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thesis entitled

IMPACT ACCELERATIONS IN
FEMALE RECREATIONAL RUNNERS

presented by

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has been accepted towards fulfillment
of the requirements for the

M.S. degree in Small Animal Clinical Sciences

Major Professor's Signature

8/18/08

Date

IMPACT FORCES IN FEMALE RECREATIONAL RUNNERS: TRACK VERSUS TREADMILL RUNNING

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillments of the requirements
for the degree of

MASTER OF SCIENCE

Small Animal Clinical Sciences

2008

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Female recreational runners are at a higher risk of injury than males. However, there are few studies that focus on female runners. The connection between impacts and injury makes studying impact accelerations valuable when looking at running. Many running studies are conducted on the treadmill, but few evaluate how these results compare to overground running, especially over longer distances. This research focuses on comparing impact accelerations during four-mile track and treadmill runs, both in the vertical and horizontal axes for the entire study population and by pace groups. Changes in impact accelerations over the course of the track and treadmill run were also examined, first by the overall study population and then by pace. By using a wireless accelerometer runners were monitored outside of a laboratory setting for the most natural runs possible. The results of the study showed that vertical impacts were not significantly different between the track and the treadmill, while horizontal impacts were significantly lower during the treadmill run. Vertical impacts also increased over time during both the track and treadmill run. Horizontal impacts increased over time with the track run, but did not change significantly over the treadmill run. These findings may have significant impact on the way future running studies are conducted, especially those trying to mimic a recreational run.

ACKNOWLEDGEMENTS

I would like to acknowledge and thank the many people that have helped me throughout the thesis process. First a huge thank you to my advisors, Drs. Steven Arnoczky and Niell Elvin for their help, advice and generous support. I appreciate all the time that you have both given me the last few years. Acknowledgments go to my committee members Drs. Hilary Clayton and Joe Hauptman, for their time and suggestions. Dr. Vilma Yuzbasiyan-Gurkan, director of the Comparative Medicine and Integrative Biology program, also deserves thanks for her help and willingness to take an engineer into the program. I would like to thank my laboratory mates Oscar Caballero, Keri Gardner, Dr. Michael Lavagnino, and Lance Visser for problem solving advice. Dr. Julie Dodds and Amy Worthing consulted during the planning phases of the study, for which I am grateful. Special thanks to Curt Munson, owner of Playmakers, for giving up his treadmill so often so we could get runners on it for the study.

One a more personal note, I would like to thank my parents, Alex and Debbie Robertson, for their overwhelming support throughout the years. My brothers, Ian and Hunter Robertson deserve thanks for their help, especially as guinea pigs. I would also like to acknowledge my boyfriend, Patrick Bigelow, who not only supported me going to graduate school, but also helped many times with data collection.

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I. INTRODUCTION

Running, once a means of fleeing predators, has in modern times gone from a competitive sport to a means of staying physically fit. There are over 12 million recreational runners in the United States alone that run at least 100 days out of every year (Running USA 2007). Of these recreational runners 48% are women (Running USA 2007). These female recreational runners are at a greater risk of injury compared to their male counterparts (Rauh et al 2000, van Gent et al 2007). Female runners are more likely to injure hips, shins and feet while running and are four times more likely to develop stress fractures (Rauh et al 2000, Zifchock et al 2006). However, even with the prevalence of female runners and the higher injury rates in this population, few studies look solely at female runners (Christina et al 2001, Gerlach et al 2005, Zifchock et al 2006).

It has been hypothesized that many injuries suffered by recreational runners are a result of the impact with which they contact the ground, with runners who develop a low impact method of running at a lower risk of injury than a runner who develops a high impact method of running (Hreljac et al 2000, Hreljac 2004). Runners with at least one previous running related injury have been shown to have higher impact magnitudes and loading rates when compared to injury-free runners (Hreljac et al 2000). The effect of these higher impacts can build up over time, as a recreational runner will experience more than 1.3 million impacts each year from running just twenty miles each week (Derrick et al 2002). In addition to causing initial injury, these continuous higher impacts can lead to reinjury. Runners with previous injury history have been shown to have a higher vertical impact, even on the uninjured side of their body (Milner et al 2006, Zifchock et al 2006).

Most of the aforementioned studies that compare high and low impact runners are done on short walkways or treadmills (Hreljac et al 2000, Milner et al 2006, Zifchock et al 2006). These studies are valuable because of the connection between impact levels and running injuries. However, studies done on walkways or treadmills may not accurately reflect running conditions in the field. Most runners do not run on short walkways or treadmills, with 69% preferring to do most workouts on roads (Taunton et al 2003). Runners will tell you that there is a great deal of difference when running overground compared to a treadmill, but there are few studies that have looked at the differences in accelerations between the two modes of running. Those studies that compare overground and treadmill running generally do so over short distances with solely male or a mixed gender population (Nelson et al 1972, Elliot and Blanksby 1976, Nigg et al 1995, Wank et al 1998). The purpose of this study was to look at female runners and determine if there are differences in peak impact accelerations when running on a track compared to a treadmill.

Peak impact accelerations were analyzed rather than peak impact forces because an accelerometer was used to collect data, rather than a force plate. The peak impact acceleration values will differ somewhat from the ground reaction forces that would be collected by a force plate because the acceleration values collected using a new wireless accelerometer are for the mass of the body segment that the accelerometer is placed on, rather than the whole body mass, as analyzed with the ground reaction forces. Using the peal impact accelerations allows comparison of runners outside of a laboratory setting by using the wireless accelerometer.

It is hypothesized that the peak vertical impact accelerations, those seen in the vertical plane while running, will be higher on the track than the treadmill. It is also believed that there will be no discernable difference between the track and treadmill when the peak horizontal accelerations, those generated in braking and push off, are analyzed. Furthermore, it is thought that the peak impact accelerations in both the vertical and horizontal axes will increase throughout the course of a run on both the track and the treadmill as runners start to tire, both physically and mentally.

To test these hypotheses female recreational runners were recruited to perform two runs, each four miles long. The first run was on an indoor track at a self-selected pace. The second run was performed on a treadmill, set to the average speed of the run performed on the indoor track to eliminate speed as a possible variable between the track and treadmill conditions. An accelerometer was attached to the runner to monitor peak impact accelerations in the vertical, horizontal and lateral axes. These data were downloaded onto a computer and analyzed using custom software to look at possible differences between the track and treadmill runs for all the runners. Peak impact accelerations in the vertical and horizontal axes were compared. The data were also examined to see if the peak vertical or horizontal accelerations changed with time over the course of the track run or over the run on the treadmill. Lastly, the runners were split into three pace groups, based on the average speed during the track run and the data was reanalyzed. Pace groups were tested to determine possible differences between track and treadmill peak acceleration impacts and any changes over the course of the runs in the peak acceleration impacts.

