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The Effects of Increasing Running Speed on vGRF and Asymmetry

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The Effects of Increasing Running Speed on vGRF and Asymmetry

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by

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ABSTRACT

The Effects of Increasing Running Speed on vGRF and Asymmetry

by

Kaela M. Hierholzer

Biomechanical and physiological parameters related to running performance are usually studied separately. However, evaluating both aspects together could be beneficial in improving athletic performance. The purpose of this study was to observe the change in peak vGRF and asymmetry as speed increases, while observing physiological responses during a $\dot{V}O_{2max}$ test. Data from athlete monitoring of 12 cross-country and triathlon athletes were analyzed. The athlete monitoring protocol included three unweighted countermovement jumps and a $\dot{V}O_{2max}$ test performed by the athletes. The athletes had an average $\dot{V}O_{2max}$ of 53.4 ± 7.7 mL/kg/min, while their average vGRF asymmetry throughout the $\dot{V}O_{2max}$ test was 1.38 ± 0.68%. A strong, positive correlation was found between average vGRF and average blood lactate (r=0.93), indicating that as vGRF increased so did blood lactate. It was concluded that physiological and biomechanical parameters are related in athletic performance. Therefore, athlete monitoring should include analysis of both physiological and biomechanical parameters in order to form a more well-rounded analysis of athlete performance.

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CHAPTER 1

INTRODUCTION

Researchers studying biomechanical and physiological parameters related to running performance usually do so separately. An example of a study that focuses on biomechanical parameters of running is an article by Keller, Weisberger, Ray, Hasan, Shiavi, and Spengler (1996), the authors of, “Relationship between vertical ground reaction force and speed during walking, slow jogging, and running”. Allen, Seals, Hurley, Ehsani, and Hagberg (1985), the authors of, “Lactate threshold and distance-running performance in young and older endurance athletes”, focused more on the physiological parameters related to running.

The aim of the current study was to examine selected biomechanical and physiological variables together in order to provide a more well-rounded analysis of the subject’s performance and to capture an overall image of how those two parameters are associated with each other at various speeds of distance running. This study was a further analysis of biomechanical and physiological parameters from athlete monitoring data performed by East Tennessee State University’s women’s cross-country and triathlon teams. Due to the amount of distance these athletes run; as well as the fact that they often need the ability to sprint at the end of the race, they cover a wide range of paces throughout a competitive race. Furlong and Egginton (2018), noted athletes may be forced to run at speeds faster or slower than they prefer due to the competition.

Kinetic asymmetry in running biomechanics increases the risk of musculoskeletal injury. Specifically, asymmetry was assessed for vertical ground reaction force (vGRF) and the difference between right and left foot vGRF (Zifchock, Davis, & Hamill, 2006). Injuries typically occur when the athlete’s running speed increases, this may occur due to the likelihood of an increase in asymmetry (Clark & Weyand, 2014). We researched GRF characteristics including: 1) left and right vGRF symmetry consistency by using symmetry index (%), 2) impact force consistency by percent change from speed to speed, 3) the percent increase of vGRF relative to speed increase, and 4) percent increase in stride length with increasing running speeds. In regards to the physiological responses, this study was an examination the subject’s; 1) volume of oxygen ($\dot{V}O_2$) with GRF consistency, 2) blood lactate concentration levels with vGRF consistency, and 3) if the subject’s ratings of perceived exertion (RPE) matches with all responses both biomechanical and physiological parameters.

This study is important to sport science because when most athletes or coaches are developing a training program, they may refer to sources that are based on distance development or physiological parameters such as lactate threshold and maximum volume of oxygen ($\dot{V}O_{2max}$) tests. Therefore, there may be a lack of education when it comes to programming and training athletes. Biomechanical parameters, especially when integrated with physiological variables, would be a powerful tool in the training process. For example, performance and injury are due to leg length discrepancies, high impact force, high loading rate, and high active (propulsive) factors (Hreljac, 2004). There is a need to explore the relationship of biomechanical factors with the physiological parameters. This study could help coaches and athletes not only develop proper training programs to improve performance, but also help reduce the risk of injury. Therefore, the purpose of this study is to observe the change in vGRF characteristics with increasing speeds while matching physiological responses during a $\dot{V}O_{2max}$ test.

CHAPTER 2

LITERATURE REVIEW

Biomechanical Parameters

Running Mechanics

Running is a cyclic motion that allows an individual to propel themselves forward (Figure 2.1). It requires movement of the lower body beginning with the foot making the initial impact with the running surface until that same foot comes back into contact at the end of the cycle (Nicola & Jewison, 2012). Running can be classified based upon speed. Jogging or a submaximal running speed is a velocity from 8 kilometers per hour (km/h) to 16 km/h (Dugan & Bhat, 2005). During running, there is an increase in joint range of motion and muscle activity, as well as reaction forces (Chan & Rudins, 1994). The running cycle differs from walking; as running has both a stance and swing phase, as well as a float phase (Nicola & Jewison, 2012). When speed increases from a walk, run, and sprint; the time spent in the stance phase will decrease while the swing and float phases increase (Chan & Rudins, 1994). Dugan and Bhat (2005), a sprint is any velocity greater than 16 km/h.

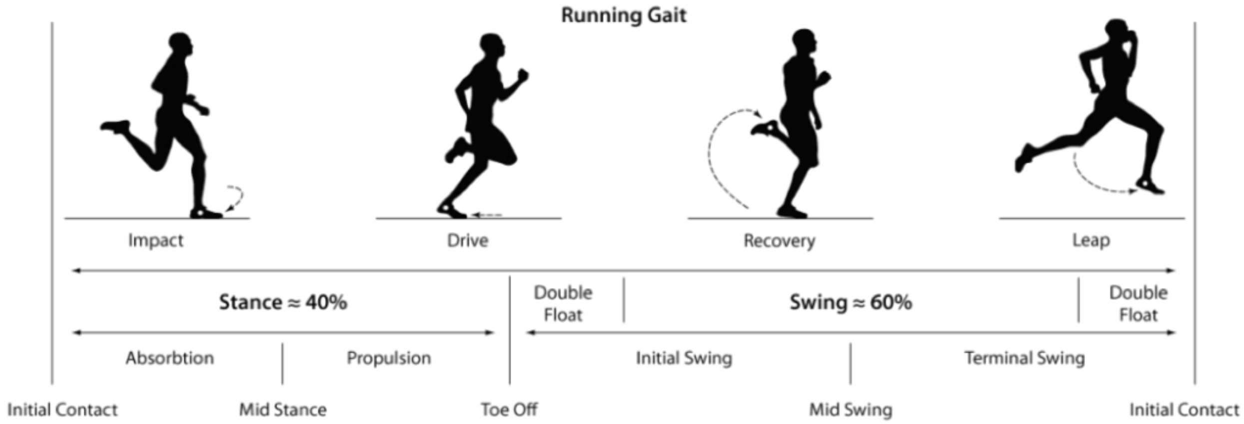

Figure 2.1 Running gait (Kintec, 2016)

The first phase of running would be initial contact and occurs from the instant of foot strike to when the foot is flat on the running surface. During this phase, the foot contacts the surface in a slightly supinated position and as the heel strike occurs the foot begins to dorsiflex (Dugan & Bhat, 2005). The muscles, tendons, bones, and joints of the lower limb must absorb the forces of the impact from distal to proximal (Nicola & Jewison, 2012). These forces are distributed via a closed kinetic chain necessitating a dorsiflexed ankle and a flexed knee (Nicola & Jewison, 2012). Proper force absorption may decrease the likelihood of a risk of injury.

The next phase is termed mid stance and occurs from foot flat to heel-off of the running surface. While this is occurring, the foot remains in contact with the ground and the ankle begins to dorsiflex and the foot pronate due to the forward motion of running (Dugan & Bhat, 2005). The tibialis posterior and gastrocnemius-soleus complex are eccentrically contracted at this point to provide control of motion (Dugan & Bhat, 2005). Contraction of the quadriceps and hamstring are used as a stabilization mechanism for the knee joint at this point in the running cycle (Dugan & Bhat, 2005). As the opposite limbs begins to swing forward, the foot in contact with the running surface begins to supinate as the foot moves into heel-off, ending this phase (Dugan & Bhat, 2005).

Next is propulsion which occurs from heel-off to toe-off is the next phase in the cyclic motion. Here, the limb swinging forward continues to do so as the opposite limb begins propulsion (Dugan & Bhat, 2005). To propel, the foot goes into plantarflexion and supination from the gastrocnemius and soleus contracting, all while the opposite limb is preparing for ground contact (Dugan & Bhat, 2005). At toe-off, muscles such as the rectus femoris and anterior tibialis are active and max vGRF is reached (Nicola & Jewison, 2012).

Following toe-off and as the opposite limb is in the swing phase just before it contacts the ground, the first float phase occurs (Dugan & Bhat, 2005). During the float phase, the pelvis is rotating forward and flexion of the hip allows this (Nicola & Jewison, 2012). Then, the opposite limb prepares for ground contact at the end of the swing phase where the posterior calf muscles eccentrically contract for stabilization (Chan & Rudins, 1994). Once the opposite limb comes in contact with the ground, the running cyclic continues (Dugan & Bhat, 2005).

As the velocity of running increases, a decrease in the amount of contact time and an increase in flight phase will occur. With increasing velocities, an increase in stride frequency, stride length, and GRF is experienced (Weyand, Sternlight, Bellizzi, & Wright, 2000).

Ground Reaction Force

Ground reaction force is the action of an equal and opposite force between the foot and the ground (Novacheck, 1997). Grabowski and Kram (2008), there is an increase in vGRF when running velocity increases. When there is a greater application of force, the athlete’s vertical velocity will increase at takeoff; therefore, there will be an increase in flight time and distance traveled between strides (Weyand, et al., 2000). Previous research has reported that at slow velocities (2 m/s), peak vGRF can reach about 1.5 times the athlete's body weight, whereas at a faster velocity (7 m/s), peak vGRF can reach 3.0 times the athlete's body weight (Grabowski & Kram, 2008). Dugan and Bhat (2005), noted the athlete's vGRF could reach up to 2.2 times the athlete's body weight after heel contact occurs during running compared to walking. In addition to increased vGRF, asymmetry in gait, has also been linked to increased risk of injury (Hreljiac, 2004; Zifchock et al., 2006).

Running Injuries

It has been estimated that recreational and competitive runners have almost a 70% chance of injury from overuse within a 1-year period (Hreljiac, 2004). Injuries of the lower extremities are especially common in runners (Shi, Li, Lui, & Yu, 2019). When the velocity of running increases, an increase in the amount of vGRF at impact is observed; leading to greater tissue stress (Hreljiac, 2004). Nicola and Jewison (2012), increasing running velocity increases the GRF, which can cause an increase stress on the lower body and therefore raise the risk of injury. Specifically, greater vertical loading rates were found to contribute to running related injuries (Dudley, Pamukoff, Lynn, Kersey, & Noffal, 2017).

Another issue that may occur and increase the risk of injury is kinetic asymmetry during running. Asymmetry is often described as the difference between limbs in regards to either kinetic or kinematic parameters (Zifchock et al., 2006). It has been found that when there is asymmetry of 15% or more, there is an increased risk of injury on the lower extremity for female collegiate athletes (Knapik, Bauman, Jones, Harris, & Vaughan, 1991). Clark and Weyand

(2014), asymmetry in GRF seems to be greatest at faster speeds. This rise in asymmetry has been found to increase the risk and occurrence of injury (Zifchock et al., 2006).

Physiological Parameters

$\dot{V}O_{2max}$ Test

A $\dot{V}O_{2max}$ test is a graded exercise test used to assess aerobic power and ability to use oxygen (O_2) (Brooks, Fahey, & Baldwin, 2005). Yoon, Kravitz, and Robergs (2007), a $\dot{V}O_{2max}$ test is a very common measure for physiological parameters. Due to the fact that O_2 consumption is proportional to the intensity of exercise, their $\dot{V}O_{2max}$ will increase as the intensity increases (Brooks et al., 2005). Many factors can affect an athlete's $\dot{V}O_{2max}$ value such as: age, conditioning status, and sex (Arena et al., 2007). Brooks et al. (2005), an individual's $\dot{V}O_{2max}$ is a good indicator of endurance performance in a heterogenous sample, including successful distance running (Yoon et al., 2007).

There are various protocols that can be used when administering a $\dot{V}O_{2max}$ test. The differences in protocols can vary from their stage duration, stage increment, total test duration, as well as the modality (Yoon et al. 2007). It has been found that a total $\dot{V}O_{2max}$ test duration time lasting between 8 and 17 minutes had higher values than other durations (Yoon et al., 2007). For women between the ages of 20 and 29 years old, a $\dot{V}O_{2max}$ value of 49.6 mL/kg/min and higher is classified as superior and anything under 32.3 mL/kg/min and lower is classified as very poor (*ACSM's Guidelines for Exercise Testing and Prescription*, 2014). For males ages 20-29, a $\dot{V}O_{2max}$ value 55.5 mL/kg/min and higher ranks them as superior and a value of 36.7 mL/kg/min and lower ranks them as very poor (*ACSM's Guidelines for Exercise Testing and Prescription*, 2014). A study by Hutchinson, Cureton, Outz, and Wilson (1991) in which their subjects completed a $\dot{V}O_{2max}$ test, the male subjects had an average $\dot{V}O_{2max}$ of 57.5 ± 5.2 mL/kg/min while the females reached an average of 52.2 ± 5.1 mL/kg/min. Another study in which active male and female subjects completed a $\dot{V}O_{2max}$ test reports reported slightly lower values. The male subjects reached an average value of 50.4 ± 4.5 mL/kg/min and the females reached 41.5 ± 6.0 mL/kg/min (Robertson, Moyna, Sward, Millich, Goss, & Thompson, 2000).

Blood Lactate

Blood lactate has been found to relate to endurance performance (Allen et al., 1985). Lactic acid dissociates to lactate; therefore, increasing the blood lactate levels increasing the acidosis which can cause diminished athletic performance (Theofilidis, Bogdanis, Koutedakis, & Karatzaferi, 2018). Brooks et al. (2005), indicate lactate formation increases as intensity increases and an increase in blood lactate levels will be experienced when the rate of clearance cannot keep up with rate of production. In a study by Maldonado-Martin, Mujika, and Padilla (2004), their subjects of male and female highly trained runners displayed max blood lactate levels of 10.4 ± 3.2 mmol/L for females and 11.7 ± 3.0 mmol/L for males during a $\dot{V}O_{2max}$ test. Another study in which a $\dot{V}O_{2max}$ test was performed on well-trained middle and long-distance runners, researchers reported a max average blood lactate level of only 9.2 ± 2.1 mmol/L (Grant, Craig, Wilson & Aitchison, 1997).

Blood Glucose

Glucose is a valuable source of fuel during rest and exercise (Goodwin, 2010). Blood glucose concentration at rest is about 100 mg/dL, and homeostatic mechanisms attempt to maintain this level during exercise (Brooks et al., 2005). At the beginning of long-term exercise, a spike in blood glucose, likely due to catecholamine release, can occur, then it will begin to fall and remain within 10% of normal values (Brooks et al., 2005). When blood glucose levels get too low, fatigue develops, leading to the cessation of exercise (Brooks et al., 2005). However, for short periods blood glucose can also increase with exercise intensity due to catecholamine accumulation and catecholamine's ability to stimulate hepatic glycogenolysis (Brooks et al., 2005). At greater intensities, carbohydrates are needed because they become the primary source of fuel (Brooks et al., 2005). Therefore, additional glucose is produced by activating pathways in addition to glycogenolysis, such as gluconeogenesis (Feo et al., 2003). Feo et al. (2003) found that there was an increase in blood glucose levels as their subjects reached higher percentages of their $\dot{V}O_{2max}$. Dohm, Beeker, Israel, and Tapscott (1986), it was found that their subjects were able to maintain homeostasis while running at 70% of their $\dot{V}O_{2max}$ in a fasted state; likely resulting from gluconeogenesis.

