marker trajectories. A modified Helen Hayes marker set of 39 reflective markers[35] was placed on subjects' body segments including the head, trunk, arm, hand, pelvis, thigh, shank, rearfoot, and forefoot. Prior to beginning the protocol and the removal of the medial knee and ankle markers, a ten second static capture of subjects with legs shoulder width apart and arms extended outwards in the frontal plane was collected.

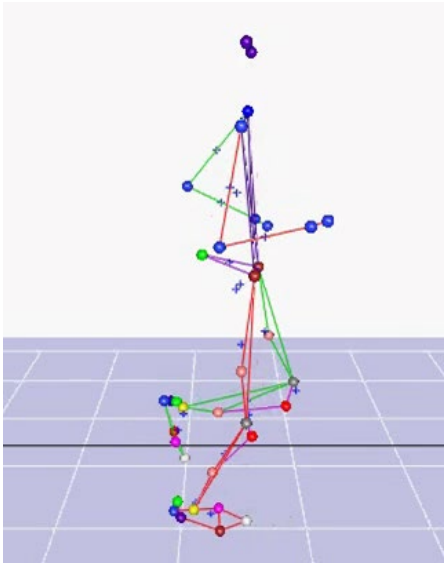


Figure 4: Sample 3-dimensional model of a subject running created from the 35 reflective markers and the 12-camera motion capture system

Subjects then began their 30-minute treadmill run at a lactate threshold pace calibrated to their most recent 5,000m time in accordance to Jack Daniel's VDOT Calculator[36] with a set of 35 reflective markers to eventually generate 3-dimensional computer models (Figure 3). Beginning at t = 0 minutes, a 30-second dynamic capture of subjects was collected every five minutes until t = 29.5 minutes, yielding a total of seven dynamic captures of subjects at different, equidistant time intervals of their protocol.

Immediately following the conclusion of the 30-minute protocol, subjects performed a post-intervention strength assessment. Using the same hip-sidelying position and limb used to perform the initial baseline strength assessment, subjects concluded the experimental protocol by completing a second series of three maximal voluntary contracts. Like before, subjects were provided with fifteen seconds of rest after each maximal voluntary contraction. They were also provided with verbal encouragement and visual feedback during this final round of MVCs.

Reflective Marker Placement:

Two markers were placed on the head directly superior to the ears, defining the head segment. Upper extremity segments were defined through a total of eight reflective markers which were placed on the acromial processes of the clavicles, lateral epicondyles of the humeri, the radiocarpal joints, and hands. The pelvis was defined with three markers, two placed on both anterior superior iliac spines and one placed between the posterior iliac spines. The thighs were defined by six markers, three per side. Per leg, two markers were placed on the medial and lateral epicondyles of the femur and another and one marker was placed equidistant between the greater trochanter and lateral epicondyles. The shanks were defined by placing markers on the tibial tuberosity, later and medial malleoli, and inferior to the calf muscle. Each foot had six markers placed to define the forefoot and rearfoot. The forefoot was defined through a triplet of markers placed on the 5^{th} metatarsal, navicular, and middle toe of the foot. The rearfoot was defined through two markers placed in line on the heel with another marker on the lateral aspect of the heel.

Data Analysis

I. *Hip Abductor Strength Analysis*

A Biodex System 3 Dynamometer recorded and the maximal torque generated by the series of three maximal voluntary contractions performed by each subject before and after the protocol. The torque values from the triplets were then averaged. This resultant averaged torque was then normalized to each subject's body mass. Using

SPSS, paired t-test were then employed to detect significant changes in normalized torque before and after completing the protocol.

II. *Individual Hip Joint Kinematic Data Calculation*

Using Cortex 6.0 Motion Capture Software, reflective marker trajectories were identified for each subject's seven dynamic captures. Analysis was directed towards the stance phase of the gait cycle, beginning at heel strike (0% stance phase) and ending at toe-off (100% stance phase). Heel strike was defined as the frame of the dynamic capture where subjects' bottom heel marker contacted the treadmill. Toe-off was defined as the frame where the toe marker was not in contact with the treadmill's surface. For each of the seven dynamic capture collected, stance phases from three gait cycles were obtained and used for joint and segment angle calculations, allowing for the assessment of pelvic drop, trunk lean, and hip adduction throughout the course of the protocol. For each of the seven time intervals, a final mean degree of pelvic drop, trunk lean, and hip adduction wasrecorded by averaging resulting degree of excursion of these variables during the stance phase of three gait cycles.

With an in-house LabView (National Instruments, Austin TX) program called Running Gait Analysis 3.0, the degree of excursion for pelvic drop, trunk lean, and hip adduction over the course of a given stance phase was calculated by measuring the joint angles in each anatomical plane for each percent of the stance phase. The degree of excursion for each of the three variables was defined by the difference between the

initial angle at heel strike and the peak angle of motion which was defined as the maximal degree of motion achieved during stance phase (Figure 5).

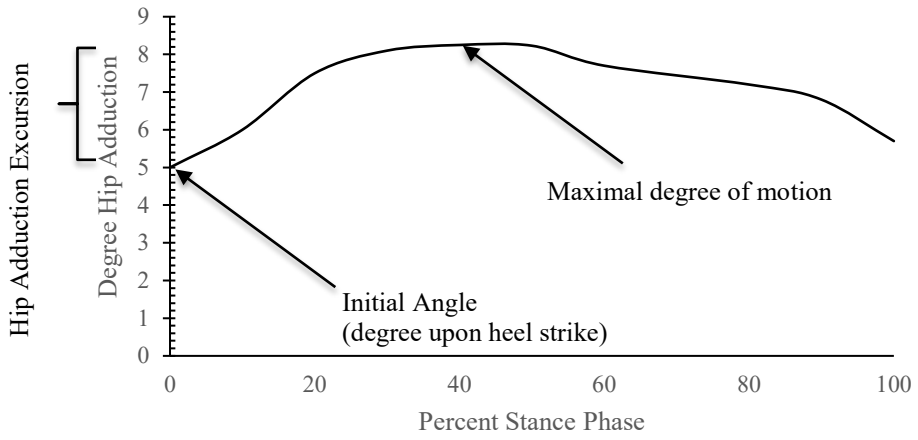


Figure 5: Sample graph detailing how kinematic variable measures were obtained, such as hip adduction in this case.

Using SPSS, paired t-tests were employed to compare pelvic drop, trunk lean, and hip adduction values before and after the protocol. For each of the three kinematic variables, a seven-leveled one-way repeated measures ANOVA with a Bonferroni correction as well as a two-way repeated measures ANOVA were employed. The 7-level one-way repeated measures ANOVA was used to detect significant within-subjects effect of time on the three variables of interest. The two-way repeated measures ANOVA was used to assess the effect of sex as a between-subjects factor over the course of the protocol and evaluate interaction effects between sex and time elapsed.

III. Intersegment Coordination; CRP Calculation

Similar to the hip kinematic data analysis, for each dynamic capture collected, stance phases from three gait cycles were identified and for data analysis. Using the processed dynamic captures and the Running Gait Analysis v3.0 program, continuous

relative phase variability data for Trunk-Pelvis and Pelvis-Thigh segment couplings were attained, for each anatomical plane, in each dynamic capture's triplet of gait cycles.