Hypotheses:

1. Peak vertical accelerations will be greater on the track than the treadmill, while peak horizontal accelerations will not be significantly different between track and treadmill.
2. Peak vertical and horizontal accelerations will increase through a run on the track.
3. Peak vertical and horizontal accelerations will increase with time on a treadmill.

Specific Aims:

1. Monitor female recreational runners, using an accelerometer, during a four mile run on a track and a treadmill.
2. Compare peak impact accelerations for the overall study population as well as by pace groups.

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II. LITERATURE SURVEY

Over the years running has evolved from a method to escape danger or chase down prey to a competitive speed/distance event to a recreational fitness sport. In 2006 there were between 38 and 40 million people in the United States that ran at least once during the year (Running USA 2007). Of these, approximately 12 to 15 million runners ran at least 100 days of the year (Running USA 2007). As with any physical activity, running can create the potential for injury. Published reports of injury rates in runners range from 20 to 70% depending upon the population of runners (Macera et al 1989, Hreljac 2004, Lun et al 2004, van Gent et al 2007). The definition of a running injury varies between studies, which could partially explain the wide range of injury rates, but most studies consider a musculoskeletal injury to be one that causes the runner to reduce mileage, stop training altogether, or consult a medical professional (Hoeberigs 1992, van Mechelen 1992, Koplan et al 1995, Duffey et al 2000, Taunton et al 2002). Running injuries are generally divided into two categories: acute injuries, caused by a sudden event, such as tripping or a fall, and overuse injuries. Overuse injuries are associated with repetitive activities and running, by its very nature, is a very repetitive sport. Of all the injuries sustained by runners, approximately 50 to 75% are caused by overuse (van Mechelen 1992). Running-related overuse injuries generally occur in the lower extremities and can include stress fractures, plantar fasciitis, Achilles tendonitis and shin splints (Hreljac et al. 2000). Approximately 70 to 75% of running related overuse injuries occur at or below the knee (Hreljac et al. 2000, Taunton et al 2002). Running-related injuries in the knee alone account for between 25 to 42% of all running injuries

(Macera et al 1989, van Mechelen 1992, Taunton et al 2002, Taunton et al 2003). Other high injury body segments include the foot (17-22% of all injuries), lower leg (13%), and Achilles tendon (6%) (Macera et al 1989, Taunton et al 2002). Almost all runners will experience some type of injury during a running career. These injuries are problematic for runners, whether male or female.

Female runners account for almost half of the population of runners, as approximately 48% percent of all runners in the United States in 2006 were female (Running USA 2007). While the numbers of female and male runners is almost equal, many running studies focus on populations that are entirely male, or are heavily skewed towards male subjects (Nelson et al 1972, Macera et al 1989, Hoeberigs 1992, van Mechelen 1992, Bus 2003, van Gent et al 2007). These studies can predict risk factors for male runners, but they do not have the power necessary to confirm or refute injury risk factors for female runners (Macera et al 1989, van Gent et al 2007). Very few studies have focused on a solely female running population (Christina et al 2001, Gerlach et al 2005, Zifchock et al 2006).

The type and occurrence of running-related injuries has been shown to differ depending on the gender of the runner. Female runners have significantly higher rates of running-related injuries (Rauh et al 2000, van Gent et al 2007). Female high school runners were significantly more likely to injure shins, hips and feet during running compared to males (Rauh et al 2000). Female runners are up to four times more likely than male counterparts to develop stress fractures related to running (Zifchock et al 2006).

Re-injury rates are also higher in female runners than in males (Rauh et al 2000). In addition to higher initial injury rates in female runners, the rates of re-injury were significantly higher for female runners in the knee, calf and feet compared with the same body sites in male runners (Rauh et al 2000). One study found that female runners with previous running-related injuries in one limb had higher peak shock values than uninjured controls, which could make them more likely to sustain future injuries in the previously injured leg (Zifchock et al 2006).

As overuse injuries are likely the combination of several factors, the higher rate of injury in female runners cannot be directly attributed to any one factor. There are several characteristics that put female runners at higher risk of injury than males. Previous injuries are thought to put a runner in a higher risk category for future running-related injuries with up to half of new injuries occurring at the same location as previous injuries (van Mechelen 1992, Taunton et al 2003, van Gent et al 2007). However, one study found that previous injury was not significantly associated with any certain type of injury (Taunton et al 2002). Running experience also has been shown to be a possible predictor of running injury, with less experienced runners at a higher risk for injury than those with greater experience (Macera et al 1989, van Mechelen 1992). Age is also a risk factor for running-related injuries in that older runners have less capability to absorb shock while running, which can lead to greater potential for overuse injuries, especially in the lower extremities (Bus 2003). Females over the age of 50 were found to be at higher risk for injury than younger female runners (Taunton et al 2003). One large prospective study of runners found that women were more likely to develop an injury when they completed two thirds of their running time on concrete surfaces (Macera et al 1989). Running pace was not significantly different between injured and non-injured control groups (Messier et al 1991). There was no association between running injuries and the level of the runner, whether beginner, recreational or elite (Taunton et al 2002). Female runners under the age of 31 were at less risk for injury (Taunton et al 2003). Stretching time is another significant indicator of injury, with one study finding that injured runners spent significantly more time stretching than uninjured runners (Duffey et al 2000). Mileage run per week is debated as a possible risk factor for injury. Several studies have shown that higher mileage per week was related to a higher incidence of injury (van Mechelen 1992). Others have found no significant difference in mileage between injured and non-injured runners (Lun et al 2004, Rauh et al 2005). Yet another study found that the control group ran approximately 31% more miles per week compared to the injured group of runners (Messier et al 1991).

Anatomical differences between men and women are thought to be the biggest reason why there are more injuries in female runners than males. While looking at females running, it was found that female runners had greater hip flexion in the sagittal plane than males (Ferber et al 2003). The same study found that female runners also had greater hip and knee abduction while running in both the sagittal and frontal planes, all while absorbing more of the impact force at the hip during the first half of each step when looking at the sagittal plane (Ferber et al 2003). The quadriceps angle, which estimates the force between the quadriceps muscle and patellar tendon, is larger in females than in males (Rauh et al 2005). This increase in quadriceps angle has been shown to be a significant risk factor for running-related overuse injuries, with runners with a quadriceps angle greater or equal to 20 degrees almost twice as likely to get injured as a runner with a quadriceps angle less than 20 degrees (Messier et al 1991, Rauh et al 2005). In contrast, another study did not find a connection with lower limb injuries in recreational runners when looking at static limb alignment (Lun et al 2004).