Ratings of Perceived Exertion

Ratings of perceived exertion (RPE) are a way for an individual to express how they are feeling during exercise (Demello, Cureton, Boineau, & Singh, 1987). RPE is a subjective measure that quantifies an athlete's perception of exercise (Ritchie, 2012). During a test, such as a $\dot{V}O_{2max}$, RPE is an estimate of the intensity of (Demello et al., 1987). Hall, Ekkekakis, and Petruzzello (2005), reported their subjects had an average RPE of 15.47 ± 2.15 after running on a treadmill for 15 minutes. Robertson et al. (2000), found their subjects progressively reached increased RPE and reached an average max RPE of 19.7 ± 0.48 (females) and 19.6 ± 0.53 (males) for a $\dot{V}O_{2max}$ test, indicating this type of exercise has a high intensity based on both physiological and psychological values. The most common RPE scale is the "Borg Scale" that ranges from 6 (no exertion) to 20 (maximal exertion) (Ritchie, 2012).

Demello et al. (1987), RPE is more affected by the lactate threshold and amount of blood lactate than the percent of $\dot{V}O_2$ at which they are performing. However, there are other factors that could be associated with RPE. One other factor that was found to be closely related to RPE values was heart rate (Scherr et al., 2013). Scherr et al. (2013), the Borg RPE Scale has a very strong relationship with heart rate and blood lactate.

Previous research has reported that increasing speed, typically increases vGRF and asymmetry; which can lead to an increased injury risk (Clark & Weyand, 2014). Similar results have been found with physiological parameters. As intensity increases, so do the responses of variables such as $\dot{V}O_2$, blood lactate, and RPE; however, blood glucose levels typically remain the same with only slight variation due to the drive to maintain homeostasis. In regards to previous research, it can be shown that varying responses of these variables can have an effect on athletic performance. In splitting the information between biomechanical and physiological parameters only, there may be a gap in the information that can be provided to coaches and athletes. Therefore, it is important to consider the effect of both parameters on athletic performance in order to develop a more well-rounded analysis rather than just one or the other.

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CHAPTER 3

PROFILING COLLEGIATE CROSS-COUNTRY AND TRIATHLON ATHLETES

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Profiling collegiate cross-country and triathlon athletes

Abstract

Research has been conducted on varying levels of runners. However, most research looks at biomechanical parameters or physiological parameters of the athletes. The purpose of this study is to profile physical characteristics of collegiate cross-country and triathlon athletes via athlete demographics, biomechanical characteristics, and physiological characteristics during a $\dot{V}O_{2max}$ test. Twelve athletes (8 females, 4 males) were profiled based on their normal athlete monitoring protocol. Average and standard deviation were calculated for all variables. The average demographics for all athletes was 19.92 ± 1.56 years old, 167.55 ± 7.23 cm tall, and they weighed 65.7 0± 9.85 kg. The athletes average vGRF throughout the $\dot{V}O_{2max}$ test was 2.69 ± 0.19 BW with an average asymmetry of 1.38 ± 0.68 %. The average $\dot{V}O_{2max}$ for all athletes was 53.37 ± 7.70 mL/kg/min. Overall, the male athletes were larger in size than the females, with corresponding variables (i.e., ventilation, heart rate, and $\dot{V}O_2$) following this trend. Our findings provide evidence that collegiate cross-country and triathlon athletes maintain relatively low kinetic asymmetry, while ranking above the 95th percentile according to the American College of Sports Medicine guidelines for $\dot{V}O_{2max}$ values.

Keywords: demographics, cross-country, triathlon

Introduction

To gain better knowledge of results regarding biomechanical or physiological parameters, it is valuable to establish the calibre of athlete performing the testing. Previous research briefly describes the demographics of their subjects, however, typically there is not an in-depth profile of athletes at the collegiate level who perform biomechanical and physiological testing.

This current study examines the physical characteristics of collegiate cross-country and triathlon athletes during a $\dot{V}O_{2max}$, while including biomechanical and physiological characteristics from athlete monitoring. The goal of this study was to further analyze and profile typical college cross-country and triathlon athletes' characteristics in order to better understand future performance research. Based on the distance these athletes run in competition, there is a necessity for them to be able to maintain a steady pace while having the capability of sprinting when needed. Furlong and Eggington (2018) reported athletes need to be able to perform a range of speeds and paces during a competitive race in order to have the best finish possible. When comparing males to females, it has been reported males were taller and weighed more than the females (Fuster, Jerez, & Ortega, 2014). Therefore, typically males would experience larger values than females in variables such as ventilation ($\dot{V}E$), heart rate (HR), vertical ground reaction force (vGRF), and loading rate.

The importance of this study to sport science is to provide information concerning collegiate cross-country and triathlon athlete's demographics, biomechanical characteristics, and physiological characteristics. This information can then be applied to future studies in order to better analyse performance measures, which can be directly applied to improve training. Therefore, the purpose of this study is to profile the physical characteristics of collegiate cross-country and triathlon athletes via athlete demographics, biomechanical characteristics, and physiological characteristics during a $\dot{V}O_{2max}$ test.

Methods

Athletes

The athletes were 12 trained male and female collegiate cross-country and triathlon athletes, ranging from age 18 to 25 years old. Tests were part of an ongoing athlete monitoring program.

Athletes must have had clearance to perform a maximal exertion exercise by the university's medical staff in order to take part in the monitoring program.

Procedures

Each athlete's age, body mass, and height were recorded prior to jump testing. Before starting the $\dot{V}O_{2max}$ test, the athletes performed 3 unweighted countermovement jumps on PASCO Force Plates (Roseville, CA) that were analyzed using ForceDecks Software (Vald Performance, London, England). A study established that the PASCO portable force plates are a reliable tool for collecting jump data (Silveira, Stergiou, Carpes, Castro, Katz, & Stefanyshyn, 2017).The athlete then performed a $\dot{V}O_{2max}$ test, until volitional fatigue, using a Parvo Medics TrueOne 2400 Metabolic Cart (Sandy, UT) for gas exchange analysis. The $\dot{V}O_{2max}$ protocol being used was a protocol and previous monitoring set in place by the strength and conditioning coach and the sport coach of the triathlon team and cross-country team in order to be able maintain consistency (Beltz, Gibson, Janot, Kravitz, Mermier, Dalleck, 2016). Prior to starting the test, each athlete's baseline measurements were recorded. The protocol used in this study was not typical compared to other studies. The majority of $\dot{V}O_{2max}$ tests follow the Balke or Bruce protocol (Beltz et al., 2016). Both these protocols not only increase in speed, but also grade with each stage (Beltz et al., 2016). However, the protocol consisted of each athlete starting at a speed of 10.1 km/h. The speed increased by 1.28 km/h every 2 minutes until the subject reached an RER of 1.00. Then, the speed increased 1.2 km/h every 1 minute until cessation of the test. This was performed in an attempt to achieve a true $\dot{V}O_{2max}$ test and max lactate concentration, while keeping the total test time as close to 12 minutes as possible, which is the preferred duration (Arena et al., 2007). Throughout the $\dot{V}O_{2max}$ test, a grade of 0% was maintained in order to properly collect and compare vGRF data from the force plates. During the $\dot{V}O_{2max}$ test, the athlete's blood lactate (2 measurements each time) was measured using a Nova Medical Lactate Plus analyzer (Waltham, MA). The Lactate Plus device reported good reliability and accuracy when being compared to an in-laboratory based blood lactate analyzer (Tanner, Fuller, & Ross, 2010). Blood glucose (2 measurements each time) was measured using an Accu-Chek Aviva Plus meter (Roche, Indianapolis, IN), and when portable blood glucometers were compared to an in-laboratory analyzer it was reported that 82% of the readings met the International Organization of Standardization's criteria for clinical accuracy (Salacinski, Alford, Drevets, Hart, & Hunt, 2014). RPE was also collected at the end of each stage. To collect this data, the athlete stepped off the belt and onto the treadmill's running board. Then athlete returned to the treadmill belt for the next stage of the test. All athletes were equipped with a Garmin heart rate monitor chest strap (Olathe, KS) to monitor changes in heart rate throughout the test. Garmin was chosen to maintain consistency with what the athletes use during training. While the athlete was running, their vGRF was being recorded using four load cells (Rice Lake, WI) collecting at 1,000 hertz (Hz) placed beneath the Tuff Tread treadmill belt (Conroe, TX) and the LabView 2018 software (National Instruments, Austin, TX) for the entirety of the $\dot{V}O_{2max}$ test. All testing ceased when the athlete ended the $\dot{V}O_{2max}$ test by stepping off the treadmill belt and onto the side platform on their own. See study design in Figure 3.1.

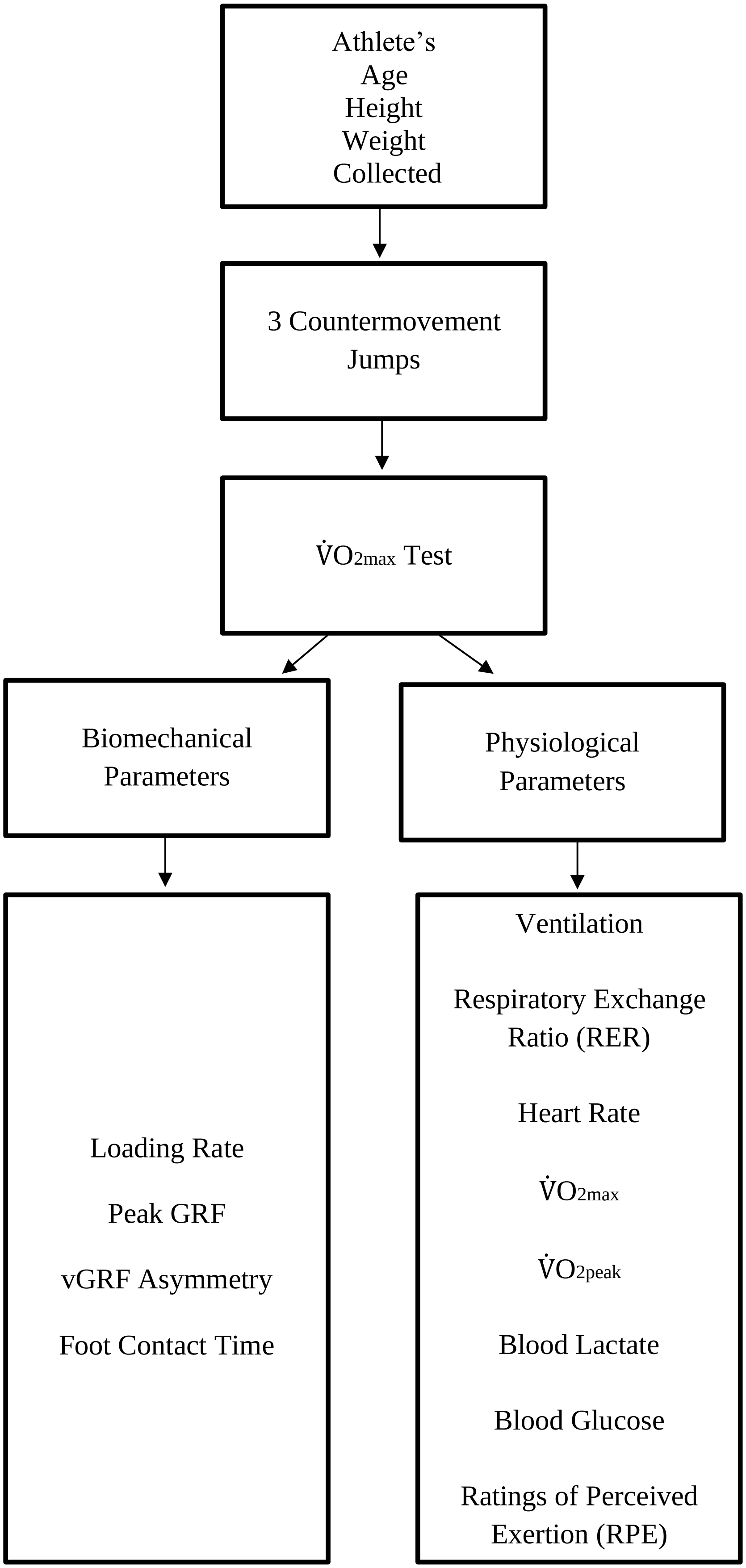

Figure 3.1 Study design.

Statistical Analysis

Data from the athlete's physical characteristics were analysed using Microsoft Excel (Microsoft Corporation, Redmond, WA, version 16.25) by calculating average and standard deviation. Intraclass correlation (ICC) and coefficient of variation (CV) were used to analyse reliability of the treadmill load cell data using Microsoft Excel and a spreadsheet developed for analysis of reliability (Hopkins, 2015).

Results

Physical Characteristics

Table 3.1 highlights the demographics of the athletes. All athletes were trained college triathlon and cross-country runners, ranging from 18 to 23 years old. The athletes consisted of 8 females and 4 males. When separating the athletes into males and females, on average the females (20.29 ± 1.60 years) were older than the males (19.40 ± 1.52 years). However, the males were taller (169.62 ± 10.12 cm) and had a higher body mass (70.02 ± 12.28 kg) than the females (166.07 ± 4.64 cm; 62.61 ± 7.13 kg). Out of all the athletes, 9 wore shoes that were considered to be for neutral feet, meaning there is no excessive pronation or supination, for daily use (3 females; 6 males) (Donatelli, 1985). There were 2 athletes that wore competition shoes for neutral feet (1 female; 1 male), while 1 female wore a shoe for stability for daily use. These shoe parameters were developed by coach-based evaluation of the athlete's foot anatomy and athlete feedback.

Table 3.1. Athlete demographics.

Variable	**All Athletes** (n=12)	**Females** (n=8)	**Males** (n=4)
Age (years)	19.92 ± 1.56	20.29 ± 1.60	19.40 ± 1.52
Height (cm)	167.55 ± 7.23	166.07 ± 4.64	169.62 ± 10.12
Weight (kg)	65.7 0± 9.85	62.61 ± 7.13	70.02 ± 12.28

Biomechanical Characteristics

Table 3.2 displays the biomechanical characteristics of the athletes. Average peak vGRF during the treadmill run for all athletes across all speeds was 2.69 ± 0.19 BW. Males elicited higher average vGRF (2.82 ± 0.22 BW) than female (2.50 ± 0.14 BW). The males also had a greater kinetic asymmetry between left and right vGRF (1.43 ± 0.04 %) than the female athletes (1.33 ± 0.03 %), while the average for all athletes was (1.38 ± 0.68 %). Females produced a lower average loading rate (0.02 ± 0.003 BW/ms) than males (0.03 ± 0.006 BW/ms), whereas the average of all the athletes was (0.03 ± 0.007 BW/ms). Males had a shorter average contact time (201.14 ± 27.69 ms) than females (217.36 ± 24.59 ms), while combined all athletes had an average of 202.96 ± 28.73 ms.

The average jump height for all athletes was 22.83 ± 8.44 cm, with the male athletes jumping much higher than the female athletes (males: 31.93 ± 4.67cm, females: 18.28 ± 5.63 cm). The average jumping peak landing force asymmetry for all athletes was 1.38 ± 15.69%, favoring the right limb. Separating the athletes by sex $\dot{V}O_2$, females had higher asymmetry (3.05 ± 14.97 % (Right)) than males (1.98 ± 20.96 % (Left)). However, the males had a higher asymmetry for average jumping takeoff peak force (9.68 ± 16.51 % (Left)) than the females (1.33 ± 7.82 % (Right)), with the average of all athletes being 2.34 ± 11.34 % favoring the left limb.

Table 3.2. Average biomechanical characteristics.

