BIOMECHANICAL ADJUSTMENTS OVER TIME OF AN EXHAUSTIVE RUN: COMPARISON OF COMPRESSION TIGHTS AND RUNNING SHORTS

A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

BY

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DECLARATION

The work presented in this thesis is, to the best of my knowledge and belief, original, except as acknowledged in the text, and the material has not been submitted, either in whole or in part, for a degree at this or any other university.

Barbara Jean Schornstein

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To God be the Glory.

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ABSTRACT

THESIS: Biomechanical adjustments over time of an exhaustive run: comparison of compression tights and running shorts

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Fatigue induces changes to running form; therefore movement is not as effective or efficient. Reducing the amount of fatigue or its effects on form would be ideal to improve performance while running. Compressive clothing has unknown effects on musculature, however it claims to reduce fatigue. The aim of this study was to see the changes in running form while running to exhaustion and to see how compression tights can effect these changes. Eleven runners ran at their current five-kilometer race pace on a treadmill to voluntary exhaustion in a repeated measures design wearing compression tights and regular shorts while their kinematics, kinetics, heart rate and rate of perceived exhaustion were recorded. There was not a significant difference in time to exhaustion. Fatigue general effects were significant from beginning to end in knee and ankle angle at initial contact with the knee becoming less extended and the ankle less dorsiflexed. Vertical ground reaction loading rate and impact peak were significantly different from beginning to mid point and beginning to end across conditions. Heart rate and rate of perceived exertion increased significantly with fatigue as well in both conditions. Condition effects were significant in stride length and rate with a decreased stride length with compression tights and an increased stride rate with compression tights. The hip experienced a decreased range of motion in the compression tights compared to running shorts. These results indicate that there are effects of fatigue on performance and differences between conditions. These differences did not affect the overall outcome of run as measured in time to exhaustion.

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NOMENCLATURE

5K- 5,000m

ASIS- Anterior Superior Iliac Spine

CWX- Compression Tights condition, CW-X Pro Compression Tights, made by Wacoal Sports Science Corporation

GRF- Ground Reaction Force

HR- Heart Rate

IC- Initial Contact, gait event when the first part of the foot touches the ground

ILC- Iliac Lateral Crest

Kinematics- Position, velocity, and acceleration of the body

Kinetics- Forces, powers, and moments acting on and within the body

Loading Reaction- Knee bending that takes place during load acceptance phase of gait

MSE- Mean Squared Error, setting of the Woltring filter in VICON Workstation

PSIS- Posterior Superior Iliac Spine

ROM- Range of Motion

RPE- Rate of Perceived Exertion, based upon Borg's 6-20 scale (see Appendix A)

SHO- Shorts Condition

Swing Phase- Gait phase when the foot is not in contact with the ground

Temporal and Spatial- Parameters of gait in reference to distances and times

TO- Toe-Off, gait event when the last part of the foot comes off the ground

TSF- Tibial Stress Facture

VO_2- Rate of Oxygen Consumption, Slow Component, the rise in VO_2 after lactate threshold has been reached

CHAPTER 1

DEVELOPMENT OF THE PROBLEM

INTRODUCTION

Compression clothing has recently become a popular choice for athletic wear. Compression clothing exerts an additional amount of pressure on the surface of the body part that it is covering than traditional clothing and even elastic form-fitting clothing. Research has shown improvements in perceptual and physiological variables including heart rate and components of VO_2 (Ali, Caine, & Snow, 2007; Ali, Creasy, & Edge, 2010; Bringard, Perrey, & Belluye, 2006; Kemmler et al., 2009). Perceptual variables include how participants felt before, during and after running in compression clothing. Kemmler et al. studied below-knee length compression stockings, and they saw an increased time under load, total work, and maximum speed with compression stockings (Kemmler, et al., 2009). Ali et al. found a trend towards a lower HR with compression socks (Ali, et al., 2007). Although this trend was not significant; it is important to note that races are not always won by significant margins. A lower energy cost was demonstrated by Bringard et al. wearing elastic tights or compression tights compared to traditional shorts (Bringard, et al., 2006). The study also demonstrated a lower slow component of VO_2 when wearing compression tights compared to elastic tights and traditional shorts (Bringard, et al., 2006). Elastic clothing is such that it is form-fitting, yet exerts only nominal pressure on the body part covered. These improvements made by compression clothing are all physiological; it has yet to be studied whether there are biomechanical improvements as well.

As a runner is fatigued, their form tends to breakdown and they are not moving as effectively as before. This reduction in effectiveness translates to a decrease in performance. Impact kinetics of fatigued runners are altered (Christina, White, & Gilchrist, 2001; Dutto, 1999; Gerlach et al., 2005; Hanley & Mohan, 2006) and many studies have shown varying kinematic changes as well with fatigue (Candau et al., 1998; Christina, et al., 2001; Derrick, Dereu, & McLean, 2002; Dutto & Smith, 2002; Elliot & Ackland, 1981; Elliott & Roberts, 1980; Gazeau, Koralsztein, & Billat, 1997; Hayes, Bowen, & Davies, 2004; Kellis & Liassou, 2009; Kyrolainen et al., 2000; Mizrahi, Verbitsky, Isakov, & Daily, 2000; Morgan, Martin, Baldini, & Krahenbuhl, 1990; Nummela et al., 2008; Nummela et al., 2006; Siler & Martin, 1991; Williams, Snow, &

Agruss, 1991; Willson & Kernozek, 1999). These alterations increase chances of injury along with decreasing performance.

Among the changes to a runner’s landing kinetics are decreases in maximum vertical force and vertical impulse (Christina, et al., 2001; Gerlach, et al., 2005; Hanley & Mohan, 2006) as well as an increase in vertical loading rate (Christina, et al., 2001; Dutto, 1999; Gerlach, et al., 2005). These kinetic changes happen when runners are fatigued and not effective in their movements, which can lead to injury (Hreljac, Marshall, & Hume, 2000; Milner, Ferber, Pollard, Hamill, & Davis, 2006).

Kinematic changes also occur with the previously mentioned kinetic changes. In literature these kinematic changes have been varied depending on the type of running (i.e., over ground running or treadmill running) and the variables assessed, such as step/stride length, stride rate, contact and flight times, joint angles, joint velocities, and joint range of motion changes (Candau, et al., 1998; Derrick, et al., 2002; Elliot & Ackland, 1981; Elliott & Roberts, 1980; Gazeau, et al., 1997; Gerlach, et al., 2005; Hanley & Mohan, 2006; Kellis & Liassou, 2009; Kyrolainen, et al., 2000; Mizrahi, et al., 2000; Morgan, et al., 1990; Nummela, et al., 2008; Nummela, et al., 2006; Siler & Martin, 1991; Verbitsky, Mizrahi, Voloshin, Treiger, & Isakov, 1998; Williams, et al., 1991; Willson & Kernozek, 1999). Changes that occur while running over ground on a track are different than those that happen while running on a treadmill (Riley et al., 2008). Maximum knee flexion is greater and minimum knee flexion is smaller over ground than on a treadmill while stride length is longer and stride rate is slower over ground than on a treadmill (Riley, et al., 2008). The most common measure studied in over ground running is stride length, and this has been shown to decrease (Elliot &

Ackland, 1981; Elliott & Roberts, 1980; Nummela, et al., 2008; Nummela, et al., 2006). In these over ground running studies there was also an increase in contact, or support, time (Elliott & Roberts, 1980; Nummela, et al., 2008; Nummela, et al., 2006) and a corresponding decrease in flight, or non-support, time (Elliott & Roberts, 1980; Nummela, et al., 2006). Trunk lean was shown to increase with fatigue, in definition then, there was a decrease in the trunk angle (Elliot & Ackland, 1981; Elliott & Roberts, 1980). This is good information; however it does not necessarily translate to running to exhaustion on a treadmill. For that information, studies taking place on a treadmill need closer attention.