Impact Forces

Impact forces are the forces generated by the runner when the foot makes contact with the running surface. These impact forces reach a maximum, known as an impact peak, within 50 ms of the first contact with the ground (Nigg et al 1995). It is estimated that running twenty miles per week for a year will generate over 1.3 million impacts of the feet on the running surface (Derrick et al 2002). There are vertical impact forces, which measure the amount of forces in the vertical direction as the runner lands, horizontal impact forces, which measure the breaking force as the runner decelerates with every step and lateral impact forces, which measure the amount of force the runner is generating from side to side, or across the body as shown by Figure 2.1.

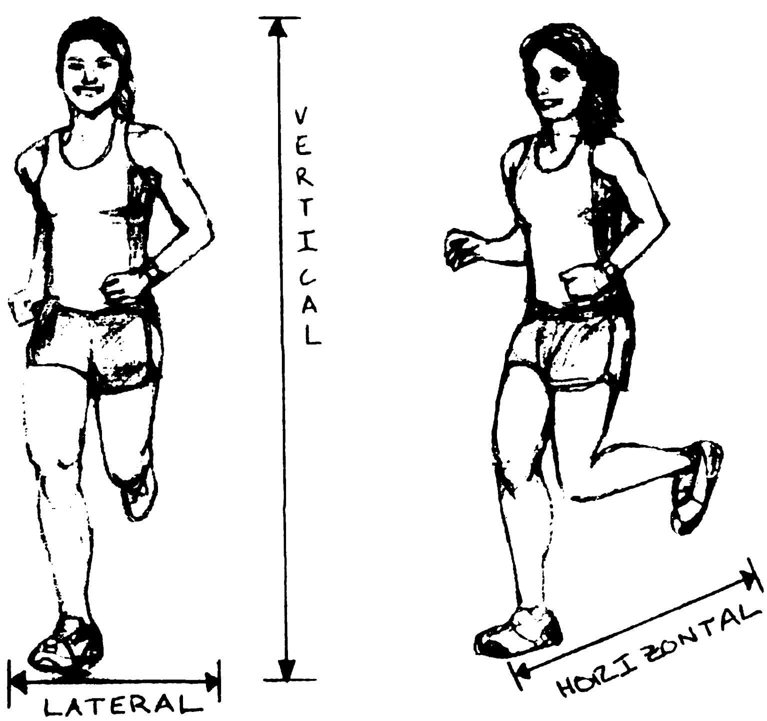

Figure 2.1. This diagram shows the three axes measured with respect to the runner.

Vertical impact forces associated with running are generally between 1 and 5 times the body weight of the runner (Wright et al 1998, Hreljac 2004).

Peak vertical impact force has been shown to be significantly greater in older runners compared to younger ones (Bus 2003). Runners with previous injuries in one leg have been shown to have higher vertical impact forces in the previously injured leg compared to the uninjured leg (Zifchock et al 2006). The peak braking forces were also shown to be significantly higher in the previously injured leg compared to the uninjured leg (Zifchock et al 2006). Regardless of which leg previously experienced a tibial stress fracture, runners with a history of tibial stress fracture demonstrated a higher vertical impact peak and a larger peak tibial shock when compared to runners without a history of tibial stress frature (Milner et al 2006). These stress fractures are fatigue fractures of the bone and are likely related to the loading rate of the bone (Milner et al 2006). There was no difference seen in the braking forces between the two groups (Milner et al 2006). Another study looked at braking forces and found that injured runners had lower braking forces when compared to non-injured runners (Messier et al 1991).

There are several studies that have looked at possible links between impact forces and injury (Hreljac et al 2000, Bennell et al 2004, Goldberg et al 2008). One study found that the magnitude and rate of impact loading were significantly greater in runners who had previously had at least one running-related overuse injury compared to runners without history of running overuse injuries, indicating that the higher impacts may be related to overuse injuries (Hreljac et al 2000). Studies have indicated that lower levels of impact reduce the risk of running-related overuse injuries (Hreljac et al 2000, Hreljac 2004). Conflicting reports also exist that did not find any significant difference in ground reaction forces between injured and non-injured runners or when looking at healthy walkers (Bennell et al 2004, Goldberg et al 2008).

Impact forces have also been shown to alter with fatigue. One study showed that peak vertical impact accelerations increased by 21% over the course of a run to fatigue (Derrick et al 2002). The same study found that shock attenuation also increased from the beginning to the completion of the fatiguing run (Derrick et al 2002). Another study found that peak vertical impacts decreased significantly with fatigue (Gerlach et al 2005). While both injured and non-injured runners had decreases in peak vertical impact forces, the peak vertical impact forces of injured running decreased at a much lesser rate (Gerlach et al 2005).

Running studies measuring fatigue are difficult to compare because there is no standard definition of what fatigue is during running. Some studies have subjects run initial tests at maximal effort, and base subsequent tests on the time of the initial run (Derrick et al 2002, Hunter and Smith 2007). Other studies fatigue specific muscles and compare runners at pre- and post-fatigue (Christina et al 2001, Flynn et al 2004). These studies can be difficult to compare because in addition to non-standardized definitions of fatigue, there are drastically different protocols to have the runner arrive at the fatigued state (Hunter and Smith 2007). Studies looking at the effect of local muscle fatigue on peak accelerations and shock attenuation contradict results from full body fatigue studies (Flynn et al 2004).

Studies looking at running fatigue have shown that there are kinematic changes over the course of the run. These changes include a more flexed knee angle at contact with the surface, and a greater maximum knee flexion angle, as well as more inversion of the subtalar joint in the foot at contact (Derrick et al 2002). When dorsiflexors are fatigued, the ankle angle at heel contact with the treadmill has been shown to be significantly less dorsiflexed, which was though to be a result of a decreased foot angle at heel strike rather than changes in the angle of the shank (Christina et al 2001). Studies have indicated that fatigued runners ran with shorter strides, but a faster stride rate so that the same velocity was maintained throughout the run (Willson and Kernozek 1999, Place et al 2004). Others have shown a decrease in stride rate in fatigued runners (Hunter and Smith 2007). There is also an increase in step variability with fatigue in runners (Candau et al 1998).

Monitoring individuals during running

Running studies are conducted in a variety of methods. While the goal is to test runners in a method that is as close to natural runing as possible, this is not always realistic because of the instrumentation needed to measure specific variables. One method of conducting running studies is to use a force platform that is embedded in the floor (Hreljac et al 2000, Bus 2003, Zifchock et al 2006, Milner et al 2006). The subject starts at the end of the runway, usually between 20 and 30-m long and runs over the entire runway, while data is collected when the subject runs over the force plate (Milner et al 2006). This way a subject is allowed to run unencumbered by instrumentation and can be filmed if desired. However, it is unclear whether these conditions accurately represent running conditions in the field.