Variable	**All Athletes** (n=12)	**Females** (n=8)	**Males** (n=4)
Peak vGRF (BW)	2.69 ± 0.19	2.50 ± 0.14	2.82 ± 0.22
Difference (Asymmetry) (%)	1.38 ± 0.68	1.33 ± 0.03	1.43 ± 0.04
Loading Rate (BW/ms)	0.030 ± 0.007	0.024 ± 0.003	0.032 ± 0.006
Contact Time (ms)	202.96 ± 28.73	217.36 ± 24.59	201.14 ± 27.69
Jump Height (cm)	22.83 ± 8.44	18.28 ± 5.63	31.93 ± 4.67
Jumping Peak Landing Force Asymmetry (%)	1.38 ± 15.69 (Right)	3.05 ± 14.97 (Right)	1.98 ± 20.96 (Left)
Jumping Takeoff Peak Force Asymmetry (%)	2.34 ± 11.34 (Left)	1.33 ± 7.82 (Right)	9.68 ± 16.51 (Left)

Physiological Characteristics

Table 3.3 shows physiological characteristics from the results of the $\dot{V}O_{2max}$ test. The average $\dot{V}O_{2max}$ for all athlete's average 53.37 ± 7.70 mL/kg/min, however, when separated between sexes the males had higher $\dot{V}O_{2max}$ values (61.23 ± 7.19 mL/kg/min) than the females (50.71 ± 5.51 mL/kg/min). All athletes had an average of 121.00 ± 12.72 mg/dL for blood glucose and 13.48 ± 3.51 mmol/L for blood lactate. However, when comparing the sexes, males had higher blood glucose levels (128.50 ± 8.27 mg/dL) and blood lactate levels (15.93 ± 0.50 mmol/L) compared to the female athletes (119.78 ± 14.57 mg/dL; 12.72 ± 3.78 mmol/L). The average max $\dot{V}E$ for all athletes was 117.25 ± 33.47 L/min, but when comparing male and females; the male athletes had higher $\dot{V}E$ values (159.15 ± 7.13 L/min) than the female athletes (96.29 ± 15.27 L/min). The female athletes displayed lower max HR values (192.67 ± 7.55 bpm) than the all subject average (193.08 ± 6.84 bpm) and the male athletes (193.25 ± 4.72 bpm). Max RER for all athletes was 1.08 ± 0.10; and the male athletes reached a higher max RER (1.13 ±

0.11) than the female athletes (1.08 ± 0.10). The female athletes also had lower max RPE (16.00 ± 2.55) when compare the all athletes (16.50 ± 2.61), as well as the male athletes (17.25 ± 2.63).

Table 3.3. Average physiological characteristics.

Variable	**All Athletes** (n=12)	**Females** (n=8)	**Males** (n=4)
$\dot{V}O_{2max}$ (mL/kg/min)	53.37 ± 7.70	50.71 ± 5.51	61.23 ± 7.19
Max Blood Glucose (mg/dL)	121.00 ± 12.72	119.78 ± 14.57	128.50 ± 8.27
Max Blood Lactate (mmol/L)	13.48 ± 3.51	12.72 ± 3.78	15.93 ± 0.50
Max $\dot{V}E$ (L/min)	117.25 ± 33.47	96.29 ± 15.27	159.15 ± 7.13
Max HR (bpm)	193.08 ± 6.84	192.67 ± 7.55	193.25 ± 4.72
Max RER ($VCO_2/\dot{V}O_2$)	1.08 ± 0.10	1.05 ± 0.09	1.13 ± 0.11
Max RPE	16.50 ± 2.61	16.00 ± 2.55	17.25 ± 2.63

Table 3.4 displays the results from intraclass correlation and coefficient of variation statistics for the treadmill load cell peak force data. The results indicate a change in both ICC and CV as the speed increases. The highest ICC occurred at 20.4 km/h and 21.7 km/h (1.00). The highest CV occurred at 17.8 km/h (22.59%), while the lowest occurred at 20.4 km/h and 21.7 km/h (7.58%).

Table 3.4. Intraclass correlation and coefficient of variation for treadmill load cell data.

Speed (km/h)	**10.1**	**11.4**	**12.7**	**14.0**	**15.2**	**16.5**	**17.8**	**19.1**	**20.4**	**21.7**
Intraclass Correlation (ICC)	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	1.00	1.00
Lower Confidence Limit	0.97	0.97	0.97	0.96	0.96	0.96	0.98	0.97	1.32	1.30
Upper Confidence Limit	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.01	1.01
Coefficient of Variation (CV) (%)	18.43%	19.11%	20.03%	20.33%	19.92%	20.32%	22.59%	21.29%	7.58%	7.81%

Discussion

Physical Characteristics

The demographics of the athletes in this study showed all athletes were similar in age due to the fact that they are all college-aged athletes. Based on averages, the males were taller than the female athletes by 3.55 cm and the males also had more body mass than the females by 7.41 kg. This was to be expected based on the size differences that exist between males and females. Fuster et al. (2014), reported their male subjects were taller and they weighed more than the females. In that study, the average of males was 12.74 cm taller and weighed 16.21 kg more than the average of females; reporting similar results to our study (Fuster et al., 2014). Millet and Bentley (2004), also reported their male subjects who were junior triathletes were taller and had a greater body mass than the female triathletes.

In addition to differences in physical characteristics between sexes, there were also physiological differences that were noted. Males, compared to females, showed higher $\dot{V}O_{2max}$ values and max $\dot{V}E$ values. This finding is supported by studies in which incremental max test on the treadmill found that the males typically showed a greater absolute increase in $\dot{V}O_2$ compared to females (Kang, Hoffman, Chaloupka, Ratamess, & Weiser, 2006). Due to the fact that all subjects were of similar age and fitness level, the researchers believed this was mainly due to differences in body size between the sexes (Kang et al., 2006).

Biomechanical Characteristics

The male athletes exhibited a greater average vGRF (2.82 ± 0.22 body weight (BW)) than the female athletes (2.50 ± 0.14 BW), however they also had greater average asymmetry (1.43 ± 0.04%) than the females (1.33 ± 0.03%). Munro, Miller, and Fuglevand (1987), found their subjects reached an average vGRF of 2.3 BW when the speed was near 17.8 km/h for active peaks. Another study that examined active peaks, reported their subjects reached average vGRF values of 2.5-2.8 BW (Cavanagh & Lafortune, 1980). Other previous research observed the change in vGRF with increasing speeds and reported that their subjects increased vGRF as speeds increased; which is the same results experienced in the current study (Brughelli, Cronin, & Chaouachi, 2011; Kluitenberg, Bredeweg, Zijlstra, Zijlastra, & Buist, 2012).

Even though the females had lower average vGRF, they had a higher average contact time (217.36 ± 24.59 ms) than the males (201.14 ± 27.69 ms). Contact time had been previously found that midfoot runners have an average ground contact time of 0.228 ± 0.009 s (228 ms) (Di Michele & Merni, 2014). Average ground contact time in middle distance runners has been reported to be 180 ± 14 ms (females) and 173 ± 16 ms (males) (Hayes & Caplan, 2012). However, this study was performed using specific distances on a track and not during a $\dot{V}O_{2max}$ test. Other research testing the change in contact time with increasing speeds and found that their subjects experienced a decrease in contact time as speeds increased; which is what was found in the current study as well (Brughelli et al., 2011; De Witt, Hagan, & Cromwell, 2008; Kluitenberg et al., 2012). However, these studies did not use exactly the same methodology as the current study; however, the data is still useful for comparisons.

Females had a lower body mass and a lower average loading rate (0.024 ± 0.003 BW/ms) than the male athletes (0.032 ± 0.006 BW/ms). This was to be expected due to the fact that the females had a lower average vGRF as well as a higher average contact time. Loading rate was collected in a study by Nordin, Dufek, and Mercer (2017), where they reported average loading rates of 0.04 ± 0.03 BW/s. In comparison, athletes in this study had lower loading rates, however, Nordin et al. (2017) only studied males. De Witt et al. (2008), found that their subjects reported and average loading rate during running of 46.39 ± 9.52 BW/s (0.046 ± 0.01 BW/ms) with zero added inertia. Even though a direct comparison cannot be made to these studies due to a difference in methodology, our athletes displayed lower contact times which could be related to better running economy.

The jump testing performed by the athletes showed the females averaged an asymmetry of 3.05 ± 14.97% in favor of the right limb for the peak landing force and an asymmetry of 1.33 ± 7.82% favoring the right limb for takeoff peak force. However, the males favored the left limb for both variables of the jumps. For peak landing force, the males had an average of 1.98 ± 20.96% asymmetry and an average of 9.68 ± 16.51% asymmetry for takeoff landing peak force. The large standard deviations indicate this these variables vary greatly for each athlete. The males jumped higher than the females, which was to be expected due to strength differences between genders. Jump testing was conducted to see if asymmetry in jump performance could be an indication of asymmetry in running. The results of this study, when comparing all athletes, demonstrated similar results of asymmetry.

While a comparison to previous research is unavailable due to the differences in methodology, there are valuable findings to be reported. Bailey, Sato, Alexander, Chiang, and Stone (2013), found that asymmetry within force production could have a negative effect on bilateral vertical jumping performance for collegiate athletes. Additionally, kinetic asymmetry could lead to an undesirable displacement during jump, which could have a negative influence on performance for division 1 baseball players (Bailey, Sato, Burnett, & Stone, 2015). A study by Pappas & Carpes (2012) reported female subjects experienced more asymmetry when landing a jump than the male subjects; leading to the assumption this could lead to greater risk of injury. In a study that reported the results of examining two-legged countermovement jumps for 28 males and 30 females (not highly trained) found that three males and four females favored the right leg at impulse and two men and three females who favored the left leg at impulse (Benjanuvatra, Lay, Alderson, & Blanksby, 2013).

Physiological Characteristics

Athletes of both sexes had relatively similar $\dot{V}O_{2max}$ values, indicating this group was homogenous with their aerobic capability. Females had an average $\dot{V}O_{2max}$ of 50.71 ± 5.51 mL/kg/min, classifying them as superior and in the 95th percentile for their age (*ACSM's Guidelines for Exercise Testing and Prescription*, 2014). The males had an average of 61.23 ± 7.19 mL/kg/min, which places them in the 99th percentile and classifies them as superior for their age (*ACSM's Guidelines for Exercise Testing and Prescription*, 2014). Males were expected to have higher $\dot{V}O_{2max}$ because they typically have higher hemoglobin concentration and greater oxygen transport, as well as greater max stroke volume and max cardiac output than females, all of which play a role in $\dot{V}O_{2max}$ values (Brooks, Fahey, & Baldwin, 2005).

Hutchinson, Cureton, Outz, and Wilson (1991), reported their male subjects as having an average $\dot{V}O_{2max}$ of 57.5 ± 5.2 mL/kg/min and their female subjects reaching an average of 52.2 ± 5.1 mL/kg/min, a difference of 5.3 mL/kg/min. Another study reported their endurance trained subjects had an average $\dot{V}O_{2max}$ of 59.5 ± 3.3 mL/kg/min (Aguiar, Santos, Cruz, Turnes, Pereira, & Caputo, 2015). Similar to these studies, the difference in our athletes was 10.52 mL/kg/min. In addition to differences in $\dot{V}O_{2max}$ values being related to size differences between sexes; The male athletes had a higher average max $\dot{V}E$ than the females by 62.86 L/min. This is to be expected due to the greater lung capacity males have compared to females (Harms, 2006). It is also important to mention the contribution of genetics and training differences that could contribute to the variation of results.

While the males had a higher average max blood glucose (128.50 ± 8.27 mg/dL) than the females (119.78 ± 14.57 mg/dL), both results were expected. Brooks et al. (2005), there can be an increase in blood glucose levels because an increase in exercise intensity can cause stimulation of hepatic glycogenolysis due to catecholamine accumulation. Similar results were found in an article by Feo et al. (2003), in which they found blood glucose at a percent of $\dot{V}O_{2max}$ increased during an incremental $\dot{V}O_{2max}$ test. Additionally, blood glucose in male and female runners at exhaustion, the subjects average a blood glucose levels were greater than 5 mmol/L (>90 mg/dL) (Tokmakidis & Karamanolis, 2008). However, a direct comparison cannot be made to the current study due to a difference in methodology and procedures.

Average max blood lactate varied between sexes (males: 15.93 ± 0.50 mmol/L; females: 12.72 ± 3.78 mmol/L), however, both exhibited responses that were to be expected based on the testing they performed. Blood lactate increases as the intensity of the exercise increases, especially when the rate of production exceeds the rate of clearance (Brooks et al., 2005). All athletes reached the blood lactate requirement of greater than 8 mmol/L for that specific criterion for achieving a true $\dot{V}O_{2max}$ (*ACSM's Guidelines for Exercise Testing and Prescription*, 2014).

In a study by Maldonado-Martín, Mujika, and Padilla (2004), their subjects reached an average max blood lactate levels of 10.4 ± 3.2 mmol/L for females and 11.7 ± 3.0 mmol/L for males while running on a treadmill that progressed towards max each stage. Another study reported average max blood lactate levels of 8.0 ± 1.9 mmol/L for females and 8.8 ± 1.9 mmol/L for males when performing a $\dot{V}O_{2max}$ test on a treadmill (Held & Marti, 1999). Therefore, our subjects reached higher values than in previous research; this could be due to differences in training status, the ability to efficiently clear lactate, or differences in test protocol.

All athletes achieved very similar average max HR values (females: 192.67 ± 7.55 bpm; males: 193.25 ± 4.72 bpm). This was to be expected because all athletes were of similar age and experienced the same testing protocol. However, none of the averages reached the HR criteria of +/- 5 bpm of age-predicted HR max for achieving a true $\dot{V}O_{2max}$ (*ACSM's Guidelines for Exercise Testing and Prescription*, 2014). A study by Robertson et al. (2000), found that when their subjects achieved max on a treadmill, they had an average max HR of 194.4 ± 5.1 bpm (females) and 191.9 ± 7.8 bpm (males). Another study reported peak heart rate values of 195.2 bpm (Steed, Gaesser, & Weltman, 1994). Similar to results found in this study where our female athletes averaged a max HR of 192.67 ± 7.55 bpm and our male athletes averaged a max HR of 193.25 ± 4.72 bpm.

Average Max RER was different when comparing sexes, however, there was only a 0.08 difference reported. The male athletes average 1.13 ± 0.11, whereas the females averaged 1.05 ± 0.09. While within each sex, there was very little deviation and only a small difference between sexes; this difference could be the difference between meeting the criterion of a true $\dot{V}O_{2max}$. In order to achieve this, an RER of 1.10 or greater must be reached, meaning the males achieved it but the females did not (*ACSM's Guidelines for Exercise Testing and Prescription*, 2014).

In a study by Maldonado-Martín et al. (2004), found their female subjects reached an average max RER of 1.09 ± 0.02 and the males reached 1.08 ± 0.04. Another study reported their subjects reached a peak RER of 1.09 ± 0.04 (Millard-Stafford, Sparling, Rosskopf, & DiCarlo, 1991). Comparable to what was found in this study, however, our females reached slightly lower values and our males reached a slightly higher average max RER. A study by Tokmakidis and Karamanolis (2008), found an average RER at exhaustion of 0.94 ± 0.01 for their male and female runners on a placebo compared to a glucose supplement. Comparing those results to this study, our athletes experienced higher max RER values.

Even though RPE is a qualitative estimation for the athlete, it is a valuable indication of the "internal" intensity of the exercise the athlete is experiencing (Demello, Cureton, Boineau, & Singh, 1987). The female athletes only achieved an average max RPE of 16.00 ± 2.55, however, the males achieved an average of 17.25 ± 2.63. Therefore, only the male athletes achieved the criterion for a true $\dot{V}O_{2max}$ in which they must reach an RPE greater than 17 (*ACSM's Guidelines for Exercise Testing and Prescription*, 2014).

These results make sense due to the fact that a strong link between RPE and $\dot{V}O_2$ have been found (Coquart, Garcin, Parfitt, Tourny-Chollet, Eston, 2014). Therefore, since the female athletes did not reach as high of a $\dot{V}O_{2max}$ value, they would not reach as high of an RPE as their male counterparts. However, all athletes had a higher average max RPE reported than that found by Hall, Ekkekakis, and Petruzzello (2005). In that study, their subjects reported an average RPE of 15.47 ± 2.15 at the end of minute 15 at an intensity greater than their ventilatory threshold (Hall et al., 2005). Steed et al. (1994), reported their subjects reached a peak RPE 18.9 during an incremental running. In a study by Robertson et al. (2000), showed that both their male and female subjects reached an average RPE of 19 for maximal exercise. Robertson et al. (2000), also showed an increase in RPE as intensity increased, which is the same we found.

Conclusion

Our study provides evidence as to what is required of a collegiate cross-country or triathlon athlete both biomechanically and physiologically. Asymmetry for all athletes throughout the $\dot{V}O_{2max}$ test remained minimal, as did the asymmetry for all athletes during the jump testing. The similarity provides evidence that jump testing and running asymmetries may be related. Based on ACSM's guidelines for $\dot{V}O_{2max}$ value classification, our athletes ranked in the 95th percentile (females) and the 99th percentile (males). In conclusion, these athletes had a large aerobic power to perform in competition; while maintaining a low kinetic asymmetry which can help decrease the risk of injury.