For each percent stance phase, the angular position ($\boldsymbol{\theta}$) and angular velocity ($\boldsymbol{\omega}$) of each segment was normalized to a value between 1 and -1 using:

$$\boldsymbol{\theta i} = \frac{2 * [\theta i - \min(\theta i)]}{\max(\theta i) - \min(\theta i)}$$

$$\boldsymbol{\omega i} = \frac{\omega i}{\max\{\max(\omega i), \max(-\omega i)\}}$$

Then, the normalized angular velocity and normalized angular position were plotted on a polar coordinate plot with the x-axis representing normalized angular position and the y-axis representing normalized angular velocity (Figure 6). The phase angle ($\boldsymbol{\varphi}$) of each percent stance phase was then calculated using:

$$\boldsymbol{\varphi = \tan{-1}(\omega/\theta)}$$

$$\boldsymbol{\varphi = \tan{-1}(\omega/\theta)}$$

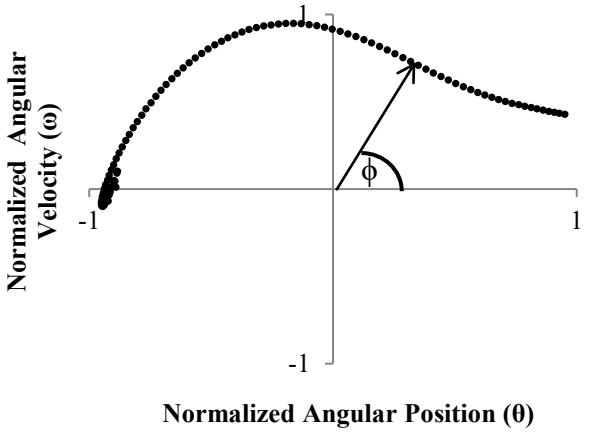


Figure 6: Normalized angular velocity (ω) on the y-axis plotted against normalized angular position (θ) on the x-axis.

The continuous relative phase between coupled segments was defined as the difference between the phase angles of adjacent segment pairings at a given percent

stance phase: phase angles of distal segments were subtracted from the phase angles of proximal segments for every percent stance phase (Figure 7).

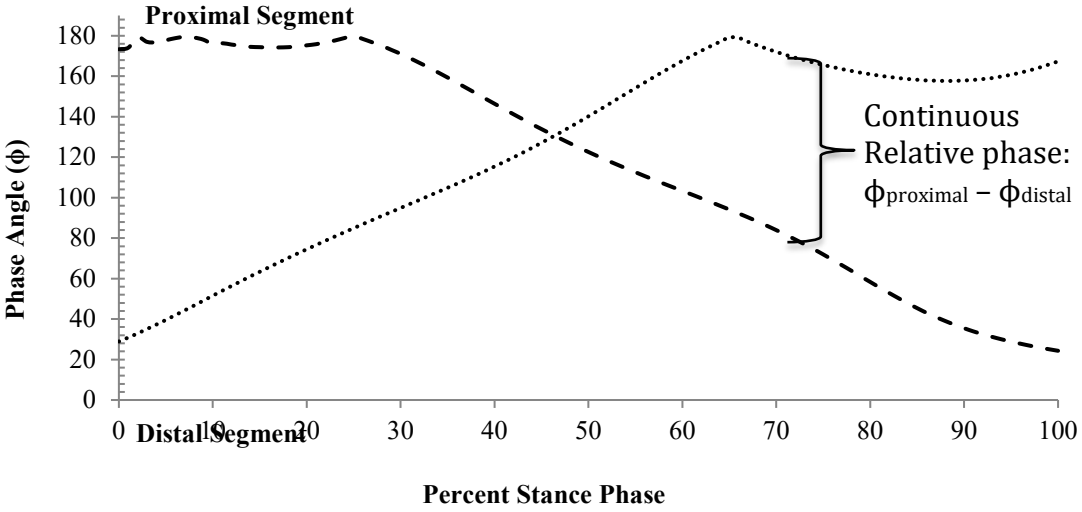


Figure 7: Phase angles (ϕ) of proximal and distal segments plotted against percent stance phase (%). Subtracting distal segment phase angles from proximal segment phase angles yield the continuous relative phase.

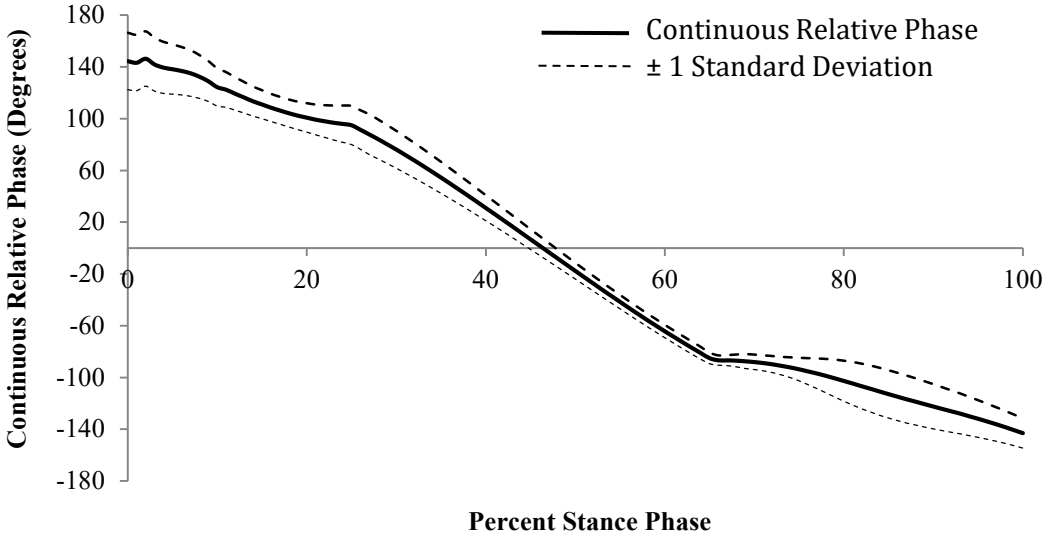


Figure 8: Continuous relative phase with standard deviation for a segment coupling plotted against percent stance phase

The CRP variability was obtained by generating the standard deviation of the CRP values across the three stance phases analyzed per data collection interval, for each percent stance phase (Figure 8). Afterwards, for each data collection interval, a

composite variability value, known as deviation phase, was obtained which represents the average coordinate variability exhibited by a segment coupling over an entire stance phase. Statistical analyses of both deviation phase variability changes over the course of the protocol as well as discrete percentage stance phase variability changes before and after the protocol were performed. SPSS was used to perform statistical analysis on all CRP variables of interest.

IV. Statistical Analysis

Strength data from the subjects were normalized to their body mass. Afterwards, a paired two-way T-test was used to assess for statistically significant strength changes in response to the 30-minute run.

For the kinematic variables of interest, a two-way repeated measures ANOVA was employed to detect if main effects of time and sex as well as any interaction effect between the latter and former were significant. If significant interaction effects are detected, subsequent one-way repeated measure ANOVAs with Bonferroni correction were used to determine significant presence of main effects pending visual analysis of data plots. If no main effect of time was detectable, a paired t-test was then used to assess if significant kinematic changes occurred in response to the experimental protocol.

V. Verification of Pre-Post Statistical Tests for CRP Deviation Phase Measures

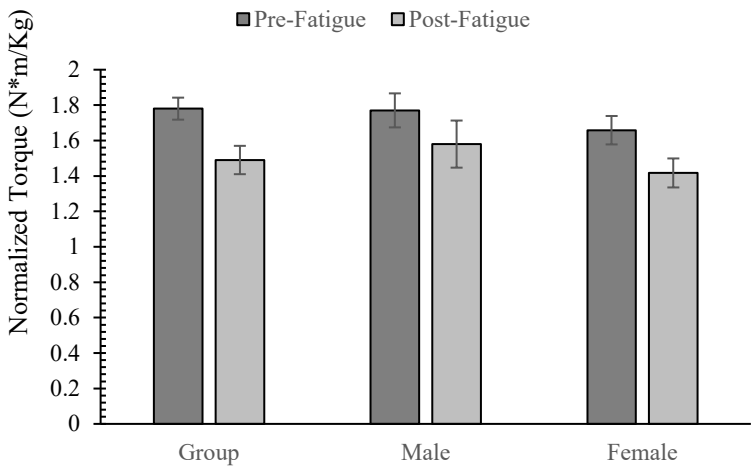
Because deviation phase gives a singular average variability value over the course of a stance phase, investigating variability changes within discrete percentage

portions of stance phase is necessary to avoid overlooking potential variability changes within key periods of the stance phase. Stance phases of dynamic captures from time interval one and time interval seven were broken into four discrete percentage intervals: 0-15%, 16-50%, 50-84%, and 85-100%, corresponding with the loading response, mid stance, terminal stance, and pre swing periods of stance phase[38]. An average variability within each discrete percentage interval was obtained for each individual subject, allowing for a group average variability of each discrete percentage interval to then be derived. Paired T-tests were then employed to assess average group variability changes in the discrete percentage portions of stance phase between the first and last time intervals, for both Trunk-Pelvis and Pelvis-Thigh segment couplings in the three anatomical planes.

