An Evaluation of Kinematic Variables during Stance Phase of a Training Endurance Run

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AN EVALUATION OF KINEMATIC VARIABLES DURING STANCE

PHASE OF A TRAINING ENDURANCE RUN

By

Joshua Paul Bailey

Bachelor of Science in Kinesiology
University of Nevada, Las Vegas
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A thesis submitted in partial fulfillment
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ABSTRACT

An evaluation of kinematic variables during stance phase of a training endurance run

by

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The purpose of the study was to evaluate kinematics of the lower extremity during the stance phase of an endurance training run. Fifteen participants (8 male, 7 female; 30.5 ±8.4 years; 71.8 ±11 kg; 1.73 ±0.07 m) reported that they were currently signed up for, or planned on signing up for, an endurance race within the next six months of participation in the study (9 half marathon, 3 marathon, 1 triathlon, 2 21k trail run). All had a weekly running mileage greater than 20 miles (23.8 ±4.6 miles). Participants were required to complete the 15-kilometer training run in less than 2 hours (1:24:34 ± 0:10:20 finish times). Participants signed an institutionally approved informed consent form upon arrival and then completed the PAR-Q. Participants were instructed to complete the 15-km run as if it were a normal training run, lacking any competitive nature. Sagittal plane kinematic data were captured and processed via MaxTraq two-dimensional (2-D) video acquisition software (Innovisions Systems Inc. 2.2.2.5; Columbiaville, MI) at 120 Hz. All stance phase variables were smoothed using a Low-Pass 4th Order Butterworth Zero-lag filter. Data analysis included descriptive statistics for all dependent variables (lap times, stance phase (StPh), step length (SL), step frequency (SF), speed, torso inclination at foot contact (TorsoFC), and all lower extremity angles at foot contact and peak flexion of
each joint during stance (AnkFC, AnkPK, KneeFC, KneePK, HipFC, and HipPK). One-way repeated measure ANOVAs were conducted for each dependent variable ($\alpha=0.05$). Results identified significant within subject differences for gait parameters in lap times ($F[2.790,39.065] = 15.829, p<0.001, \eta^2 = 0.531$), StPh ($F[2.427,33.983] = 8.877, p<0.001, \eta^2 = 0.388$), SL ($F[1.223, 17.119] = 6.025, p=0.020, \eta^2 = 0.301$) and speed ($F[1.299, 18.191] = 6.131, p=0.017, \eta^2 = 0.305$). Pairwise comparisons showed Lap_1 was significantly faster than Lap_2 (6.20s $p=0.002$), Lap_3 (9.81s, $p<0.001$), Lap_4 (12.98s, $p<0.001$) and Lap_5 (10.39s, $p = 0.013$), while Lap_2 was significantly faster than Lap_3 (3.61s, $p=0.010$) and Lap_4 (6.78s, $p=0.012$) for lap times. Pairwise comparisons showed StPh for Lap_1 was significantly shorter than Lap_2 (0.01s $p=0.011$), Lap_3 (0.01s, $p=0.030$) and Lap_4 (0.02s, $p=0.007$). The knee joint showed the only significant difference for joint position at foot contact ($F[4,56] = 2.674, p = 0.041, \eta^2 = 0.160$) and peak flexion during stance ($F[4,56] = 3.304, p = 0.017, \eta^2 = 0.191$). Runners in the current study were able to maintain their lower extremity joint kinematics at foot contact and during the stance phase even while there were measured differences in lap times, speed and step lengths. The knee joint appeared to be the most highly affected lower extremity joint by speed and time during an endurance run.
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CHAPTER 1
INTRODUCTION

Endurance running has become a highly popular mode of exercise and goal achievement. The increase in popularity over the last couple of decades has also seen with it an increase in the number of lower extremity injuries, both acute and chronic. Chronic injuries have been associated with the repeated high loads introduced and absorbed by the body following each foot strike and associated impact (James, Dufek, & Bates, 2006). Kinetic research, identifying impact forces, shock attenuation and joint moments, has been conducted in laboratory settings due to their reliance on force platforms for data collection. These protocols incorporate either a force plate instrumented treadmill or having the subject perform repeated trials running over a force platform. Protocols utilizing treadmills create a fixed speed of travel with less variance in speed from stride to stride (Dillman, 1975; Nelson et al., 1972), which may limit the runners’ natural variance in their gait pattern kinematics. Over ground running allows for more variability in gait characteristics from stride to stride, resulting from the effects of speed changes on the kinematic variables (Williams, 1987; Chan & Rudins, 1994).

To fully understand the affects of endurance running on running technique, fatigue must be identified as a mechanism that yields changes (Elliot & Ackland, 1981). As fatigue encompasses multiple aspects of the human body, both physiological and psychological, identification of the origin of fatigue is difficult. Performance decrement of a variable against a baseline measurement (Bates et al. 1977; Elliot & Ackland, 1981) has become a generalized field method used to imply fatigue has occurred when physiological methods of measurement are not available. As maximum voluntary
contraction and strength measurements will not be conducted during the current study, these performance measures can be employed to measure whether or not fatigue becomes a factor.

The recent interest in over ground running studies has produced studies that have investigated competitive races with limited analysis points. In an evaluation of kinematic variables at the 8 and 40 km distances of the 2010 Salt Lake City Deseret News Marathon, a difference was shown across many of the variables between the 32 km traveled. While stride length, contact time, peak knee and hip flexion during swing increased, peak hip extension during swing and peak knee flexion during support decreased (Chan-Roper, Hunter, Myrer, Eggert, & Seeley, 2012). In studies involving foot strike, speed was shown to have an effect on foot strike pattern, creating a more mid-foot strike pattern with an increase in speed, while the majority of runners ran with a rear-foot strike pattern (Hasegawa, Yamauchi, and Kraemer, 2007). In a comparison of foot strike patterns between the 10 and 32 km distance markers of a distance race, the majority of runners that ran with a mid-foot of fore-foot strike pattern at the 10 km distance marker, transitioned to a rear-foot strike pattern at the 32 km distance marker (Larson, Higgins, Kaminski, Decker, Preble, Lyons, McIntyre, & Normile, 2011).

**Purpose of the Study**

The purpose of the study was to evaluate kinematics of the lower extremity during the stance phase of an endurance training run.
Research Questions

I. Do individuals alter running gait characteristics (parameters) across time during an endurance run?

II. Do individuals alter joint angles during the stance phase across time during an endurance run?

III. Do individuals alter center of mass vertical excursion during the stance phase across time during and endurance run?

Significance of the Study

The current research on over ground running has identified changes in kinematic patterns during one or two discrete points throughout an endurance race. It is theorized that individuals continually adjust kinematic variables during an endurance run to attenuate the kinetic factors produced from repeated footfalls. A more accurate description of the changes in kinematic variables throughout a distance run may be gleaned by assessing across more time points of analysis. This evaluation of multiple time points throughout a run may lead to a better understanding of the strategies individuals adopt to avoid and overcome injury, fatigue and environmental challenges presented during an endurance run. Additionally, the current research investigated the ability of runners to control running gait parameters and kinematics without the influence of the competitive nature of a race.

Statistical Hypothesis

I. The null hypothesis is that there are no significant alterations in running gait characteristics during the stance phase across time during an endurance run. The alternate hypotheses are: Lap times will become significantly slower across time
during an endurance run. Step length will become significantly shorter and step
frequency will significantly decrease across time during an endurance run. Stance
phase period will significantly increase across time during an endurance run.

II. The null hypothesis is that there are no significant alterations in joint angles during
the stance phase across time during an endurance run. The alternate hypotheses are:
Torso inclination angle at foot contact will significantly decrease during the stance
phase across time during an endurance run. Hip, Knee and Ankle angles at foot
contact will become more flexed during the stance phase across time during an
endurance run. Hip, ankle and knee maximum flexion during stance phase will
significantly decrease during the stance phase across time during an endurance run.

III. The null hypothesis is that there is no significant difference in center of mass vertical
excursion during the stance phase across time during an endurance run. The alternate
hypothesis is that there is a significant decrease in center of mass vertical excursion
during the stance phase across time during an endurance run.

Definition of Terms

Aerial (double float) phase: Period of a cycle in which there is no contact made with the
ground and either foot of the runner. One leg has just completed stance phase, while the
other is preparing for foot contact.

Center of mass: Point at which all the matter of a system is centered in three dimensions.

Center of gravity: Point in which the gravity pull toward the ground acts on the system.

Forefoot strike: Initial foot contact is made with front third of the foot typically with the
ball of the foot and slightly pronated. The heel does not make contact with the ground at
the same time and in some instances, not at all.
Gait cycle: Period between the occurrence of a particular event and the subsequent occurrence of that event happening again.

Ground reaction force: The force exerted by the running surface in response to the force of the system on the ground creating contact. It occurs in three planes: vertical, anterior-posterior, and medial-lateral.

Heel strike: Initial ground contact between the foot and the ground is created by the heel only.

Initial ground contact: The moment the foot makes contact with the ground; Kinetically defined with a threshold of 20 Newtons in vertical ground reaction force for running.

Kinematics: The study of the movement outcome without regard for the forces causing the motion.

Kinetics: The study of the forces that cause motion.

Mid-foot strike: Initial contact is made between the ground and the foot with the majority of the foot ranging from the ball of the foot to the heel simultaneously.

Mid-stance: Point during the contact phase where the system’s center of mass travels over the ankle transitioning

Range of motion: Range of degrees a segment or joint travels through during a given period of time.

Stance phase: Period of time a foot is in contact with the ground.

Step frequency: The number of steps taken (right foot to left foot) per second.

Step length: Distance between toe off of the trailing foot to the heel off of the lead foot during foot contact.
**Stride length**: The length between a distinct event within cycle to the occurrence of the event occurring again. For the purposes of this study, stride length refers to foot contact of one foot until the same foot contacts the ground again.

**Toe-off**: The point when the contact between the stance leg and the ground is lost the anterior-posterior ground reaction force from braking to propulsion. Kinetically defined as the point in which the vertical ground reaction force reaches below 20N for running.

**Limitations/delimitations**

I. Participants did not run an actual race.

II. One camera location may cause individuals to perform “for the camera”.

III. Only kinematic data were collected.

IV. Kinematic analysis was limited to two-dimensions limiting analysis to the sagittal plane.

V. Type of footwear was not standardized, which could introduce footwear effects among participants.

VI. The analysis was limited to stance phase.

VII. The analysis was limited to miles/times during the race that you select.

VIII. Warm-up was self-selected.
CHAPTER 2
REVIEW OF RELATED LITERATURE

The previous chapter introduced the purpose of the current study: evaluate kinematic changes of the lower extremity during the stance phase of an endurance training run. The focus of the current chapter will be to define and identify kinematic variables viewed influential to injury prevention and performance enhancement during endurance running. A review of the current literature develops a well-defined kinematic running gait model, defining phases of a gait cycle for analysis. Following the introduction into the running gait cycle and how a kinematic analysis of the cycle is accomplished, a currently popular topic of endurance running injuries and injury prevention will be reviewed. The final section will examine the effects of fatigue, heart rate and intensity on running kinematics. The conclusion will provide evidence to support a single-subject analysis design focused on identifying the changes within each individual across a time series analysis.