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CHAPTER 4

CHANGES IN BIOMECHANICAL PARAMETERS WITH INCREASING SPEEDS

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Changes in biomechanical parameters with increasing speeds

Abstract

Previous research has reported biomechanical data on various speeds of running, especially sprinting; however, there is less information on collegiate 5k runners. The purpose of this study is to research the effects of increasing speeds on biomechanical parameters during an incremental $\dot{V}O_{2max}$ test. This study tested 12 college cross-country and triathlon athletes (8 females, 4 males). Statistical analysis such as average and percent change of variables were calculated, as well as a correlation matrix and regression analysis of biomechanical parameters (IV) and $\dot{V}O_2$ (DV). The largest increase in vGRF took place from 19.1 km/h to 20.4 km/h with an increase of 4.31%. The athletes experienced the largest asymmetry (2.95%) at 21.7 km/h, and the smallest asymmetry (0.62%) at 17.8 km/h. A correlation matrix showed that the highest correlation was between speed and contact time *r*(11)=-0.991 (*p*=0.000). Indicating that as speed increases, the amount of ground contact time decreases. In conclusion, our findings provide evidence that collegiate cross-country and triathlon athletes are more symmetrical at faster speeds, likely due to the wide range of speeds they cover in competition.

Keywords: biomechanics, vGRF, $\dot{V}O_{2max}$ test

Introduction

Collegiate cross-country and triathlon athletes need to be able to perform at a wide range of speeds during competition (Furlong & Eggington, 2018). Therefore, it is useful to investigate how increasing speeds and intensities effect biomechanical parameters for performance. The purpose of this study is to research the effects of increasing speeds on biomechanical parameters during an incremental $\dot{V}O_{2max}$ test.

Vertical ground reaction force (vGRF) has been reported among recreationally trained athletes, that females produced vGRF of 2.28 ± 0.32 BW and males produced 2.46 ± 0.33 BW (Keller, Weisberger, Ray, Hasan, Shiavi, & Spengler, 1996); indicating athletes undergo a large amount of stress during running. More importantly, is the degree to which asymmetry could take place during activity. Kinetic Asymmetry is believed to increase the risk of injury, therefore, the larger amount of kinetic asymmetry the higher the risk (Furlong & Eggington, 2018). Bailey, Sato, Burnett, and Stone (2015) reported that strength seems to play a large role in decreasing the amount of asymmetry between limbs. Therefore, asymmetry may be an indication of weak athletes.

The importance of this study is to provide detailed information on the effect of increasing speeds on the biomechanical parameters of college cross-country and triathlon athletes. The knowledge that could be found could directly help coaches and athletes provide an optimal strength and sport specific training program in order to increase an athlete’s performance.

Methods

Athletes

The athletes were 12 trained male and female collegiate cross-country and triathlon, ranging from age 18 to 25 years old. Tests were part of an ongoing athlete monitoring program. Athletes must have had clearance to perform a maximal exertion exercise by the university’s medical staff in order to take part in the monitoring program.

Procedures

Each athlete’s age, body mass, and height were recorded prior to jump testing. Before starting the $\dot{V}O_{2max}$ test, the athletes performed 3 unweighted countermovement jumps on PASCO Force Plates (Roseville, CA) that were analyzed using ForceDecks Software (Vald Performance, London, England). A study established that the PASCO portable force plates are a reliable tool for collecting jump data (Silveira, Stergiou, Carpes, Castro, Katz, & Stefanyshyn, 2017).The athlete then performed a $\dot{V}O_{2max}$ test, until volitional fatigue, using a Parvo Medics TrueOne 2400 Metabolic Cart (Sandy, UT) for gas exchange analysis. The $\dot{V}O_{2max}$ protocol being used was a protocol and previous monitoring set in place by the strength and conditioning coach and the sport coach of the triathlon team and cross-country team in order to be able maintain consistency (Beltz, Gibson, Janot, Kravitz, Mermier, Dalleck, 2016). Prior to starting the test, each athlete’s baseline measurements were recorded. The protocol used in this study was not typical compared to other studies. The majority of $\dot{V}O_{2max}$ tests follow the Balke or Bruce protocol (Beltz et al., 2016). Both these protocols not only increase in speed, but also grade with each stage (Beltz et al., 2016). However, the protocol consisted of each athlete starting at a speed of 10.1 km/h. The speed increased by 1.28 km/h every 2 minutes until the subject reached an RER of 1.00. Then, the speed increased 1.28 km/h every 1 minute until cessation of the test. This was performed in an attempt to achieve a true $\dot{V}O_{2max}$ test and max lactate concentration, while keeping the total test time as close to 12 minutes as possible, which is the preferred duration (Arena et al., 2007). Throughout the $\dot{V}O_{2max}$ test, a grade of 0% was maintained in order to properly collect and compare vGRF data from the force plates. During the $\dot{V}O_{2max}$ test, the athlete’s blood lactate (2 measurements each time) was measured using a Nova Medical Lactate Plus analyzer (Waltham, MA). The Lactate Plus device reported good reliability and accuracy when being compared to an in-laboratory based blood lactate analyzer (Tanner, Fuller, & Ross, 2010). Blood glucose (2 measurements each time) was measured using an Accu-Chek Aviva Plus meter (Roche, Indianapolis, IN), and when portable blood glucometers were compared to an in-laboratory analyzer it was reported that 82% of the readings met the International Organization of Standardization's criteria for clinical accuracy (Salacinski, Alford, Drevets, Hart, & Hunt, 2014). RPE was also collected at the end of each stage. To collect this data, the athlete stepped off the belt and onto the treadmill's running board. Then athlete returned to the treadmill belt for the next stage of the test. All athletes were equipped with a Garmin heart rate monitor chest strap (Olathe, KS) to monitor changes in heart rate throughout the test. Garmin was chosen to maintain consistency with what the athletes use during training. While the athlete was running, their vGRF was being recorded using four load cells (Rice Lake, WI) collecting at 1,000 hertz (Hz) placed beneath the Tuff Tread treadmill belt (Conroe, TX) and the LabView 2018 software (National Instruments, Austin, TX) for the entirety of the $\dot{V}O_{2max}$ test. All testing ceased when the athlete ended the $\dot{V}O_{2max}$ test by stepping off the treadmill belt and onto the side platform on their own. See study design in Figure 4.1.

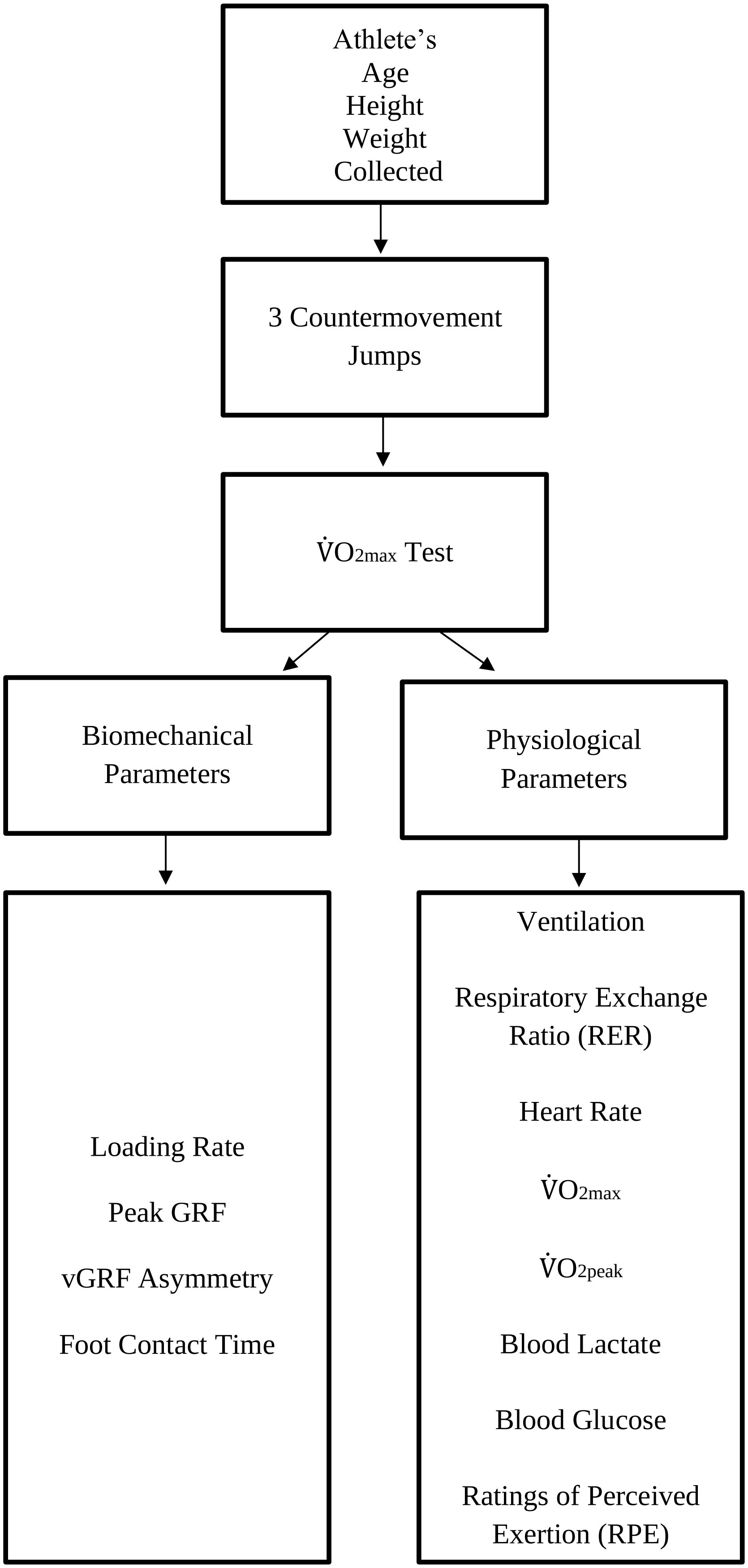

Figure 4.1. Study design.

Statistical Analysis

Data was analysed using Microsoft Excel (Microsoft Corporation, Redmond, WA, version 16.25) by calculating average and percent change. SPSS (IBM Corporation, Armonk, NY) was used to perform a correlation matrix of the average values to establish relationships between variables. SPSS was also used to perform a regression analysis between biomechanical parameters (IV) and $\dot{V}O_2$ (DV). Intraclass correlation (ICC) and coefficient of variation (CV) were used to analyse reliability of the treadmill load cell data using Microsoft Excel and a spreadsheet developed for analysis of reliability (Hopkins, 2015).

Results

Biomechanical Parameters

Table 4.1 displays the percent change in each biomechanical parameter from speed to speed. The largest increase in vGRF for all athletes occurred from speed 19.1 km/h to 20.4 km/h (4.31%). Loading rate had the largest percent change from 19.1 km/h to 20.4 km/h with an increase of 15.28%. For contact time, the largest percent change was a decrease from 12.7 km/h to 14.0 km/h (-5.99%).

Table 4.1. Percent change from speed to speed for biomechanical parameters for all athletes.

Speed (km/h)	**vGRF** (BW)	**vGRF** (% Change)	**Loading Rate** (BW/ms)	**Loading Rate** (% Change)	**Contact Time** (ms)	**Contact Time** (% Change)
10.1 (n=12)	2.38	-	0.02	-	251.20	-
11.4 (n=12)	2.49	4.27%	0.02	8.07%	237.98	-5.55%
12.7 (n=12)	2.56	2.63%	0.02	5.40%	226.16	-5.23%
14.0 (n=12)	2.62	2.34%	0.03	5.57%	213.39	-5.99%
15.2 (n=12)	2.66	1.78%	0.03	5.13%	202.76	-5.24%
16.5 (n=11)	2.69	1.11%	0.03	3.92%	194.86	-4.05%
17.8 (n=9)	2.76	2.32%	0.03	8.26%	185.63	-4.97%
19.1 (n=7)	2.83	2.63%	0.03	10.29%	179.23	-3.57%
20.4 (n=4)	2.96	4.31%	0.04	15.28%	172.43	-3.95%
21.7 (n=4)	2.92	-1.46%	0.04	2.73%	165.97	-3.89%

Figure 4.2 shows the right and left leg vGRF at each speed for all athletes. The data indicates that as the speed increased during the $\dot{V}O_{2max}$ test, the vGRF of both the left and right leg also increased until the final speed of 21.7 km/h where there is a slight decrease.

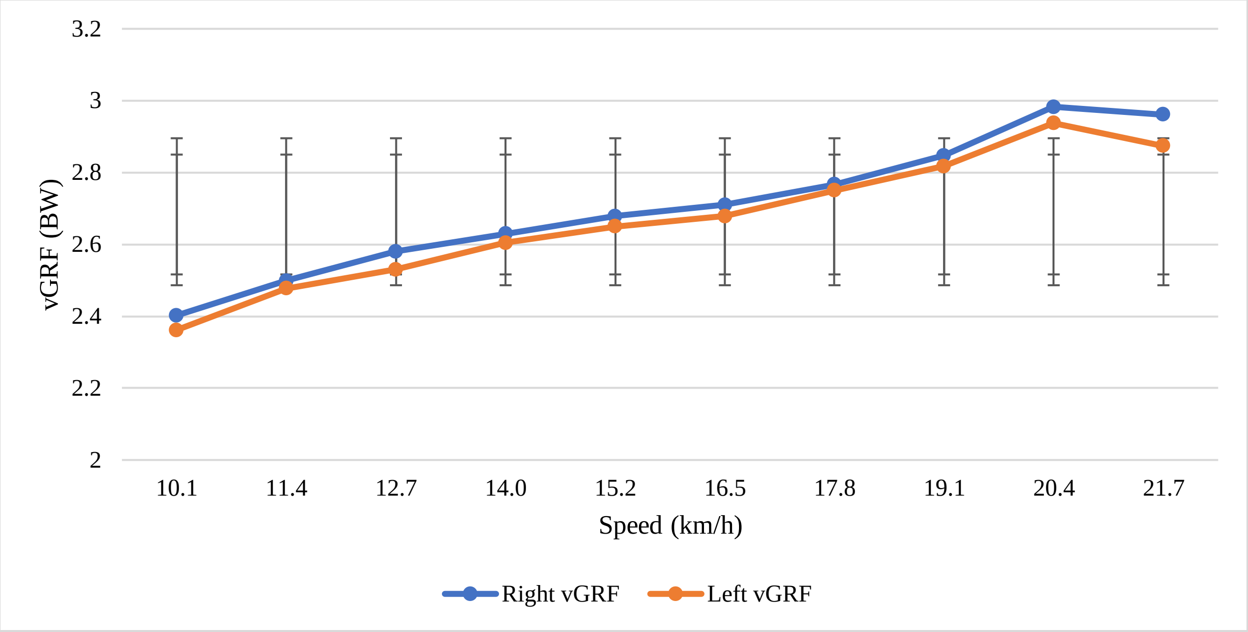

Figure 4.2. Right and left leg vGRF at each speed for all athletes.

Table 4.2 displays the vGRF asymmetry between the right and left legs at each speed that was depicted above in figure 4.1. It was noted that the largest asymmetry occurred at 21.7 km/h (2.95%); however, the smallest asymmetry occurred at 17.8 km/h (0.62%).

Table 4.2. vGRF asymmetry between right and left leg for all athletes at each speed.

Speed (km/h)	**Right vGRF** (BW)	**Left vGRF** (BW)	**Asymmetry** (%)
10.1 (n=12)	2.402	2.361	1.69%
11.4 (n=12)	2.498	2.477	0.85%
12.7 (n=12)	2.580	2.530	1.93%
14.0 (n=12)	2.629	2.604	0.96%
15.2 (n=12)	2.678	2.649	1.09%
16.5 (n=11)	2.710	2.678	1.18%
17.8 (n=9)	2.766	2.749	0.62%
19.1 (n=7)	2.847	2.817	1.06%
20.4 (n=4)	2.983	2.937	1.52%
21.7 (n=4)	2.961	2.874	2.95%

Figure 4.3 displays the change in vGRF from speed to speed for all athletes. The figure displays that the average vGRF increases as the speed increases. It is indicated that the largest increase occurred between 19.1 km/h and 20.4 km/h (4.31%), while the smallest increase occurred from 15.2 km/h to 16.5 km/h (1.11%). A decrease in vGRF occurred from 20.4 km/h to 21.7 km/h by 1.46%.