One commonly studied variable in treadmill running is the knee angle at various points in the gait cycle. At initial contact, the knee was shown to become more flexed (Derrick, et al., 2002; Gazeau, et al., 1997; Mizrahi, et al., 2000) and at toe-off it was shown to be more extended (Gazeau, et al., 1997; Hanley & Mohan, 2006). The maximum knee angle varied in the results of these studies with two studies demonstrating a decrease in extension angle (Derrick, et al., 2002; Siler & Martin, 1991) and one demonstrating increased angle to be more extended (Mizrahi, et al., 2000). Varying changes in stride rate and stride length have been shown as well using different methods from pre/post runs for a marathon and other fatiguing protocols to incremental treadmill tests and exhaustive treadmill protocols at distinct and different speeds (Candau, et al., 1998; Gazeau, et al., 1997; Gerlach, et al., 2005; Kyrolainen, et al., 2000; Mizrahi, et al., 2000; Siler & Martin, 1991; Williams, et al., 1991; Willson & Kernozek, 1999).

A better understanding is needed to determine what changes occur in running gait kinematics and kinetics as a person runs to exhaustion and what impact compression clothing can have.

PURPOSE

The purpose of this study is twofold. The first purpose was to determine the effects of an exhaustive run on running form and the second is to determine if these effects were altered by wearing compression tights during an exhaustive run.

SIGNIFICANCE

Compression tights have not been thoroughly studied in relation to improving exhaustive performances during long-distance running. It is not well established whether they give the athlete an advantage over others wearing traditional running shorts. The mechanism for potential improvements is not well understood. It is theorized that compression may help to support the muscles by reducing muscle oscillation (Doan et al., 2003). This may be especially true for the type of compression tights used in this study: CW-X Pro Compression Tights. These tights have strategically placed support bands designed to create a suspension system to support the hamstrings and quadriceps muscles that support the knee while running. While physiological studies involving compression clothing have been performed, very few have been performed looking at running kinetics and kinematics.

METHODS

Thirteen subjects were recruited from Ball State University and the surrounding cities. Subjects were 22.5 (3.3 SD) years old (range 18-30 years), nine males and two females, and in good cardiovascular health, not having any injuries in the past three months. They ran at least three times a week and fifteen miles a week, and their 5k race time was between 17:00 and 23:00 minutes. Written consent, approved by the Ball State University Institutional Review Board, was obtained from all participants prior to study involvement.

Three testing sessions were required for each participant. For the first session, each subject raced a 5k time trial on a 200m indoor track and their overall time was recorded. At the second and third sessions, the subjects came to the Biomechanics Laboratory at Ball State University where they were given clothing (shirt and compression tights or shorts) and a Polar HR monitor (Polar Electro Oy, Kempele, Finland) to wear during each testing session. Each subject wore their own shoes and socks and used the same footwear for all three testing sessions. Anthropomorphic measurements were taken before the subject was prepared by attaching retro-reflective markers to anatomical landmarks. Retro-reflective markers were used within the VICON motion capture system (VICON, Los Angeles, CA, USA) to collect and calculate kinematic variables. Kinetics were collected within the VICON system as well by a custom built AMTI End-to-End Force Instrumented Treadmill (AMTI, Inc., Watertown, MA, USA). The subject preformed static and ROM calibration trials and then warmed up on the treadmill at a self-selected pace for 7-10 minutes. After this, each subject was given time to do any self-directed stretching and additional warm up procedures they felt were necessary. Following which time the test began with the subject on the treadmill accelerating up to 100% of their 5k race pace from their 5k indoor time trial. Once the treadmill hit the correct pace, the official trial time began. Kinematic, kinetic and RPE data were collected every three minutes using VICON Workstation while HR data were collected continuously throughout the trial. Every three minutes, two trials of 7 seconds were recorded. RPE was assessed every three minutes by asking the subject to indicate their RPE score on a chart or verbally. The trial stopped when the subject indicated to the research team that they were unable to continue running. At that time the treadmill was stopped and the official trial time ended. Session three was the same as session two, except that anthropomorphic measures were not taken and the opposite clothing condition was worn.

Kinematic and kinetic data were originally processed in VICON Workstation and imported into Visual 3D (C-Motion, Germantown, MD, USA) for further processing and analysis. HR data were analyzed in Polar Protrainer 5 software (Polar Electro Oy, Kempele, Finland).

Statistical analysis was performed in SPSS 19.0 (IBM Corp., Armonk, NY, USA). Time to exhaustion was analyzed using a paired t-test. Comparison was done between conditions and time points with a repeated measures (2 conditions by 3 time points) ANOVA to analyze joint angles, SL, SR, RPE, HR, and components of the vertical GRFs between groups. Statistical significance was set at an alpha level of 0.05 and pairwise comparisons were performed when significance was found between time points.

LIMITATIONS

Each participant was following their own training schedule and there was no uniformity in the type of runner recruited as long as they met the qualifications for the study. Data collection took place over a ten month period and therefore some runners were in a competitive training cycle while others were in a building training cycle. Testing took place when subjects were available not necessarily when they felt that they run their best. Subjects may have preconceived notions about compression tights and there was no way to blind them towards the condition tested.

DELIMITATIONS

Subjects were given guidelines to follow for the day before and of testing, there is no certainty that they were followed. Pre-testing energy consumption may have been different because of these guidelines than what subjects would normally do before racing. This study investigated interactions with compression tights at the 5k distance/time frame and the findings may not apply to shorter or longer distances/time frames. While 3D motion analysis was used to collect the data, the subjects were only analyzed in the sagittal plane.

SUMMARY

Research has shown that when running to exhaustion, changes occur that degrade running biomechanics and reduce performance (Candau, et al., 1998; Christina, et al., 2001; Derrick, et al., 2002; Dutto, 1999; Dutto & Smith, 2002; Elliot & Ackland, 1981;

Elliott & Roberts, 1980; Gazeau, et al., 1997; Hayes, et al., 2004; Kellis & Liassou, 2009; Kyrolainen, et al., 2000; Mizrahi, et al., 2000; Morgan, et al., 1990; Nummela, et al., 2008; Nummela, et al., 2006; Siler & Martin, 1991; Williams, et al., 1991; Willson & Kernozek, 1999). Movement is not as effective as before and chances of injury increase. Compression clothing has been shown to improve physiological and perceptual variables (Ali, et al., 2007; Ali, et al., 2010; Bringard, et al., 2006; Kemmler, et al., 2009). However, little is known about compression tights' effect on running biomechanics such as: stride length and rate; joint angles and velocities; and ground reaction forces. Physiological variables that improved included: 1) components of oxygen uptake and usage, 2) time under load, 3) total work, 4) maximum speed, 5) heart rate (HR), and 6) energetic cost of running (Ali, et al., 2007; Bringard, et al., 2006; Kemmler, et al., 2009). The proposed mechanism behind the possible benefits to compression clothing is that compression may help to support the muscles. This may be especially true for the type of compression tights used in this study: CW-X Pro Compression Tights. These tights have targeted support using CW-X Support Web™ technology. Strategically placed support bands aim to create a suspension system to support the hamstrings and quadriceps the muscles that support the knee while running. This could reduce the biomechanical changes that occur when running to exhaustion thereby improve performance while also reducing injury.

CHAPTER 2

REVIEW OF LITERATURE

INTRODUCTION

Methods and variables used to assess fatigue vary greatly as fatigue is hard to define. Some studies have defined fatigue in a localized setting (i.e. using isokinetic muscle contractions of a particular muscle or group and setting a standard to define an end point) (Christina, et al., 2001; Kellis & Liassou, 2009) or systemically (i.e. oxygen consumption measures, rating of perceived exertion, voluntary exhaustion or time trial situations) (Candau, et al., 1998; Derrick, et al., 2002; Elliot & Ackland, 1981; Elliott & Roberts, 1980; Gazeau, et al., 1997; Gerlach, et al., 2005; Hanley & Mohan, 2006; Kyrolainen, et al., 2000; Mizrahi, et al., 2000; Nummela, et al., 2008; Nummela, et al., 2006; Siler & Martin, 1991; Verbitsky, et al., 1998). Protocols for studying fatigue vary from running repeated sprints to marathons and looking at differences pre- and post fatigue or from the beginning of a test to the last stages of it (Gerlach, et al., 2005; Kyrolainen, et al., 2000). Many methods and variables are used as fatigue is a very individual specific and no gold standard exists to encompass all aspects of it: localized, overall, muscular, and psychological.

Compression clothing has become popular athletic apparel in recent years. The benefits from wearing compression clothing are undetermined as it has a complex interaction on different systems that do not easily separate affects from one another. There are reported physiological benefits and biomechanical studies that show improved performance or affect on performance (Ali, et al., 2007; Ali, et al., 2010; Bringard, et al., 2006; Kemmler, et al., 2009). However, the interaction between physiological and biomechanical benefits is not clear or easily separable. More studies are needed to better identify how compression clothing can aid in performance.