Treadmill

Another commonly used tool for running studies are treadmills (Candau et al 1998, Derrick et al 2002, Gerlach et al 2005, Hunter and Smith 2007). Unlike force plates mounted in runways, treadmills have several advantages. They can be used in studies where the runner needs to be observed for more than just a few meters. Treadmills also allow researchers to vary the intensity of the running workout while still having the runner monitored closely (Nelson et al 1972). Treadmills instrumented with force plates allow the measurement of vertical and horizontal impact forces (Gerlach et al 2005). VO_2max calculations can also be collected when using treadmills because the runner is in one location and can be outfitted with the proper equipment (Gerlach et al 2005). While treadmills allow for longer running samples, there is some contention as to whether they accurately replicate the same movements as overground running, or running that is not constrained (Bennell et al 2004). As 69% of runners surveyed in one study run primarily on roads, it is important to confirm that the treadmill shows identical biomechanical conditions to overground running (Taunton et al 2003).

Few running studies have compared runners on the track or free running overground. Monitoring runners outside of the laboratory can be difficult because of the great variability in weather conditions and running surfaces. Further difficulties can occur depending on the variables the study is looking at. While a force plate in a laboratory setting is able to show the impact forces of a runner, it is unrealistic to place force plates in a full-sized track. Studies comparing treadmill use and overground running have shown that the stride length is shorter on the treadmill, while the rate of the stride increases to compensate for the shorter length, still allowing the runner to run the equivalent distance at the same pace (Elliot and Blanksby 1976, Wank et al 1998). Female runners had more pronounced changes in stride length than male runners, with a 10% reduction in stride length, compared to a 3% reduction in males (Elliot and Blanksby 1976). The 1976 study by Elliot and Blanksby also found an 11% increase in stride rate with female runners, compared to a 3% increase by male counterparts. The study also showed that the differences in stride rate and length were only present in velocities between 4.85-5.76 m/s for female runners, and that there were no significant differences for female runners between the overground and treadmill runs at velocities between 3.45-4.8 m/s (Elliot and Blanksby 1976). The movement of the foot on the treadmill also differs from movement overground, as the movement of the belt causes the foot to slip backwards slightly more during pushoff (Wank et al 1998). In a study looking at treadmill versus overground walking it was shown that, even though there were slight changes between the two including reduced peak braking, there was no significant difference in the total propulsion between the two surfaces (Goldberg et al 2008). It has also been shown that while running on a treadmill, a subject will adjust running style so that the lead foot reaches out further in front of the body and then uses the movement of the treadmill belt to bring the foot back into a normal position, which would lead to a decrease in speed if done overground (Nelson et al 1972). Differences in running style between overground and treadmill running have been seen even when the subjects are familiar with running on a treadmill (Nelson et al 1972, Elliot and Blanksby 1976, Wank et al 1998). One study found that runners landed with a different angle of foot flexion between treadmill and overground running (Nigg et al 1995). Another study by Milgrom et al. 2003 tested a treadmill run against free running on asphalt and found that treadmill runners were less likely to develop tibial stress fractures because of lower strain rates in the tibia compared to overground running. The authors believed that running on the treadmill is a more repetitive act than running over ground because the kinematics, pace, direction and stride length, are more controlled (Milgrom et al 2003).

The biggest limitation in running studies is the constrained condition in which many are performed. Studies try and control many variables, so that any results seen can be attributed to factors being studied and not outside factors, but this extra control can lead to factors that may not have previously been an issue. Other studies will have all the participants wear the same style of shoe to eliminate a possible variable (Derrick et al 2002, Milgrom et al 2003). Several studies recognize that runners perform most naturally in personal shoes, and so conduct tests with the runners in their own shoes (Duffey et al 2000, Hreljac et al 2000, Gerlach et al 2005). Differences between hard and soft shoes do not cause differences in peak impact forces, which supports allowing runners to use personal shoes for running studies (Wright et al 1998). Many running studies also control pace when testing subjects so as to eliminate another variable between runners, (Nelson et al 1972, Hreljac et al 2000, Bennell et al 2004). When setting the speed for track and overground comparisons, studies often will allow the subject to run at a self-selected pace overground, and then set the treadmill to the same speed for tests (Elliot and Blanksby 1976). Evidence shows no significant correlation between pace of a runner and running-related injuries (van Gent et al 2007).

Accelerometers

Wireless accelerometers are devices that measure accelerations. Lightweight and portable, they are ideal for measuring accelerations outside of a laboratory setting

(Herren et al 1999, Elvin et al 2007). A wireless accelerometer is a small, self-contained system that is able to collect and store data without needing to be attached to wires, as it contains a battery and memory bank as part of the system (Elvin et al 2007). Wired accelerometers have been used in several running studies to date (Derrick et al 2002, Zifchock et al 2006). Some studies will use accelerometers that only measure one axis so that they can only study the vertical or horizontal axis (Zifchock et al 2006). A more complete picture of running habits in a study can be gained by using a tri-axial accelerometer which can measure the accelerations and decelerations in the vertical, horizontal and lateral directions all at the same time.

Placement of the accelerometers used in running studies varies. One study used two accelerometers mounted to the right tibia and front of the skull (Derrick et al 2002). Another study used two triaxial accelerometers, one on each hip, to monitor walking and jogging on a treadmill (Nichols et al 1999). Other studies have used three separate uniaxial accelerometers all placed together or one triaxial accelerometer on a belt which held them in the small of the back to measure vertical, horizontal and lateral accelerations during running (Herren et al 1999, LeBris et al 2006). The ability to measure impact forces of both limbs with a single accelerometer over the course of the entire run is important to get an accurate idea of running biomechanics (Gerlach et al 2005). Accelerometers have been shown to have correlation values of 0.8 or better with various physical activities when compared to force plates including vertical jumping (Elvin et al 2007).

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III. IMPACT FORCES IN FEMALE RECREATIONAL RUNNERS

Materials and Methods

Use of Human Subjects

All research was conducted in accordance with federal, state and local laws. Approval was obtained from the Michigan State University institutional review board prior to the start of the study (IRB #07-895). Volunteers were informed about the study procedure and taken through an informed consent procedure. Each participant was required to sign an informed consent form (Appendix A) prior to inclusion in the study.

Subject Population

Subjects were recruited from a local running club and an email request sent to the Michigan State University College of Veterinary Medicine. Inclusion criteria for the study required that subjects be female, recreationally active and have the ability to run four miles continuously. Subjects were excluded if they could not run four miles at one time, if they were injured within six months prior to the beginning of the study, or if they were not able to complete two runs within seven days of each other. Subjects were also excluded if they could not perform two runs a week apart or were not able to make any of the scheduled indoor track times. Based on the inclusion and exclusion criteria twelve, female, recreational runners participated in the study. Height, weight, and age were recorded for each subject and each subject filled out a running questionnaire to determine average weekly mileage run and injury history in the previous six months. Body mass index (BMI) values were calculated using the height and weight collected from the runners. The BMI is calculated to compare the height and weight of the runners and to make sure that the runners in the study were of a healthy weight. This information is presented in Table 3.1.