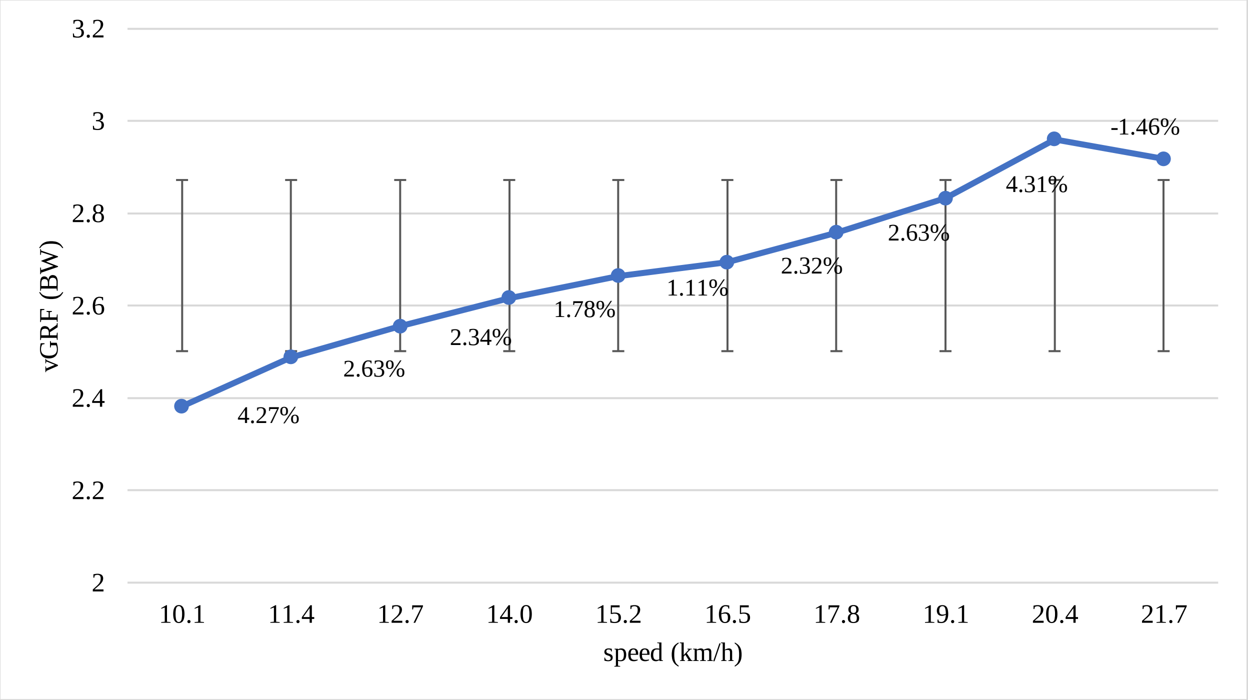

Figure 4.3. Average vGRF at each speed for all athletes with percent change.

A Pearson correlation was performed on all variables to estimate relationships. Table 4.3 below displays the relationships between the biomechanical parameters of this study. The highest correlation was between speed and contact time with an *r* value of -0.991, indicating a strong, negative correlation. Other notable relationships are between speed and vGRF ($r(11)=0.986$, $p=0.000$), between loading rate and vGRF ($r(11)=0.965$, $p=0.000$), and between vGRF and contact time ($r(11)=-0.982$, $p=0.000$). However, asymmetry had weak correlations with all other variables.

Table 4.3. Biomechanical parameter correlation matrix.

Variable	**Speed** (km/h)	**vGRF** (BW)	**Asymmetry** (%)	**Loading Rate** (BW/ms)	**Contact Time** (ms)
Speed (km/h)	-	0.986*	0.291	0.965*	-0.991*
vGRF (BW)	0.986*	-	0.242	0.965*	-0.982*
Asymmetry (%)	0.291	0.242	-	0.430	0.201
Loading Rate (BW/ms)	0.965*	0.965*	0.430	-	-0.927*
Contact Time (ms)	-0.991*	-0.982*	-0.201	-0.927*	-

Note: *denotes significant correlation, *p*<.05.

Table 4.4 shows the results from a regression analysis was conducted using $\dot{V}O_2$ (L/min) as the dependent variable and all biomechanical variables as the independent variables. vGRF (*p*=0.012) and contact time (*p*=0.047) were statistically significant with $\dot{V}O_2$. However, there was no statistical significance with loading rate.

Table 4.4. Regression analysis of biomechanical parameters with $\dot{V}O_2$.

Variable	**P-Value**
vGRF (BW)	0.012*
Loading Rate (BW/ms)	0.376
Contact Time (ms)	0.047*

Note: *denotes significant correlation, *p*<.05.

Table 4.5 displays the results from intraclass correlation and coefficient of variation statistics for the treadmill load cell peak force data. The results indicate a change in both ICC and CV as the speed increases. The highest ICC occurred at 20.4 km/h and 21.7 km/h (1.00). The highest CV occurred at 17.8 km/h (22.59%), while the lowest occurred at 20.4 km/h and 21.7 km/h (7.58%).

Table 4.5. Intraclass correlation and coefficient of variation for treadmill load cell data.

Speed (km/h)	**10.1**	**11.4**	**12.7**	**14.0**	**15.2**	**16.5**	**17.8**	**19.1**	**20.4**	**21.7**
Intraclass Correlation (ICC)	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	1.00	1.00
Lower Confidence Limit	0.97	0.97	0.97	0.96	0.96	0.96	0.98	0.97	1.32	1.30
Upper Confidence Limit	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.01	1.01
Coefficient of Variation (CV) (%)	18.43%	19.11%	20.03%	20.33%	19.92%	20.32%	22.59%	21.29%	7.58%	7.81%

Discussion

The biomechanical parameters and how they changed as speed increased, specifically focusing on the vGRF as the speed increases, a clear trend can be observed. A correlation of 0.99 was calculated between speed and vGRF, indicating a very strong, positive correlation. However, the correlation between speed and asymmetry was only 0.29, indicating a weak relationship between these two variables.

The percent change in vGRF increased as the running speed increased from stage to stage. Starting at the beginning an increase of 4.27% was reported for average percent vGRF change from 10.1 km/h to 11.4 km/h. During this transition, the amount of asymmetry from 10.1 km/h to 11.4 km/h decreased from 1.69% asymmetry to 0.85% asymmetry, respectively. Perhaps the first speed was too slow for the athletes, due to the training distance and speed to which they were accustomed, they were not as comfortable at slower speeds. Even though the athletes experienced an increase in vGRF from 16.5 km/h (2.69 BW) to 17.8 km/h (2.75 BW), they experienced the most symmetry at 17.8 km/h with only 0.62% asymmetry between left and right vGRF. Due to the training level of the athlete's in this study, perhaps they were most symmetrical at this speed because they are used to training at faster paces. As the speed increased, there was a decrease in vGRF for the athletes who reached 21.7 km/h. At this point, not only did they go from an average of 2.96 BW (20.4 km/h) to 2.91 BW (21.7 km/h), but they experienced an increase in asymmetry from 1.52% at 20.4 km/h to an asymmetry of 2.95% at 21.7 km/h. At 21.7 km/h was also the speed the athletes experienced the greatest average asymmetry throughout the entire $\dot{V}O_{2max}$ test. It is likely that the decrease in vGRF is due to the shortest amount of contact time experienced.

Keller et al. (1996), reported vGRF in male and females who were recreational athletes found that at similar speed, females experienced vGRF of 2.28 ± 0.32 BW and the males experienced 2.46 ± 0.33 BW. Based on another study, female runners who were injury free found reached a max vGRF of 3.1 ± 2.5 BW (Zifchock, Davis, & Hamill, 2006). Other previous research has reported their subjects increased in vGRF as speed increased; as observed in the current study (Brughelli, Cronin, & Chaouachi, 2011; De Witt, Hagan, & Cromwell, 2008; Kluitenberg, Bredeweg, Zijlstra, Zijlstra, & Buist, 2012).Even though these research studies do not directly match with methodology in previous studies; the observations made in the current study match the results previously found in vGRF studies. Despite the greatest asymmetry experienced by the athletes in this study being 2.95%, previous research provides evidence that a smaller asymmetry may be less likely to cause a risk of injury. Furlong and Eggington (2018) state that asymmetry is thought to have a negative effect on injury risk; therefore, the less asymmetry the better. The asymmetry reported in this study may not be large enough to indicate an increased risk of injury. As expected, the vGRF did increase with speed increases indicating a need for strength training programs for college cross-country and triathlon teams. Bailey et al.

(2015) reported that bilateral strength training may help decrease the amount of asymmetry experienced.

It is important to further examine the vGRF asymmetry found in this current study. For example, the most asymmetrical speed of 21.7 km/h where the difference in left and right leg was 2.95% or 0.087 BW. Even though this seems like a minimal difference, it could cause greater stress on an individual athlete. For example, if an athlete weighed 60 kg, this would be the difference of 5.23 kg per step. A runner typically takes an average of about 150-190 steps per minute (Lenhart, Thelen, Wille, Chumanov, & Heiderscheit, 2014). Therefore, if the athletes run a 5k in 18 minutes and takes 150 steps per minute, that is a total of 2,700 steps throughout the race. This means they are experiencing a total of 14,121 kg of stress on a specific limb which could be detrimental to performance and the risk of injury.

At each increase in speed, the average loading rate for all athletes increased. A correlation between speed and loading rate was calculated at 0.965, indicating a strong, positive relationship. This was to be expected due to the fact that speed and vGRF had a strong positive correlation. The largest increase being from 19.1 km/h (0.034 BW/ms) to 20.4 km/h (0.040 BW/ms) with a 15.28% increase. Due to the fact that loading rate is BW/ms, this large increase in loading rate is most likely due to the increase on vGRF by 4.31%, as well as the decrease in contact time by -3.95%. The smallest change in loading rate occurred from 15.2 km/h (0.027 BW/ms) to 16.5 km/h (0.028 BW/ms), which is where there was only a small increase in vGRF of 1.11% and a relatively small decrease in contact time of -4.05%.

Observation of loading rate in male and females recreational athletes showed that at similar speeds producing the largest loading rate in the current study; the female subjects had a loading rate 22.3 ± 4.61 BW/s (0.0223 BW/ms) and the male subjects had a loading rates of 22.8

± 4.51 BW/s (0.0228 BW/ms) (Keller, et al, 1996). In addition to that, data indicates that injury free female runners showed an average loading rate of 23.3 ± 17.4 BW/s (0.0233 BW/ms) (Zifchock et al., 2006). De Witt et al. (2008), reported their subjects had higher loading rates while running, compared to running with zero added inertia. Therefore, comparing our current findings to previous research, at the fastest speeds (19.1, 20.4, and 21.7 km/h), our loading rates were slightly higher than previous research. It has been found that higher loading rates could cause an increase in injury risk (Dudley, Pamukoff, Lynn, Kersey, & Noffal, 2017). However, the majority of loading rate values and general trend reported during the $\dot{V}O_{2max}$ test agrees with previous findings, despite differences in methodologies.

Contact time decreased as speed increased throughout the max test as speeds increased. There was a correlation of -0.991, indicating a strong, negative relationship. It was expected there would be a negative relationship because previous research exhibits that as speed increases, a decrease in contact time should be experienced (Hayes & Caplan, 2012). The largest decrease in contact time occurred from 12.7 km/h to 14.0 km/h when contact time went from 226.16 ms to 213.38 ms, a decrease of -5.99%. Interestingly, the athletes experienced a decrease in asymmetry from 1.93% (12.7 km/h) to 0.96% (14.0 km/h) leading to the assumption the athletes felt more comfortable at 14.0 km/h compared to 12.7 km/h of their efficiency was greater at that pace. The smallest change in contact time took place from 17.8 km/h (185.63 ms) to 19.1 km/h (179.23 ms), a decrease of -3.57%.

Research with male and female high-calibre runners found average ground contact times of 180 ± 14 ms (females) and 173 ± 16 ms (males) during a 1500 m run (Hayes & Caplan, 2012). That study also found shorter ground contact times could translate into faster race speeds within their subjects (Hayes & Caplan, 2012). Investigation of sub-elite male distance runners found that during a 400 m run on a track, they had an average contact time of 0.228 seconds (228 ms) (Di Michele & Merni, 2014). Other previous work has reported that as the running speed increased, contact times decreased for their subjects (Brughelli et al., 2011; De Witt et al., 2008; Kluitenberg et al., 2012). Therefore, our research findings agree with that found in previous research despite a difference in methodology. With shorter ground contact times at the faster speeds, the importance of rate of force development (RFD) increases. When the athletes near the end of a race, they may need to increase their running speed to have a better performance. As pace increases contact time shortens, thus maintaining high vertical forces resulting from an increase in RFD is necessary. Because of the need to produce high RFD, it may be advantageous to emphasize RFD development in the weight room as well as running training (Martinez-Valencia, Romero-Arenas, Elvira, Gonzalez-Rave, Navarro-Valdivielso, & Alcaraz, 2015).

Conclusion

This study provides data to show that collegiate cross-country and triathlon athletes may biomechanically be affected by increasing speeds. With the steady increase in vGRF, loading rate, and decrease in contact time; it can be determined these variables are all effected by the incremental increase in speed. Interestingly, the degree of asymmetry did not follow a trend, leading to the assumption that our athletes are more efficient at certain speeds. In conclusion, our athletes were capable of maintaining a minimal amount of kinetic asymmetry throughout the $\dot{V}O_{2max}$ test, therefore, keeping their injury risk minimal.

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CHAPTER 5

CORRELATION BETWEEN BIOMECHANICAL PARAMETERS AND PHYSIOLOGICAL PARAMETERS WITH INCREASING SPEEDS

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Correlation between biomechanical parameters and physiological parameters with increasing speeds

Abstract

Previous research has typically investigated only biomechanical parameters or physiological parameters on runners during exercise. However, in order to produce a well-rounded analysis of an athlete; it is important to observe both parameters togethers. The purpose of this study the purpose of this study is to observe the change in vGRF characteristics with increasing speeds while matching physiological responses during a $\dot{V}O_{2max}$ test. This study was conducted on 12 college cross-country and triathlon athletes (8 females, 4 males). Statistical analysis of average and percent change were calculated, as well as a regression analysis between biomechanical parameters (IV) and $\dot{V}O_2$ (DV), and between difference in asymmetry (DV) and physiological parameters (IV). In addition, a correlation matrix between all variables was performed. Our research reported that all physiological parameters increased as speed increased. A strong, positive correlation of $r(11)=0.977$ ($p=0.000$) was found between vGRF and $\dot{V}O_2$. Additionally, vGRF and blood lactate also had a strong, positive correlation ($r(11)=0.930$, $p=0.000$). A regression analysis showed that there was an association between blood lactate and asymmetry ($p=0.031$). In conclusion, this study reported biomechanical parameters and physiological parameters to be highly correlated. Once the blood lactate appeared in the blood at an elevated rate, asymmetry experienced large increases; indicating blood lactate may affect the amount of asymmetry experience by the athlete.

Keywords: $\dot{V}O_{2max}$, vGRF, biomechanical, physiological

Introduction

Biomechanical parameters and physiological parameters typically researched separated for running, however, in order to establish a well-rounded analysis of an athlete; it is important to explore the correlation between them. The purpose of this study the purpose of this study was to observe the change in vGRF characteristics with increasing speeds while matching physiological responses during a $\dot{V}O_{2max}$ test.

Asymmetry has been reported to increase with increasing speeds (Clark & Weyand, 2014). More importantly, this increase has been linked to an increase in injury risk (Zifchock, Davis, & Hamill, 2006). Therefore, it is important to monitor vGRF and kinetic asymmetry for the athletes. However, there may be a correlation with physiological alterations and how these alterations affect biomechanical parameters.

During an incremental $\dot{V}O_{2max}$ test, many variables change as the intensity increases. Blood lactate appearance and the ability to clear it has been linked to endurance performance (Allen, Seals, Hurley, Ehsani, & Hagberg, 1985). Maldonado-Martin, Mujika, and Padilla (2004) reported max blood lactate levels of 10.4 ± 3.2 mmol/L for females and 11.7 ± 3.0 mmol/L for males during a $\dot{V}O_{2max}$ test. Therefore, the subjects performing that study were most likely experiencing discomfort in their legs; which could affect one's running form. Blood glucose is also a factor that could inhibit an athlete's $\dot{V}O_{2max}$ test. Glucose is an important source of fuel, especially during a max test, therefore, when blood glucose levels get too low fatigue develops

(Brooks, Fahey, & Baldwin, 2005). Once the athletes begin to experience fatigue, this could affect their gait and overall performance (Qu & Yeo, 2011).