Running Gait

During human locomotion, the transition from walking to running is reported to be a function of the velocity of transport and the physiological cost of the movement pattern (Usherwood & Bertram, 2003). As walking becomes less economical, the pattern shifts to a running gait, defined by the presence of an aerial phase (Dillman, 1975; Novacheck, 1998). Within these gait patterns, a cycle is considered the basic unit of description (Novacheck, 1998). A cycle is defined by the occurrence of two identical events separated by a series of events and phases. Foot contact of one foot marks the beginning of the cycle with completion marked by foot strike of the same foot occurring
again (Novacheck, 1998). The cyclical nature of a running gait pattern is created by alternating events of stance and swing phases each foot travels through during locomotion.

Stance phase begins with foot contact, the moment in which the foot contacts the surface in which running occurs and terminates with toe-off, the point at which the foot loses contact with the running surface (Dillman, 1975; Novacheck, 1998). This period of time in which the foot is in contact with the running surface is further divided into phases separated by mid-stance, kinetically the point in which the anterior-posterior ground reaction force is neutral (Winter, 1980). A kinematic description of mid-stance is that the system’s center of mass passes over the ankle of the stance leg with the center of mass at the lowest point (James & Brubaker, 1972). The two phases surrounding mid-stance are named for the events that occur during those phases. Loading, or absorption phase (Dugan & Bhat, 2005), is the period of time from initial foot contact to mid-stance (Novacheck, 1998). This is kinetically termed the braking phase is due to the deceleration effect of the anterior-posterior ground reaction forces, opposing the direction of movement (Winter, 1980; Farley & Ferris, 1998). During this phase, the stance leg is loaded with the mass of the system, with energy absorption the main goal (Dugan & Bhat, 2005). Following mid-stance, the body shifts from the absorption phase into the generative, propulsive phase (Dugan & Bhat, 2005; Farley & Ferris, 1998), in which the system’s center of mass shifts forward and upward (Novacheck, 1998). The propulsive phase is responsible for generating enough impulse to create the aerial phase of the cycle, generating ground reaction forces as high as 2.8 times body weight (Dugan & Bhat, 2005) or more. It is the transition from absorption or loading to the generation or
propulsion that reveals great importance of the stance limb during running mechanics (Winter, 1980). According to Dillman (1975), the stance phase represents approximately 52% of the forward displacement during a single stride, with 70% of stance phase forward displacement associated with the propulsive phase.

Toe-off, the point in which the contact foot loses contact with the running surface, begins the swing phase (Navacheck, 1998). Swing phase division follows a similar path as that of stance. Initial swing represents the period from toe-off until approximately mid-stance of the opposing stance limb (Dugan & Bhat, 2005). Mid-swing is the period of transition from initial to terminal swing in which the swing leg is preparing for foot contact and support (Novacheck, 1998). Terminal swing represents the preparation of the leg for stance phase following mid-swing (Dugan & Bhat, 2005). Hip extension during terminal swing prepares and controls the leg for foot strike and the absorption phase of stance, returning the foot toward the midline for foot contact (Novacheck, 1998). Horizontal momentum during running is created through the swing phase, rather than the stance phase (Dugan & Bhat, 2005). The importance of the swing phase on momentum is evident as speed increases, stance phase decreases and swing and aerial phases increase (Dugan & Bhat, 2005).

**Running Kinematics**

The primary goal of endurance running research is oriented around performance enhancement and injury prevention (Dillman, 1975). Kinematic research analyses identify movement outcomes, without regard for forces that cause the movement. A kinematic analysis may simply employ high-speed videography, or specialized equipment ranging from accelerometers to electro-goniometers. Due to the effects of speed on
multiple kinematic variables, a proper kinematic analysis identifies speed as a dependent variable (Williams, 1987; Chan & Rudins, 1994). In addition, the values of many kinematic variables are not reported due to their dependence on a participants training status. Rather, variables are reported as timing of events and percentages of a stride, allowing for the comparisons across participants and studies (Dillman, 1975; Novacheck, 1998).

In addition to the two main modes of running identified by Dillman (1975), accelerated and constant velocity, a third identified mode is decelerated running. Endurance running possesses a goal of constant velocity over an extended period, achieved by a steady state of stride length and stride rate (Dugan & Bhat, 2005). Stride length is the horizontal displacement of the system’s center of mass from the foot strike of one foot until the foot strike of the same foot again, or completion of a single stride (Hay, 1993; Dillman, 1975). Stride rate, or cadence, is the time it takes to complete a single stride (Hay, 1993) and is the summation of stance time and aerial time of the same leg (Derrick, Dereu, & McLean, 2002). Endurance running may encompass speeds ranging from 5 to 10 miles per hour (Dugan & Bhat, 2005), dependent upon skill level, in which the major goal of the movement pattern is the economy of the movement (Bushnell & Hunter, 2007). Bushnell & Hunter (2007) showed in a study comparing distance runners and sprinters, the majority of the differences in kinematic variables were evident during maximum speed trials as opposed to matched speed trials. Distance runners were shown to be less economical as speeds increased, with greater variability in measured variables (Bushnell & Hunter, 2007). Research has investigated the effect of speed on stride rate and stride length (Williams, 1987; Dillman, 1975; Dugan & Bhat, 2005;
Mercer, Bezodis, Russell, Purdy, & DeLion, 2005; Mercer, Vance, Hreljac, & Hamill, 2002; Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011), as well as stance phase variables ranging from stance time (Williams, 1987; Mann & Hagy, 1980; Dugan & Bhat, 2005; Novacheck, 1998), foot contact (Williams, 1987; James & Brubaker, 1972; Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011), center of mass displacement (Williams, 1987; Novacheck, 1998), and stance limb joint motion (Heiderscheit et al., 2011; Mann & Hagy, 1980).

Endurance runners change speeds by altering their stride length, stride rate, or some combination of the two (Dugan & Bhat, 2005). Increases in speed up to 6.5 m/s are shown to cause greater increases in stride length, while those speeds in excess of 6.5 m/s are shown to incorporate more significant increases in stride frequency (Dillman, 1975). Mercer et al. (2005) provided evidence that when subjects freely choose stride length and stride frequency at different speeds, greater stride length increases were shown due to a need to minimize oxygen consumption. Increase in oxygen consumption resulting from stride frequency increases, are created from the lack of energy return from less peak knee flexion during stance (Heiderscheit et al., 2011). Increases in stride frequency during treadmill running created a footstrike closer to the system’s center of mass yielding less energy absorption and generation during stance phase (Heiderscheit et al., 2011). Further evidence of the relationship between speed, stride length and stride frequency come from their correlation during constant velocity treadmill running. Mercer et al. (2002) showed a greater correlation between stride length and speed than stride frequency and speed (r = 0.92 and r = .089 respectively).
The stance phase of a running cycle is the important phase for performance and injury prevention due to its responsibility for energy absorption and the generation of the ground reaction forces that are important for the trajectory of the system’s center of mass (Dugan & Bhat, 2005). Increases in speed result in decreases in foot contact from 31% as endurance running speeds to 22% of a gait cycle during sprinting (Mann & Hagy, 1980). Decreases in stance time result in less time to absorb impact magnitudes up to 2.2 times body weight and a decreased generation period for the production of ground reaction forces that are up to 2.8 times body weight for propulsion (Dugan & Bhat, 2005; Novacheck, 1998). The decreases in knee flexion and extension during the absorption and generation phases of stance are replaced with propulsion created by momentum of arm and leg swing (Dugan & Bhat, 2005).

Foot strike marks the beginning of the stance phase and has been the focus of a plethora of research, which will be investigated in a later section. Increases in speed affect both foot strike pattern and placement of foot strike in relation to system’s center of mass horizontally. Increases in speed create a general transition from a rear-foot striking pattern to that of a more forefoot or mid-foot pattern (Novacheck, 1998; Dillman, 1975). Following a more fore-foot striking pattern, the foot placements falls closer to the midline and center of mass (Heiderscheit et al., 2011; James & Brubaker, 1972). Increases in speed with a foot strike pattern closer to the center of mass, reduces the braking anterior-posterior ground reaction force, which reduces the deceleration of the system’s horizontal velocity during the absorption phase of stance (James & Brubaker, 1972).
The system’s center of mass trajectory follows a wave-like pattern created with the lowest vertical position occurring during midstance and the highest during the parabolic motion of the aerial phase (Dillman, 1975). As speed increases, the difference between the highest and lowest vertical position decreases, creating a more level wave-like pattern (Dillman, 1975). The more level trajectory of the system’s center of mass is created from an increase in leg compliance as speed increases (Dugan & Bhat, 2005). The increase in leg compliance is seen through the increase in knee joint angle at foot contact as speeds increase with a decrease in knee extension at toe-off (Heiderscheit et al., 2011; Mann & Hagy, 1980). Mann & Hagy (1980) also found an increase in hip flexion responsible for the more level trajectory of the center of mass as speeds increase.

**Endurance Running Injuries**

As the number of American runners has increased dramatically over the years, the high rates of injury occurrence has sparked interest in the identification of kinematic variables that may decrease the injury rate. RunningUSA.com reports that according to both the Sports and Fitness Industry Association (SFIA) and the National Sporting Goods Association (NSGA), the number of Americans reported to run at least once a year reached above 50 million in 2012. The SFIA indicated Americans that reported running more than 50 days out of the year reached more than 29 million and the NSGA reported more than 9 million Americans ran more than 110 days during 2012 (Running USA, 2013).

Novacheck (1998) defines a running injury as significant enough to yield a break in running behavior, either during practice or performance. Rates of injury for runners range from 19.4% to 79.3% (Goss & Gross, 2012; Van Gent, Van Middelkoop, Van Os,
The injury rate for recreational runners changes from a range of 37% to 56% (Gallo, Plakke, & Silvis, 2012) to nearly 90% for those training for a marathon (Fredericson & Misra, 2007). Other reports suggest injury rates range from one quarter (Novacheck, 1998) to two-thirds (Fredericson & Misra, 2007) of American runners. These statistics are specific to participation in endurance running activities.

Most of the research regarding endurance, or long-distance running, has focused on overuse injuries resulting from the accumulation of multiple repetitive foot-strikes comprised of multiple sub-maximal impacts (James, Dufek, & Bates, 2006) for distances starting at 3,000 meters (Gallo, Plakke, & Silvis, 2012). Endurance running injuries have been categorically organized in multiple fashions: systemic and training error (Van Gent et al., 2007), extrinsic versus intrinsic (Goss & Gross, 2012), etiology of injury (James & Brubaker, 1972) or training, anatomical and shoe-surface relationship (James et al., 1978). It is important to identify the etiology of endurance running injuries as multifaceted (Macintyre, Taunton, Clement, Lloyd-Smith, McKenzie, & Morrell, 1991), with training errors accounting for as much as 60% of endurance related running injuries (James, Bates, & Osternig, 1978). In addition to training errors, individual biomechanical factors such as muscle weakness and imbalance, foot insufficiencies, and morphological abnormalities account for as much as 40% of running injuries (Goss & Gross, 2012; Gallo, Plakke, & Silvis, 2012; Subotnick, 1977).