Table 3.1. Table detailing the age, weight, height, body mass index and average weekly mileage of all twelve subjects in the study.

SUBJECT	AGE	WEIGHT (kg)	HEIGHT (m)	BMI	WEEKLY MLEAGE
1	23	63.5	1.73	21.3	20
2	24	56.7	1.75	18.5	30+
3	30	58.1	1.70	20	25
4	33	54.4	1.61	20.9	15-20
5	35	65.8	1.63	24.9	20-25
6	27	58.1	1.80	17.9	8
7	22	52.2	1.60	20.4	3
8	26	65.3	1.70	22.6	10-20
9	46	62.1	1.63	23.5	10-15
10	30	68.0	1.78	21.5	8
11	48	59.0	1.60	23	5-10
12	49	58.5	1.52	25.2	25

Study Design

All runners were asked to perform two four-mile runs, the first on a track and the second on a treadmill, with a week between runs. The four-mile distance was chosen to ensure that runners had adequate time to establish and maintain a comfortable pace without pushing them to fatigue. This distance also allowed the researcher to examine possible changes in peak impact accelerations over the course of a track run and a treadmill run as the runner starts to get tired. Each runner wore her own clothing and shoes for both runs so that she would be comfortable and that differences seen in peak impact accelerations were not the result of an unknown shoe. An accelerometer was worn for both runs, positioned in the small of the back and secured with triathlon belts. Running data were collected and stored on the accelerometer for the duration of each run and downloaded to a laptop following the run. Runners were not allowed any listening devices for either run, including mp3 players so that there would be no outside influence on pace. Runners were allowed to wear a watch or drink water during the runs as they wanted. Ten second video clips were recorded for both runs at every ¼ mile. Data was analyzed looking at all the runners grouped together as well as the runners divided into three groups based on average running pace. Pace groups were determined after the run by average speed of the track run and were as follows: Group 1 included runners between 6:30-8:15 minutes/mile, group 2 was runners between 8:16-9:15 minutes/mile and group 3 had runners between 9:16-10:30 minutes/mile. Each pace group had four runners. By analyzing the data looking at pace groups as well it could be determined if different paces led to greater peak impact accelerations or a change in these impacts over time.

Track

The track used for the study is located in the Jenison Fieldhouse, on the campus of Michigan State University in East Lansing, Michigan. The surface of the track is made of synthetic material. The middle lane of the track, which runners used for the study, is 1/8 of a mile. An indoor track was chosen to reduce weather variability between the runners. This specific indoor track was used because the track itself was flat and there were no sloped or banked turns.

Treadmill

A 9.33 by Precor treadmill (Woodinville, Washington) was used in the study. The treadmill was housed inside Playmakers in Okemos, Michigan, a local running store. The treadmill was set for no incline during the run to match the flat surface of the indoor track.

Accelerometer

To monitor each run a tri-axial accelerometer was used from ZeroPoint Technology (Johannesburg, South Africa). The accelerometer collected data at a rate of 1000Hz and stored all data on the accelerometer, which is shown in Figure 3.1. The accelerometer was attached to a custom built acrylic plate using carpet tape and held on to the runner using two modified triathlon belts from Nathan Sports (Sharon Hill, PA). The final accelerometer setup is shown in Figure 3.2.

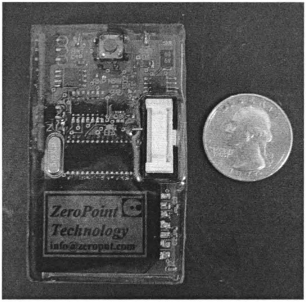

Figure 3.1. A photo of the accelerometer used for the study next to a quarter for scale.

Data collected during the run was stored on the accelerometer until downloaded to a laptop after completion of a run. Data were downloaded from the accelerometer using a custom USB cable. The accelerometer was always placed on the plate with the button to the left so that the vertical, horizontal and lateral axes were the same for all runners. Figure 3.3 shows a diagram of the vertical, horizontal and lateral axes in respect to the runner. Figure 3.4 shows a runner wearing the accelerometer, with Figure 3.4A showing the runner from the side and Figure 3.4B showing the runner from the back.

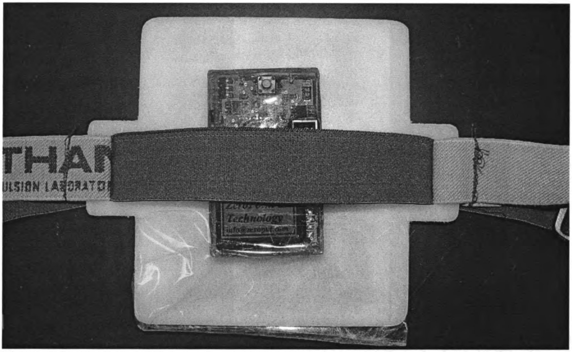

Figure 3.2. A photo of the accelerometer mounted on the custom acrylic plate and attached to the triathlon belts.

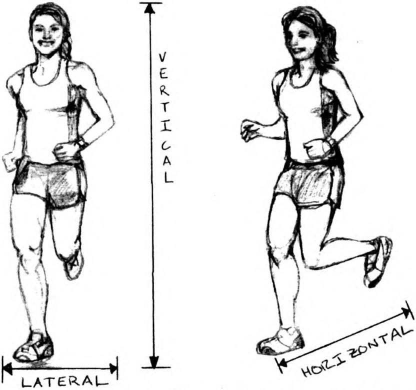

Figure 3.3. This diagram shows the three axes as defined for the study when compared to the runner.

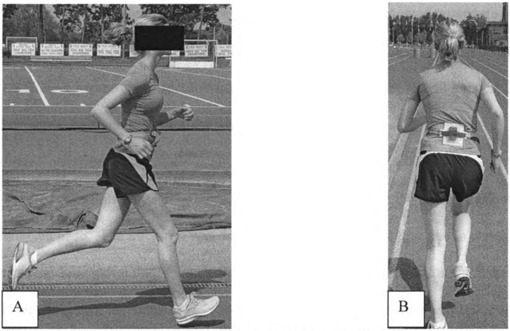

Figure 3.4. These photographs show a runner wearing the accelerometer connected to the belt system. The runner is shown from the side in (A) and from the back in (B).