The importance of this study to sport science is to investigate both biomechanical and physiological parameters and how they interact during an incremental max test. Evidence from this information could have large practical applications with coaches and athletes. This knowledge could help optimize training programs, leading to superior athletic performance.

Methods

Athletes

The athletes were 12 trained male and female cross-country and triathlon athletes, ranging from age 18 to 25 years old. Tests were part of an ongoing athlete monitoring program. Athletes must have had clearance to perform a maximal exertion exercise by the university's medical staff in order to take part in the monitoring program.

Procedures

Each athlete's age, body mass, and height were recorded prior to jump testing. Before starting the $\dot{V}O_{2max}$ test, the athletes performed 3 unweighted countermovement jumps on PASCO Force Plates (Roseville, CA) that were analyzed using ForceDecks Software (Vald Performance, London, England). A study established that the PASCO portable force plates are a reliable tool for collecting jump data (Silveira, Stergiou, Carpes, Castro, Katz, & Stefanyshyn, 2017).The athlete then performed a $\dot{V}O_{2max}$ test, until volitional fatigue, using a Parvo Medics TrueOne 2400 Metabolic Cart (Sandy, UT) for gas exchange analysis. The $\dot{V}O_{2max}$ protocol being used was a protocol and previous monitoring set in place by the strength and conditioning coach and the sport coach of the triathlon team and cross-country team in order to be able maintain consistency (Beltz, Gibson, Janot, Kravitz, Mermier, Dalleck, 2016). Prior to starting the test, each athlete's baseline measurements were recorded. The protocol used in this study was not typical compared to other studies. The majority of $\dot{V}O_{2max}$ tests follow the Balke or Bruce protocol (Beltz et al., 2016). Both these protocols not only increase in speed, but also grade with each stage (Beltz et al., 2016). However, the protocol consisted of each athlete starting at a speed of 10.1 km/h. The speed increased by 1.28 km/h every 2 minutes until the subject reached an RER of 1.00. Then, the speed increased 1.28 km/h every 1 minute until cessation of the test. This was performed in an attempt to achieve a true $\dot{V}O_{2max}$ test and max lactate concentration, while keeping the total test time as close to 12 minutes as possible, which is the preferred duration (Arena et al., 2007). Throughout the $\dot{V}O_{2max}$ test, a grade of 0% was maintained in order to properly collect and compare vGRF data from the force plates. During the $\dot{V}O_{2max}$ test, the athlete's blood lactate (2 measurements each time) was measured using a Nova Medical Lactate Plus analyzer (Waltham, MA). The Lactate Plus device reported good reliability and accuracy when being compared to an in-laboratory based blood lactate analyzer (Tanner, Fuller, & Ross, 2010). Blood glucose (2 measurements each time) was measured using an Accu-Chek Aviva Plus meter (Roche, Indianapolis, IN), and when portable blood glucometers were compared to an in-laboratory analyzer it was reported that 82% of the readings met the International Organization of Standardization's criteria for clinical accuracy (Salacinski, Alford, Drevets, Hart, & Hunt, 2014). RPE was also collected at the end of each stage. To collect this data, the athlete stepped off the belt and onto the treadmill's running board. Then athlete returned to the treadmill belt for the next stage of the test. All athletes were equipped with a Garmin heart rate monitor chest strap (Olathe, KS) to monitor changes in heart rate throughout the test. Garmin was chosen to maintain consistency with what the athletes use during training. While the athlete was running, their vGRF was being recorded using four load cells (Rice Lake, WI) collecting at 1,000 hertz (Hz) placed beneath the Tuff Tread treadmill belt (Conroe, TX) and the LabView 2018 software (National Instruments, Austin, TX) for the entirety of the $\dot{V}O_{2max}$ test. All testing ceased when the athlete ended the $\dot{V}O_{2max}$ test by stepping off the treadmill belt and onto the side platform on their own. See study design in Figure 5.1.

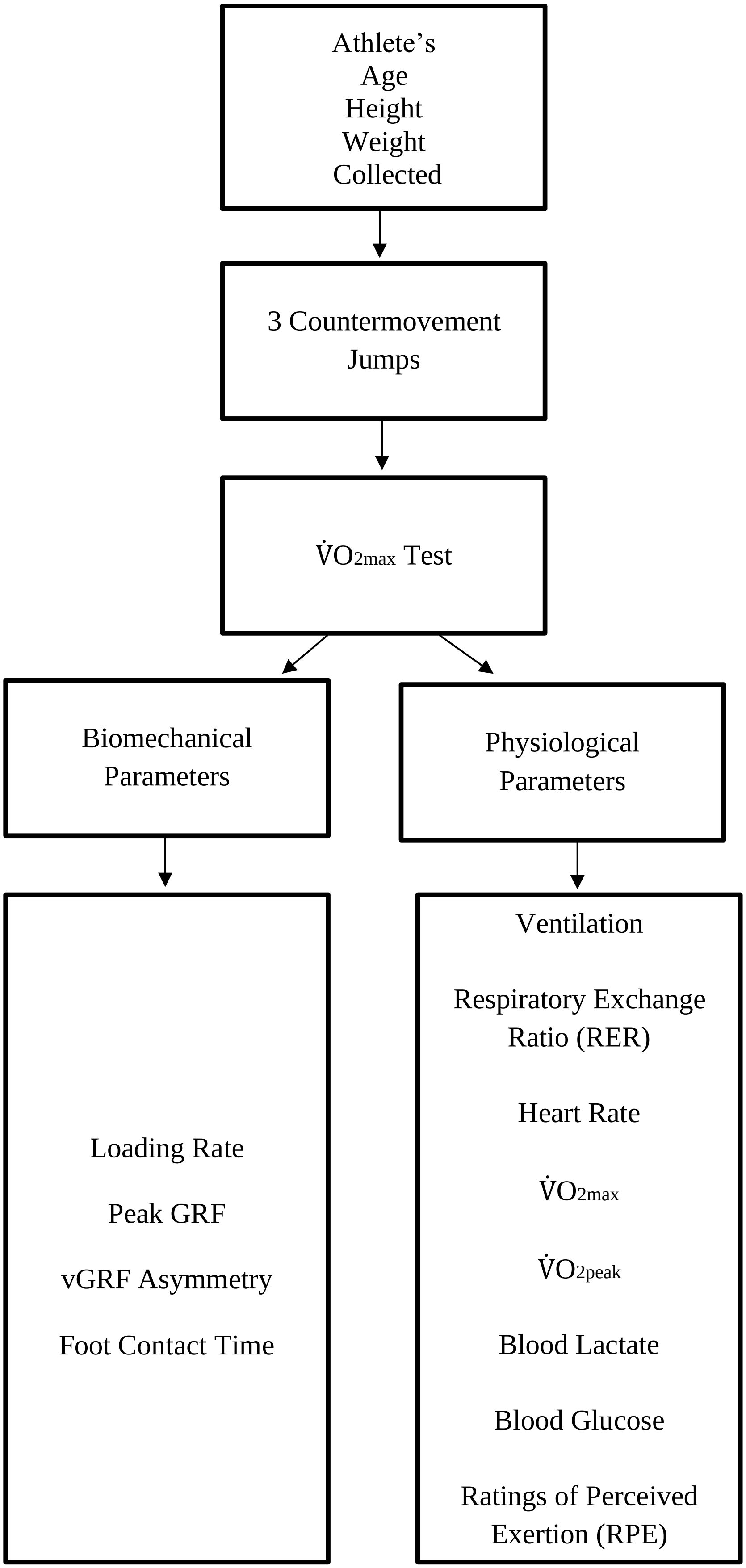

Figure 5.1. Study design.

Statistical Analysis

Data was analysed using Microsoft Excel (Microsoft Corporation, Redmond, WA, version 16.25) by calculating average and percent change. SPSS (IBM Corporation, Armonk, NY) was used to perform a correlation matrix of the average values to establish relationships between variables. SPSS was also used to perform a regression analysis between biomechanical parameters (IV) and $\dot{V}O_2$ (DV), as well as between difference in asymmetry (DV) and physiological parameters (IV). Intraclass correlation (ICC) and coefficient of variation (CV) were used to analyse reliability of the treadmill load cell data using Microsoft Excel and a spreadsheet developed for analysis of reliability (Hopkins, 2015).

Results

Biomechanical Parameters

Table 5.1 displays the percent change in each biomechanical parameter from speed to speed. The largest increase in vGRF for all athletes occurred from speed 19.1 km/h to 20.4 km/h (4.31%). Loading rate had the largest percent change from 19.1 km/h to 20.4 km/h with an increase of 15.28%. For contact time, the largest percent change was a decrease from 12.7 km/h to 14.0 km/h (-5.99%).

Table 5.1. Percent change from speed to speed for biomechanical parameters for all athletes.

Speed (km/h)	**vGRF** (BW)	**vGRF** (% Change)	**Loading Rate** (BW/ms)	**Loading Rate** (% Change)	**Contact Time** (ms)	**Contact Time** (% Change)
10.1 (n=12)	2.38	-	0.02	-	251.20	-
11.4 (n=12)	2.49	4.27%	0.02	8.07%	237.98	-5.55%
12.7 (n=12)	2.56	2.63%	0.02	5.40%	226.16	-5.23%
14.0 (n=12)	2.62	2.34%	0.03	5.57%	213.39	-5.99%
15.2 (n=12)	2.66	1.78%	0.03	5.13%	202.76	-5.24%
16.5 (n=11)	2.69	1.11%	0.03	3.92%	194.86	-4.05%
17.8 (n=9)	2.76	2.32%	0.03	8.26%	185.63	-4.97%
19.1 (n=7)	2.83	2.63%	0.03	10.29%	179.23	-3.57%
20.4 (n=4)	2.96	4.31%	0.04	15.28%	172.43	-3.95%
21.7 (n=4)	2.92	-1.46%	0.04	2.73%	165.97	-3.89%

Figure 5.2 displays the right and left leg vGRF at each speed for all athletes. The data displays that as the speed increased during the $\dot{V}O_{2max}$ test, the vGRF of both the left and right leg also increased until the final speed of 21.7 km/h where there is a slight decrease.

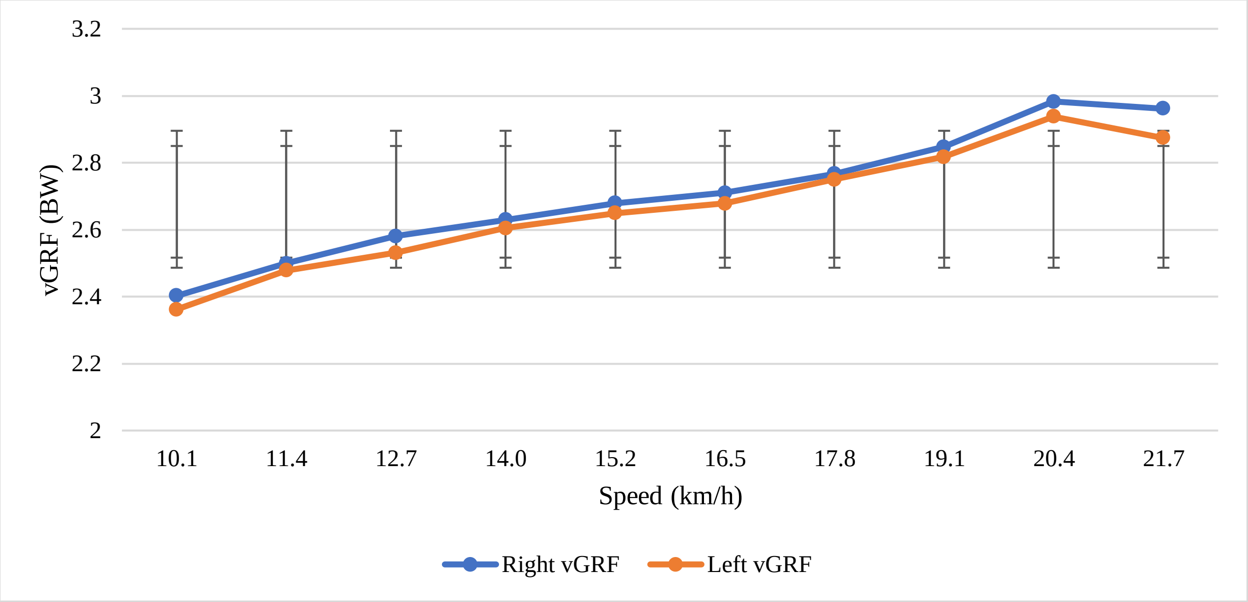

Figure 5.2. Right and left leg vGRF at each speed for all athletes.

Table 5.2 displays the vGRF asymmetry between the right and left legs at each speed that was depicted above in figure 4.1. It was reported that the largest asymmetry occurred at 21.7 km/h (2.95%); however, the smallest asymmetry occurred at 17.8 km/h (0.62%).

Table 5.2. vGRF asymmetry between right and left leg for all athletes at each speed.

Speed (km/h)	**Right vGRF** (BW)	**Left vGRF** (BW)	**Asymmetry** (%)
10.1 (n=12)	2.402	2.361	1.69%
11.4 (n=12)	2.498	2.477	0.85%
12.7 (n=12)	2.580	2.530	1.93%
14.0 (n=12)	2.629	2.604	0.96%
15.2 (n=12)	2.678	2.649	1.09%
16.5 (n=11)	2.710	2.678	1.18%
17.8 (n=9)	2.766	2.749	0.62%
19.1 (n=7)	2.847	2.817	1.06%
20.4 (n=4)	2.983	2.937	1.52%
21.7 (n=4)	2.961	2.874	2.95%

Figure 5.3 displays the change in vGRF from speed to speed for all athletes. The figure displays that the average vGRF increases as the speed increases. It is indicated the largest increase occurred between 19.1 km/h and 20.4 km/h (4.31%), while the smallest increase occurred from 15.2 km/h to 16.5 km/h (1.11%). A decrease in vGRF occurred from 20.4 km/h to 21.7 km/h by 1.46%.

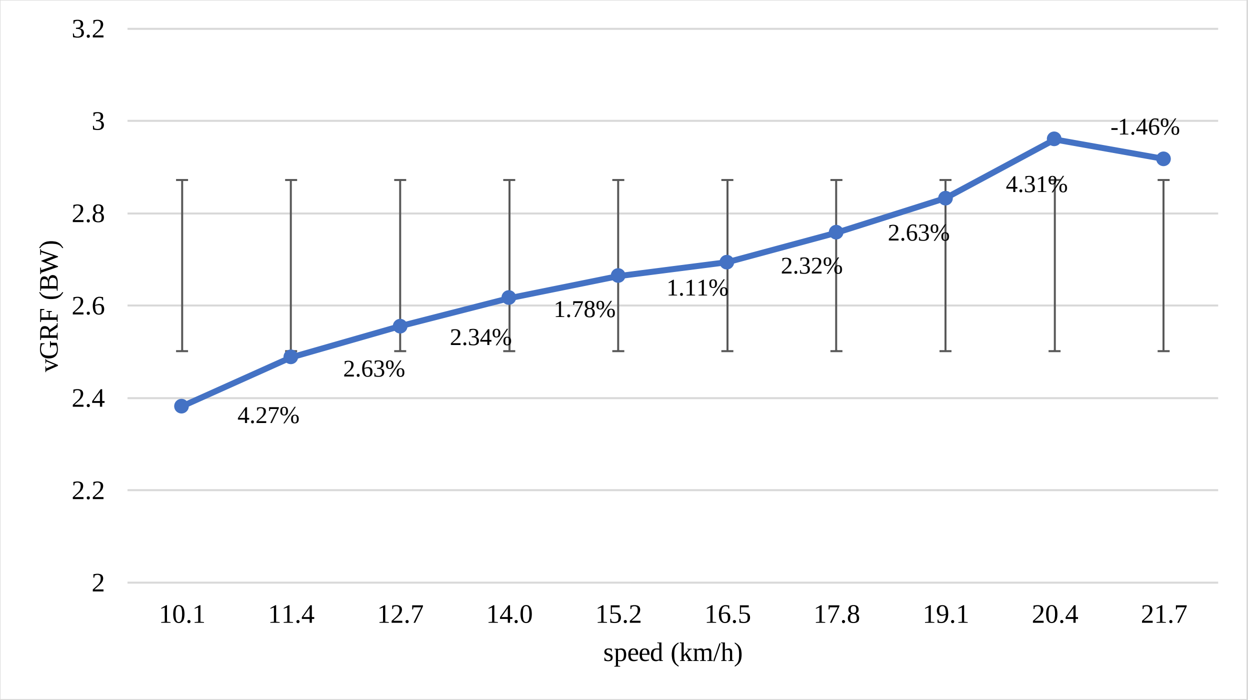

Figure 5.3. Average vGRF at each speed for all athletes with percent change.