Results

Hip Abductor Muscle Strength Data

Mean normalized torque values and associated standard deviations are depicted on figure x and table x. Table x also displays percent decline in normalized torque for the entire participant pool and sex-based sub-groups. T-tests performed indicate statistically significant ($p < \alpha = 0.05$) decreases in normalized torque across the entire subject pool ($p < 0.001$) as well as male and female subgroups ($p < 0.05$).



Grouping	Mean Pre-Intervention Torque (N*m/Kg)± SE	Mean Post-Intervention Torque (N*m/Kg)± SE	Percent Decline in Normalized Torque	P-Value
All Participants	1.71 ± 0.28	1.49 ± 0.34	12.7%	0.0009*
Males (n=9)	1.73 ± 0.29	1.54 ± 0.40	15.3%	0.039*
Female (n=11)	1.67 ± 0.26	1.41 ± 0.27	11.5%	0.014*

Figure 9: Normalized torque (N·m/Kg), generated by subject' MVCs, prior to and following the protocol for the entire participant group, males, and females

Table 1: Normalized torque values and changes within the participant pool

* Indicate statistically significant changes, $p < 0.05$

Pelvic Drop, Trunk Lean, Hip Adduction Data

Two-way repeated measures ANOVAs performed on pelvic drop, trunk lean, and hip adduction did not detect a statistically significant within-subjects main effect of time or between-subjects effect of sex. No statistically significant presence of interaction effects were observed either. Paired t-tests did not detect statistically

Measure	2-way repeated measures ANOVA p-value (effect of time):	2-way repeated measures ANOVA p-value (effect of sex):	Interaction effect (time * sex) p-value

significant changes in trunk lean or hip adduction following the protocol but did indicate a significant increase in pelvic drop following the intervention ($p < 0.001$). It should be noted that within-subjects effect of time was trending towards significance in the case of pelvic drop.

Measure	Time Interval 1	Time Interval 7	P-Value
Pelvic Drop	p = 0.07	p = 0.62	p = 0.27
Trunk Lean	p = 0.85	p = 0.15	p = 0.55
Hip Adduction	p = 0.68	p = 0.93	p = 0.881

Table 2:

Measure	Mean Degree Excursion ± SE	Mean Degree Excursion ± SE	P-Value
Pelvic Drop	12.9 ± 4.3	15.5 ± 3.8	p = 0.0001*
Trunk Lean	1.6 ± 0.45	1.6 ± 0.32	p = 0.87
Hip Adduction	7.3 ± 9.70	6.9 ± 0.83	p = 0.87

Resultant p-values from one-way and two-way ANOVAs performed on pelvic drop, trunk lean, and hip adduction across the entire participant pool

* Indicate statistically significant changes, $p < 0.05$

Table 3: Paired t-test and average degree of excursion for pelvic drop, trunk lean, and hip adduction at time interval one (T1) and time interval seven (T7)

* Indicate statistically significant changes, $p < 0.05$

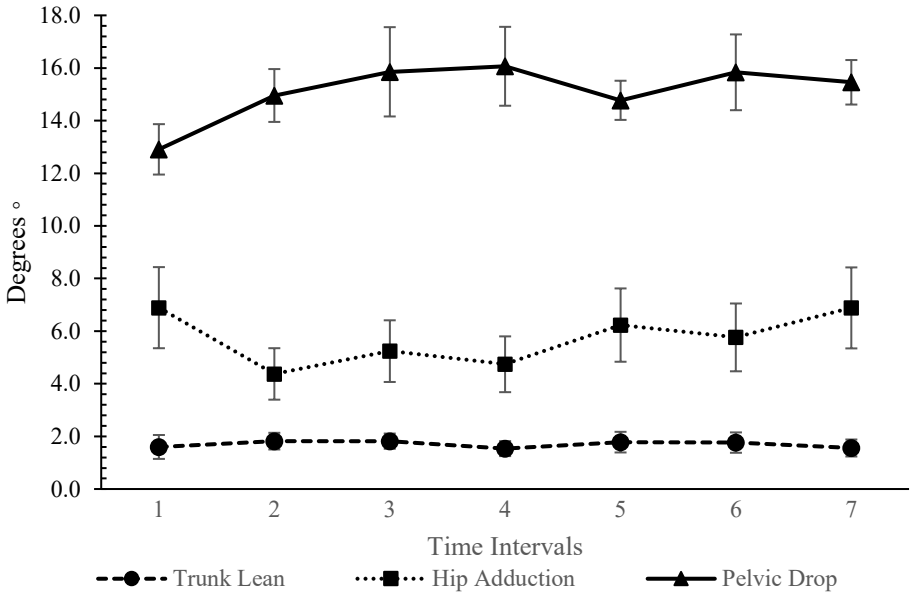


Figure 10: Trunk lean, hip adduction, and pelvic drop values in degrees plotted against the seven data collection intervals (with interval 1 = 0 minutes, and interval 7 = 29.5 minutes). No significant within-subjects effect of time was detected.

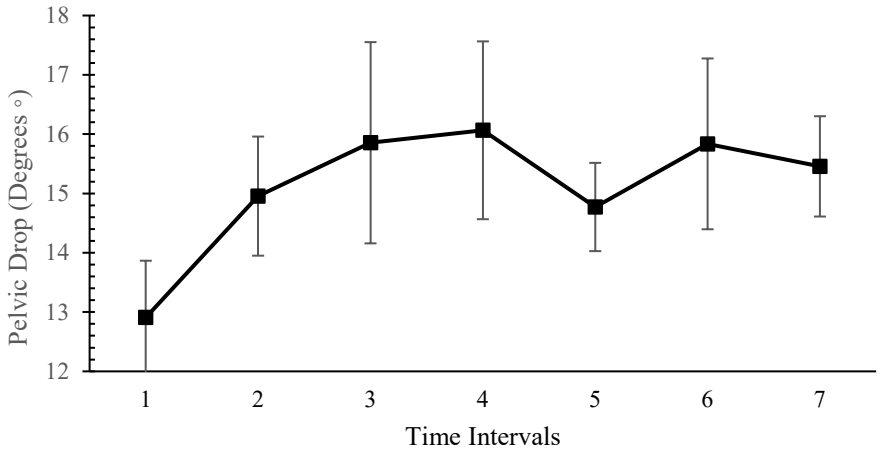


Figure 11: Pelvic drop, with standard error bars, in degrees plotted against the seven data collection intervals. Within-subjects effect of time was found to be trending towards significance.

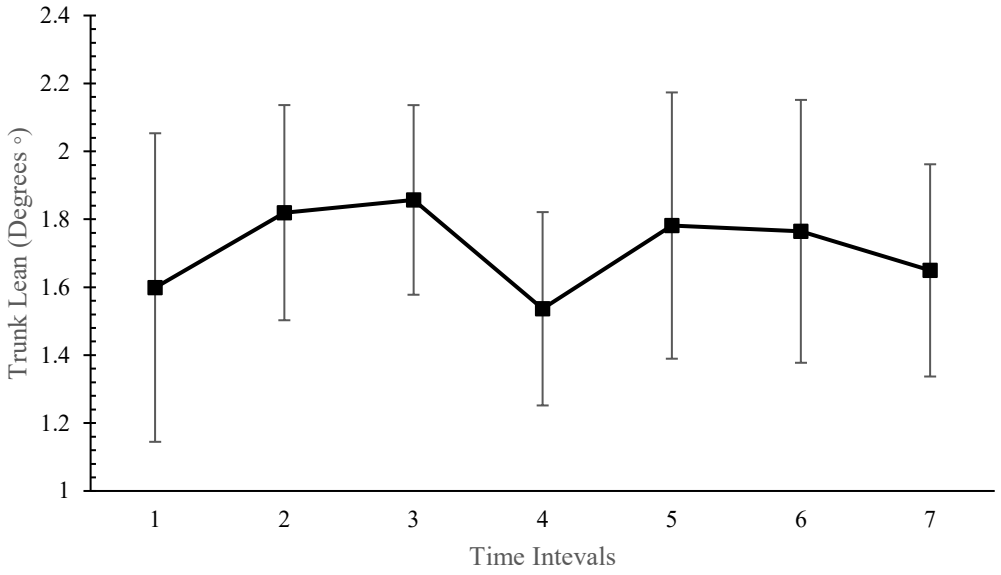


Figure 12: Trunk lean, with standard error bars, in degrees plotted against the seven data collection intervals. No significant within-subjects effect of time was detected.