Accelerometer Calibration

An MTS 810 mechanical testing machine from MTS Systems Corp. (Eden Prairie, MN) was used for the accelerometer calibration. The accelerometer was attached securely to the testing machine using double-sided tape. The testing machine was programmed to apply a displacement amplitude of ±4mm, at starting harmonic frequencies between 10Hz and 45 Hz in 5Hz increments. One hundred cycles were applied at each loading frequency.

After the data was downloaded from the accelerometer, a custom programmed MATLAB file (Mathworks Inc., Nattick MA) was used to analyze the data. Each 5Hz increment between 10 and 45 Hz was manually identified by the researcher. A non-linear sine function of the form $y = A \sin(2\pi f+\phi)$ was used for curve fitting the accelerometer data; where A is the amplitude of the curve, f is the frequency of loading and ϕ is the phase lag. A and ϕ are the fitted parameters. A linear least squares procedure was used to fit the loading input acceleration and the accelerometer amplitudes (A). The calibration coefficient for the accelerometer was found to be 29.08 for the lateral axis, 28.21 for the horizontal axis and 29.74 for the vertical axis.

Data Collection

Each runner was asked to perform a four-mile run on the indoor track at a self-selected pace. The track run was done indoors to limit variability due to weather. Each run was done individually with only the runner present on the track at the time of the test. Prior to the run, the subject was asked to perform a self-selected warm-up. Following the warm-up the subject was fitted with the accelerometer mounted on the triathlon belt. The accelerometer was placed over the small of the back and held in place by the researcher while the runner tightened the first triathlon belt. The runner was instructed to tighten the belt as much as possible without causing discomfort. The runner then buckled the second triathlon belt and tightened it so that it was also as tight as possible without causing discomfort. The researcher then tested the tightness of the belts by gently tugging on the belts and making sure the accelerometer did not move. The subject was asked to jump up and down several times so the researcher could verify no discernable movement of the accelerometer. The runner was then instructed to move to a predetermined starting line at the beginning of one straight section on the track, with the same starting line used for all the runners. Time of the run was measured, starting with the runner's first step and recorded every 1/8-mile. The researcher called out the mileage for the runner at 1 mile, 2 miles, 3 miles and 3 7/8 miles. Data was downloaded from the accelerometer following the run. A ten second video clip was recorded every ¼ mile during the four mile run.

The treadmill run was scheduled for seven days after the track run. All but two of the subjects completed the treadmill run at the scheduled time. Two subjects had to reschedule the treadmill run at the last minute and they completed the treadmill run within fourteen days of the track run. The runner was asked to perform a self-selected warm-up and was given time to familiarize herself to the treadmill to be used in the study. The subject was then asked to put on the accelerometer, following the same procedure used for the track run. The runner stepped onto the treadmill while the belt was stopped. Treadmill speed was set at the average pace from the track run with no incline. The runner started running as the belt started moving, reaching the average pace from the track run as the treadmill did. Each runner completed a four-mile run based on the mileage display of the treadmill. Running data was downloaded at the completion of the run. Training between the track and treadmill runs was left to the discretion of each runner.

Data Analysis

At the end of each subject's track and treadmill run, the acceleration data was downloaded to a laptop computer using 3dPEbble software from ZeroPoint Technology (Johannesburg, South Africa). Track data files were run through a custom written program in Matlab in which runner body weight and ¼ mile times were entered. The Matlab program isolated the peak impact points for the entire run, as shown in Figure 3.5. Splitting the run using the inputted times, the program calculated the mean and standard deviation for the peak impacts in the vertical and horizontal directions for each ¼ mile throughout the run. Lateral accelerations were not looked at for the present study. These mean and standard deviation values were entered manually into an Excel spreadsheet.

For the treadmill runs the same procedure was followed, with different ¼ mile times inputted due to slight consistency differences in the individual runner's pace between the track and treadmill runs.

The same data set was used for all statistical analyses. Each subject had 32 data lines entered, one for each ¼ mile marker throughout both the track and treadmill runs beginning at ¼ mile through 4 miles. Each data line consisted of the randomly assigned subject number, group number, mileage marker, either track or treadmill depending on the run, mean vertical and horizontal accelerations averaged over each ¼ mile. The raw data are included in Appendix B.

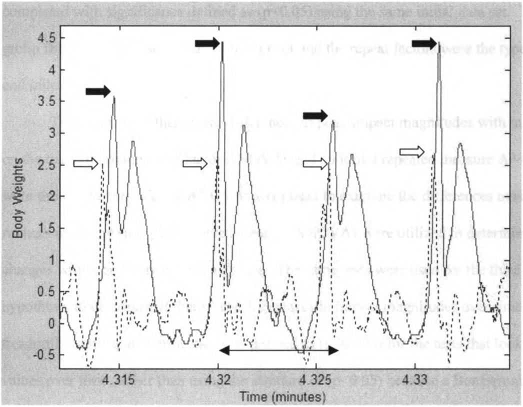

Figure 3.5. This graph shows a representation of four steps taken during a run. The solid line is the vertical acceleration, with peaks indicated by solid arrows. The dotted line is the horizontal accelerations, with peaks indicated by unfilled arrows. The double arrow line shows the duration of one step.

The first hypothesis compared impact accelerations from the track run and the treadmill run in both the vertical and horizontal directions. In order to determine if there were differences in the peak impact accelerations between the track and treadmill runs for the entire group of runners a three-factor ANOVA was run performed with statistical significance considered ($p<0.05$). The fixed factors were defined as track or treadmill run and mileage, while subject was the random factor. The ANOVA compared all the runners for all the mileage points, looking at just the difference between the track and treadmill accelerations. To determine if there were differences between the pace groups for the vertical and horizontal accelerations a split plot repeated measure ANOVA was completed with significance defined as ($p<0.05$) using the same initial data set. The group factor was the pace group of the runner and the repeat factors were the type of run and mileage.

To determine if there were differences in peak impact magnitudes with mileage on the track, the same three-factor ANOVAs and split plot repeated measure ANOVAs were used. The three-factor ANOVAs were used to examine the differences over all the runners while the split plot repeated measure ANOVAs were utilized to determine changes within and between pace groups. The same tests were used for the third hypothesis to determine if there were differences in impact magnitudes over time on the treadmill. Statistical significance was defined as ($p<0.003$) for the tests that looked at values over time, rather than using the standard of ($p<0.05$) because a Bonferroni test was used. The Bonferroni test enables comparison between the first mileage point and every subsequent mileage. Dividing the p-value of 0.05 by 15, the number of comparisons when using 16 mileage points ($p<0.003$) preserves the Type I error rate of 0.05 when performing these multiple comparisons.