EFFECTS OF FATIGUE ON RUNNING

Fatigue has an overall effect to decrease performance in running because of the changes that occur in running form. A runner is wasting energy when they are not moving as effectively and efficiently as before. For example oxygen consumption increases when knee mechanics are altered (Derrick, et al., 2002). This leads to a decrease in performance as well as possibly increasing the potential for injury. There are indicators in a runner's gait that signal fatigue has set in, however they depend whether the athlete is running overground or on a treadmill (Riley, et al., 2008).

Temporal and Spatial Changes

Temporal changes in running gait include those that can be measured in distances or times, for example: stride length and rate as well as contact and flight times.

While running time trials over ground at maximal speeds for distances from 3k to 10k, there have been noticeable decreases in stride length (Elliot & Ackland, 1981; Elliott & Roberts, 1980; Nummela, et al., 2008; Nummela, et al., 2006; Verbitsky, et al., 1998) with corresponding increases in stride rate in order to maintain speed (Elliott & Roberts, 1980). Change in stride length is not a consistent measure though, as studies performed with on treadmills have come up with both increased (Gazeau, et al., 1997; Gerlach, et al., 2005; Siler & Martin, 1991) and decreased (Kyrolainen, et al., 2000; Willson & Kernozek, 1999) stride lengths. Again, those studies that included measuring both stride length and stride rate, there were corresponding decreases in the stride rate (Candau, et al., 1998; Gerlach, et al., 2005; Mizrahi, et al., 2000) and increases in stride rate (Kyrolainen, et al., 2000; Willson & Kernozek, 1999) in order to maintain speed. Changing stride length seems to be an individual preference, though, as a study by Dutto et al. found that nine runners decreased their stride rate, three runners increased and three had no significant change (Dutto & Smith, 2002).

There have also been corresponding changes in contact and flight times of track runners as a result of fatigue. Contact time is when a runner’s feet are in contact with the ground while flight time is defined as the time when there is no contact with the ground. This is measured per gait cycle. It has been demonstrated that while running on a track contact times increase (Elliott & Roberts, 1980; Nummela, et al., 2008; Nummela, et al., 2006) while flight time decreases (Elliott & Roberts, 1980; Nummela, et al., 2006).

Running on a treadmill has been demonstrated increases (Gazeau, et al., 1997) and decreases (Hanley & Mohan, 2006) in contact time.

Kinematic Changes

Kinematic changes caused by fatigue have primarily result in joint angle changes and velocity and acceleration of those joints and segments. While a few studies have found no significant changes in kinematics with fatigue (Abt et al., 2011; Collins et al., 2000; Hayes, et al., 2004), there are many that do find significance changes (Christina, et al., 2001; Derrick, et al., 2002; Elliot & Ackland, 1981; Elliott & Roberts, 1980; Gazeau, et al., 1997; Hanley & Mohan, 2006; Kellis & Liassou, 2009; Mizrahi, et al., 2000; Morgan, et al., 1990; Siler & Martin, 1991; Williams, et al., 1991).

The knee is a dynamic indicator of fatigue in most cases. The knee angle at initial contact has been shown to decrease after fatigue (Derrick, et al., 2002; Elliott & Roberts, 1980; Gazeau, et al., 1997; Mizrahi, et al., 2000) while at toe-off the knee angle increases (Gazeau, et al., 1997; Hanley & Mohan, 2006; Kellis & Liassou, 2009). During swing phase the knee angle becomes more flexed (Siler & Martin, 1991; Williams, et al., 1991) and maximum extension can increase (Mizrahi, et al., 2000) or decrease (Derrick, et al., 2002; Siler & Martin, 1991). These different knee positions indicate whether the leg stiffness is changing over the course of a run. A stiffer knee during loading of the vertical ground reaction force was present in those individuals that had a history of tibial stress fracture compared to an injury-free control group (Milner, et al., 2006; Milner, Hamill, & Davis, 2007). Also, a study by Derrick et al. suggests that more flexion in the knee during loading also increases oxygen consumption, reducing the effectiveness of the runner (Derrick, et al., 2002).

Hip or thigh angle, as it is called in some papers, increased at initial contact (Elliot & Ackland, 1981) and was less extended at toe-off (Elliott & Roberts, 1980). After a fatiguing protocol to the knee extensors, however, hip extension at toe-off was shown to increase (Kellis & Liassou, 2009). The overall range of motion was increased as well as the maximum thigh flexion angle (Siler & Martin, 1991). This would lead to a more open hip position throughout the gait cycle and improve positioning of the lower leg in its mechanics. Trunk lean is also a measure to look at as an indicator of fatigue. It has been shown to increase with fatigue overall (Elliott & Roberts, 1980) and at maximum hip extension (Siler & Martin, 1991).

Ankle angles and foot angle are less commonly studied than knee or hip angles while running to fatigue. The ankle has been shown to decrease dorsiflexion at initial contact after local dorsiflexor fatiguing protocol (Christina, et al., 2001) and increase plantar flexion angle at toe-off one day post fatiguing protocol (Morgan, et al., 1990). Rearfoot angles increase at initial contact but overall they have a decrease in maximum angle (Derrick, et al., 2002). Ankle and foot angles indicate whether a heel to toe strategy is used or if a midfoot strike is used. This can shift the outcomes of the vertical ground reaction forces and plantar pressures.

Flexion velocities of the hip and knee can increase or decrease depending on the fatigue introduced to them. After a knee extensor fatigue protocol, both hip and knee flexion velocity was shown to decrease, however after a ankle plantar flexor fatigue hip extension and ankle plantar flexion velocities were shown to increase (Kellis & Liassou, 2009). Gazeau et al. had subjects run to exhaustion at maximum aerobic speed and saw that there was an increase in the maximum knee angular velocity during flexion of the swing phase and a decrease in the maximum angular acceleration of the hip during the support phase (Gazeau, et al., 1997). Another study also found and increase in maximum knee flexion velocity (Derrick, et al., 2002).

Kinetic Changes

The most studied kinetic changes with fatigue are the components of the vertical ground reaction force including the impact peak, active peak and the loading rate of the force. Peak force at impact decreases with fatigue significantly (Christina, et al., 2001; Gerlach, et al., 2005) as well as decreasing with a non-significant trend (Dutto, 1999). In Dutto & Smith's research into this they concluded that as well as trending towards a decrease in impact force, the increased loading rate led to a stiffer leg at impact (Dutto, 1999). Christina et al. also showed an increase in loading rate with localized dorsiflexor fatigue (Christina, et al., 2001) while Gerlach et al. demonstrated a decrease in loading rate with an exhaustive exercise test (Gerlach et al., 2003). Peak active force of the vertical ground reaction force has both decreased (Hanley & Mohan, 2006) and stayed the same (Dutto & Smith, 2002). As previously stated, leg stiffness increased in one study by Dutto & Smith (Dutto, 1999) while vertical stiffness and leg stiffness decreased in another (Dutto & Smith, 2002). Vertical impulse also showed significant decreases from the beginning of a 10k to the end of it (Hanley & Mohan, 2006). A stiffer leg and higher loading rates increases the chance of lower leg injuries, specifically tibial stress fractures (Edwards, Taylor, Rudolphi, Gillette, & Derrick, 2009; Milner, et al., 2006; Milner, et al., 2007).

COMPRESSION CLOTHING

Several styles of form fitting clothing have become a popular choice in athletics for many reasons. Elastic and compression clothing are two of them. While elastic clothing is form fitting, it only exerts a nominal amount of pressure on the skin and underlying tissues. Compression garments can be further divided into static compression, graduated compression, and support bands. Static compression provides a single amount of pressure, can be low or high, to the body part covered while graduated compression changes the amount of compression from one part of the garment to another. Support bands in compressive garments focus their compression to specific areas of the garment and are typically tighter than the surrounding compression.