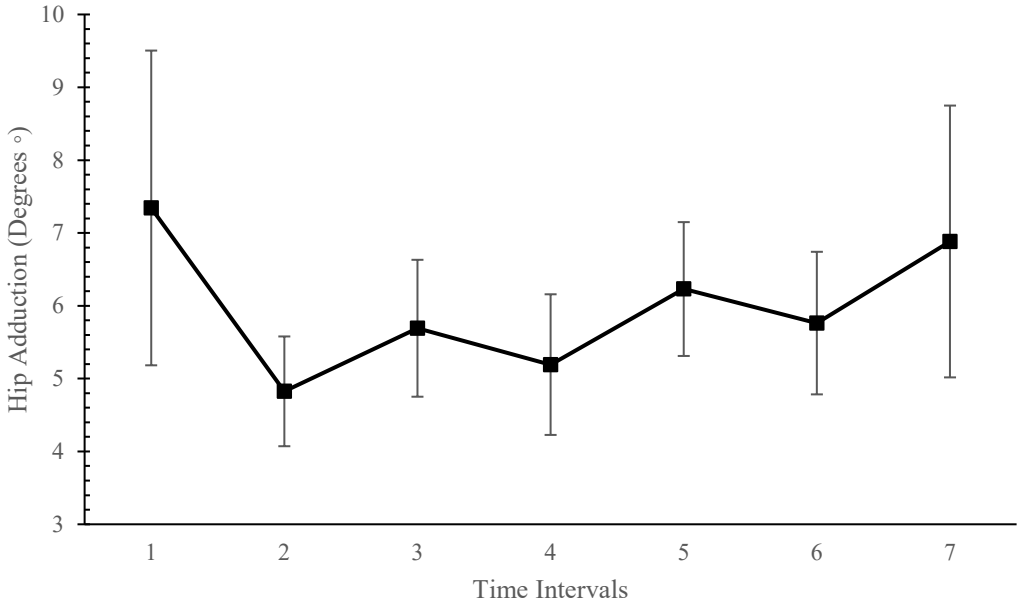


Figure 13: Hip Adduction, with standard error bars, in degrees plotted against the seven data collection intervals. No significant within-subjects effect of time was detected.

CRP Deviation Phase Data

Two-way repeated measures ANOVAs conducted on the above segment couplings in the three anatomical planes revealed a significant between-subjects effect of sex for only the Pelvis-Thigh segment coupling ($p < 0.05$) in the transverse plane. No significant within-subjects main effect of time was found. Significant interaction effects between time elapsed and sex were detected in the Tr-P frontal plane, the Tr-P transverse plane, and the P-T Sagittal plane ($p < 0.01$). Subsequent one-way repeated ANOVAs performed for the CRP DP data of male and female subjects showed a significant main effect of time for females in the Tr-P Frontal and P-T Sagittal planes ($p < 0.05$).

Measure	2-way rmANOVA p-value	2-way rmANOVA p-value	2-way rmANOVA interaction

Table 4: Two-way repeated measures ANOVA (rmANOVA) p-values detailing effects of time and sex as well as the interaction effect of time by sex for the variability of sagittal, frontal, and transverse planes of both Trunk-Pelvis and Pelvis-Thigh segment couplings.

	(effect of time):	**(effect of sex):**	**effect (time*sex) p-value:**
Tr-P Sagittal	p = 0.57	p = 0.51	p = 0.597
Tr-P Frontal**	p = 0.25	p = 0.77	p = 0.028*
Tr-P Transverse**	p = 0.65	p = 0.09	p = 0.089
P-T Sagittal	p = 0.45	p = 0.14	p = 0.006*
P-T Frontal	p = 0.83	p = 0.63	p = 0.593
P-T Transverse	p = 0.69	p = 0.01*	p = 0.944

*indicates significance ($p < \alpha = 0.05$)
**greenhouse-geisser corrected p-value

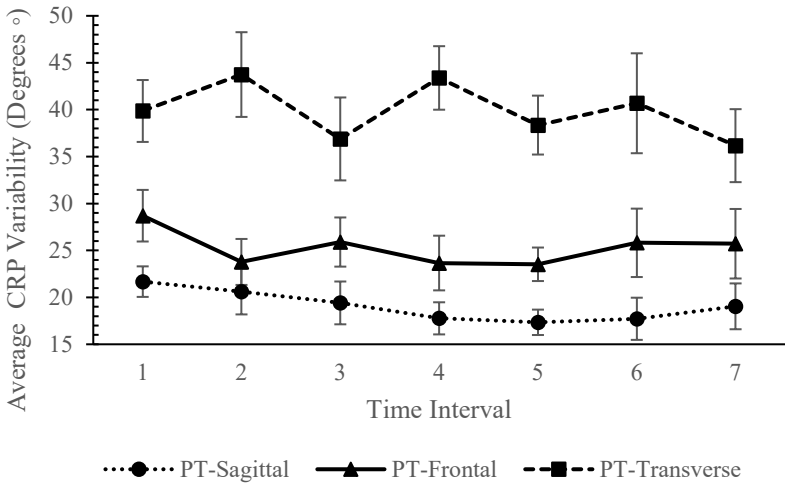


Figure 14: Average CRP variability, across the entire participant pool, for the Pelvis-Thigh segment coupling in the three anatomical planes and respective standard error bars plotted against the seven time intervals of data collection. No significant effect of time was detected.

Measure	Group Percent Variability	Male (n=9) Percent	Female (n=11) Percent

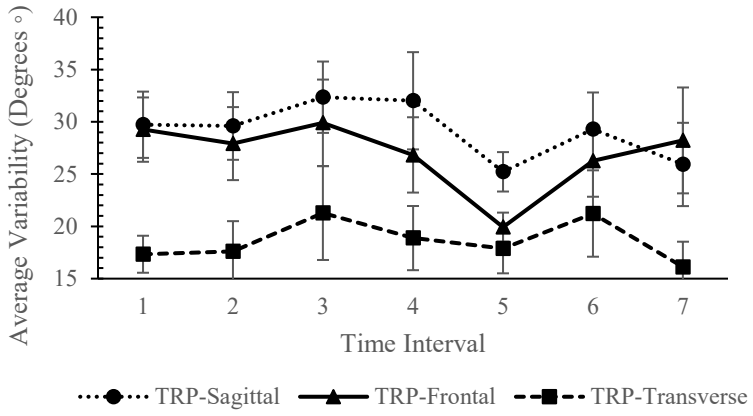


Figure 15: Average CRP variability, across the entire participant pool, for the Trunk-pelvis segment coupling in the three anatomical planes and respective standard error bars plotted against the seven time intervals of data collection. No significant effect of time was detected.

	Change (T1-T7) (%)	Variability Change (T1-T7) (%)	Variability Change (T1-T7) (%)
P-T Sagittal	- 4.9 ± 12.6	32.9 ± 21.7	-35.9 ± 4.9
P-T Frontal	4.3 ± 17.4	21.6 ± 29.0	-9.8 ± 21.3
P-T Transverse	5.7 ± 15.8	1.2 ± 26.3	-9.3 ± 20.1
Tr-P Sagittal	9.2 ± 20.4	34.3 ± 39.4	-11.3 ±18.0
Tr-P Frontal	11.1 ±19.7	61.8 ± 36.2	-30.3 ± 9.4
Tr-P Transverse	8.5 ±19.9	51.3 ± 38.8	-6.5 ± 9.7

Table 5: Percent change in P-T and Tr-P segment coupling variability, in all three anatomical planes, with standard error for the entire subject group as well as male and female subgroups: between time interval 1 and time interval 7.