Training errors resulting in injury during endurance running are related to a combination of intensity, frequency and distance of runs (Goss & Gross, 2012; Jacobs & Berson, 1986). Distance ranging from greater than 40 miles and 64 kilometers are associated with an increased risk of developing lower extremity injury (Fredericson &
Training for a marathon often incorporates a sudden increase in weekly mileage which drastically increases the risk of developing a lower extremity injury documented to be 90% (Fredericson & Misra, 2007; James, Bates, & Osternig, 1978). In addition to running distance, changing the terrain in which runs are conducted in preparation for an upcoming event are related to increased injury rates (Subotnick, 1977).

In addition to the etiology of injury during endurance running, investigators have identified common sites and types of injuries. Subotnick (1977) identified running related overuse injuries as runners knee, shin splints, stress fractures and tendonitis. James et al. (2006) identify that stress fractures may rank as high as the second most common lower extremity injury as a result of the shock attenuation of the impact forces. Multiple reviews of running literature have identified the knee as the most common site of injury ranging from 28.7 – 50.0% of lower extremity injuries (Macintyre et al., 1991; Van Gent et al., 2007; Van Middelkoop, Kolkman, Van Ochten, Bierma-Zeinstra, & Koes, 2008). The high incidence of knee injuries occurs across genders (Fredericson & Misra, 2007). Lower leg stress fractures, calf strains and achilles tendonitis account for the second highest rates of injury ranging from 20% to 32% of injuries (Macintyre et al., 1991; Van Gent et al., 2007; Van Middelkoop et al., 2008). Middle distance runners possess a higher injury rate of the lower leg than the knee injuries, indicating a possible speed relationship to injury (Fredericson & Misra, 2007). Injury rates of the foot round out the top three injury sites reaching upwards of 39% occurrences (Macintyre et al., 1991; Van Gent et al.,
Subotnick (1977) relates the top three injury sites to the importance of foot contact and proper mechanics during running.

Foot Strike Debate

In response to the high incidence rate of running injuries, researchers have focused attention on the impact created during the initial foot contact. The debate has ranged from type of footwear, whether or not to run barefoot and foot strike patterns. For the purpose of the current research, the effects of different foot strike patterns on the kinematics of stance phase within the current literature have been investigated. Contact has been divided into three descriptive patterns: rear-foot, mid-foot and forefoot (Hasegawa, Yamauchi, & Kraemer, 2007; Larson, et al., 2011; Kasmer, Liu, Roberts, & Valadao, 2013). A rearfoot strike (RFS) pattern occurs when initial contact with the running surface is created by the rear one-third portion of the sole (Hasegawa, Yamauchi, & Kraemer, 2007; Larson, et al., 2011). RFS patterns have been observed to occur in 75-80% of runners (Hasegawa, Yamauchi, & Kraemer, 2007; Lieberman, 2012; Perl, Daoud, & Lieberman, 2012), but has been shown to be less common in faster runners (Kasmer, Liu, Roberts, & Valadao, 2013). A midfoot strike (MFS) pattern occurs when initial contact with the surface is made simultaneously by the sole of the foot from the heel to the ball of the foot (Hasegawa, Yamauchi, & Kraemer, 2007; Larson et al., 2011). The third foot strike pattern, a forefoot strike (FFS) pattern, has become highly associated with barefoot running and the transition into a more minimalistic foot wear approach (Lieberman, 2012). A FFS pattern occurs when initial contact is created by the front half of the sole, lacking heel contact during initial foot contact (Hasegawa, Yamauchi, & Kraemer, 2007; Larson et al., 2011). A FFS pattern has become highly associated with
injury prevention due to the general lack of high impact transients following footstrike (Kulmala, Avela, Pasanen, & Parkkari, 2013; Lieberman, 2012). Each footstrike pattern creates unique differences in the kinetic chain following initial contact.

Kinematically, the lower extremity has been shown to prepare for the impact of footstrike differently according to footstrike pattern. Lieberman (2012) identified RFS with a more extended knee, which creates increased stiffness at footstrike compared to FFS. The increased extension of the knee creates a foot landing further from the systems’ center of mass horizontally than the knee (Kulmala, Avela, Pasanen, & Parkkari, 2013), creating a stiffer limb at contact (Perl, Daoud, & Lieberman, 2012). The findings of Shih et al. (2013) further support the differences in lower extremity joint angles, with FFS representative of a more flexed knee at impact independent of shoe wear condition. The increased knee flexion at contact was attributed to an effort to dampen the impact of foot strike by an increase in lower extremity absorption (Shih, Lin, & Shiang, 2013). Shock absorption begins at the ankle in FFS accomplished through increased plantarflexion and a less stiff ankle (Lieberman, 2012).

The differences in footstrike kinematics is continued throughout the stance phase of running. Following footstrike, RFS exhibits greater peak knee flexion during stance than does FFS (Kulmala, Avela, Pasanen, & Parkkari, 2013; Perl, Daoud, & Lieberman, 2012). FFS also is shown to produce a lower peak hip adduction during the stance phase while running over ground (Kulmala, Avela, Pasanen, & Parkkari, 2013). Temporal variables indicate shorter contact times with decreased stride lengths for FFS compared to RFS in multiple studies (Kulmala, Avela, Pasanen, & Parkkari, 2013; Lieberman, 2012), but were found to be not significantly different across foot strike patterns by Gruber,
Umberger, Braun, & Hamill (2013). Gruber et al. (2013) found contact times, stride length and cadence to be significantly different across speeds rather than footstrike patterns.

The kinematic variables describe actions observed of the lower extremity when absorbing the high impacts created by foot contact during running. RFS creates a 26% (p = 0.001) greater impact peak than FFS as a result of the ankle and lower leg action, (Kulmala, Avela, Pasanen, & Parkkari, 2013). The more extended lower extremity at foot contact during RFS yields a 47% (p = 0.001) greater average loading rate than FFS (Kulmala, Avela, Pasanen, & Parkkari, 2013). In a study conducted while treadmill running at 9 km/hr, a shoe (SHOD) versus barefoot condition failed to create a significant difference in loading rate, whereas RFS patterns produced higher loading rates in both SHOD and barefoot conditions (Shih, Lin, & Shiang, 2013). The difference in loading rates were greater in the barefoot condition [RFS 44.29 ± 6.98 BW/s: FFS 22.69 ± 5.98 BW/s (p<.001)] vs the SHOD condition [RFS 36.88 ±6.99 BW/s: FFS 25.79 ± 4.12 BW/s (p<.001)] (Shih, Lin, & Shiang, 2013). Lieberman (2012) found a similar difference in loading rates. RFS produced upwards of 600 body mass per second (BM/s) being which is significantly greater than the high  of 250 BM/s loading rate for FFS pattern.

**Leg Compliance**

Footstrike patterns have been the focus to identify how the body responds to the initial impact forces between the foot and ground. Additionally, the focus has been on how the body responds up the kinetic chain from foot to torso to the forces imposed on the body by the ground. Researchers for years have attempted to simplify the integral connections between the joints, muscles and tendons of the lower extremity by creating a
simplistic mass-spring model of the lower extremity (Bishop, Fiolkowski, Conrad, Brunt, & Horodyinski, 2006; Brughelli & Cronin, 2008; Farley & Ferris, 1998; Farley & Gonzalez, 1996; McMahon, Valiant, & Frederick, 1987; Morin, Tomazin, Samozino, Edouard, & Millet, 2012). The simplistic approach removes the muscles, joints and tendons of the lower extremity and replaces them with a simple spring concept representative of the energy absorption and generation created by the compression of the spring (Bishop et al., 2006). The idea of the lower extremity represented as a mass-spring model originates in Hooke’s Law, \( F = -Kx \), in which the force produced by the spring is proportional to the displacement from its resting length (Brughelli & Cronin, 2008). With regards to the human lower extremity, the deformation is the change in leg length that produces vertical displacement of the system’s center of mass (Bramble & Lieberman, 2004).

In reference to the lower extremity and the mass-spring model, researchers have identified three types of stiffness describing what is occurring as the lower extremity is in contact with the ground during stance phase: vertical, joint and leg (McMahon et al., 1987; Brughelli & Cronin, 2008; Butler et al., 2003; Hobara, et al., 2010; Farley & Gonzalez, 1996). Leg stiffness during running is calculated from the relationship of horizontal velocity, time of foot contact, resting length of lower extremity and the vertical component of the ground reaction force (Butler et al., 2003). The overall measurement of stiffness is affected by the change in leg length which creates the displacement of the center of mass from resting to midstance. Simply stated, stiffness is the relationship of this displacement to the force applied to the system (Butler et al., 2003). While the proper amount of stiffness needed for the stretch-shortening reflex that is essential for sport
performance (Butler et al., 2003; James, Dufek, & Bates, 2006), excess or inefficient stiffness may lead to injury to the musculoskeletal system (Butler et al., 2003). Decreases in lower extremity stiffness are related to decreased risk for lower extremity bony injuries through joint positioning during stance (Bishop et al., 2006; Hobara et al., 2010; Pratt, 1989). Through joint angle manipulation, leg stiffness may be consciously altered in response to proprioception and surface changes in an attempt to attenuate the high impact forces of foot contact (Dutto & Smith, 2002; Butler et al., 2003; James et al., 2006; Pratt, 1989).

References to the lower extremity as a spring and the stiffness in response to the forces applied, require a kinetic measurement and analysis. As stiffness is a function of the deformation during the force application, a simplified kinematic analysis focuses on the deformation without regard for the force application. Center of mass vertical excursion, therefore is used to identify the compression of the leg created during the stance phase of running represented by the vertical displacement of the center of mass (Hobara et al., 2008). The vertical excursion of the lower extremity is created by the interactions between muscle and tendons storing and releasing the strain energy created during stance (Bramble & Lieberman, 2004). The displacement of the center of mass is a function of the ankle, knee and hip joints, with the knee and ankle compliance possessing a greater connection to overall vertical excursion than the hip (Bishop et al., 2006; Chan & Rudins, 1994). As knee flexion increases, vertical excursion increases creating greater vertical displacement of the center of mass (Dutto & Smith, 2002).