Physiological Changes

In a review article by Millet et al. it is explained that one of the mechanisms behind external compression's physiological benefits, is that they reduce the cross sectional area of the limb or tissue increasing the velocity of the blood flow within the veins (Millet, Perrey, Divert, & Foissac, 2006). It would then be logical to conclude that they would increase lactate clearance and other byproducts leading to a higher lactate threshold and less post exercise soreness. However, this has not always been proven. No significant difference in blood lactate concentration have been shown (Ali, et al., 2010; Kemmler, et al., 2009) but a significant difference in post exercise muscular soreness with compression socks (Ali, et al., 2007). There was also no difference in how subject felt while exercising in compression garments as measured by RPE (Ali, et al., 2007; Ali, et al., 2010; Bringard, et al., 2006). A study by Ali et al. paced runners on the road in a 10k time trial while wearing knee-length compression socks and found that even though runners were paced, 10 out of 14 ran faster with the socks and they demonstrated a trend towards a lower heart rate while running (Ali, et al., 2007). However, three other studies found varying results for heart rate between compressive and non-compressive conditions (Ali, et al., 2010; Bringard, et al., 2006; Kemmler, et al., 2009). Another result that has varied is the amount of oxygen consumed while exercising. Ali et al. and Kemmler et al. found no differences in VO_2max while Bringard et al. found differences between regular shorts, elastic tights and compression tights (Ali, et al., 2010; Bringard, et al., 2006; Kemmler, et al., 2009). Bringard demonstrated a 36% and 26% decrease in the slow component of VO_2 for shorts and elastic tights respectively when compared to compression tights (Bringard, et al., 2006). Respiratory exchange ratio a measure of the ratio between the amounts of carbohydrate and fat used for fuel was not affected by wearing knee-length compression stocks (Kemmler, et al., 2009).

Biomechanical Changes

There have been relatively few biomechanical studies performed on biomechanical changes when wearing compressive garments. Kemmler et al. assessed both physiological and biomechanical effects of below-knee compression socks using a stepwise speed-incremented treadmill test to exhaustion. The subjects demonstrated an increased time under load, an increase in total work and an increase in maximum speed (Kemmler, et al., 2009).

CW-X Specifics

One brand of commercial available compression garments is CW-X Conditioning Wear®. This brand of garments falls into both the support band as well as the graduated compression types of compression garments. It includes support bands called CW-X Support Web™ into its compression tights. The bands are graduated compression to facilitate blood flow and venous return to reduce the buildup of lactic acid as well as during activity and post muscle soreness ("Gear Technology,"). When wearing these compression tights oxygen consumption was 26% less than regular compression tights and 36% less than running shorts alone (Bringard, et al., 2006). They mimic kinesiological taping for injury prevention and create an exoskeleton support system. This exoskeleton system helps band ligaments together to stabilize the knee joint and decrease injury chances ("Gear Technology,"). In a study performed by the Human Science Research Center in Kyoto, Japan, CW-X tights helped stabilized the knee 10% more than regular compression tights ("Gear Technology,"). The “Pro” CW-X compression tights are reported to bring the hips, knees, and ankles into alignment. The support bands in the “Pro” tights create a suspension system for the quadriceps and hamstrings reducing the workload for both push and pull phases of gait ("Gear Technology,"). They also support the quadriceps to reduce the shock and speed at which the knee bends under workload for increased overall speed and power as well as reducing the shock experienced by the knee by 12% than regular compression tights ("Gear Technology,"). The Pro tights increase your circulation and reduce fatigue so that you don’t have to work as hard over time ("Gear Technology,").

SUMMARY

Fatigue has a role in reducing performance. Whether the runner is overground or on a treadmill, there are indicators of fatigue that can be studied. Temporal and spatial parameters, kinematics, and kinetics change as a byproduct of fatigue resulting in ineffective form and a drop in performance. Compression clothing is reported to have performance benefits ranging from decreasing the amount of oxygen needed to perform the task, decreasing muscle soreness, increasing time under work, increasing the total work performed, and increasing the velocity of the task (Ali, et al., 2007; Bringard, et al., 2006; Kemmler, et al., 2009). There is little research studying the interaction and possible biomechanical benefits into wearing compression clothing during running. The possible benefits could include attenuating the changes due to fatigue and increase performance.

CHAPTER 3

METHODS

INTRODUCTION

The purpose of this study was to determine if there was a distinct biomechanical effect of wearing compression tights during an exhaustive run. Subjects ran until voluntary exhaustion at their current 5k race pace on a treadmill in a randomized condition of compression tights or running shorts. Kinematic and kinetic data were collected during the treadmill runs. These data were processed to determine whether the compression tights had an impact on performance characteristics. This study was carried out in the Ball State University Biomechanics Laboratory and Field Sports Building in compliance with the Ball State University Institutional Review Board (IRB).

PARTICIPANTS

Thirteen individuals were recruited to participate in this study from Ball State University and surrounding cities. Two of those subjects dropped out of the study citing injury sustained separate from the study as the cause. The remaining subject’s demographics (mean (SD)) are as follows for age, height, weight, 5k race time, and treadmill pace respectively: 22.5 (3.3) years, 1.78 (.08) m, 71.1 (8.8) kg, 1215.1 (91.2) sec, and 4.1 (0.3) m/s.

Recruiting was accomplished through flyers and email advertisements as well as word of mouth to students, faculty and staff of the university and local running clubs and fitness centers. The flyer information was also made available at a local bike shop and on the internet web site of a local running store.

Participation were eligible for the study if they were between the ages of 18 and 40, they ran at least three times a week and fifteen miles a week, they were able to race a 5k at maximal intensity between 17:00 and 23:00 minutes, they were in good cardiovascular health including no history of musculoskeletal injury in the past three months nor any previously diagnosed neurological or orthopedic disorders presenting an abnormal movement pattern.

TESTING SESSIONS

Three total testing sessions were required for this research study: a 5k time trial and two exhaustive treadmill sessions. The two treadmill sessions were exactly the same except for the clothing that the subjects wore. They wore either compression tights or loose running shorts in a controlled randomization pattern. This means that six subjects wore the compression tights for their first treadmill session and the loose running shorts condition for their second session, while five subjects wore the opposite.

The first testing session was held at a 200m indoor track and included each subject reading and signing an informed consent document agreeing with the procedures and practices that the study entailed. This was in accordance with the university approved IRB. They also filled out a brief health history and running history questionnaire to ensure that they were qualified for the study. After the paperwork was completed, subjects were given as much time as they needed to warm up and prepare for a maximal intensity 5k time trial on the indoor track. Once the subject was ready they gave the investigator notice and they proceeded with final instructions for running on the indoor track including: the proper lane to run in (1st lane), informing of the splits that would be given as the time trial progressed (each mile, cumulative time), the number of laps (25) and when the runner would be told the number of remaining laps (counting down from 5 to go). Data recorded at this time was each lap's time and cumulative lap times as well as final time. Subjects wore their own loose fitting clothing and running shoes for this testing session.

For the second testing session, subjects reported to the biomechanics laboratory five to ten days after their 5k time trial. At this time their predetermined condition was revealed to them. They were given clothing to wear for that day's testing session (shirt and compression tights or running shorts) and wore their own training shoes and socks. Also, they were given and instructed how to put on a Polar RS400sd Heart Rate Monitor (Polar Electro Oy, Kempele, Finland). This was used to monitor HR during the trials and for later download to computer file post run. After the subject changed, anthropometric measurements were taken and retro-reflective markers were placed on the subject using a cluster-based marker set. The markers and clusters were attached to the subject using double stick tape and Tuf-Skin (Cramer Products Inc., Gardner, KS, USA), a spray tape adherent. Clusters were additionally secured using PowerFlex cohesive bandage (Andover Healthcare, Inc., Salisbury, MA, USA). The cluster-based marker set using retro-reflective markers is configured as follows for each left and right sides: shoulder marker, ASIS 2-marker clusters, PSIS, ILC, thigh 4-marker cluster, knee, medial knee, shank 4-marker cluster, ankle, medial ankle, heel, toe, and 5th metatarsal head. Two additional markers were place on the clavicle and sternal notch to define upper body positioning. Once the markers were in place, static and range of motion trials were captured by the VICON motion capture system (VICON, Los Angeles, CA, USA). The trials were checked for accuracy and to confirm marker visibility. At this time, the subject warmed up on the custom built AMTI End-to-End Force Instrumented Treadmill (AMTI, Inc., Watertown, MA, USA) at a self-selected pace for seven to ten minutes. Following the warm up period the subject was given as much time as needed for any self-directed stretching and final preparations they may have had. The research team then checked the marker attachments and adjustments were made if necessary. When the subject indicated that they were ready to begin the exhaustive run, the HR monitor was started and the subject was instructed to stand on the sides of the treadmill belt. The treadmill was started and allowed to reach 3 kph. It was at this speed that the treadmill's indwelling force plates were zeroed. After they were zeroed, the subject was instructed to step on the treadmill and it was accelerated to the subject's race pace determined by their 5k time (100% of 5k race pace). When the treadmill reached its final speed, the trial time started. Data were captured starting after the third minute had elapsed and every three minutes after that until the subject indicated that they were ready to stop. At each collection point two seven second trials were recorded. Thirty second before each data collection time point, one of the research team showed the subject a RPE chart and asked them what their RPE score was. The RPE scale used was the Borg 6-20 scale (See Appendix A). It is a numerically based scale of 6-20 where 6 is a 20% effort and 20 is exhaustion. The subject either indicated their score on the chart or verbally to the researcher. At the time when the subject indicated they were ready to stop, they either stepped to the sides of the treadmill, flagged the researcher to stop/slow the treadmill speed, or hit the emergency stop button on the treadmill. At this point the trial time stopped. The HR monitor was stopped as soon as possible after each trial was over by the researcher. Each subject was given the opportunity to recover by walking around the laboratory or on the treadmill at their own pace as long as was needed. Water and a towel were also provided to each subject for comfort following the end of the trial. After the subject was sufficiently recovered, markers and clusters were removed from the subject and they were free to change out of the experimental clothing and leave for the day.