Table 6: P-values from one-way repeated measures ANOVA for male and female subgroups. Significant main within-subjects effect of time was found for females in P-T sagittal and Tr-P frontal planes.

*indicates significance ($p < \alpha = 0.05$)

Measure	2-way rmANOVA Female p-value:	2-way rmANOVA Male p-value:
P-T Sagittal	p = 0.043*	p = 0.28
Tr-P Frontal	p = 0.017*	p = 0.23

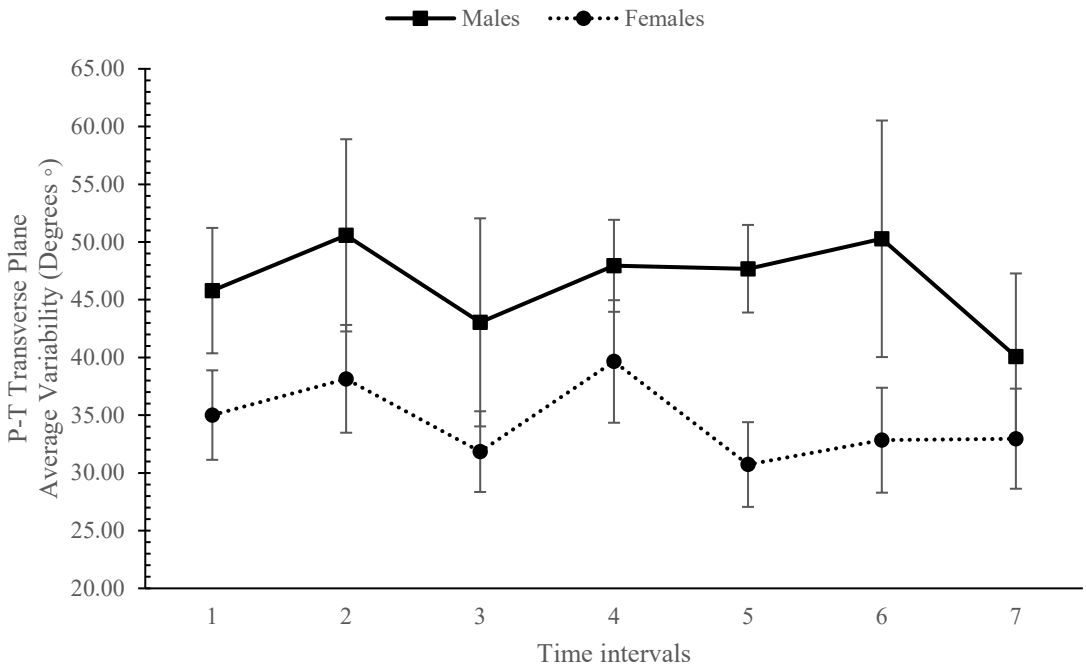


Figure 16: Average P-T transverse plane variability for male and female participants and respective standard error bars plotted against the seven time intervals of data collect.

Time Interval	Male Average Variability ± SE	Female Average Variability± SE
1	45.79 ± 5.43	35.01 ± 3.87
2	50.58 ± 8.32	38.15 ± 4.67
3	43.04 ± 9.01	31.85 ± 3.49
4	47.94 ± 3.98	39.65 ± 5.31
5	47.69 ± 3.79	30.73 ± 3.67
6	50.28 ± 10.2	32.83 ± 4.53
7	40.08 ± 7.19	32.96 ± 4.33

Table 7: Male and female average variability in the P-T segment coupling's transverse plane with standard error for each time interval of data collection.

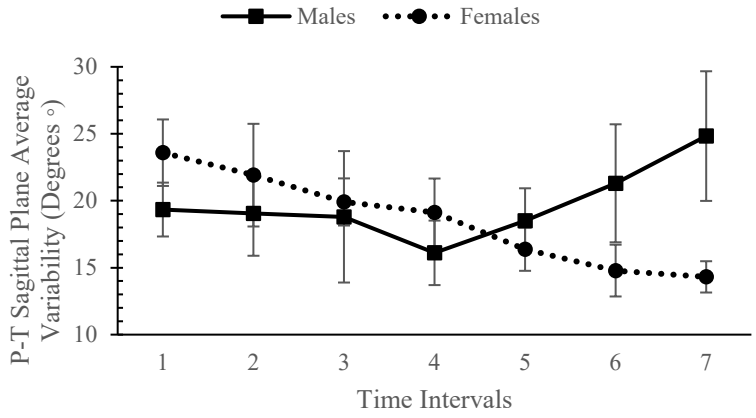


Figure 17: Average P-T sagittal plane variability with standard error bars for male and female participants plotted against the seven time intervals of data collection. Note that males increased in variability following the protocol while females demonstrated a decline in variability.

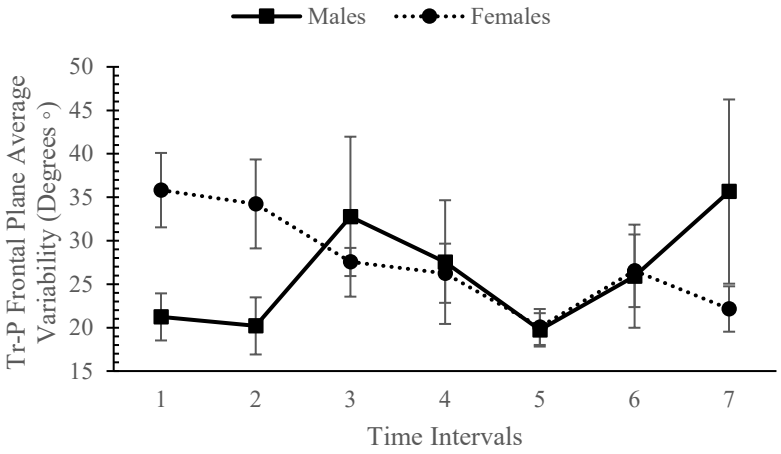


Figure 18: Average Tr-P frontal plane variability with standard error bars for male and female participants plotted against the seven time intervals of data collection. Similar to the previous figure, males demonstrate increased variability after completing the protocol whereas female demonstrate a decrease.

CRP Stance Phase Data

Paired t-tests performed to assess group pre-intervention to post-intervention variability changes in the loading response, mid stance, terminal stance, and pre swing portions for the stance phase did indicate statistically significant changes in neither the Trunk-Pelvis or Pelvis-Thigh segment couplings in the three anatomical planes. These results corroborate the data listed on table x in the previous section.

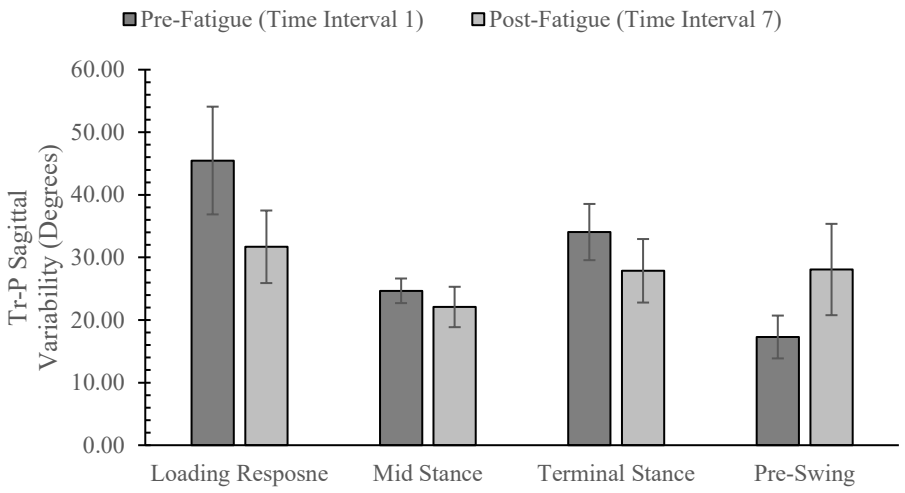


Figure 19: Pre-intervention and post-intervention CRP variability values with standard error bars of the Tr-P segment coupling in the sagittal plane. No signficant changes were detected.