A Pearson correlation was performed on all variables to estimate the relationships. Table 5.3 below shows the relationships between the biomechanical parameters of this study. The highest correlation was between speed and contact time with an *r* value of -0.991, indicating a strong, negative correlation. Other notable relationships are between speed and vGRF (*r*(11)=0.986, *p*=0.000), between loading rate and vGRF (*r*(11)=0.965, *p*=0.000), and between vGRF and contact time (*r*(11)=-0.982, *p*=0.000). However, asymmetry had weak correlations with all other variables.

Table 5.3. Biomechanical parameter correlation matrix.

Variable	**Speed** (km/h)	**vGRF** (BW)	**Asymmetry** (%)	**Loading Rate** (BW/ms)	**Contact Time** (ms)
Speed (km/h)	-	0.986*	0.291	0.965*	-0.991*
vGRF (BW)	0.986*	-	0.242	0.965*	-0.982*
Asymmetry (%)	0.291	0.242	-	0.430	0.201
Loading Rate (BW/ms)	0.965*	0.965*	0.430	-	-0.927*
Contact Time (ms)	-0.991*	-0.982*	-0.201	-0.927*	-

Note: *denotes significant correlation, *p*<.05.

Table 5.4 displays the results from a regression analysis that was conducted using $\dot{V}O_2$ (L/min) as the dependent variable and all biomechanical variables as the independent variables. vGRF (*p*=0.012) and contact time (*p*=0.047) were statistically significant with $\dot{V}O_2$. However, there was no statistical significance with loading rate.

Table 5.4. Regression analysis of biomechanical parameters with $\dot{V}O_2$.

Variable	**P-Value**
vGRF (BW)	0.012*
Loading Rate (BW/ms)	0.376
Contact Time (ms)	0.047*

Note: *denotes significant correlation, *p*<.05.

Table 5.5 displays the results from intraclass correlation and coefficient of variation statistics for the treadmill load cell peak force data. The results indicate a change in both ICC and CV as the speed increases. The highest ICC occurred at 20.4 km/h and 21.7 km/h (1.00). The highest CV occurred at 17.8 km/h (22.59%), while the lowest occurred at 20.4 km/h and 21.7 km/h (7.58%).

Table 5.5. Intraclass correlation and coefficient of variation for treadmill load cell data.

Speed (km/h)	**10.1**	**11.4**	**12.7**	**14.0**	**15.2**	**16.5**	**17.8**	**19.1**	**20.4**	**21.7**
Intraclass Correlation (ICC)	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	1.00	1.00
Lower Confidence Limit	0.97	0.97	0.97	0.96	0.96	0.96	0.98	0.97	1.32	1.30
Upper Confidence Limit	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.01	1.01
Coefficient of Variation (CV) (%)	18.43%	19.11%	20.03%	20.33%	19.92%	20.32%	22.59%	21.29%	7.58%	7.81%

Physiological Parameters

Table 5.6 shows the percent change in the physiological parameters from speed to speed. Large changes were reported when the athletes transitioned from baseline to 10.1 km/h. The largest increase for $\dot{V}O_2$ for all athletes during the test was from 19.1 km/h to 20.4 km/h with an increase of 20.25%. Blood glucose decreased by 3.55% from 10.1 km/h to 11.4 km/h, however, later had the highest increase of 8.42% from 20.4 km/h to 21.7 km/h. Blood lactate, amongst all athletes, had the largest increase (28.31%) from 12.7 km/h to 14.0 km/h. RPE and heart rate had the largest increase from 11.4 km/h to 12.7 km/h (20.00%; 6.13%, respectively). The largest increase in RER was from 10.1 km/h to 11.4 km/h. As for $\dot{V}E$, the largest increased occurred from 19.1 km/h to 20.4 km/h by 32.28%.

Table 5.6. Percent change from speed to speed for physiological parameters for all athletes.

Speed (km/h)	**$\dot{V}O_2$** (L/min)	**Blood Glucose** (mg/dL)	**Blood Lactate** (mmol/L)	**RPE**	**RER**	**$\dot{V}E$** (L/min)	**Heart Rate** (bpm)
10.1 (n=12)	-	-	-	-	-	-	-
11.4 (n=12)	10.29%	-3.55%	8.65%	10.23%	8.19%	18.48%	6.07%
12.7 (n=12)	12.31%	-2.16%	-11.76%	20.00%	5.60%	14.99%	6.13%
14.0 (n=12)	3.50%	-1.40%	28.31%	12.00%	3.81%	6.62%	2.98%
15.2 (n=12)	4.65%	5.23%	15.31%	12.59%	5.53%	11.85%	3.73%
16.5 (n=11)	5.33%	5.67%	15.26%	9.60%	1.96%	8.25%	1.62%
17.8 (n=9)	-1.24%	1.23%	1.71%	8.74%	1.98%	12.06%	1.50%
19.1 (n=7)	8.26%	4.50%	25.19%	3.70%	1.64%	8.71%	0.32%
20.4 (n=4)	20.25%	-1.22%	16.28%	-1.69%	1.30%	32.28%	0.54%
21.7 (n=4)	-9.88%	8.42%	15.94%	10.61%	8.13%	1.81%	0.78%

Figure 5.4 displays the relationship between $\dot{V}O_2$ and vGRF. Between these variables, a Pearson correlation was calculated at *r*(11)=0.977, *p*=0.000, indicating a strong, positive correlation.

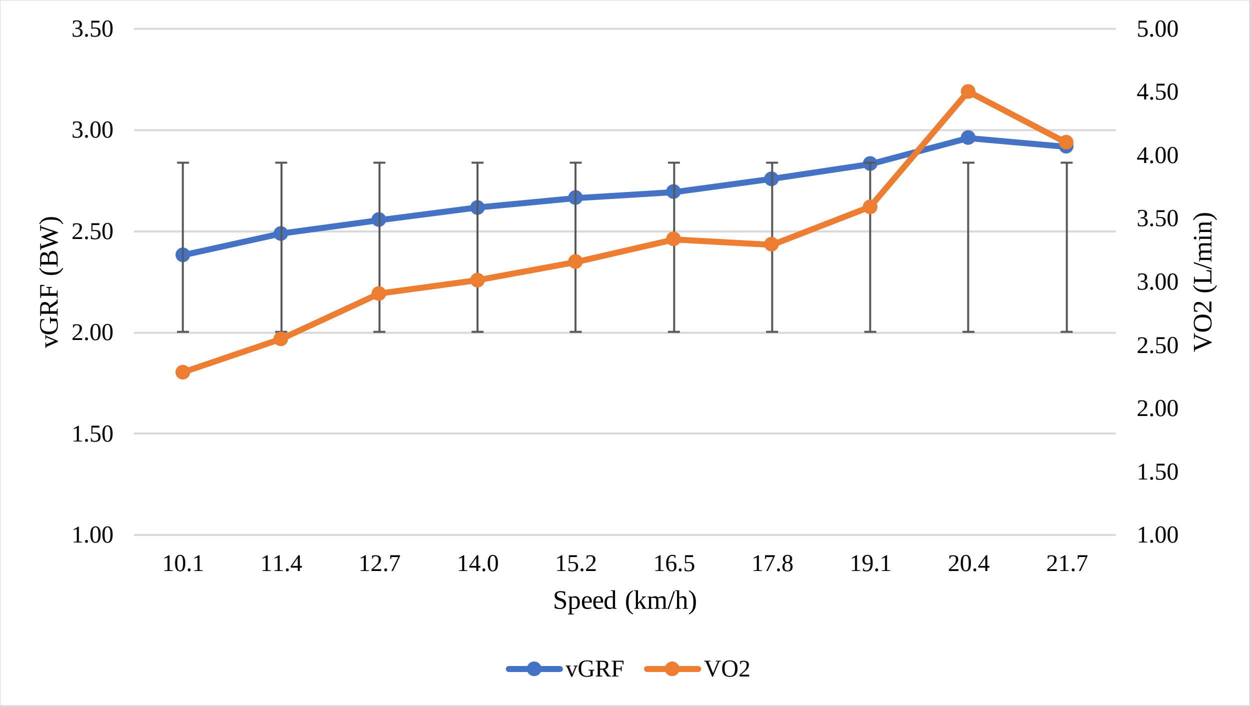

Figure 5.4. vGRF and $\dot{V}O_2$ for all athletes at each speed.

Figure 5.5 depicts the relationship between vGRF and blood lactate for all athletes across all speeds. There is a strong, positive relationship between these variables (*r*(11)=0.930, *p*=0.000).

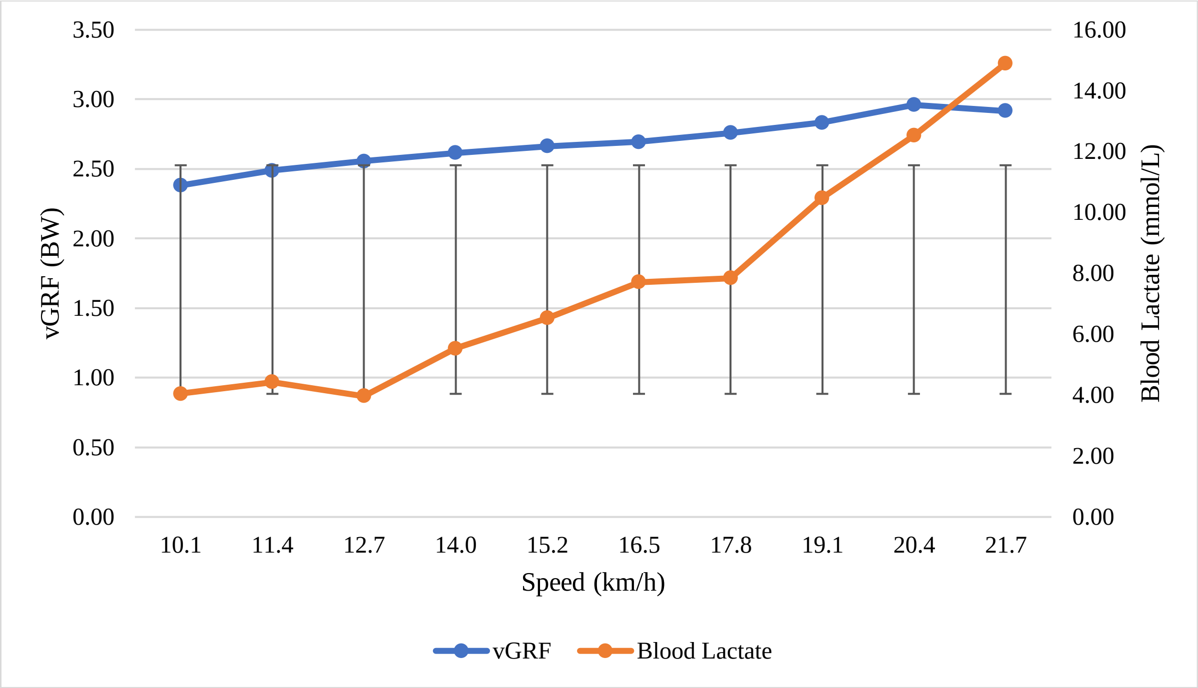

Figure 5.5. vGRF and blood lactate for all athletes at each speed.

Table 5.7 displays the relationship of all the physiological variables of this study. The highest correlation amongst the physiological parameters is between speed and RPE ($r(11)=0.983$, $p=0.000$). Other high correlations are between RPE and RER ($r(11)=0.982$, $p=0.000$), $\dot{V}E$ and blood lactate ($r(11)=0.973$, $p=0.000$), and $\dot{V}E$ and $\dot{V}O_2$ ($r(11)=0.970$, $p=0.000$); all indicating strong, positive correlations.

Table 5.7. Physiological parameter correlation matrix.

Variable	**Speed** (km/h)	**$\dot{V}O_2$** (L/min)	**Blood Glucose** (mg/dL)	**Blood Lactate** (mmol/L)	**RPE**	**RER**	**$\dot{V}E$** (L/min)	**Heart Rate** (bpm)
Speed (km/h)	-	0.946*	0.860*	0.953*	0.983*	0.977*	0.948*	0.931*
$\dot{V}O_2$ (L/min)	0.946*	-	0.758*	0.922*	0.891*	0.902*	0.970*	0.866*
Blood Glucose (mg/dL)	0.860*	0.758*	-	0.932*	0.817*	0.789*	0.859*	0.650*
Blood Lactate (mmol/L)	0.953*	0.922*	0.932*	-	0.894*	0.906*	0.973*	0.788*
RPE	0.983*	0.891*	0.817*	0.894*	-	0.982*	0.879*	0.966*
RER	0.977*	0.092*	0.789*	0.906*	0.982*	-	0.898*	0.960*
$\dot{V}E$ (L/min)	0.948*	0.970*	0.859*	0.973*	0.879*	0.898*	-	0.802*
Heart Rate (bpm)	0.931*	0.866*	0.650*	0.788*	0.966*	0.960*	0.802*	-

Note: *denotes significant correlation, *p*<.05.

Table 5.8 shows the magnitude of relationship between the biomechanical and physiological parameters of this study. The highest correlation was between $\dot{V}E$ and loading rate with a strong, positive relationship (*r*(11)=0.994, *p*=0.000). Other positive, strong correlations were: vGRF and $\dot{V}O_2$ (*r*(11)=0.977, *p*=0.000), loading rate and blood lactate (*r*(11)=0.984, *p*=0.000), and loading rate and $\dot{V}O_2$ (*r*(11)=0.965, *p*=0.000). Other notable relationships were between contact time and RPE (*r*(11)=-0.993, *p*=0.000) and contact time and RER (*r*(11)=-0.984, *p*=0.000), both are a strong, negative relationship.

Table 5.8. Biomechanical and physiological correlation matrix.

Variable	**$\dot{V}O_2$** (L/min)	**Blood Glucose** (mg/dL)	**Blood Lactate** (mmol/L)	**RPE**	**RER**	**$\dot{V}E$** (L/min)	**Heart Rate** (bpm)
vGRF (BW)	0.977*	0.791*	0.930*	0.957*	0.955*	0.953*	0.930*
Loading Rate (BW/ms)	0.965*	0.881*	0.984*	0.902*	0.912*	0.994*	0.820*
Contact Time (ms)	-0.931*	-0.797*	-0.908*	-0.993*	-0.984*	-0.908*	-0.970*

Table 5.9 displays the results from a regression analysis using asymmetry as the dependent variable and all physiological parameters as the independent variables. Statistical significance existed with certain variables, such as: $\dot{V}O_2$ (*p*=0.029), blood lactate (*p*=0.031), RER (*p*=0.019), $\dot{V}E$ (*p*=0.044), and heart rate (*p*=0.025). However, there was no statistical significance for blood glucose or RPE.

Table 5.9. Regression analysis of physiological parameters with asymmetry.

Variable	**P-Value**
$\dot{V}O_2$ (L/min)	0.029*
Blood Glucose (mg/dL)	0.418
Blood Lactate (mmol/L)	0.031*
RPE	0.052
RER	0.019*
$\dot{V}E$ (L/min)	0.044*
Heart Rate (bpm)	0.025*

Note: *denotes significant correlation, *p*<.05.

Discussion

Our research showed that our athletes all ranked in the 95th percentile or higher for their $\dot{V}O_{2max}$ values according to ACSM Guidelines. We found several strong relationships between biomechanical parameters and physiological parameters.

The relationship between vGRF and $\dot{V}O_2$ showed a strong, positive correlation. As speed increased, both average vGRF and average $\dot{V}O_2$ increased until 21.7 km/h; at this point both decreased slightly. This was expected to happen due to the fact that the athletes were performing an incremental exercise and previous research has shown these variables to increase as intensity increases. One of the larger increases in average $\dot{V}O_2$ values occurred from 19.1 km/h to 20.4 km/h. Interestingly, this is also where the largest increase in average vGRF occurred. This could be due to the fact that the speed had reached a point at which that athletes were experiencing a greater demand physiologically along with increased fatigue. It was also found that there was statistical significance between asymmetry and $\dot{V}O_2$, indicating that the changes reported for each variable did not follow the same pattern. This was to be expected because unlike $\dot{V}O_2$, asymmetry did not increase linearly for each speed increase increment.