Results

Hypothesis 1

The differences in the vertical impacts between track and treadmill runs for each group and the overall study population are shown in Figure 3.6. There was no significant difference (p=0.52) in vertical impacts between the track and treadmill for the overall study population. Similar results were seen in group 1 (p=0.94), group 2 (p=0.47), and group 3 (p=0.64) as they did not have a significant difference between track and treadmill impacts in the vertical direction.

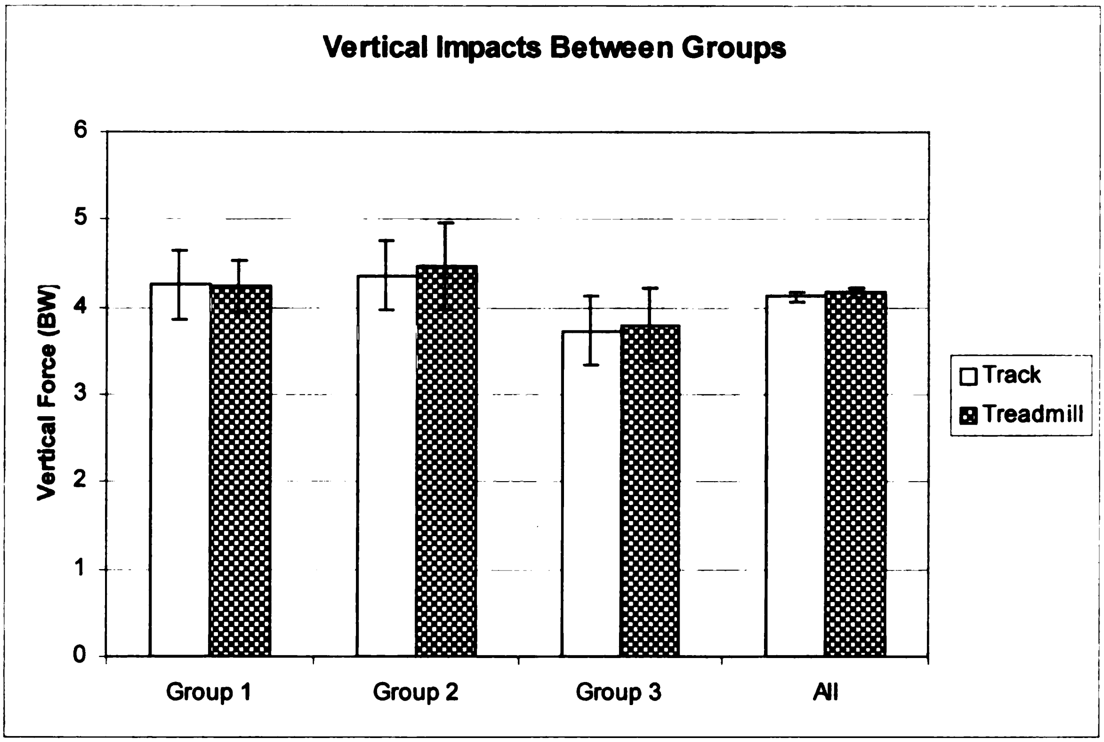

Figure 3.6. Graph showing the difference in vertical impacts between the track and treadmill runs for each pace group as well as the overall study population. Error bars indicate the standard error of the mean (SEM).

The differences between track and treadmill runs in the horizontal direction are shown in Figure 3.7 for all three pace groups and all the runners. There was a statistically significant difference between horizontal track and treadmill impacts (p=0.0012). There were significantly greater horizontal impacts on the track compared to the treadmill in group 1 (p=0.0084) and group 2 (p=0.0015) but not in group 3 (p=0.8381).

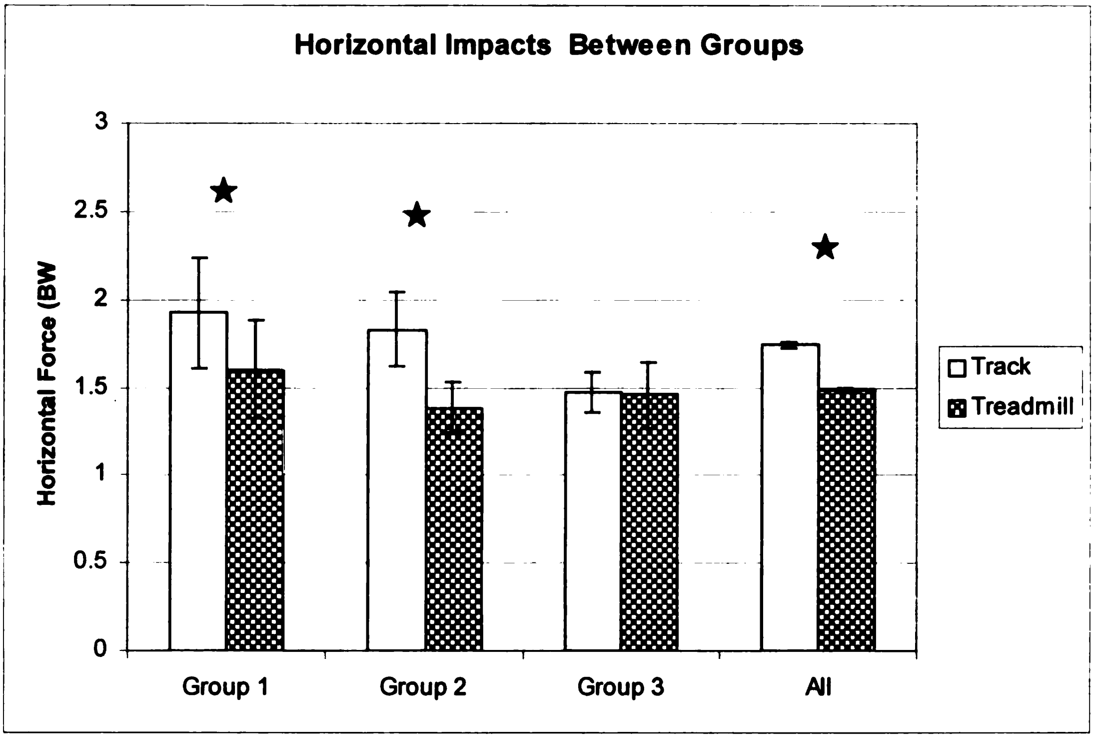

Figure 3.7. A graph showing the horizontal impacts on the track and treadmill for each pace group and the overall running population. Stars represent statistical differences between the track and treadmill impacts. Error bars represent the SEM.

Hypothesis 2

The vertical impacts during the first quarter mile were significantly lower than quarter miles from 0.75-4miles ($p<0.0001$) (Figure 3.8). There was no difference from the first quarter mile in group 1, a significant difference ($p<0.0001$) from the first quarter mile in quarter miles 0.75-4miles in group 2 and a difference ($p<0.0001$) from the first quarter mile in quarter miles from 1-4 miles in group 3. There was no significant difference in vertical impacts between pace groups on the track (group 1 and group 2 (p=0.87), group 1 and group 3 (p=.38) and group 2 and group 3 (p=0.30) (Figure 3.9).