The third testing session was exactly the same as the second with the following two exceptions 1) anthropomorphic measures were not repeated and 2) the opposite clothing condition was worn (i.e., if the subject wore compression tights for the second testing session, then they wore shorts for the third testing session). Subjects were given the clothing to wear for the trial when they arrived to the laboratory that day. They wore the same shoes for both the second and third testing sessions.

DATA ACQUISITION

Subject anthropomorphic measurements taken at the second testing session were as follows 1) height, 2) weight, 3) inter-ASIS distance, 4) left/right leg length (measured from ASIS to medial malleolus), 5) left/right knee width, and 6) left/right ankle width.

A VICON 14 camera MX-40 system captured bilateral kinematics at 120 Hz. The cluster-based marker set using retro-reflective markers was configured as follows for each left and right sides: shoulder marker, ASIS 2-marker clusters, PSIS, ILC, thigh 4-marker cluster, knee, medial knee, shank 4-marker cluster, ankle, medial ankle, heel, toe, and 5th metatarsal head. Two additional markers were place on the clavicle and sternal notch to define upper body positioning. Once the subject was prepared with all markers in place, a static calibration trial was completed. The trials were checked for marker visibility and were repeated until all markers were visible for the trial. At which time the medial markers and the ILC markers were taken off the subject as they were used for the static calibration trials only. Next, each subject preformed ROM trials for each hip and knee. For the hip ROM trial, each subject was captured moving their leg in a five point star pattern including a circumduction movement at the end. The knee and ankle were kept stiff so that movement only occurred at the hip joint. This was repeated on each side and checked for marker visibility before moving on to the knee ROM trials. For the knee

ROM, the subject was captured flexing and extending their knee about 10-15 degrees five times with the only movement occurring about the knee joint.

The force instrumented treadmill collected both forces and moments in the x, y, and z directions at 2400 Hz. The treadmill was brought up to 3 kph and the force plates were zeroed. Once the subject stepped on the belts of the treadmill, it was accelerated at a rate of 0.5 kph/s until the subject's running pace was reached. At that point, the subject's official trail time started. Trials were seven seconds in length and two trials were collected every three minutes during the trial using VICON Workstation (VICON, Los Angeles, CA, USA).

Heart rates were collected continuously throughout the trial at 5 second intervals by the HR monitor. After the trial was complete HR data were uploaded to a computer using Polar ProTrainer 5 software (Polar Electro Oy, Kempele, Finland).

DATA PROCESSING

Data were collected every three minutes during each trial in sessions two and three for two trials of seven seconds at each collection point. Data collected at the first time point was used as the baseline, while data collected at the last time check before the subject stopped running was used as the final data set. The mid-point data was determined to be the middle data set, or in the case of two mid-point sets, the latter set was used. The first of the trials was used unless there were not enough data points, then the second trial was used to complete the data set.

Heart rate data was graphed in the Polar Protrainer 5 software to find the endpoint of the run. This time point (“polar time”) was determined to be when the graph had a sharp decline at the end of the collection period since the watch was not stopped directly at the end of the trial. The actual trial time was compared to the polar time and used to find the collection points to determine the subject’s HR. Using the chart tool in the software, the data points were recorded in each subject’s file.

VICON Workstation was used for initial processing of the data. Each trial was labeled (3% max. deviation, 50 fields min. overlap), cropped, gaps filled (restricted to 10 samples), and filtered using the Woltring filtering routine (predicted MSE 20).

Trials were then imported to Visual 3D (C-Motion, Germantown, MD, USA) for further processing and analysis. First a lower body model was built and joint centers were calculated from the ROM trials of the hip and knee. This model was applied to all the running trials. The force plate data were filtered using a second order Butterworth filter (cutoff frequency 40 Hz, 10 samples reflected). Then each trial was opened and the force plate data was zeroed manually. A kinetic recalculation pipeline was run for calculations including joint angles, powers and moments. The automatic gait events pipeline was also run to detect foot strike events. This was checked to ensure proper placement of events. A report of temporal and distance metrics was generated to calculated additional variables of interest including stride length and stride rate.

STATISTICAL ANALYSIS

Variables of interest were: knee angle at initial contact, maximum during loading response, maximum during swing, and at toe-off; ankle angle at initial contact and maximum dorsiflexion; hip angle at initial contact; impact peak, active peak and loading rate of the vertical ground reaction force; heart rate; rate of perceived exertion; range of motion at the hip, knee and ankle; stride length and stride rate; and time of exhaustive run. Data for joint angles and vertical ground reaction forces were averaged over at least five strides. Statistical analyses were preformed in SPSS 19.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were generated for age, height, weight, 5 k time trial time, and speed of exhaustive run. Time to exhaustion was compared between conditions using a paired t-test. Multiple 2x3 repeated measures (condition by time) ANOVA were used to analyze the rest of the variables collected including joint angles, stride length and rate, rate of perceived exertion, heart rate, and impact peak, active peak and loading rate of the vertical ground reaction force. No adjustments were used and there were planned pairwise comparisons between time point data when significance was found. Statistical significance was set at $p<0.05$.

CHAPTER 4

RESEARCH ARTICLE

The following article will be submitted to Sports Biomechanics for review.

BIOMECHANICAL ADJUSTMENTS DURING AN EXHAUSTIVE RUN: COMPARISON OF COMPRESSION TIGHTS AND RUNNING SHORTS

Original Research

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ABSTRACT

Fatigue induces changes to running form resulting in a movement that is not as effective or efficient. Reducing the amount of fatigue or its effects on form would be ideal to improve running performance. Compressive clothing has unknown effects on musculature, however it claims to reduce fatigue. The aim of this study was to determine whether compressive tights would be beneficial to wear compared to running shorts for improving performance while running to exhaustion. Eleven runners ran at their current five-kilometer race pace on a treadmill to voluntary exhaustion in a repeated measures design wearing compression tights and running shorts while their kinematics, kinetics, heart rate and rate of perceived exhaustion were recorded. There was not a significant difference in time to exhaustion between conditions (p=0.88). Fatigue effects showed a less extended knee angle (p=0.03) and a lower ankle dorsiflexion angle (p=0.04) at initial contact. Vertical ground reaction loading rate (p=0.02) and impact peak (p=0.05) increased with fatigue. Condition effects demonstrated a shorter stride length (p=0.01), a faster stride rate (p=0.01), and less hip range of motion (p=0.02) in compression tights. The altered mechanics have an effect on the potential for injury.

INTRODUCTION

Athletes of all ages and sports want to maximize their performance while reducing their effort and chance of injury. When running to exhaustion, fatigue induces changes in running form, resulting in movements that are not as effective or efficient as before fatigue. Changes due to fatigue include changes to temporal parameters (i.e., stride length and rate), kinematics (i.e., joint angles) and kinetics (i.e., ground reaction forces).