There was also a strong, positive relationship between vGRF and blood lactate. This too was expected as previous research has shown these two variables increase with incremental exercise (Costill, 1970; Grabowski & Kram, 2008; Held & Marti, 1999). Blood lactate rose steadily until 17.8 km/h, after which there was a large increase in blood lactate. As previously stated, average vGRF increased the most from 19.1 km/h to 20.4 km/h. Average blood lactate values had two large increases, one from 12.7 km/h to 14.0 km/h and one from 17.8 km/h to 19.1 km/h. It is possible that due to a large increase in blood lactate and accompanying biochemical alterations and fatigue could be a reason for the large increase in average vGRF in following stage.

Another variable that had the largest increase from 19.1 km/h to 20.4 km/h was $\dot{V}E$, therefore, average vGRF, average loading rate, average $\dot{V}O_2$, and average $\dot{V}E$ all exhibited the largest increases at the same point in the $\dot{V}O_{2max}$ test. During this period of the test, the athletes apparently experienced an increase in intensity which was indicated by an average RPE of 15. Increased intensity would then cause an increase in average $\dot{V}O_2$ which would coincide with an increase in average $\dot{V}E$. Since previous research reports that vGRF increases with speed, it is expected that the average vGRF would be high at this speed and therefore increase average loading rate. From a practical standpoint this would not be the ideal zone for an athlete to perform during a long steady run. This is due to the level of intensity and fatigue that would accompany this response. This level of intensity would be better applied during high intensity interval training (HIIT) days or short tempo run days in which a higher physiological and biomechanical response is desired.

Regarding vGRF and loading rate, it is possible these increases could have been affected by the large increase of blood lactate that occurred the stage before. This occurs because there is a lag in the appearance of blood lactate due to the shuttle system Goodwin, Harris, Hernandez, & Gladden, 2007). Therefore, the lag from the previous stage could greatly influence variables for the remainder of the test. In addition, it is possible that vGRF and loading rate may have an association with vertical oscillation in a practical sense. This likely occurs because if an athlete is feeling tired perhaps reflected by increased blood lactate, they are more likely to have and increase in vGRF and loading rate; increasing vertical oscillation.

When comparing asymmetry and physiological parameters, it is valuable to consider average blood lactate changes. From 17.8 km/h to 19.1 km/h there was an increase in average blood lactate of 25.19% followed by an increase of 16.28% from 19.1 km/h to 20.4 km/h, indicating 2 large increases. It is interesting to note that the most asymmetry occurred from 20.4 km/h to 21.7 km/h. As previously stated, blood lactate has a delay affecting its accumulation in the blood. Even though the vGRF and asymmetry increased when the athletes hit the fastest speed, which is to be expected; the researchers also believe some of the asymmetry may be caused by fatigue due to increases in blood lactate levels accompanied with other biochemical alterations.

Conclusion

The results of this study provide evidence that biomechanical and physiological parameters can be highly correlated during a $\dot{V}O_{2max}$ test for collegiate cross-country and triathlon athletes. Therefore, when monitoring athletes, it is valuable to monitor all aspects of their athletic performance. Evidence from this study shows that blood lactate levels could affect an athlete’s amount of asymmetry. This is valuable knowledge because if a training program was devised to increase blood lactate clearing abilities, that athlete may experience less asymmetry and then decrease their risk of injury. In conclusion, a complete analysis of an athlete’s current athletic performance should be collected and used to develop a training plan that can further optimize their athletic performance abilities.

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CHAPTER 6

CONCLUSION

In conclusion, athletes in this study were all trained cross country or triathlon athletes that matched with previous data for anthropometrics, physiological, as well as biomechanical responses when compared to similar studies. However, a primary difference between our results and previous research was in regards to kinetic asymmetry. This study indicated that our athletes had an average kinetic asymmetry throughout the $\dot{V}O_{2max}$ test of only 1.38 ± 0.68%. According to previous research, this is not a large enough asymmetry to lead to an increased rate of injury risk. Even though the athletes in this study may have enough strength to maintain symmetry, this is an indication of the importance a strength training has in a practical setting. According to our analysis, there was a strong, positive relationship between vGRF and blood lactate. The changes between stages showed large increases in average blood lactate could have influenced the large increases in average vGRF that occurred later in the test. The delayed appearance of blood lactate would then not have an effect until minutes later. Due to this, not only could the increase in average blood lactate have an effect on average vGRF, but it could have also effected average asymmetry. Therefore, it is suggested that cross country and triathlon athletes incorporate a strength training program in order to decreases asymmetry. It is also suggested that when monitoring athletic performance, the coaches and athletes investigate both physiological and biomechanical parameters in order to provide a well-rounded analysis of performance.

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APPENDICES

APPENDIX A

Data Collection Sheets

Height:	**Weight:**

Stage Number	**Speed (km/h)**	**Stage Duration (min)**	**Blood Glucose 1 (mg/dL)**	**Blood Glucose 2 (mg/dL)**	**Blood Lactate 1 (mmol/L)**	**Blood Lactate 2 (mmol/L)**	**RPE**
BASELINE	0.0						
1	10.1						
2	11.4						
3	12.7						
4	14.0						
5	15.2						
6	16.5						
7	17.8						
8	19.1						
9	20.4						
10	21.7						

Height:	**Weight:**

Stage Number	**Speed (km/h)**	**Stage Duration (min)**	**VO_{2max} (mL/kg/min)**	**RER**	**$\dot{V}E$ (L)**	**Heart Rate (bpm)**
BASELINE	0.0					
1	10.1					
2	11.4					
3	12.7					
4	14.0					
5	15.2					
6	16.5					
7	17.8					
8	19.1					
9	20.4					
10	21.7					

Height:			**Weight:**					
Stage Number	**Speed (km/h)**	**Stage Duration (min)**	**Right vGRF (N)**	**Left vGRF (N)**	**Right Loading Rate (N/ms)**	**Left Loading Rate (N/ms)**	**Right Contact Time (ms)**	**Left Contact Time (ms)**
BASELINE	0.0							
1	10.1							
2	11.4							
3	12.7							
4	14.0							
5	15.2							
6	16.5							
7	17.8							
8	19.1							
9	20.4							
10	21.7							

APPENDIX B

Athlete Profiles

Subject 1 Athlete Profile

Variable	Value
Age (years)	19.00
Height (cm)	171.50
Weight (kg)	67.98
Peak vGRF (BW)	2.58
Average Difference (Asymmetry) (%)	2.42
Average Loading Rate (BW/ms)	0.022
Average Contact Time (ms)	216.74
Average Jump Height (cm)	28.70
Average Jumping Peak Landing Force Asymmetry (%)	4.70 (R)
Average Jumping Takeoff Peak Force Asymmetry (%)	8.00 (L)
$\dot{V}O_{2max}$ (mL/kg/min)	54.60
Max Blood Glucose (mg/dL)	96
Max Blood Lactate (mmol/L)	11.60
Max $\dot{V}E$ (L/min)	87.67
Max HR (bpm)	199
Max RER ($VCO_2/\dot{V}O_2$)	1.03
Max RPE	19

Subject 2 Athlete Profile

Variable	Value
Age (years)	19.00
Height (cm)	170.18
Weight (kg)	73.05
Peak vGRF (BW)	2.88
Average Difference (Asymmetry) (%)	1.12
Average Loading Rate (BW/ms)	0.029
Average Contact Time (ms)	201.68
Average Jump Height (cm)	29.93
Average Jumping Peak Landing Force Asymmetry (%)	16.70 (R)
Average Jumping Takeoff Peak Force Asymmetry (%)	14.50 (L)
$\dot{V}O_{2max}$ (mL/kg/min)	65.0
Max Blood Glucose (mg/dL)	140
Max Blood Lactate (mmol/L)	16.4
Max $\dot{V}E$ (L/min)	154.9
Max HR (bpm)	189
Max RER ($VCO_2/\dot{V}O_2$)	1.05
Max RPE	15

Subject 3 Athlete Profile

Variable	Value
Age (years)	120
Height (cm)	165.1
Weight (kg)	49.9
Peak vGRF (BW)	2.75
Average Difference (Asymmetry) (%)	3.56
Average Loading Rate (BW/ms)	0.024
Average Contact Time (ms)	218.20
Average Jump Height (cm)	18.73
Average Jumping Peak Landing Force Asymmetry (%)	14.7 (R)
Average Jumping Takeoff Peak Force Asymmetry (%)	7.7 (L)
$\dot{V}O_{2max}$ (mL/kg/min)	54.1
Max Blood Glucose (mg/dL)	115
Max Blood Lactate (mmol/L)	6.6
Max $\dot{V}E$ (L/min)	79.1
Max HR (bpm)	194
Max RER ($VCO_2/\dot{V}O_2$)	0.98
Max RPE	17

Subject 4 Athlete Profile

Variable	Value
Age (years)	121
Height (cm)	163.1
Weight (kg)	58.3
Peak vGRF (BW)	2.72
Average Difference (Asymmetry) (%)	2.77
Average Loading Rate (BW/ms)	0.025
Average Contact Time (ms)	208.42
Average Jump Height (cm)	19.67
Average Jumping Peak Landing Force Asymmetry (%)	20.2 (L)
Average Jumping Takeoff Peak Force Asymmetry (%)	14.2 (R)
$\dot{V}O_{2max}$ (mL/kg/min)	52.3
Max Blood Glucose (mg/dL)	134
Max Blood Lactate (mmol/L)	13.5
Max $\dot{V}E$ (L/min)	102.1
Max HR (bpm)	193
Max RER ($VCO_2/\dot{V}O_2$)	1.05
Max RPE	16

Subject 5 Athlete Profile

Variable	Value
Age (years)	19
Height (cm)	169.4
Weight (kg)	71.6
Peak vGRF (BW)	3.17
Average Difference (Asymmetry) (%)	6.26
Average Loading Rate (BW/ms)	0.037
Average Contact Time (ms)	191.93
Average Jump Height (cm)	34.83
Average Jumping Peak Landing Force Asymmetry (%)	7.1 (R)
Average Jumping Takeoff Peak Force Asymmetry (%)	18.4 (L)
$\dot{V}O_{2max}$ (mL/kg/min)	61.3
Max Blood Glucose (mg/dL)	123
Max Blood Lactate (mmol/L)	16.3
Max $\dot{V}E$ (L/min)	157.4
Max HR (bpm)	189
Max RER ($VCO_2/\dot{V}O_2$)	1.29
Max RPE	19

Subject 6 Athlete Profile

Variable	Value
Age (years)	20
Height (cm)	159.2
Weight (kg)	59.8
Peak vGRF (BW)	2.56
Average Difference (Asymmetry) (%)	1.02
Average Loading Rate (BW/ms)	0.023
Average Contact Time (ms)	222.36
Average Jump Height (cm)	13.63
Average Jumping Peak Landing Force Asymmetry (%)	9.4 (R)
Average Jumping Takeoff Peak Force Asymmetry (%)	3.8 (L)
$\dot{V}O_{2max}$ (mL/kg/min)	46.0
Max Blood Glucose (mg/dL)	118
Max Blood Lactate (mmol/L)	10.7
Max $\dot{V}E$ (L/min)	96.0
Max HR (bpm)	195
Max RER ($VCO_2/\dot{V}O_2$)	1.13
Max RPE	16

Subject 7 Athlete Profile

Variable	Value
Age (years)	18
Height (cm)	153.0
Weight (kg)	48.8
Peak vGRF (BW)	2.66
Average Difference (Asymmetry) (%)	0.46
Average Loading Rate (BW/ms)	0.025
Average Contact Time (ms)	221.07
Average Jump Height (cm)	12.30
Average Jumping Peak Landing Force Asymmetry (%)	7.2 (R)
Average Jumping Takeoff Peak Force Asymmetry (%)	3.2 (L)
$\dot{V}O_{2max}$ (mL/kg/min)	46.6
Max Blood Glucose (mg/dL)	120
Max Blood Lactate (mmol/L)	9.4
Max $\dot{V}E$ (L/min)	89.3
Max HR (bpm)	194
Max RER ($VCO_2/\dot{V}O_2$)	1.11
Max RPE	16

Subject 8 Athlete Profile

Variable	Value
Age (years)	19
Height (cm)	165.0
Weight (kg)	65.1
Peak vGRF (BW)	2.64
Average Difference (Asymmetry) (%)	1.03
Average Loading Rate (BW/ms)	0.024
Average Contact Time (ms)	203.71
Average Jump Height (cm)	20.77
Average Jumping Peak Landing Force Asymmetry (%)	20.5 (L)
Average Jumping Takeoff Peak Force Asymmetry (%)	0.5 (R)
$\dot{V}O_{2max}$ (mL/kg/min)	49.9
Max Blood Glucose (mg/dL)	92
Max Blood Lactate (mmol/L)	14.2
Max $\dot{V}E$ (L/min)	3.15
Max HR (bpm)	199
Max RER ($VCO_2/\dot{V}O_2$)	0.96
Max RPE	17

Subject 9 Athlete Profile

Variable	Value
Age (years)	23
Height (cm)	166.1
Weight (kg)	71.0
Peak vGRF (BW)	2.60
Average Difference (Asymmetry) (%)	6.72
Average Loading Rate (BW/ms)	0.021
Average Contact Time (ms)	237.21
Average Jump Height (cm)	11.80
Average Jumping Peak Landing Force Asymmetry (%)	17.1 (R)
Average Jumping Takeoff Peak Force Asymmetry (%)	1.5 (R)
$\dot{V}O_{2max}$ (mL/kg/min)	48.6
Max Blood Glucose (mg/dL)	133
Max Blood Lactate (mmol/L)	5.6
Max $\dot{V}E$ (L/min)	105.8
Max HR (bpm)	174
Max RER ($VCO_2/\dot{V}O_2$)	0.93
Max RPE	10

Subject 10 Athlete Profile

Variable	Value
Age (years)	22
Height (cm)	177.1
Weight (kg)	79.7
Peak vGRF (BW)	3.12
Average Difference (Asymmetry) (%)	0.89
Average Loading Rate (BW/ms)	0.032
Average Contact Time (ms)	202.90
Average Jump Height (cm)	26.33
Average Jumping Peak Landing Force Asymmetry (%)	0.0 (L)
Average Jumping Takeoff Peak Force Asymmetry (%)	14.8 (R)
$\dot{V}O_{2max}$ (mL/kg/min)	56.4
Max Blood Glucose (mg/dL)	122
Max Blood Lactate (mmol/L)	17.4
Max $\dot{V}E$ (L/min)	160.7
Max HR (bpm)	193
Max RER ($VCO_2/\dot{V}O_2$)	1.11
Max RPE	15

Subject 11 Athlete Profile

Variable	Value
Age (years)	19
Height (cm)	178.3
Weight (kg)	76.9
Peak vGRF (BW)	2.90
Average Difference (Asymmetry) (%)	1.08
Average Loading Rate (BW/ms)	0.030
Average Contact Time (ms)	208.02
Average Jump Height (cm)	36.60
Average Jumping Peak Landing Force Asymmetry (%)	31.7 (L)
Average Jumping Takeoff Peak Force Asymmetry (%)	20.6 (L)
$\dot{V}O_{2max}$ (mL/kg/min)	69.4
Max Blood Glucose (mg/dL)	118
Max Blood Lactate (mmol/L)	12.0
Max $\dot{V}E$ (L/min)	153.2
Max HR (bpm)	198
Max RER ($VCO_2/\dot{V}O_2$)	1.03
Max RPE	17

Subject 12 Athlete Profile

Variable	Value
Age (years)	21
Height (cm)	172.5
Weight (kg)	66.0
Peak vGRF (BW)	2.78
Average Difference (Asymmetry) (%)	1.78
Average Loading Rate (BW/ms)	0.028
Average Contact Time (ms)	214.68
Average Jump Height (cm)	20.60
Average Jumping Peak Landing Force Asymmetry (%)	12.0 (R)
Average Jumping Takeoff Peak Force Asymmetry (%)	9.5 (R)
$\dot{V}O_{2max}$ (mL/kg/min)	42.4
Max Blood Glucose (mg/dL)	117
Max Blood Lactate (mmol/L)	13.0
Max $\dot{V}E$ (L/min)	125.5
Max HR (bpm)	196
Max RER ($VCO_2/\dot{V}O_2$)	1.14
Max RPE	18

VITA

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