The magnitude of center of mass vertical excursion is inversely related to speed (Chan & Rudins, 1994, Farley & Gonzalez, 1996). As speed increases, the range of
motion of the lower extremity joints increase, but the center of mass vertical displacement decreases, creating a decrease in lower limb compliance (Chan & Rudins, 1994). If speed remains constant and stride length is manipulated by increasing distance, lower extremity stiffness decreases creating a more compliant leg (Butler et al., 2003). Increasing the stride frequency at the same speed creates a stiffer lower extremity which results in a decreased vertical excursion (Farley & Gonzalez, 1996). Farley and Gonzalez (1996) found that as the stride frequency increased from lowest velocity to the highest, there was a decrease in the center of mass vertical displacement by 76%. Runners may choose to make stride length and stride frequency changes based on the effect each has on the center of mass vertical excursion, as more compliant lower extremities are related to a less economic movement pattern (Chan & Rudins, 1994).

**Fatigue Effects on Kinematics**

When discussing an endurance run, it is important to address the possible effects that fatigue may play in the measurement differences from the beginning to the end of the run. Multiple theoretical models have been formed in an attempt to identify the mechanisms behind fatigue ranging from Noakes’ central governor model to the cardiovascular/anaerobic model to the supply and energy depletion model (Millet, 2011). The definitions of fatigue in the current literature ranges from a “reduction in the force-generating capacity of the neuromuscular system” (Nummela, Stray-Gundersen, & Rusko, 1996) to a strength loss measured by the decrease in maximum voluntary contraction of the peripheral muscles (Millet, 2011). Additionally, fatigue affects muscle activation (Mizrahi, Verbitsky, & Isakov, 2000; Nummela et al., 1996) and muscle stiffness (Candau, Belli, Millet, Georges, Barbier, & Rouillon, 1998). The origins of
fatigue focus on the global, or physiological, base versus the localized, biomechanical, nature (Hunter & Smith, 2007; Mizrahi et al., 2000).

Regardless of the cause or nature of fatigue, measurements of fatigue on performance require baseline measurements followed by fatigue induced exercise bouts that cause a decrease in performance (James et al., 2006). It becomes difficult to isolate the causes of individual dependent variables associated with fatigue because most performance decrements are multi-faceted, affecting many dependent variables. Bates and Osternig (1977) are quoted as saying “the results appear to support the concept that fatigue does not simply produce a uniform reduction in the components of a movement pattern but, rather, changes their relationship completely”.

In a review of the running studies associated with fatigues effect on running kinematics, Morin et al. (2012) found that the studies were inconclusive due to the variety of fatigue inducing methods and measurement tools. Study design must be oriented around eliciting the type of fatigue that is relevant to the mode of exercise being tested. Explosive activities require short duration, high intensity designed studies and endurance activities require long duration, low intensity studies. The intensity and duration of exercise are among the most important factors affecting fatigue onset (Millet, 2011), in addition to mental status (Marcora, Staiano, & Manning, 2009). Mental fatigue is highly related to studies of volitional fatigue, lacking a finishing goal, rather encouraging the participant to exercise for as long as possible. Mental fatigue influences the rating of perceived exertion (Marcora et al., 2009), causing Millet (2011) to recommend that all studies incorporating fatigue, should also incorporate a rating of perceived exertion measure.
Multiple kinematic variables are affected by fatigue, but many connections are inconclusive. Multiple studies found an increase in stride length (SL) post-fatigue (Candau, Belli, Millet, Georges, Barbier, & Rouillon, 1998; Chan-Roper, Hunter, Myrer, Eggett, & Seeley, 2012), while another found a decrease in SL (Nummela et al., 1996). Chan-Roper et al. (2012) identified SL during stages of a marathon, with normalized data to the running speed at the mile markers and Nummela et al. (1996) performed a high intensity, short duration 400-meter track time-trial run. The differences in the previously stated study designes may be responsible for the differences in the findings, as is the case with stride frequency (SF). A runner’s sensitivity to fatigue also affects their response to fatigue (Paavolainen, Nummela, Hakkinen, & Rusko, 1999), as seen from the individual differences in SL with 2 of the participants decreasing and 3 increasing, but the study failed to show a significant difference in the group design (Mercer et al., 2003).

The alterations in SL and SF as a result of fatigue are associated with increases in cycle time (Williams, Snow, & Agruss, 1991) and contact times (Chan-Roper et al., 2012). Both increases are reported to be a result of the decrease in velocity associated with fatigue (Bates & Osternig, 1977). Determination of which component of velocity to adjust, SL or SF, may relate to the level of fatigue and the association of the variables to the cost of transport (Candau et al., 1998).

Further kinematic changes during running in a post-fatigue state occur at the joints of the lower extremity during the stance phase creating an increase in the vertical displacement of the system center of mass during stance (Williams et al., 1991). Morin et al. (2012) found in a study to volitional fatigue of an ultra-long distance treadmill run, that although knee flexion increased during the later stages of the run, the overall
stiffness and vertical displacement of the system center of mass decreased creating a less compliant lower extremity during stance (Candau et al., 1998). The adjustments made to knee flexion and center of mass displacement are associated with an attempt to maintain preferred stride mechanics (Hayes, Bowen, & Davies, 2004).

The current research is interested in the individual variability experienced by runners during an endurance run over ground. Functional variability is another factor affected by speed (Meardon, Hamill, & Derrick, 2011). As a result of this relationship, research has shown how fatigue through it’s effect on speed, affects the variability of dependent variables throughout an endurance run (Candau et al., 1998; Hunter & Smith, 2007; Meardon et al., 2011; Mizrahi et al., 2000). An over ground track run until volitional fatigue produced more unpredictable patterns in stride time, creating greater variability in frequency (Meardon et al., 2011). Foot strike characteristics become more impulsive rather than controlled creating more variability during RFS patterns increasing the impact and shock characteristics across foot strikes (Mizrahi et al., 2000).

The adjustments made while running in a fatigued state are inconclusive due to the differences in study design. Identifying the cause of alterations in running mechanics remains a question of strategy or failure of the system (Morin et al., 2012).

Over Ground Studies

The current literature has produced many contradictory answers in response to the same questions regarding running kinematics. The cause for this is the discrepancy in methods from treadmill running (Dugan & Bhat, 2005; Dillman, 1975; Mercer et al., 2002), over ground in a laboratory setting versus track or observational studies during a marathon (Chan-Roper et al., 2012; Hasegawa, Yamauchi, & Kraemer, 2007; Kasmer,
Liu, Roberts, & Valadao, 2013; Larson, et al., 2011). Opposition to treadmill running in an attempt to measure changes in running patterns argue that runners are forced into a more secure running pattern due to the constant velocity of the treadmill (Dugan & Bhat, 2005; Williams et al., 1991) controlling the environment (Dillman, 1975). As joint ranges of motion, along with multiple other kinematic variables previously shown, vary with speed (Chan & Rudins, 1994), researchers have attempted to identify if these variables are controlled differently during running on the treadmill versus over ground.

Current literature supports general similarities between the direction of the adjustments made in the dependent variables comparing treadmill running and over ground running with the magnitudes representing the true difference (Nelson, Dillman, Lagasse, & Bickett, 1972). Decreased variability in the control of the center of mass during the stance phase shown during treadmill running compared to over ground running (Dillman, 1975; Nelson et al., 1972). Treadmill studies have shown a different response to increases in speed than have over ground protocols with a lack of a plateau in SL, which is created in over ground studies as increases beyond a certain speed are made through SF (Mercer et al., 2002; Nummela et al., 1996). Foot placement relative to vertical position of the center of mass have been reported to be different in treadmill running and overground with different foot strike patterns (Shih, Lin, & Shiang, 2013).

There is a gap that exists in the current race literature investigating both footstrike patterns and kinematic changes affected by distance running in race conditions. RFS patterns are the dominant foot strike pattern during marathons and half-marathons with the percentages ranging from 74.9 – 93.0% depending on if the video was recorded at the 15-kilometer mark or the 32-kilometer mark respectively (Hasegawa et al., 2007; Larson
Runners show a tendency to transition away from FFS at the 10-km mark of a marathon to either MFS or RFS at the 32-km mark in response to fatigue (Larson et al., 2011). Identification of foot strike patterns during over ground studies utilizing one or two discrete foot strikes during a race comprising of multiple foot strikes seems to remove any variability present from stride to stride. This variance among foot strike patterns is seen in the assymetrical foot strike patterns recorded in a percentage of runners during the New Manchester City Marathon 2009 (Larson et al., 2011). Foot strike patterns were further correlated to finishing order at the Sapporo International Half Marathon 2004 showing a higher percentage of MFS runners, 36%, in the top 50 finishers compared to the 32%, 18%, 20% and 19% for the following groupings of 50 finishing times respectively (Hasegawa, Yamauchi, & Kraemer, 2007).

The Salt Lake City Deseret News Marathon 2010 provided further knowledge into the effects of fatigue on multiple kinematics during an endurance race (Chan-Roper et al., 2012). Runners were analysed at the 8 kilometer and 40 kilometer marks of the marathon to investigate the effects of fatigue on joint motion as well as other kinematics associated running mechanics. The general overall research question for the study was to investigate the kinematic changes of an actual marathon. Chan-Roper et al. (2012) found that all dependent variables significantly changed from the initial data collection point of the marathon to the second data collection point of the race. Stride frequency, running speed, peak knee flexion during support and peak hip extension during swing decreased during the later stages of the run, while stride length, contact time, peak knee flexion during swing, and peak hip flexion during swing all increased (Chan-Roper et al., 2012). The findings suggested that on average, across speeds, participants ran slower affecting all
kinematic variables. Given the larger range of finishing times, Chan-Roper et al. (2012) further investigated the changes across fast and slow runners. A significant decrease in peak knee flexion for faster runners compared to slow runners during support ($t = 3.19$, $p < .002$) was the only significant interaction across speed conditions (Chan-Roper et al., 2012).

The race studies previously mentioned have limited data collection to one or two discrete points during an actual race. The limited data available for each participant may have caused them to inaccurately identify a runner’s overall running pattern by an isolated frame of videography. Individual variability and inter-subject differences may create a more well-defined example of the effects of fatigue on running mechanics.

**Single Subject Analysis**

The discrepancies in the current running literature lie within the concept of analyzing the data utilizing a group format. By reducing the data into a simple mean and standard deviation table, mathematically creates a separation of the participants into groups where half the participants were measured higher than the mean and the other half behaved either less favorably or even in the opposite direction of the mean. This creates a situation in which the individual differences, or variability, between subjects becomes averaged out telling only a portion of the true phenomenon (Bates, 1996). The overall goal of the group design analysis is to average out this individual variability, and errors in measurement, in order to generalize the results to a population (Bates, 1996), discounting the limits of the generalizability to represent that represented by the participant pool studied. Recognizing there is “no single template” (Williams & Cavanagh, 1985) and that “no two runners can run essentially the same because variations in anatomical structure,
anthropometric proportions, posture, muscular strength, physiological factors and even mental attitude” (James & Brubaker, 1972), analysis of the individual creates a greater understanding of how people respond differently to the similar stimulus.