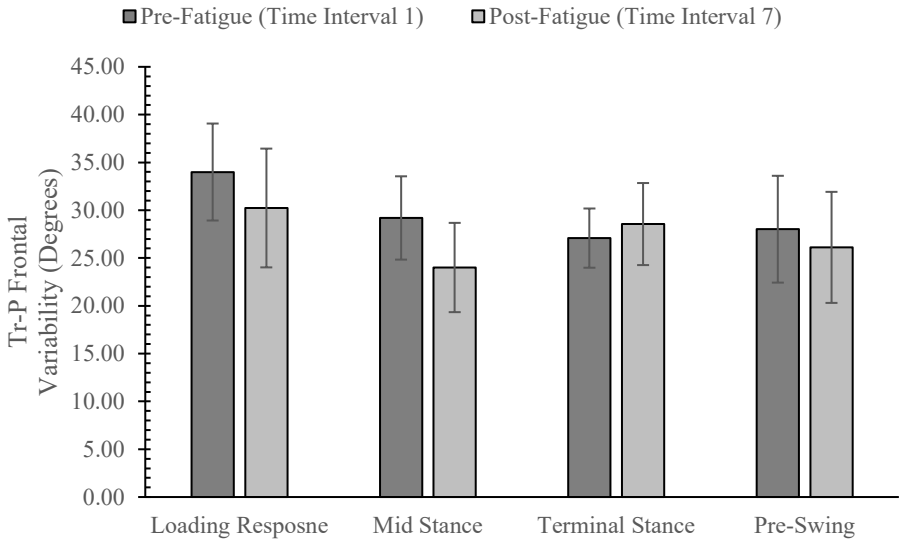


Figure 20: Pre-intervention and post-intervention CRP variability values with standard error bars of the Tr-P segment coupling in the Frontal plane. No signficant changes were detected.

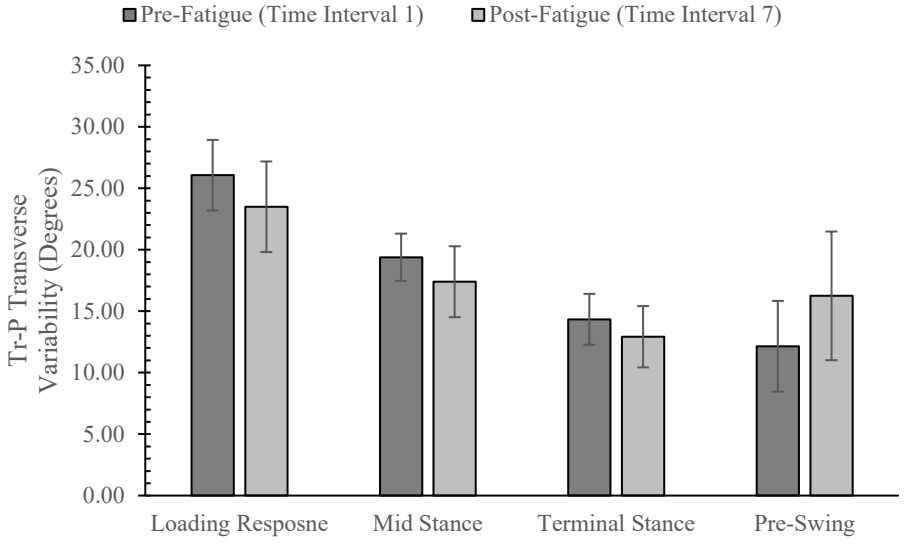


Figure 21: Pre-intervention and post-intervention CRP variability values with standard error bars of the Tr-P segment coupling in the transverse plane. No signficant changes were detected.

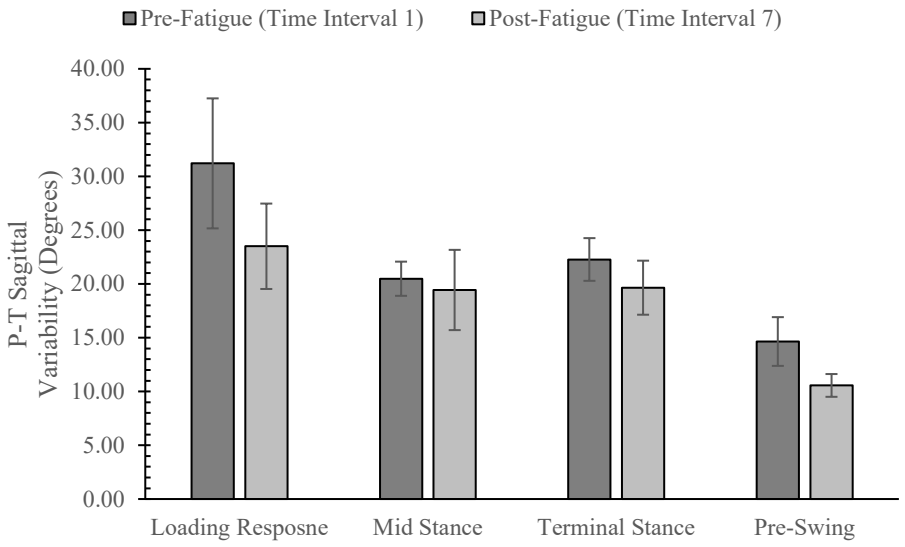


Figure 22: Pre-intervention and post-intervention CRP variability values with standard error bars of the P-T segment coupling in the sagittal plane. No signficant changes were detected.

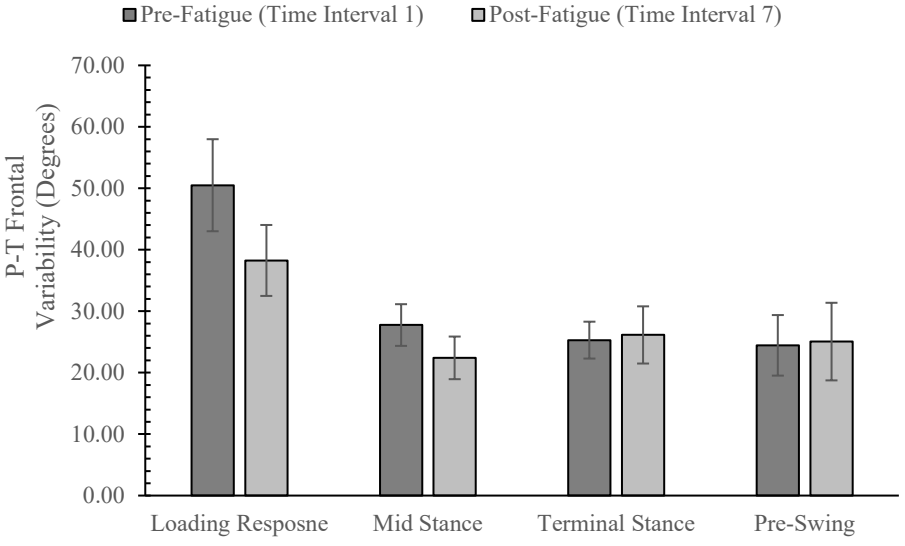


Figure 23: Pre-intervention and post-intervention CRP variability values with standard error bars of the P-T segment coupling in the frontal plane. No signficant changes were detected.