Most commonly stride length has been shown to increase with a corresponding decrease in stride rate when a runner is fatigued (Candau et al., 1998; Gazeau, Koralsztein, & Billat, 1997; Gerlach et al., 2003; Mizrahi, Verbitsky, Isakov, & Daily, 2000; Siler & Martin, 1991; Verbitsky, Mizrahi, Voloshin, Treiger, & Isakov, 1998; Williams, Snow, & Agruss, 1991). Joint angles studied have included the hip, knee and ankle at initial contact, toe-off and during the loading response of body weight to determine the positioning of a person when they are fatigued. This positioning alters the runner's effectiveness as well as increasing the potential for injury (Dutto & Smith, 2002; Milner, Ferber, Pollard, Hamill, & Davis, 2006; Milner, Hamill, & Davis, 2007; Verbitsky, et al., 1998). A few studies reported no change in kinematics (Abt et al., 2011; Collins et al., 2000; Hayes, Bowen, & Davies, 2004); however, more studies have shown changes with fatigue (Candau, et al., 1998; Derrick, Dereu, & McLean, 2002; Elliot & Ackland, 1981; Elliott & Roberts, 1980; Gazeau, et al., 1997; Gerlach et al., 2005; Hanley & Mohan, 2006; Kyrolainen et al., 2000; Mizrahi, et al., 2000; Nummela et al., 2008; Nummela et al., 2006; Siler & Martin, 1991; Verbitsky, et al., 1998; Williams, et al., 1991; Willson & Kernozek, 1999). Kinetics changes in running when fatigued are studied along with risk of injury as tibial stress fractures are a common running overuse injury (Hreljac, Marshall, & Hume, 2000; Milner, et al., 2006; Milner, et al., 2007). Humans are less capable of handling shock when muscles are significantly fatigued and this contributes to injury risk factors (Verbitsky, et al., 1998). Vertical ground reaction force has three components that are mainly studied: impact peak, active peak and impact loading rate. Impact peak and the active peak have been shown to significantly decrease (Christina, White, & Gilchrist, 2001; Gerlach, et al., 2005; Hanley & Mohan, 2006) or maintain (Dutto & Smith, 2002) with fatigue while loading rate either increases (Christina, et al., 2001; Dutto & Smith, 1999) or decreases (Gerlach, et al., 2005).

The use of compression stockings has demonstrated physiological benefits when running to exhaustion including a reduction in oxygen consumption, less post exercise soreness, increased time under load, increased total work and an increase in velocity (Ali, Caine, & Snow, 2007; Bringard, Perrey, & Belluye, 2006; Kemmler et al., 2009). These benefits have not definitively improved performance as measured in all subjects. Compressive garments, specifically tights, are reported to reduce fatigue while increasing performance ("Gear Technology,"); however, it is not specified how they accomplish this, whether it is through physiological or biomechanical, or both, means. It remains to be studied whether they help with running biomechanics when running to exhaustion or in fatiguing conditions.

The present study is twofold in purpose, combining the known effects of fatigue biomechanically with the unknown effects of compression tights while running. The first purpose is to demonstrate that there are changes in form with fatigue. The second purpose is to see how these changes may be affected by using compression tights. No other study known has studied these two effects in this way. The hypotheses are that there would be an effect of fatigue on running biomechanics similar to literature and that the compression tights would alter these effects or changes that are brought about by fatigue.

METHODS

Subjects

Thirteen subjects were recruited from the university and the surrounding cities. Two subjects dropped out during the study citing injuries sustained separate from the study as the cause. Subjects who were between the ages of 18 and 40, ran at least three times a week and fifteen miles a week, could race a 5k at maximal intensity between 17:00 and 23:00 minutes, and were in good cardiovascular health without a history of musculoskeletal injury in the past three months nor any previously diagnosed neurological or orthopedic disorders presenting an abnormal movement pattern were able to participate in the study. Subject characteristics are shown in Table 1.

Protocol

Subjects were required to make three visits to the laboratory for this study. The first visit started by each subject reading and signing an informed consent document, and agreeing with the procedures and practices that the study entailed in accordance with the university approved IRB. They also filled out a brief health history and running history questionnaire to ensure that they were qualified for the study. After the paperwork was completed, subjects were given as much time as they needed to warm up and prepare for a maximal intensity 5 k time trial on the 200 m indoor track. Once the subject was ready they gave the investigator notice and they proceeded with the time trial. Cumulative time was recorded to later calculate their race pace. Each lap time was also recorded to ensure proper counting of the laps and feedback was given to each subject such as mile split times and a countdown of the laps remaining in the run.

Subjects reported to the laboratory for their second session five to ten days after the first. Each subject was informed of their randomized-controlled condition once they reported to the laboratory for their second test session. The condition order was randomized so that there were approximately equal numbers of each condition-order pair. Their height and weight were taken to determine the proper size for the compression tights as well as other measurements needed for computer analysis: leg length, inter ASIS distance, ankle and knee widths. At this time the subject changed into proper attire (running shorts or compression tights) and was prepared for testing. This included putting on a heart rate monitor (RS400sd, Polar Electro Oy, Kempele, Finland) and retro-reflective markers for use with the 14 camera motion capture system (VICON, Los Angeles, CA, USA). Markers were placed on each subject in a custom cluster based set. The cluster-based marker set using retro-reflective markers is configured as follows for each left and right sides: shoulder marker, ASIS 2-marker clusters, PSIS, ILC, thigh 4-marker cluster, knee, medial knee, shank 4-marker cluster, ankle, medial ankle, heel, toe, and 5th metatarsal head. Two additional markers were place on the clavicle and sternal notch to define upper body positioning. Calibration trials for use in processing the data were completed at this time. The subject then completed a 7-10 minute warm up on the treadmill at a self-selected pace. After the warm up period subjects were given as much time as needed for final preparations including self directed stretching and checks of marker placement and security.

The Force Instrumented End-to-End Treadmill (AMTI, Inc., Watertown, MA, USA) was started at 3 kph and zeroed with the subject standing off to the sides of the belt. Once it was zeroed, the subject was instructed to step on the front belt and the speed was increased to the test velocity. The set velocity for each subject was their 5 k race pace from the first session of the study. The trial time started when the test velocity was reached and ended when the subject could not keep pace with the treadmill and stopped running by pressing the emergency stop button, stepped off the belt of the treadmill, or signaled to the researchers that they were done and to slow the treadmill. Heart rate was collected continuously throughout the run automatically by the HR monitor at 5 s intervals and RPE was asked of the subject every three minutes. Additionally, marker position (collected at 120 Hz) and forces (collected at 2400 Hz) were captured every three minutes for two-seven second trials during the run. Only the first collection period at 3 minutes, the individual's middle collection period and last collection period before the subject stopped the test were analyzed. The first of the two trials at each period was used unless there were insufficient data points, and then the second trial was also used.

The third session was exactly the same as the second except that the opposite clothing condition was tested (running shorts or compression tights) and took place five to seven days after the second session. Each subject wore the same pair of their own running shoes for the trials.

Data Analysis

Each trial was initially processed in VICON Workstation using the Woltring filtering routine for kinematic data with a predicted MSE of 20. Labeled, filtered and cropped trials were imported to Visual 3D (C-Motion, Germantown, MD, USA) for further processing of the kinetics and kinematics. A lower body model was built using functional joints and range of motion calibration trials. This model was applied to all the motion trials. The ground reaction force data was filtered using a second order Butterworth filter (cutoff frequency of 40 Hz). Joint angles were calculated from the model and a gait events pipeline was run using the corrected kinetic data. A report of temporal and distance metrics was generated to calculate stride length and rate.

Statistical Analysis

Variables of interest were: knee angle at initial contact, maximum knee angle during loading response, swing, and at toe-off; ankle angle at initial contact and maximum dorsiflexion; hip angle at initial contact; impact peak, active peak and loading rate of the vertical ground reaction force; heart rate; rate of perceived exertion; range of motion at the hip, knee and ankle; stride length and stride rate; and time of exhaustive run. Data for joint angles and vertical ground reaction forces were averaged over at least 5 strides. Statistical analyses were preformed in SPSS 19.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were generated for age, height, weight, 5 k time trial time, and speed of exhaustive run. Time to exhaustion was compared between conditions using a paired t-test. Multiple 2x3 repeated measures (condition by time) ANOVAs were used to analyze the rest of the variables collected including joint angles, stride length and rate, rate of perceived exertion, heart rate, and impact peak, active peak and loading rate of the vertical ground reaction force. No adjustments were used and there were planned comparisons between time point data. Statistical significance was set at $p<0.05$ and when significance was found between time points, pairwise comparisons were used to distinguish when the significance occurred. Results are presented mean (standard deviation) in the results section.