Multiple studies have identified the occurrence of inter-subject discrepancies relating to multiple dependent variables found significant in a group design, as well as studies in which the group found variables insignificant. Dutto and Smith (2002) found a significant decrease in the vertical stiffness in the runners, but reported that two of the fifteen actually increased their stiffness while running on a treadmill to exhaustion. When runners participated in an one-hour high-intensity treadmill run, individual differences were exhibited in both leg stiffness (3 subjects increased, 3 increased and 6 showed no change) and step frequency (8 subjects increased, 2 increased and 6 showed no change) following the effects of fatigue from the beginning of the run to the end (Hunter & Smith, 2007).

The masking of inter-participant variability was further identified in an endurance run testing the effects of localized muscular fatigue on running kinematics (Hayes, Bowen, & Davies, 2004). While the group result found no significant difference, Hayes et al. (2004) reported that the “interindividual variability” was covered with 3 participants increasing stride length, 2 decreasing and the remaining participants having no change. Additional studies have suggested that altering stride lengths have different affects on physiological measures and performance during endurance running (Williams & Cavanagh, 1985). Stride length was also shown to affect shock attenuation in a number of the participants (2 decreased and 3 increased) but not all (5 remained unchanged), creating a mean group increase of 2% (Mercer et al., 2003 ).
As a method to identify how individuals respond to changes in their running mechanics, it becomes essential that each participant is treated as an individual understanding that the effects of fatigue are experienced differently according to physiological and anatomical differences. Additionally, the differences among participants in a study transcend to their experiences (Bates, 1996).

Summary

The current literature on the changes of endurance running kinematics due to fatigue has produced widespread results. It is understood that each runner is an individual and responds differently to stimuli and perturbation during a run. In addition to the inter-individual differences, the high amounts of freedom in the human body and uncertain interactions with the environment (Bates, 1996) have identified the intra-individual variability in running kinematics throughout a run. By investigating the overall variability at multiple points throughout a run, the attempt of the current study is to better understand the changes that occur during an endurance run due to fatigue.
CHAPTER 3

METHODS

Subject Characteristics

The purpose of the study was to evaluate kinematics of the lower extremity during the stance phase of an endurance training run. A convenience sample was taken from local running clubs and the University of Nevada, Las Vegas. 15 participants (8 male, 7 female; 30.5±8.4 years; 71.8±11 kg; 1.73±0.07m) reported that they were currently signed up for, or planed on signing up for, an endurance race within the next six months of participation in the study (9 half marathon, 3 marathon, 1 triathlon, 2 21k trail). The inclusion criteria for participation in the study were an age range from 18-45 years with weekly running mileage of more than 20 miles (23.8 miles ±4.6). Each runner had to be able to complete a 15-kilometer distance in 2 hours or less. Participants were generally healthy and free from injury in which had sidelined them from running for at least two weeks within the previous six months. Participants signed an institutionally approved informed consent form prior to participation in the study in addition to a Physical Activity Readiness Questionnaire (PAR-Q).

Instrumentation

Two-dimensional Motion Capture

Data were collected via MaxTraq two-dimensional (2-D) video acquisition and digitization software (Innovisions Systems Inc. 2.2.2.5; Columbiaville, MI) at 120 Hz with a resolution of 659x494. 2-D videography was captured using a Basler GigE Scout high-speed camera (model scA640-120gm; Exton, PA) with Pentax CCTV 8-48mm lenses (Hoya Corporation, Tokyo, Japan). The camera was oriented perpendicular to the
direction of travel in order to capture sagittal plane movement as the runners pass through the field of view. The camera was placed 9 meters from the running lane. Participants were instructed to run within the lane marked on the ground to ensure consistent image size within the field of view.

Footwear

Footwear is not a control of the current study. Therefore, participants were encouraged to bring a current pair of their own running shoes. The recommendation will be for participants to bring a style of shoe that they run the majority of their weekly mileage in and that are not brand new. A new shoe may hinder their natural running mechanics due to comfort. Information will be gathered about individual footwear regarding type, name, approximate mileage run in the particular pair, and any particular obvious wear pattern on the footwear.

Heart Rate Monitors

A Garmin Forerunner 910xt sport watch (Figure 1, Garmin International, Inc., Olathe, Kansas) was used to monitor heart rate (average and peak HR), GPS recorded run distance, lap time and total time taken to complete the run.

Figure 1: Garmin Forerunner 910xt
Procedure

Upon arrival to the Sports & Injury Research Center at the University of Nevada, Las Vegas, participants read and signed an university approved informed consent form, as well as a Physical Activity Readiness Questionnaire (PAR-Q) to determine if they were healthy enough to perform the necessary task. Additionally, participants were asked a series of questions regarding injury history and running behavior. Basic descriptive information was gathered to include age, height, weight and gender.

Following anthropometric measurements, six markers were placed on landmarks of the lower extremity and torso of the right side for digitization purposes: 1) greater trochanter, 2) lateral aspect of the knee joint center, 3) lateral malleolus, and 4) lateral aspect of the shoe corresponding to the lateral aspect of the fifth metatarsal, 5) lateral aspect of neck inferior to ear, 6) iliac crest of pelvis (Figure 2). Markers were attached using athletic cover-roll stretch tape (BSN medical, Inc., Charlotte, NC) to adhere during the possible high sweat rate during the running protocol (Figure 3). For areas that were prone to excess sweating, Tuf-Skin (Cramer Products, Inc., Gardner, Kansas) was used to increase adhesion of the markers.

Figure 2: Marker placement
Following marker placement, participants were instructed to perform a self-selected warm-up, which lasted up to ten minutes, but no less than five. As the participants were training for a race, they possessed a comfortable warm-up routine specific to themselves.

Following the warm-up, participants were instructed that a marked path around the campus of the University of Nevada, Las Vegas designed to provide them with a half kilometer running path. Three participants ran a 0.540 km path due to construction on campus, which interfered with the original course. The path consisted of a combination of concrete and asphalt, traveling through the parking lot area of the Environmental Protection Agency. They were informed that the Garmin watch they were wearing was equipped with a GPS monitor to track the actual path taken in addition to monitoring their heart rate throughout the run.

Participants were instructed to complete approximately a 15-kilometer run, 30 laps, as though it were a normal training run for their upcoming race. This run was not a competitive run, in which the best time wins against the other participants, but rather a normal run for each individual participant as though they were attempting to run a given distance within the amount of time allotted. Participants were informed that as they passed through every half-kilometer, they would be video taped.
Participants were instructed to bring water and/or a sports beverage of their choice. The consumption of beverages was not controlled, but rather ingested ad libitum. The consumption ad libitum ensured that each individual is consuming the amount of liquid that they are comfortable with, representing their individual training routine.

**Data Analysis**

Following data collection, MaxTraq was used to digitize the markers and identify the stance phase period of the right leg. Stance phase was determined visually by identifying the frame in which any portion of the foot contacted the ground to the point where the foot lost contact with the ground, or toe-off. Step frequency (SF), step length (SL) and contact time (StPh) was extracted from video analysis. Digitization of the markers provided extraction of the trunk inclination angle, in addition to the hip, knee and ankle relative angles. Trunk inclination (Torso) were represented by the absolute angle of the torso relative to right distal horizontal. Torso was calculated by digitizing the iliac crest marker and the neck marker. The hip angle (Hip) is a relative angle defined by angle created by the pelvis and the thigh segment. The Hip was calculated by digitizing the three markers placed at the iliac crest, greater trochanter and the lateral aspect of the knee joint center. The knee angle (Knee) is a relative angle defined by the angle created by the thigh and leg. The Knee was calculated by digitizing the three reflective markers placed on the greater trochanter, knee joint center and the lateral malleolus. A fully extended lower extremity was represented by an angle of 180 degrees. The ankle angle (Ank) is a relative angle defined by angle created by the leg and foot. The Ank was calculated by digitizing the three reflective markers placed at the knee joint center, lateral malleolus and lateral aspect of the fifth metatarsal head (Figure 4).
Angle measurements are reported for foot contact (TorsoFC, HipFC, KneeFC, AnkFC) and peak flexion of each joint during stance phase (HipPK, KneePK, AnkPK) independent of the degree of flexion of other joints. Greater trochanter vertical displacement (GrtroDIS) was measured as the difference in the vertical position of the greater trochanter marker at foot contact (GrtroFC) and the lowest vertical position (GrtroMIN) during stance phase. GrtroDIS was used to represent the center of mass vertical excursion during the stance phase.

The camera was oriented to capture a single stance phase of the right leg per lap. Each stance phase captured was analyzed independently, creating a total of 30-stance phase periods per 15-kilometer run. Stance phases were grouped together in three-kilometer (six laps) combinations, creating five, three-kilometer laps (Lap_1, Lap_2, Lap_3, Lap_4, Lap_5).
Variables were extracted from MaxTraq using a customized Matlab script. All stance phase variables were smoothed using a Low-Pass $4^{th}$ Order Butterworth Zero-lag filter.

**Statistical Analysis**

**Research Question 1**

Descriptive statistics for running gait characteristic dependent variables (DV; lap times, StPh, SL, SF and speed) are reported as the mean ± standard deviation for each Lap. Multiple one-way repeated measures analyses of variance (ANOVAs) were conducted for each DV using SPSS Statistics software (IBM; Armonk, NY) across the five Laps (time) with $\alpha = 0.05$. When appropriate, Sidak *post-hoc* tests were run to determine differences among Laps.

**Research Question 2**

Descriptive statistics for all joint angle DVs (TorsoFC, HipFC, KneeFC, AnkFC, HipPK, KneePK, AnkPK) are reported as the mean ± standard deviation for each of the five Laps. Multiple one-way repeated measures ANOVAs were conducted using SPSS Statistics 20 software for each DV across the five Laps (time) with $\alpha = 0.05$. When appropriate, Sidak *post-hoc* tests were run to determine differences among Laps.

**Research Question 3**

Descriptive statistics for GrtroDIS are reported as the mean ± standard deviation for each of the five Laps. A one-way repeated measures ANOVA was conducted using SPSS Statistics 20 software across the five laps (time) with $\alpha = 0.05$. 

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CHAPTER 4

RESULTS

The purpose of the study was to evaluate kinematics of the lower extremity during the stance phase of an endurance training run. A high speed Basler camera was used to capture a single stance phase from the sagittal plane during an endurance run over ground. Participants ran thirty half-kilometer laps, which were grouped into six 3-kilometer segments, creating 5 laps for data analysis. The mean values for each of the 5 laps per participant were then analyzed using one-way repeated measures ANOVAs to determine significant differences within subjects.

Lap Times

The mean and standard deviation values for each lap from the ANOVA results are reported in Table 1. Lap times showed a significant difference within subjects \( (F[2.790,39.065] = 15.829, \ p<0.001, \ \eta^2 = 0.531) \) among laps. Pairwise comparisons showed Lap_1 was significantly faster than Lap_2 (6.20s, \( p=0.002 \)), Lap_3 (9.81s, \( p<0.001 \)), Lap_4 (12.98s, \( p<0.001 \)) and Lap_5 (10.39s, \( p=0.013 \)). Pairwise comparisons showed Lap_2 was significantly faster than Lap_3 (3.61s, \( p=0.010 \)) and Lap_4 (6.78s, \( p=0.012 \)).