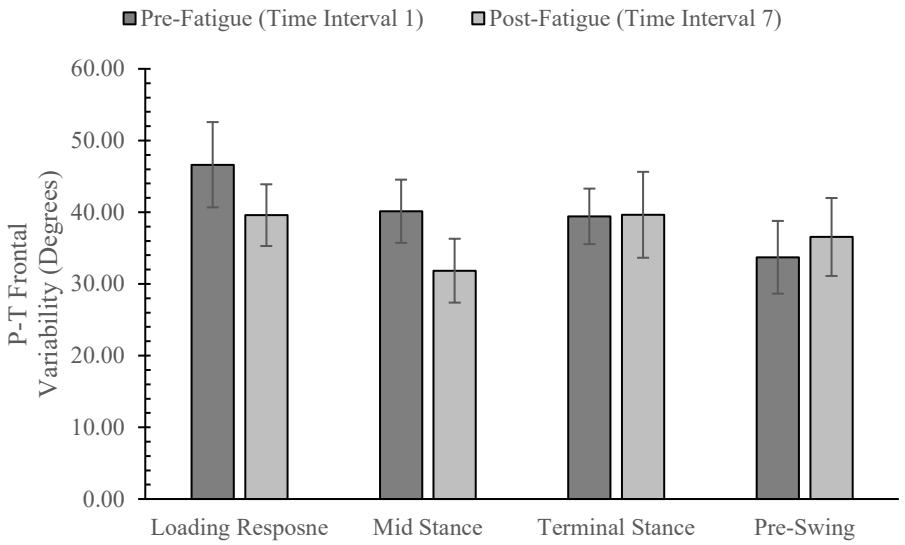


Figure 24: Pre-intervention and post-intervention CRP variability values with standard error bars of the P-T segment coupling in the transverse plane. No signficant changes were detected.

Tr- P Sagittal			
Stance Phase Period	**Time 1 Variability**	**Time 7 Variability**	**p-value**
Loading Response	45.48 ± 8.61	31.70 ± 5.79	$p = 0.13$
Mid Stance	24.67 ± 1.96	22.09 ± 3.22	$p = 0.51$
Terminal Stance	34.06 ± 4.49	27.87 ± 5.04	$p = 0.38$
Pre-Swing	17.29 ± 3.42	28.07 ± 7.29	$p = 0.16$

Table 8: Average time 1 and time 7 variability values with standard error for the Tr-P segment coupling in the sagittal plane as well as paired t-test p-values.

*indicates significance ($p < \alpha = 0.05$)

Table 9: Average time 1 and time 7 variability values with standard error for the Tr-P segment coupling in the frontal plane as well as paired t-test p-values.

Tr-P Frontal			
Stance Phase Period	**Time 1 Variability**	**Time 7 Variability**	**p-value**
Loading Response	34.01 ± 5.07	30.23 ± 6.21	$p = 0.55$
Mid Stance	29.19 ± 4.35	24.01 ± 4.66	$p = 0.44$
Terminal Stance	27.08 ± 3.09	28.55 ± 4.29	$p = 0.76$
Pre-Swing	28.01 ± 5.59	26.11 ± 5.81	$p = 0.82$

*indicates significance ($p < \alpha = 0.05$)

Table 10: Average time 1 and time 7 variability values with standard error for the Tr-P segment coupling in the transverse plane as well as paired t-test p-values.

Tr-P Transverse			
Stance Phase Period	**Time 1 Variability**	**Time 7 Variability**	**p-value**
Loading Response	26.06 ± 2.87	23.50 ± 3.69	p = 0.53
Mid Stance	19.39 ± 1.92	17.40 ± 2.88	p = 0.54
Terminal Stance	14.34 ± 2.07	12.92 ± 2.49	p = 0.63
Pre-Swing	12.15 ± 3.69	16.25 ± 5.23	p = 0.47

*indicates significance ($p < \alpha = 0.05$)

Table 11: Average time 1 and time 7 variability values with standard error for the P-T segment coupling in the sagittal plane as well as paired t-test p-values.

P-T Sagittal			
Stance Phase Period	**Time 1 Variability**	**Time 7 Variability**	**p-value**
Loading Response	31.21 ± 6.03	23.50 ± 3.97	p = 0.14
Mid Stance	20.48 ± 1.59	19.44 ± 3.73	p = 0.79
Terminal Stance	22.27 ± 1.99	19.65 ± 2.51	p = 0.39
Pre-Swing	14.65 ± 2.27	10.56 ± 1.06	p = 0.10

*indicates significance ($p < \alpha = 0.05$)

P-T Frontal			
Stance Phase Period	**Time 1 Variability**	**Time 7 Variability**	**p-value**
Loading Response	50.50 ± 7.49	38.26 ± 5.77	p = 0.16
Mid Stance	27.75 ± 3.39	22.41 ± 3.47	p = 0.27
Terminal Stance	25.29 ± 2.99	26.14 ± 4.65	p = 0.87
Pre-Swing	24.44 ± 4.92	25.06 ± 6.31	p = 0.94

Table 12: Average time 1 and time 7 variability values with standard error for the P-T segment coupling in the frontal plane as well as paired t-test p-values.

*indicates significance ($p < \alpha = 0.05$)

P-T Transverse			
Stance Phase Period	**Time 1 Variability**	**Time 7 Variability**	**p-value**
Loading Response	46.63 ± 5.95	39.59 ± 4.30	p = 0.37
Mid Stance	40.14 ± 4.41	31.85 ± 4.46	p = 0.14

Terminal Stance	39.42 ± 3.87	39.64 ± 5.99	p = 0.98
Pre-Swing	33.72 ± 5.07	36.55 ± 5.43	p = 0.67

Table 13: Average time 1 and time 7 variability values with standard error for the P-T segment coupling in the transverse plane as well as paired t-test p-values.

*indicates significance ($p < \alpha = 0.05$)

Discussion

Strength Data Analysis

The strength data collected demonstrated that the 30-minute run showed that the intervention imposed on subjects successfully induced statistically significant decreases in hip abduction strength ($p < 0.001$). Additionally, upon analyzing the strength data of male and female sub-groups of the participant pool, both sexes demonstrated a significant decrease in normalized torque generated (Figure 9). However, an interesting point to note is that male participants exhibited a greater percentage decrease in abductor strength than female participants following the protocol, which seems to contradict what the literature indicates[6]. Considering that paired t-tests applied to the entire participant group as well as male and female subgroups returned significant p-values (Table 1), the implemented 30-minute estimated lactate threshold run successfully altered the hip abductor strength of participants..

Pelvic drop, Hip Adduction, and Trunk Lean Data Analysis

It was hypothesized that pelvic drop, hip adduction, and trunk lean would all increase over the course of the protocol as well as in response to the protocol. However, contrary to our expectations, two-way repeated measures ANOVA results indicated that none of these three variables exhibited a significant within-subjects effect of time or between-subjects effect of sex (Table 2). Though in the case of pelvic drop, the effect of time was trending towards significance with a p-value of 0.07 (Table 2). Furthermore, the paired t-tests performed between the first and seventh data collection intervals, to determine if significant changes in the individual hip kinematic variables of interest

occurred following the 30-minute protocol, indicated that only pelvic drop demonstrated a statistically significant increase ($p < 0.05$), which was also contrary to the initially hypothesized outcomes.

The statistical results of the paired t-tests performed to assess group changes in pelvic drop following the protocol indicate that analyzing pelvic drop changes could be a useful method of assessing hip abductor strength changes and the propensity for developing lower extremity overuse injuries in healthy subjects. Because no between between-subjects effect of sex or interaction effects were detected, decreased hip abductor strength is suspected to induce pelvic drop in male and females by affecting the same neuromuscular control mechanisms employed by both sexes while running.

When the results of the paired t-tests and the two-way repeated measures ANOVA are assessed in tandem, it seems that pelvic drop was the only individual hip kinematic variable of the three examined to have altered in response to the protocol (Figures 10,11 and Table 3), implicating that excess trunk lean and hip adduction are not influenced by hip abductor strength deficits in healthy runners. It is worth noting that the identification of trunk lean and hip adduction as markers of potential overuse injury was accomplished in past studies by comparing gait characteristics of healthy participants with participants that suffer from lower extremity overuse injuries[39]. Because this study, which involved only healthy participants, did not detect changes in trunk lean and hip adduction, it may be possible that trunk lean and hip adduction are characteristics specific to injured runners: occurring as a result of kinematic adjustments made to mitigate pain rather than resulting from hip abductor strength decreases.