RESULTS

There was not a significant difference ($t(10)=0.15$, $p<0.88$) for time to exhaustion between conditions as the average time in compression tights was 1055.4 (298.4) seconds and shorts 1043.5 (236.0) seconds.

The physiological measures of heart rate and rate of perceived exertion had significant increases during the exhaustive run ($F_{(1.15, 6.91)}= 106.6$, $p<0.001$, $\eta^2=0.95$) and ($F_{(1.96, 19.56)}= 99.81$, $p<0.001$, $\eta^2=0.91$) for heart rate and rate of perceived exertion, respectively. Follow-up pairwise contrasts revealed significant differences at all three time points. The average heart rate was 172 (8), 184 (6), 188 (7) bpm for tights at the start, mid and end time points, respectively and 171 (8), 184 (7), 188 (7) bpm for shorts at the start, mid and end time points, respectively. Average rate of perceived exertion scores were as follows for tights and shorts at the start, mid and end points respectively: 13 (1), 16 (2), 19 (1) and 13 (2), 16 (2), 18 (1).

Temporal and spatial characteristics of the stride were significantly different between the two conditions. Stride length was measured and showed that compression tights condition had a shorter stride length than running shorts ($F_{(1, 10)}= 12.82$, $p=0.01$,

$\eta^2=0.56$). Tights had an average length of 2.91 (0.28) m and shorts had a length of 2.95 (0.29) m. The cadence or stride rate was also measured and showed that tights had a faster rate than shorts ($F_{(1,10)}= 11.11$, $p=0.01$, $\eta^2=0.53$). Tights had an average rate of 85.5 (4.1) rpm and shorts had an average of 84.3 (4.6) rpm.

Kinematics measures of joint differences are found in Table 2. The only significant differences were demonstrated in an increased knee angle ($F_{(2, 20)}= 4.34$, $p=0.03$, $\eta^2=0.3$) and decreased ankle angle ($F_{(1.16, 10.43)}= 5.6$, $p=0.04$, $\eta^2=0.38$) at initial contact. These differences were between the start of the exhaustive run and the end of the run. There were not any other significant differences between conditions for joint angles. Overall active range of motion of the lower extremity joints demonstrated significant differences between conditions only at the hip joint ($F_{(1, 10)}= 7.21$, $p=0.02$, $\eta^2=0.42$). The total range of motion was 69.0 (6.3) degrees for compression tights and 70.7 (6.8) degrees for shorts.

There was a significant increases in the impact peak ($F_{(1.36, 12.23)}= 4.24$, $p=0.05$, $\eta^2=0.32$) and loading rate ($F_{(2, 20)}= 4.64$, $p=0.02$, $\eta^2=0.32$) between the start and mid points and the start and end points of the run. There were no significant differences for the active peak of the ground reaction force. The results can be found in Table 3.

DISCUSSION AND IMPLICATIONS

This study was the first of its kind to combine the biomechanical effects of fatigue with the use of compression tights. Overall there was not a direct performance benefit to wearing compression tights as studied in this research as there was no significant difference between the two conditions in time to exhaustion.

Physiological results, heart rate and rate of perceived exertion, increased as expected with fatigue. There were not significant differences between conditions as was shown in other studies and it shows that subjects perceived to give the same effort while running in both conditions (Ali, et al., 2007; Ali, Creasy, & Edge, 2010; Bringard, et al., 2006; Kemmler, et al., 2009). RPE is repeatable between testing days (Doherty, Smith, Hughes, & Collins, 2001) and indicates that the two test conditions were not significantly different than each other and that subjects worked at the same percentage of their maximum capacity in each test.

Temporal and spatial results of stride length and rate did not change with fatigue, but were different between conditions of shorts and compression tights. While wearing compression tights, runners had a shorter stride length and a corresponding increased stride rate compared to wearing shorts. This indirect relationship exists because subjects were running on a treadmill where they are not allowed to slow down. To achieve the same speed in both conditions with a different stride length, stride rate must also be altered. One possible reason for this difference could be that the compression tights are restrictive and do not allow for a complete range of motion. A reduction in stride length is not bad; however, as a study and simulation by Edwards et al. showed that reducing stride length decreases the probability of stress fracture in the distal tibia by 3-6% (Edwards, Taylor, Rudolphi, Gillette, & Derrick, 2009). Edwards et al. also saw that the number of loading cycles was not as important as the magnitude of the shock delivered to the bone meaning that a reduction in stride length will decrease chances of stress fracture even with weekly mileage as high as 49 miles a week (Edwards, et al., 2009). In the current study there is an increased number of loading cycles as the stride rate increased;

however, as seen by Edwards et al., it will not increase the chances of developing a stress fracture as much as an increased load from overstriding. As noted by Verbitsky et al., a decreased stride rate increases the amplitude of the shock wave from impact (Verbitsky, et al., 1998). This combined with the musculoskeleton’s decreased ability of handling shock when fatigued (Verbitsky, et al., 1998) could lead to increased risk of injury.

Knee angle at initial contact increased to become less extended at the last stage of the run compared to the beginning. This finding agrees with other studies demonstrating a significant affect of fatigue (Derrick, et al., 2002; Elliott & Roberts, 1980; Gazeau, et al., 1997). The initial contact angle changed to be more flexed and the angle during loading did not change leading to a stiffer leg at impact. Two separate studies compared runners with a history of stress fracture to a control group free from injury and found that the group with previous stress fractures had higher knee stiffness during loading of the leg (Milner, et al., 2006; Milner, et al., 2007). Ankle angle at initial contact decreased to a less dorsiflexed position at the last stage of the run compared to the beginning. This result has not been studied in the past as much as other variables. One study by Christina et al. selectively fatigued the dorsiflexors in an isokinetic setting and found that after fatigue, dorsiflexion at initial contact decreased by 3.2 degrees (Christina, et al., 2001). This agrees with our result; however, the change in our study was not as severe as the study by Christina et al. indicating there was not as much fatigue in the dorsiflexors (Christina, et al., 2001).

The decrease in hip range of motion while wearing compression tights may indicate that there was some restriction at the hip from wearing the compression tights. This possible restriction at the hip could be responsible for the decrease stride length while wearing the compression tights. Since there are no other factors that changed as a result of the condition, it is likely that the hip joint is where the decreased stride length originated.

Peak loading rate increased significantly with fatigue form the beginning to the middle and the beginning to the end of the fatiguing run. An increased loading rate has been shown to occur in groups with tibial stress fractures or other lower leg injuries (Hreljac, et al., 2000; Milner, et al., 2006). This combined with a stiffer knee during the loading phase, which was seen in this study as the knee became more flexed at initial contact and remained the same throughout load acceptance, is one difference between a group of runners with a history of tibial stress fractures and a control group (Milner, et al., 2007). Increased impact force with fatigue, demonstrated from beginning to middle and beginning to end of the exhaustive run also compiles to the increase in loading rate to increase the risk of tibial stress fracture (Hreljac, et al., 2000). This result of an increased loading rate and impact force indicates a stiffer leg at impact and was seen in another study of healthy individuals (Dutto & Smith, 1999). This trend was also noticed in between a group of runners with a history of tibial stress fractures and a control (Milner, et al., 2006), and was significant in runners with a history of lower leg injury compared to a control group (Hreljac, et al., 2000).

This study is not meant to be the definitive word on compression tights and running performance, only a base for future studies. Those studies could focus their research on longitudinal training effects of wearing compression tights as their effects appear to be influential in preventing tibial stress fractures. Other areas of research that could further be explored is longer distance races such as fatigue during marathon running or faster running in sprint races.

CONCLUSIONS

As a base for future research, the present study gives an indicator that there is a possibility for improvements in running technique when fatigued wearing compression tights. Time was not significantly different between conditions indicating at the basic level there are no performance improvements of wearing compression tights in a 5 k race. Changes in heart rate and rate of perceived exertion, knee and ankle angle, and impact peak and loading rate of the vertical ground reaction force were significant for fatigue effects regardless of clothing condition. There were significant differences between conditions for stride rate and length and hip range of motion. Compression tights did not seem to outright help runners, however a more in depth study may demonstrate potential for reducing injuries when wearing compression tights. This reduction comes from a protective mechanism of a reduced stride length that helps in reducing the impact peak and loading rate of the shock when landing. This shock over time has the potential to cause stress fractures of the lower leg and compression tights may help to reduce this shock.