Table 1: Descriptive statistics (mean ± standard deviation) for lap times.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lap_1</th>
<th>Lap_2</th>
<th>Lap_3</th>
<th>Lap_4</th>
<th>Lap_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lap Times (sec)</td>
<td>162.5±21.7</td>
<td>168.7±21.9*</td>
<td>172.3±21.6**</td>
<td>175.5±23.0***</td>
<td>172.9±20.3*</td>
</tr>
</tbody>
</table>

*Significant differences with Lap_1 (\( p < 0.05 \))

**Significant differences with Lap_2 (\( p < 0.05 \))
Speed Characteristics

The mean and standard deviation values for stance phase (s), step length (m), step frequency (steps/second) and speed (m/sec) from the ANOVA results are reported in Table 2. Stance phase showed a significant difference ($F[2.427,33.983] = 8.877$, $p<0.001$, $\eta^2 = 0.388$) within subjects among laps. Pairwise comparisons showed the stance phase for Lap_1 was significantly shorter than Lap_2 (0.01s $p=0.011$), Lap_3 (0.01s, $p=0.030$) and lap_4 (0.02s, $p=0.007$).

Step length showed a significant difference ($F[1.223, 17.119] = 6.025$, $p=0.020$, $\eta^2 = 0.301$) within subjects among laps. Pairwise comparisons showed no significant main effects among laps ($p > 0.05$) for step length. No significant difference was shown within subjects for step frequency ($p = 0.087$) among laps. Speed showed a significant difference ($F[1.299, 18.191] = 6.131$, $p=0.017$, $\eta^2 = 0.305$) within subjects among laps. Pairwise comparisons showed no significant main effects among laps ($p > 0.05$) for speed.

Table 2: Descriptive statistics (mean ± standard deviation) for step characteristics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lap_1</th>
<th>Lap_2</th>
<th>Lap_3</th>
<th>Lap_4</th>
<th>Lap_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance Phase (sec)</td>
<td>.265±.028</td>
<td>.274±.030</td>
<td>.276±.027</td>
<td>.280±.029</td>
<td>.274±.029</td>
</tr>
<tr>
<td>Step Length* (m)</td>
<td>1.38±.19</td>
<td>1.30±.18</td>
<td>1.28±.17</td>
<td>1.26±.17</td>
<td>1.26±.17</td>
</tr>
<tr>
<td>Step Frequency (steps/sec)</td>
<td>2.91±.14</td>
<td>2.89±.15</td>
<td>2.90±.14</td>
<td>2.89±.15</td>
<td>2.91±.16</td>
</tr>
<tr>
<td>Speed * (m/s)</td>
<td>4.01±.49</td>
<td>3.73±.44</td>
<td>3.69±.42</td>
<td>3.63±.41</td>
<td>3.66±.44</td>
</tr>
</tbody>
</table>

* Significant main effects difference with Lap_1 ($p < 0.05$)
* Significant within subjects ($p < 0.05$)

Joint Angles at Contact

The mean and standard deviation values for joint angles and torso inclination (degrees) at foot contact from ANOVA results are reported in Table 3. Ankle angle at foot contact (AnkFC) showed no significant difference ($p = .916$) within subjects among
laps. Knee angle at foot contact (KneeFC) showed a significant difference ($F[4,56] = 2.674, p = 0.041, \eta^2 = 0.160$) within subjects among laps. Pairwise comparisons showed less flexion for KneeFC between Lap_1 and Lap_5 (1.60°, $p = 0.041$). Hip angle at foot contact (HipFC) showed no significant difference ($p = 0.591$) within subjects among laps. The angle of torso inclination at foot contact (TorsoFC) showed a significant difference ($F[4,56] = 5.354, p = 0.001, \eta^2 = 0.277$) within subjects among laps. Pairwise comparisons showed no TorsoFC significant main effects, but showed a trend for Lap_2 with Lap_4 (1.67°, $p = 0.058$) and Lap_5 (1.43°, $p = 0.056$).

Table 3: Descriptive statistics (mean ± standard deviation) for joint angles at contact.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lap_1</th>
<th>Lap_2</th>
<th>Lap_3</th>
<th>Lap_4</th>
<th>Lap_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>AnkFC (deg)</td>
<td>114.90±5.44</td>
<td>114.51±4.30</td>
<td>115.22±4.19</td>
<td>115.02±4.60</td>
<td>114.99±3.06</td>
</tr>
<tr>
<td>KneeFC (deg)</td>
<td>164.81±4.39*</td>
<td>164.14±4.59</td>
<td>163.83±4.45</td>
<td>164.31±4.40</td>
<td>163.21±3.71*</td>
</tr>
<tr>
<td>HipFC (deg)</td>
<td>148.82±8.09</td>
<td>149.47±7.98</td>
<td>150.20±6.45</td>
<td>150.58±7.66</td>
<td>150.49±8.03</td>
</tr>
<tr>
<td>TorsoFC (deg)</td>
<td>84.92±1.87</td>
<td>85.64±2.28</td>
<td>85.04±2.23</td>
<td>83.97±2.35</td>
<td>84.21±2.42</td>
</tr>
</tbody>
</table>

* showed significant main effect ($p = 0.048$)

Peak Flexion of Joint Angles During Stance

The mean and standard deviation values for peak flexion of joint angles (degrees) during stance period from the ANOVA results are reported in Table 4. There were no significant differences shown for peak ankle angle (AnkPK; $p = 0.951$) or peak hip angle (HipPK; $p = 0.591$) within subjects among laps. Peak knee angle (KneePK) showed a significant difference ($F[4,56] = 3.304, p = 0.017, \eta^2 = 0.191$) within subjects among laps. Pairwise comparisons showed KneePK was significantly more flexed for Lap_2 and Lap_5 (0.94°, $p = 0.041$).
Table 4: Descriptive statistics (mean ± standard deviation) for peak joint flexion during stance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lap_1</th>
<th>Lap_2</th>
<th>Lap_3</th>
<th>Lap_4</th>
<th>Lap_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>AnkPK (deg)</td>
<td>101.03±2.78</td>
<td>101.34±3.51</td>
<td>100.98±2.92</td>
<td>101.26±3.87</td>
<td>101.03±4.77</td>
</tr>
<tr>
<td>KneePK (deg)</td>
<td>139.32±4.77</td>
<td>139.15±4.42*</td>
<td>139.36±4.51</td>
<td>139.73±4.30</td>
<td>140.09±4.44*</td>
</tr>
<tr>
<td>HipPK (deg)</td>
<td>145.28±7.74</td>
<td>146.88±6.99</td>
<td>147.43±6.71</td>
<td>146.81±7.49</td>
<td>146.28±8.51</td>
</tr>
</tbody>
</table>

* Showed significant main effect (p = 0.041)

Greater Trochanter Vertical Excursion

The mean and standard deviation values for the greater trochanter vertical excursion (cm) during stance period from ANOVA results are reported in Table 5. There were no significant differences for the vertical excursion (GrtroDIS; p = 0.693).

Table 5: Descriptive statistics (mean ± standard deviation) for greater trochanter vertical excursion.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lap_1</th>
<th>Lap_2</th>
<th>Lap_3</th>
<th>Lap_4</th>
<th>Lap_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>GrtroDIS (cm)</td>
<td>7.04±1.52</td>
<td>6.72±1.35</td>
<td>6.82±1.49</td>
<td>7.00±1.83</td>
<td>6.97±2.05</td>
</tr>
</tbody>
</table>
CHAPTER 5
DISCUSSION

The purpose of the study was to evaluate kinematics of the lower extremity during the stance phase of an endurance training run. It was hypothesized that there would be no within subject changes across laps in gait characteristics of an endurance run over ground throughout the run. Results indicated that the only gait characteristic that failed to show significant within subject differences was step frequency. Total lap times significantly increased within subjects across laps. Running speed analyzed during the stance phase showed a significant increase within subjects across Laps. All Laps were an average of six on-half kilometer trials. Post hoc testing showed the lap time for the first Lap was significantly faster than each successive Lap. Post hoc testing failed to show significant differences for speed between the first Lap and any successive Laps. Stance phases were significantly longer during Lap 2 through Lap 4 than during the initial Lap. The final Lap showed no significant difference from the initial Lap. Step length significantly decreased across time, but post hoc testing showed no significant difference among Laps.

Hypothesis two suggested that there would be no change in the joint position across Laps. Knee joint angle at foot contact and peak flexion during stance showed the only significant changes within subjects throughout the laps, with Lap_5 showing the greater flexion than Lap_1. The null hypothesis was retained for all joint angles, both at foot contact and peak flexion during stance, except for the knee.

Hypothesis three identified no significant difference in the vertical excursion of the greater trochanter (as a representation of the system center of mass; COM) during the stance phase. The null hypothesis was retained as a result of no significant difference in
the vertical excursion of the greater trochanter. This result is understandable given the lack of significant differences among the majority of the joints of the body. However, in light of the observed significant change in knee joint flexion, it is possible that the mathematically true system COM did change throughout the endurance run. This suggestion cannot be substantiated given the kinematic model used in this study.

**Hypothesis 1**

The statistical results of the current study have shown that there was a greater change, more significant differences among Laps, in the lap times than were observed in any of the gait characteristics analyzed through the stance phase. The *post hoc* testing showed a continual increase in the time to complete each lap from Lap_1 to Lap_4, but the speed changes through the field of view of the videography area failed to detect significant differences between or among Laps. This may be attributed to the lack of overall differences in the kinematic variables that speed has been shown to affect (Williams, 1987; Dillman, 1975). Additionally, the lack of significant differences between or among Laps may be attributed to the participants performing for the camera when they knew they were being filmed.

The observed changes, and lack thereof, in gait characteristics across Laps are consistent with the current over ground running research although there are slight differences caused by the nature of the runs. Chan-Roper et al. (2012) found a decrease in running speed (3.23 – 2.89 s), stride length (2.26 – 2.04 m) and stride frequency (1.43 – 1.41 strides/s) from the 8 km point to the 40 km point of a marathon. Chan-Roper et al. (2012) showed greater differences in speed, contact time, stride length and stride frequency due to both distance of the run and the intensity level of the run. The current
research identified a speed range in line with the distance covered ranging from 4.01±0.49 m/s during Lap_1 to 3.66±0.44 m/s during Lap_5. Speeds during a 5k race show faster speeds ranging from 5.95 to 5.67 m/s for men and 5.41 to 5.11 m/s for women, from the first analysis point to the second analysis point separated by 2.9 km (Hanley et al., 2011). The 10 km racers experienced a linear decrease in velocity from 5.52 m/s to 5.04 m/s (Elliot & Ackland, 1981). Although the speeds in the current research followed the pattern of speed and distance reported in the previous over ground studies, it is important to note that the current research used recreational runners while both Elliot & Ackland (1981) and Hanley et al. (2011) used elite runners. The speeds used in the current study did not detect the same significant differences that the other studies did, which may be attributed to the participants’ ability to perform differently for the entire trial than they did in front of the camera. The competitive nature of the race studies may produce less concern of the part of the runners to the idea of being filmed. Table 6 shows the measured speeds for each of the measured distances among the comparative studies.