Given the statistical results of the two-way repeated measures ANOVA and paired t-test performed to assess group changes in pelvic drop following the protocol, pelvic drop changes could be a useful method of assessing hip abductor strength changes and the propensity for developing lower extremity overuse injuries in healthy subjects. Because no between between-subjects effect of sex or interaction effects were detected, decreased hip abductor strength is suspected to induce pelvic drop in male and females by negatively affecting the similar neuromuscular control mechanisms employed by both sexes while running. With a within-subjects effect of time trending towards significance, future investigations should investigate pelvic drop changes in response to temporal decreases in hip abductor.

The two-way repeated measures ANOVAs employed did not detect significant between-subjects effect of sex or interaction effect between sex and time for any of the three individual hip kinematic variables measured (Table 2), corroborating with our hypothesized outcomes. Considering the findings of past studies[7,39] which seem to suggest that sex-related kinematic changes should exist in response to the intervention, these statistical findings suggest that healthy runners do not exhibit significant between-sex differences in the way their hip kinematics change in response to hip abductor strength changes. However, the statistical findings also potentially suggest that pelvic drop, trunk lean, and hip adduction are ineffective markers of between-sex hip kinematic adjustments in response to hip abductor strength decreases. Upon reviewing the CRP statistical results, the latter case was found to be more probable.

CRP Data Analysis

The statistical findings of the CRP deviation phase variability data were validated through the paired t-tests used on the discrete periods of stance phase, which also did not indicate any significant changes between the pre-intervention and post-intervention variability value of the two segment couplings of interest in any of the three anatomical planes (Figures 19-24 and Tables 8-13). In contradiction to our hypothesized outcomes, two-way repeated measures ANOVAs of CRP deviation phase data did not detect a significant within-subjects effect of time in the three anatomical planes of the Trunk-Pelvis and Pelvis-Thigh segment couplings in the entire participant group (Figures 14,15 and Table 4). Furthermore, A significant between-subjects main effect of sex was detected only in the transverse plane of the P-T segment coupling ($p < 0.05$). The two-way repeated measures ANOVAs employed did indicate a significant interaction effect in the frontal plane of Tr-P segment coupling and the sagittal plane of the P-T segment coupling ($p < 0.05$).

As seen on table 7, female participants demonstrated lower CRP variability in the transverse plane of the Pelvis-Thigh segment compared to their male counterparts at all seven time intervals of data collection. Additionally, a between-subjects effect of sex was found to be trending towards significance in the transverse plane of the Trunk-pelvis segment coupling (Table 4), after applying a greenhouse-geisser correction. It is suspected that there may potentially be significant sex differences in the CRP variability in the transverse plane of both Tr-P and P-T segment couplings. However, further investigation is needed to confirm this suspicion. No previous studies have detected or analyzed this phenomenon.

After detecting significant interaction effects of sex by time in the frontal plane of the Trunk-Pelvis segment coupling and the sagittal plane of the Pelvis-Thigh segment coupling (Table 4). The male and female CRP variability data for these segment couplings in their respective anatomical planes were plotted against the time intervals of data collection. On these plots, a general decrease in CRP variability in female subjects was visibly evident as time of protocol increased (Figures 17,18). Subsequent one-way repeated measures ANOVAs were performed on the male and female subjects to detect a main within-subjects effect of time in in the frontal plane of the Tr-P segment coupling and the sagittal plane of the P-T segment coupling. The results of these one-way repeated measures ANOVAs indicated a main effect of time for only female subjects whose CRP variability decreased over time while their male counterparts did not come close even trend towards significance in response to the 30-minute protocol (Table 6). Understanding that males failed to demonstrate any significant CRP variability alterations but successfully demonstrated a significant decrease in hip abduction strength in response to the protocol, it seems that the intersegment coordination of the Trunk-Pelvis and Pelvis-Thigh segment couplings in males are either not affected by or at least are less sensitive to hip abductor strength decreases than in female counterparts. This could potentially be a result of males employing neuromuscular mechanisms that effectively adjust segment kinematics to ensure a wide range of repeatable, coordinated segment actions while running despite temporal hip abductor strength alterations.

However, for females, given the significant interaction effects of sex by time to were found to accompany significant decreases in CRP variability within the sagittal

and frontal planes of the P-T and Tr-P segment couplings over time, females seem more prone to exhibiting a narrower range of segment movement as they progress in a running task and experience hip abductor strength alterations. When the results of the one-way repeated measures ANOVA performed to elucidate the interaction effects between male and female participants are taken in conjunction with the significant between-subjects effect of sex found in the transverse plane of the P-T segment coupling, where females displayed lower CRP variability during every time interval of data collection, our findings support the notion that females are more prone to lower extremity overuse injuries. As mentioned earlier, the literature has linked lower coordinate variability with the presence of lower extremity overuse injuries[22] and provided ample evidence of females being more predisposed to the development of lower extremity overuse injuries[30]. Considering that this study's results have shown the presence of both existing CRP variability deficits and induced CRP variability deficits in response to hip abductor strength decreases within the female subjects, it seems that females do indeed demonstrate a greater predisposition towards the development of overuse injuries.

It is interesting to note that the effect of sex and interaction effects of sex by time were only detectable in the statistical analyses of the CRP variability data and not in the individual hip joint kinematic variable data. A possible explanation for this is that females lack the adaptive neuromuscular capabilities to prevent changes in coordinated segment movements; rendering females consequently unable to mitigate undesirable changes in segment coordination when experiencing strength deficits in their hip abductors.

Conclusion

The results of this study show that a temporal decrease in hip abductor strength induces a increase in pelvic drop, a conventional individual hip joint kinematic marker of overuse injuries, while decreasing the coordinative variability of the Tr-P and P-T segment couplings in the frontal and transverse planes. Additionally, the results indicate that there are potential sex-dependent variability differences in the transverse planes of both segment couplings investigated, with healthy females demonstrating lower CRP variability compared to their male counterparts.

From the analysis of the individual hip joint kinematic variables, it appears that pelvic drop is the only individual hip joint kinematic variable of the three investigated that is linked to hip abductor strength deficits in healthy runners. Regarding the CRP variability data of the Tr-P and P-T segment couplings, males do not demonstrate significant changes in their coordinate variability. However, based on the interaction effects and subsequent pair t-tests performed, females also demonstrated a significant decrease in coordinate variability in the frontal and sagittal planes of the Tr-P and P-T segment couplings, respectively. Additionally, females demonstrated lower coordinate variability in the transverse plane of the P-T segment coupling, beginning at the onset of the protocol.

There are two particularly important implications of this study. The first being the demonstrated usefulness of employing a dynamical approach, specifically continuous relative phase, as a means of detecting sex-dependent kinematic changes in response to muscle strength changes within healthy subjects. As observed in this study, these sex-dependent differences would have been overlooked if an assessment of CRP

variability was not performed. The second implication worth mentioning is that this study, through the analysis of coordinate variability changes in the segment couplings of interest, corroborates the biomechanical literature and advances the notion that females are more predisposed to developing lower extremity overuse injuries.

Limitations of this study primarily stemmed from the inability to assess real time strength changes as the protocol progressed. While the implemented protocol allowed for the temporal assessment of changes in the individual hip joint kinematic variables and CRP variability, the protocol only allowed for hip abductor strength evaluation at the beginning and end of the protocol, preventing the results from demonstrating a correlation between increases in hip abductor strength and changes in hip kinematics. Given that this study failed to show statistically significant effect of time for any of the variables measured, being able to correlate kinematic changes with graded hip abductor strength changes could would have helped clarify potential associations between hip kinematics and hip abductor strength.

Other potential limitations include not standardizing the type of shoes runners used to perform the 30-minute running intervention. Participants also ran at different paces and their footstrike patterns could vary, some runners may have landed on their forefoot first while others may have made contact with the ground using their rearfoot first.

The use coordinate variability as a means of analyzing hip kinematic changes in response to hip abductor strength changes requires further investigation. Considering the decreases in coordinate variability observed in female subjects, future areas of research should investigate the interaction effects of sex by time observed in the

respective frontal and sagittal planes of the Tr-P and P-T segment couplings. However, pelvic drop was shown to be a useful indicator of hip abductor muscle strength deficits and could potentially be used to assess the risk of developing lower extremity injuries in both male and female healthy recreational runners.

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