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Table 1. Subject Characteristics (mean (SD); N=11)

Age (years)	22.5	(3.3)
Height (m)	1.78	(0.07)
Weight (kg)	71.1	(8.8)
Gender (M/F)	9/2	
Leg Dominance (R/L)	9/2	
5,000 m Race Time (s)	1215	(91)
Exhaustive Run Pace (m/s)	4.1	(0.3)

Table 2. Average Joint Angles in Degrees During the Exhaustive Run (mean (SD); N=11)

Joint	Gait Phase	Condition	Start	Mid	End
Hip					
	At Initial Contact				
		Tights	41.7 (6.0)	41.4 (6.9)	41.7 (7.4)
		Shorts	41.1 (5.0)	40.8 (5.3)	41.1 (5.6)
Knee					
	At Initial Contact				
		Tights	13.7 (3.3)	14.2 (4.2)	14.6 (4.1)*
		Shorts	13.5 (4.9)	14.2 (3.6)	14.8 (3.8)*
	Max. During Stance				
		Tights	41.1 (5.8)	41.3 (5.3)	41.8 (5.2)
		Shorts	40.5 (4.3)	40.7 (4.6)	40.2 (4.5)
	At Toe-Off				
		Tights	10.8 (4.4)	11.0 (4.0)	11.4 (3.5)
		Shorts	11.2 (3.8)	11.1 (3.8)	10.7 (4.5)
	Max. During Swing				
		Tights	115.2 (10.4)	114.6 (9.4)	114.2 (8.9)
		Shorts	114.8 (10.1)	115.1 (9.4)	115.4 (8.6)
Ankle					
	At Initial Contact				
		Tights	6.0 (5.9)	4.4 (5.9)	4.7 (5.4)*
		Shorts	6.7 (4.2)	5.2 (3.6)	4.4 (4.3)*
	Max. Dorsiflexion				
		Tights	27.9 (3.0)	25.8 (3.8)	26.4 (3.3)
		Shorts	26.3 (2.2)	26.1 (1.7)	25.3 (1.9)

*Significant difference between start and end point ($p<0.05$)

Table 3. Characteristics of the Vertical Ground Reaction Force (mean (SD); N=11)

vGRF Component	Condition	Start	Mid	End
Impact Peak	Tights	1.99 (0.18)	2.06 (0.24)*	2.07 (0.30)*
(BW)	Shorts	1.97 (0.27)	2.00 (0.28)*	2.09 (0.24)*
Active Peak	Tights	2.71 (0.23)	2.72 (0.24)	2.71 (0.23)
(BW)	Shorts	2.71 (0.21)	2.71 (0.23)	2.72 (0.22)
Peak Loading Rate	Tights	115.2 (28.7)	122.8 (28.6)*	119.3 (32.1)*
(BW/s)	Shorts	110.5 (25.8)	115.0 (29.2)*	118.5 (32.0)*

*Significant difference between start and mid point, start and end point ($p<0.05$)
vGRF: vertical ground reaction force

CHAPTER 5

SUMMARY AND CONCLUSIONS

SUMMARY

Fatigue has a role in the performance of runners towards the end of a run. Physiological factors of heart rate and rate of perceived exertion were found to increase with fatigue at all time points during the run. Knee and ankle angles at initial contact also changed with fatigue to become more flexed at the knee and less dorsiflexed at the ankle from the beginning to the middle and beginning to the end of a fatiguing run. Also changing with fatigue from the exhaustive run was an increasing loading rate of the vertical ground reaction force and an increasing impact peak. The differences between conditions of compression tights and loose running shorts was in a decreased stride length with the tights, an increased stride rate with the compression tights and a decreased range of motion at the hip joint with the compression tights.

CONCLUSIONS

This study was the first of its kind to combine the biomechanical effects of fatigue with the use of compression tights. Overall there was not a direct performance benefit to wearing compression tights as studied in this research as there was no significant time to exhaustion difference between the two conditions of compression tights and loose running shorts.

Physiological results, heart rate and rate of perceived exertion, increased as expected with fatigue; however, there were not significant differences between conditions. This is in agreement with previous studies as they did not show differences in HR or RPE between conditions (Ali, et al., 2007; Ali, et al., 2010; Bringard, et al., 2006; Kemmler, et al., 2009). Subjects perceived that they gave the same effort during both testing sessions and heart rate showed that they in fact did.

Temporal and spatial results of stride length and rate did not change with fatigue, but were different between conditions of shorts and compression tights. While wearing compression tights, runners had a shorter stride length and a corresponding increased stride rate compared to wearing running shorts. This result leads to injury prevention as overstriding and even a “preferred” stride length can lead to stress fracture (Edwards, et al., 2009).

Knee angle at initial contact increased to become less extended at the last stage of the run compared to the beginning. This change in loading response leads to a stiffer knee at impact and during loading. Stiffer legs are more at risk for developing a stress fracture (Milner, et al., 2006; Milner, et al., 2007). Ankle angle at initial contact decreased to a less dorsiflexed position at the last stage of the run compared to the beginning. This result has been shown with selected fatigue of the ankle dorsiflexors and has been postulated to indicate a shift to a more midfoot striking pattern instead of a heel to toe pattern (Christina, et al., 2001). A midfoot pattern changes the vertical ground reaction force curve and will also change the impact forces that a runner generates. The decreased hip range of motion, while wearing the compression tights, is most likely the mechanism behind the reduction in stride length. The compression tights may be constricting; however, the reduction in stride length could be a positive change as it can aid in the prevention of injury (Edwards, et al., 2009).

Peak loading rate increased significantly with fatigue from the beginning to the middle and the beginning to the end of the fatiguing run. An increased loading rate has been shown to occur in groups with tibial stress fractures or other lower leg injuries (Hreljac, et al., 2000; Milner, et al., 2006). This combined with a stiffer knee during the loading phase, which was seen in this study as the knee became more flexed at initial contact and remained the same throughout load acceptance, is one difference between a group of runners with a history of tibial stress fractures and a control group (Milner, et al., 2007). Significantly higher impact peak at the middle and end of the exhaustive run compared to the beginning was also observed in this study. This trend was also noticed in between a group of runners with a history of tibial stress fractures and a control

(Milner, et al., 2006), and was significant in runners with a history of lower leg injury against a group of controls (Hreljac, et al., 2000).

This study is not meant to be the definitive word on compression tights; it serves as a base for future studies. It appears that compression tights may aid in the reduction of injury as the decreased stride rate indicates. It may be the case that this particular fatiguing protocol was not extensive enough to show greater effects of fatigue on runners near exhaustion. When these effects are extrapolated over a longer period of time; however, such as during a marathon or daily training, compression tights may reduce the chance of stress fractures.

RECOMMENDATIONS FOR FUTURE RESEARCH

As a base for future research, the present study gives an indicator that there is a possibility for improvements in running technique when fatigued and when wearing compression tights. Future studies could focus on longitudinal training effects of wearing compression tights as the results from this study could be extended to a longer time frame and these results may indicate a reduced risk of acquiring a lower extremity stress fracture. The effects of marathon fatigue could also be a future direction as the miles of repeated stress in a relatively short period of time also aids in stress fracture production. A more homogenous and defined subject pool, as far as the race distance and level of competitiveness, would give more consistent results and allow for a more specific application of the results. For example, comparing the results of an elite runner running a marathon in nearly 2 hours as opposed to a recreational runner running it in 5 hours places different needs on each of the runners mechanically and this would change the aim of the compression tights.

CHAPTER 6

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APPENDIX A

Borg 6-20 RPE Scale

- 6 – 20% effort
- 7 – 30% effort – Very, very light (Rest)
- 8 – 40% effort
- 9 – 50% effort – Very light – gentle walking
- 10 – 55% effort
- 11 – 60% effort – Fairly light
- 12 – 65% effort
- 13 – 70% effort – Somewhat hard – steady pace
- 14 – 75% effort
- 15 – 80% effort – Hard
- 16 – 85% effort
- 17 – 90% effort – Very hard
- 18 – 95% effort
- 19 – 100% effort – Very, very hard
- 20 – Exhaustion