Table 6: Mean (+/- sd) of reported running speed (m/s) at given distance of an endurance run.

<table>
<thead>
<tr>
<th>Study</th>
<th>1-3 km</th>
<th>4-6 km</th>
<th>7-9 km</th>
<th>10-12 km</th>
<th>13-15 km</th>
<th>40 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan-Roper et al. 2012</td>
<td></td>
<td>3.23(0.43)</td>
<td></td>
<td></td>
<td></td>
<td>2.89(0.50)</td>
</tr>
<tr>
<td>Current study</td>
<td>4.01(0.49)</td>
<td>3.73(0.44)</td>
<td>3.69(0.42)</td>
<td>3.63(0.41)</td>
<td>3.66(0.44)</td>
<td></td>
</tr>
<tr>
<td>Elliot &amp; Ackland, 1981</td>
<td>5.52(0.15)</td>
<td>5.27(0.21)</td>
<td>5.14(0.32)</td>
<td>5.04(0.32)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanley et al. 2011</td>
<td>5.95(0.93)M</td>
<td>5.69(1.19)M</td>
<td>3.85 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.41(0.54)F</td>
<td>5.09(0.65)F</td>
<td>5.67(1.40)M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.11(0.57)F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: M = male; F = female
The period of foot contact (StPh: 0.265 ± 0.028 to 0.280 ± 0.029 s) also fell in between the distance ranges from the marathon and 5 km race data. The marathon showed ranges from 0.29 to 0.31 s (Chan-Roper et al., 2012) with the 5 km run showing the shortest contact times of 0.18 – 0.21 s (Hanley et al., 2011). The current study showed results ranging 0.265 ± 0.028 s during Lap_1 to 0.280 ± 0.029 s during Lap_4. The trend of an increase in stance time (StPh) did not continue during Lap_5 as the contact time increased to 0.274 ± 0.029 s. Taken together, the studies provide further evidence that contact time is partially dependent upon speed. Table 7 shows the measured contact times for each of the measured distances of the referenced studies.

Table 7: Mean (+/- sd) of reported contact time (s) at given distance of an endurance run.

<table>
<thead>
<tr>
<th>Study</th>
<th>1-3 km</th>
<th>4-6 km</th>
<th>7-9 km</th>
<th>10-12 km</th>
<th>13-15km</th>
<th>40 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan-Roper et al. 2012</td>
<td>0.27(0.03)</td>
<td>0.27(0.03)</td>
<td>0.28(0.03)</td>
<td>0.28(0.03)</td>
<td>0.27(0.03)</td>
<td>0.31(0.04)</td>
</tr>
<tr>
<td>Current study</td>
<td>0.27(0.03)</td>
<td>0.27(0.03)</td>
<td>0.28(0.03)</td>
<td>0.28(0.03)</td>
<td>0.27(0.03)</td>
<td></td>
</tr>
<tr>
<td>Hanley et al. 2011</td>
<td>0.18(0.01)M</td>
<td>0.19(0.02)F</td>
<td>2.4 km</td>
<td>0.19(0.01)M</td>
<td>3.85 km</td>
<td>0.19(0.01)M</td>
</tr>
<tr>
<td></td>
<td>0.19(0.01)M</td>
<td>0.20(0.01)F</td>
<td></td>
<td>0.21(0.01)F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: M = male; F = female

Step length measurements in the current study fell within the range of step length associated with the distance requirements from the marathon to the 5 km race (Chan-Roper et al., 2012; Elliot & Ackland, 1981; Hanley et al., 2011). Taken in combination, the studies show that marathon runners possess the shortest step lengths throughout their run. Step lengths were shown to increase as the distance requirement decreased, reaching the longest step lengths in the 5 km distance requirement (Chan-Roper et al., 2012; Elliot & Ackland, 1981; Hanley et al., 2011). The previous race studies found significant differences in the runners’ step lengths from the first measured distance to the last measured distance (Chan-Roper et al., 2012; Elliot & Ackland, 1981; Hanley et al.,
The current study found significant within subject differences across the Laps, but failed to find significant differences between any of the consecutive analyzed laps. Step length differences coincided with the significant differences in speed through the analyzed field of view. Table 8 lists the step lengths for the studies at the measured distances.

Table 8: Mean (+/- sd) of reported step length (m) at given distance of an endurance run.

<table>
<thead>
<tr>
<th>Study</th>
<th>1-3 km</th>
<th>4-6 km</th>
<th>7-9 km</th>
<th>10-12 km</th>
<th>13-15 km</th>
<th>40 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan-Roper et al.</td>
<td></td>
<td></td>
<td></td>
<td>2.26(0.30)</td>
<td>2.04(0.33)</td>
<td></td>
</tr>
<tr>
<td>2012*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current study</td>
<td>1.38(0.19)</td>
<td>1.30(0.18)</td>
<td>1.28(0.17)</td>
<td>1.26(0.17)</td>
<td>1.26(0.17)</td>
<td></td>
</tr>
<tr>
<td>Elliot &amp; Ackland,</td>
<td>1.76(0.12)</td>
<td>1.73(0.14)</td>
<td>1.68(0.10)</td>
<td>1.66(0.12)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1981*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanley et al. 2011</td>
<td>1.86(0.09)M</td>
<td>1.83(0.13)M</td>
<td>1.81(0.14)M</td>
<td>3.85 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.68(0.09)F</td>
<td>1.61(0.08)F</td>
<td>1.61(0.08)F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.4 km</td>
<td>3.85 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: M = male; F = female
*Reported as stride length

The current findings of no significant differences within subjects for step frequency may be due to the minimization of the energy cost of running (Mercer et al., 2005). The participants in the current research choose step length changes in response to speed changes rather than step frequency changes, similar to Elliot et al. (1981). These results differ from those of the marathon and the 5 km races in which both identified significant decreases in step frequency in addition to step length (Chan-Roper et al., 2012; Hanley et al., 2011). Table 9 shows the changes in step frequency that occurred during each run.
The running gait characteristic changes in the current study provide further evidence of the importance of speed of travel on the kinematics of running. The significant differences in lap times versus the speed changes through the field of video analysis show that there may have been modified performance for the camera by the participants in the study. Runners seem to be able to revert to their most comfortable running gait pattern when they focus on their pattern, whether consciously or subconsciously. The null hypothesis for the first research question was rejected and the alternate hypothesis was accepted. There were differences for speed, step length and StPh, with StPh showing significant differences. It is important to understand that these changes seem to be related to the speed of running.

**Hypothesis 2**

The null hypothesis for the second research question was that there would be no significant change in the joint angles at foot contact and peak flexion angle during stance in addition to torso inclination angle at foot contact across Laps and time. The angle measures were analyzed at foot strike and at the greatest degree of flexion during the stance phase (foot contact) period. The methods of joint angular measurements differed

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Table 9: Mean (+/- sd) of reported step frequency (steps/s) at given distance of an endurance run.

<table>
<thead>
<tr>
<th>Study</th>
<th>1-3 km</th>
<th>4-6 km</th>
<th>7-9 km</th>
<th>10-12 km</th>
<th>13-15 km</th>
<th>40 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan-Roper et al. 2012*</td>
<td></td>
<td></td>
<td>1.43(0.07)</td>
<td></td>
<td>1.41(0.07)</td>
<td></td>
</tr>
<tr>
<td><strong>Current study</strong></td>
<td>2.91(0.14)</td>
<td>2.89(0.15)</td>
<td>2.90(0.14)</td>
<td>2.89(0.15)</td>
<td>2.91(0.16)</td>
<td></td>
</tr>
<tr>
<td>Elliot &amp; Ackland, 1981</td>
<td>3.13(0.21)</td>
<td>3.04(0.12)</td>
<td>3.03(0.18)</td>
<td>3.03(0.16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanley et al. 2011</td>
<td>3.20(0.15)M</td>
<td>2.4 km</td>
<td>3.12(0.16)M</td>
<td>3.12(0.15)M</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.23(0.19)F</td>
<td>3.85 km</td>
<td>3.17(0.19)F</td>
<td>3.17(0.20)F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: M = male; F = female
*Reported stride frequency (strides/s)
from study to study with the current study employing the relative angle between subsequent segments to define the joint angle. The joint flexion angle has been reported using the mean absolute angle of the segments (Hanley et al., 2011), while Elliot & Ackland (1981) used the absolute angles to report the angular position of the segments in radians. Both studies that employed the segment inclination technique to calculate relative angles found no significant differences in angles at initial foot contact (Elliot & Ackland, 1981; Hanley et al., 2011). The current study identified significant differences within subjects at foot contact for only knee joint angles, with significant differences occurring between Lap_1 and Lap_5 (p = 0.048). The different findings compared to the previous studies may be related to the method of identifying joint angles in addition to the differences in speed during the analysis points. The previous research studies identified the location of the leg in relation to the distal right horizontal as a measure of the knee.

The second aspect of the joint angle analysis was the peak flexion that occurred during contact time (StPh). The current study found a significant decrease in peak knee flexion within subjects with a significant difference between Lap_2 and Lap_5 (p = 0.041). The previous marathon study also found a decrease in peak knee flexion during the contact phase (p < 0.002; Chan-Roper et al., 2012). Although both studies measured the peak flexion during stance using different methods, Chan-Roper et al. (2012) measured peak knee flexion as the difference from foot contact angle to the smallest angle during foot contact with a fully extended lower extremity representing zero degrees. The current study found no other significant differences for any other angle during stance phase. The lower extremity joint angle changes support previous findings.
that the knee joint is the joint most affected by changes in speed and time running (Heiderscheit et al., 2011; Morin et al., 2012).

The second null hypothesis was rejected for knee flexion at foot contact and peak flexion during stance. For all other measures, ankle angle, hip angle and torso inclination, the null hypotheses was retained. Participants in the current study remained consistent with their joint angles, except for knee angle, during the laps of the 15 km run.

Hypothesis 3

The greater trochanter vertical excursion in the current study was used to represents changes in the participants’ center of mass. The vertical excursion of center of mass has been previously related to the compliance of the lower extremity through joint angle changes reflective of speed (Chan & Rudins, 1994, Farley & Gonzalez, 1996). The previous research suggested that as speed decreases, the vertical excursion of the center of mass increases (Chan & Rudins, 1994). The current research failed to produced a significant difference for the vertical excursion of the greater trochanter (GtroDIF; p > 0.05) causing a retention of the null hypothesis. The lack of significant differences throughout the training run may have been a result of the kinematic model used in the current study, as speed was shown to significantly decrease within subjects throughout the run.

The effects of the known videography area and the investigator’s presence may have caused the runners to focus more on their running gait pattern when they were in front of the camera as opposed to the remaining period of the lap. This is evident in the significant differences that were present in the lap times, but were not identified for speed. Because speed affects many kinematic variables, the ability of the runners to
maintain their speed throughout the run limited the effects of the distance on kinematic changes. Runners seem to be able to maintain their comfortable running gait pattern for the 15 km run when they are instructed to go out for a normal training run as opposed to a competitive run in which fatigue generally causes greater differences in gait kinematic variables.

**Performance Variability**

There were inconsistent changes across laps for the group averages of all DVs. The lack of uniformity in changes across laps may be attributed to the differences in lower extremity responses to endurance running from runner to runner. This phenomena is illustrated graphically in Appendix I.

**Limitations**

The major limitation of the present study was the single camera set to capture sagittal plane kinematic during a single stance phase of each lap. As evidenced by the post hoc significant differences in lap times, participants seem to change the speeds in which they were running each lap when they ran in front of the camera versus when they were running away from the videography area. Limiting the analysis to the sagittal plane does not account for frontal plane movement in which many of the changes may have occurred. Stance phase also may be an area in which fewer aspects changed versus swing phase when the body is preparing for the next foot fall and responding to the nature of the toe-off. Limiting the analysis to kinematics fails to account for the ground reaction force data that may better define stance phase, while increasing the knowledge to the response to the forces the body experiences and produces throughout the laps of the race.
Conclusion

The current research differs from the previous over ground studies in that it focuses on a training run lacking the competitive nature of a race, which may have decreased the effect of fatigue on gait characteristics. The participants in the training run followed the pattern in gait characteristic changes across time shown in the competitive studies, with the exception of the lack of changes in step frequency. Runners in the current study were able to maintain their lower extremity joint kinematics at foot contact and during the stance phase even while there were measured differences in lap times, speed and step lengths. Knee joint angle changes seem to be more affected by the changes in speed over a normal training run than any other of the lower extremity joints.

Recommendations

Further research points toward investigating changes in a normal training run in recreational runners with lesser weekly mileage than the current study sample. Frontal plane movement may show areas of greater changes in running gait mechanics including foot strike width and foot strike patterns. Examination of foot strike patterns across a distance run is also an avenue of further investigation.
APPENDIX I

GRAPHS BY LAPS

The following set of graphs represent the group averages for each Lap (1-5) consisting of 6 trials (0.05 km laps).

Gait Characteristics by Trial for each Lap

Graph 1: *Lap Times*

![Graph 1: Lap Times](image)

Graph 2: *Speed*

![Graph 2: Speed](image)
Joint Angles at Foot Contact by Trial for each Lap

Graph 6: TorsoFC

Graph 7: AnkFC

Graph 8: KneeFC
Graph 9: *HipFC*

Peak Joint Flexion Angle During Stance by Trial for each Lap

Graph 10: *AnkPK*
Graph 11: *KneePK*

Graph 12: *HipPK*

Greater Trochanter Inclination by Trial for each Lap

Graph 13: *GrtroDIS*
APPENDIX II
IRB FORM

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

INFORMED CONSENT
Department of Kinesiology and Nutrition Sciences

TITLE OF STUDY: Lower Extremity Kinematic Changes during the Stance Phase of an Endurance Training Run
INVESTIGATORS: Joshua P. Bailey & Janet S. Dufek, Ph.D.
CONTACT NUMBER: J. P. Bailey 702.406.7470

Purpose of study:
You are invited to participate in a running research study. The purpose of the study is to better understand the kinematic changes of the lower extremity during an endurance training run.

Participants:
You are being asked to participate in the study because you are a healthy adult between the ages of 18-45 years of age, currently run at least 20 miles per week, and can finish 15 km in less than 2 hours. You have, or are planning to sign up for, an endurance race within six months of today. You do not have any lower extremity injury, nor have you had a lower extremity injury over the past six months, that has caused a change in your running program for at least two weeks.

Procedures:
If you volunteer to participate in this study, you will be asked to do the following:
1) Arrive at the Sports Injury Research Center and provide written consent of your voluntary willingness to participate.
2) To complete a survey of your running habits, training and health history.
3) You will have 6 reflective markers attached to your lower extremity and torso. As the markers will be attached with non-latex free material, please pay attention to any adverse reaction (allergic) to the material and terminate participation if reaction to material is noticed.
4) You will also wear a Garmin GPS watch and heart rate strap used to measure the actual distance covered and heart rate during the run. The heart rate strap will be placed over the xiphoid process and around the chest.
5) Complete a self-selected warm-up lasting a minimum of 5 minutes and a maximum of 10 minutes, which may include dynamic warm-up drills, walking, or jogging.

Your Initials

Approved by the UNLV IRB. Protocol #1403-4758
Received: 03-28-14 Approved: 04-01-14 Expiration: 03-31-15
TITLE OF STUDY: Lower Extremity Kinematic Changes during the Stance Phase of an Endurance Training Run

6) Complete endurance training run, consisting of 30 laps around a marked path, as though it were a normal training run at a comfortable pace. The marked path will be around UNLV beginning in front of the SIRC.

7) You will be video recorded by two cameras, each capturing a single stance phase, every lap. Following completion of the 30 laps, you will be asked to cool down and stretch, as if you would normally do during a training run.

Course Map:

Benefits of Participation:
There may be no direct benefits to you as a participant in this study. However, this information may lead to an improved understanding of fundamental gait mechanics with broad implications for footwear, orthotics, and prosthetics, as well as potential for injury reduction in the population at large.

Risks of Participation:
The risks associated with participation in the present study will be no different from any typical training-run. There are no unique obstacles on the half-kilometer course. All possible risks are related to the normal risks of running outdoors. It is possible that you might experience delayed discomfort or acquire a muscle strain as a result of your physical performance during overground running. It is unlikely that an injury will occur as the running is at a speed that you prefer and the distance is a distance you are capable of achieving. At any point during the run you feel discomfort that you feel may lead to injury, please stop running and terminate the run.

Cost / Compensation:
There will be no financial cost to you to participate in this study. The study will take between 90 to 120 minutes of your time. You will not be compensated for your time.

Your Initials

Approved by the UNLV IRB. Protocol #1403-4758
Received: 03-28-14 Approved: 04-01-14 Expiration: 03-31-15
TITLE OF STUDY: Lower Extremity Kinematic Changes during the Stance Phase of an Endurance Training Run

Contact Information:
If you have any questions or concerns about the study, you may contact Joshua Bailey at 702-406-7470. For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted you may contact the UNLV Office of Research Integrity – Human Subjects at 702-895-2794 or toll free at 877-895-2794 or via email at IRB@unlv.edu.

Voluntary Participation:
Your participation in this study is voluntary. You may refuse to participate in this study or any part of this study. You may withdraw at any time without prejudice to your relations with the university. You are encouraged to ask questions about this study at the beginning or any time during the study.

Confidentiality:
All information gathered in this study will be kept completely confidential. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be destroyed.

Participant Consent:
I have read the above information and agree to participate in this study. I am at least 18 years of age. A copy of this form has been given to me.

Signature of participant ___________________________ Date: ___________________________

Participant Name (Print) ___________________________

Audio/Video Taping:
This study involves audio/video taping. It is my understanding that I will appear within the field of view of the camera.

Signature of participant ___________________________ Date: ___________________________

Participant Name (Print) ___________________________

Approved by the UNLV IRB. Protocol #1403-4758
Received: 03-28-14 Approved: 04-01-14 Expiration: 03-31-15
**APPENDIX III**

**PAR-Q FORM**

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

If you answered NO honestly to any of the above questions, tell your fitness or health professional.

![ PAR-Q & YOU](image-url)

### YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.

- Find out which community programs are safe and helpful for you.

### NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.

- take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

**PLEASE NOTE:** If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

**DELAY BECOMING MUCH MORE ACTIVE:**

- If you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or

- If you are or may be pregnant — talk to your doctor before you start becoming more active.

**IMPORTANT USE OF THE PAR-Q:** The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

**No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.**

**NOTE:** If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

- "I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

<table>
<thead>
<tr>
<th>NAME</th>
<th>SIGNATURE OF PARENT or GUARDIAN (for participants under the age of majority)</th>
<th>DATE</th>
<th>WITNESS</th>
</tr>
</thead>
</table>

**Note:** This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.
• Have you had a lower extremity injury during the past 6 months that has caused a change in your running routine? ________________

• If so, what was the injury and how long did it affect your routine? ________________________

• How many miles per week have you averaged over the past 2 months? ________

• What is a long run for you? _________________

• How often do you run your long runs? _____________________

• What is the longest endurance race you have participated in? ________________
Which race was it? ___________________________________

• Are you/or do you plan on signing up for an endurance run over the next 6 months? ______ Which one? ________________________________
When? __________________________

• What surface do you run the majority of your mileage on?
  Treadmill       Trails       Asphalt       Track       Concrete       Combo

• What type of running shoes are you running in? __________________________

• Approximately how many miles have you run in these shoes? ________________
REFERENCES


VITA

Joshua P. Bailey

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Education:

M.S. University of Nevada, Las Vegas (Proposed) Summer 2014
  Kinesiology, Biomechanics (Emphasis)

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

Academic Experience:

Graduate Assistantship University of Nevada, Las Vegas
  Teaching Assistant 2012-2013
  Undergraduate Biomechanics Lab (KIN 346)
  SIRC Laboratory Calendar Manager

  Research Assistant – Physical Therapy 2013-2014
  Equipment Integration
  Research Liaison for DPT students
  Data Acquisition and Analysis Mentor

Professional Memberships:

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

Grants:

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

Research:

PUBLICATIONS

Refereed technical paper or conference proceedings:

**PRESENTATIONS:**

**Refereed poster presentations:**


Nordin A.D., **Bailey, J.P.,** & Dufek, J.S. Variations in leg stiffness and lower extremity range of motion variability from stride length perturbations during gait. 2013 Meeting of the American Society of Biomechanics, Omaha, USA, September 2013.

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

Nordin A.D., **Bailey, J.P.,** & Dufek, J.S. Implications of increased lower extremity movement variability on fall susceptibility at increased stride lengths during locomotion. 2013 American Society of Mechanical Engineers International Mechanical Engineering Congress and Exposition, San Diego, USA, November 2013.

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

Masumoto, K., **Bailey, J.P.,** & Mercer, J.A. Exploration of muscle activation as a determinate of preferred movement pattern during running in water. American College of Sports Medicine (ACSM) 61st Annual Meeting, 5th World Congress on Exercise is Medicine and World Congress on the Role of Inflammation in Exercise, Health and Disease, Orlando, USA, May 2014.

**Non-refereed poster presentations:**


**Non-refereed podium presentations:**