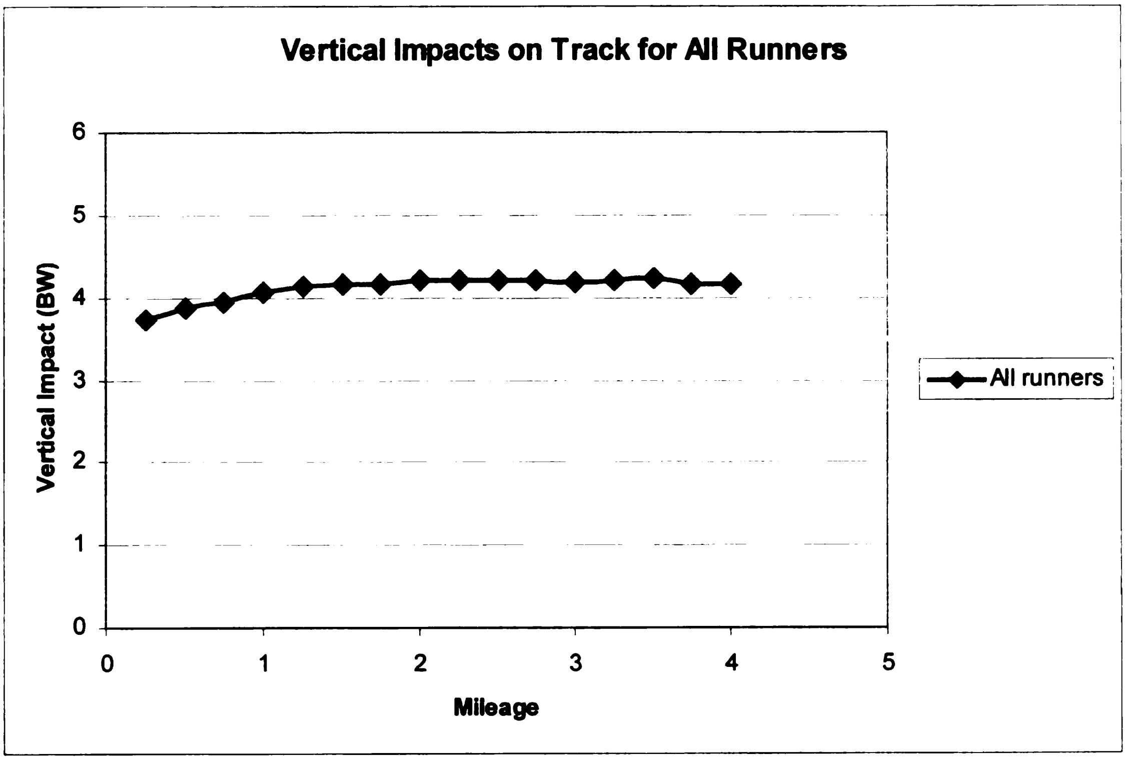

Figure 3.8. Graph showing the mean vertical impacts on the track for the entire study population. Error bars indicate the SEM.

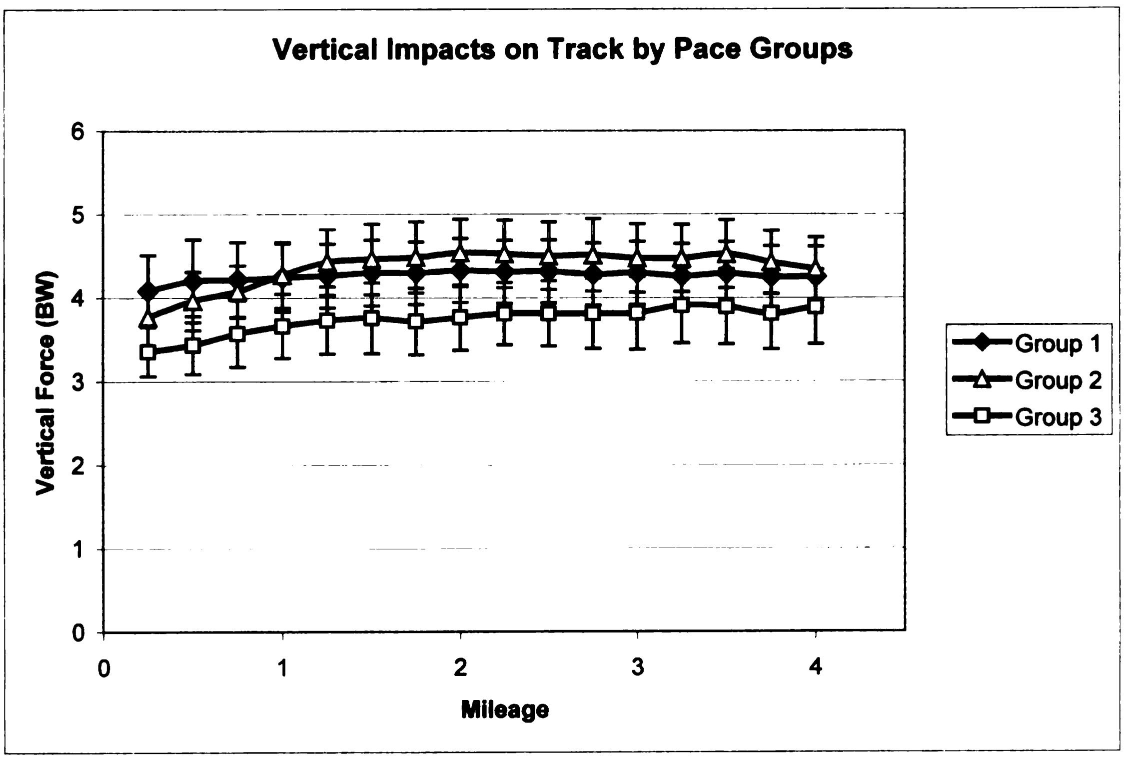

Figure 3.9. Graph showing the vertical impacts on the track by pace group. Error bars indicate the SEM.

There was a significant difference with mileage between the horizontal impacts on the track for all runners (p=0.001) in nine of the fifteen comparisons to the original quarter mile as shown in Figure 3.10. Neither group 1 nor group 3 had any significant difference between the first quarter mile and any of the remaining quarter miles. Group 2 was significantly different after three-fourths of a mile (p<0.0001). Group 1 compared to group 2 (p=0.74), group 1 compared with group 3 (p=0.18) and group 2 compared with group 3 (p=0.30) were not significantly different in the change in horizontal impact accelerations between groups as shown in Figure 3.11.

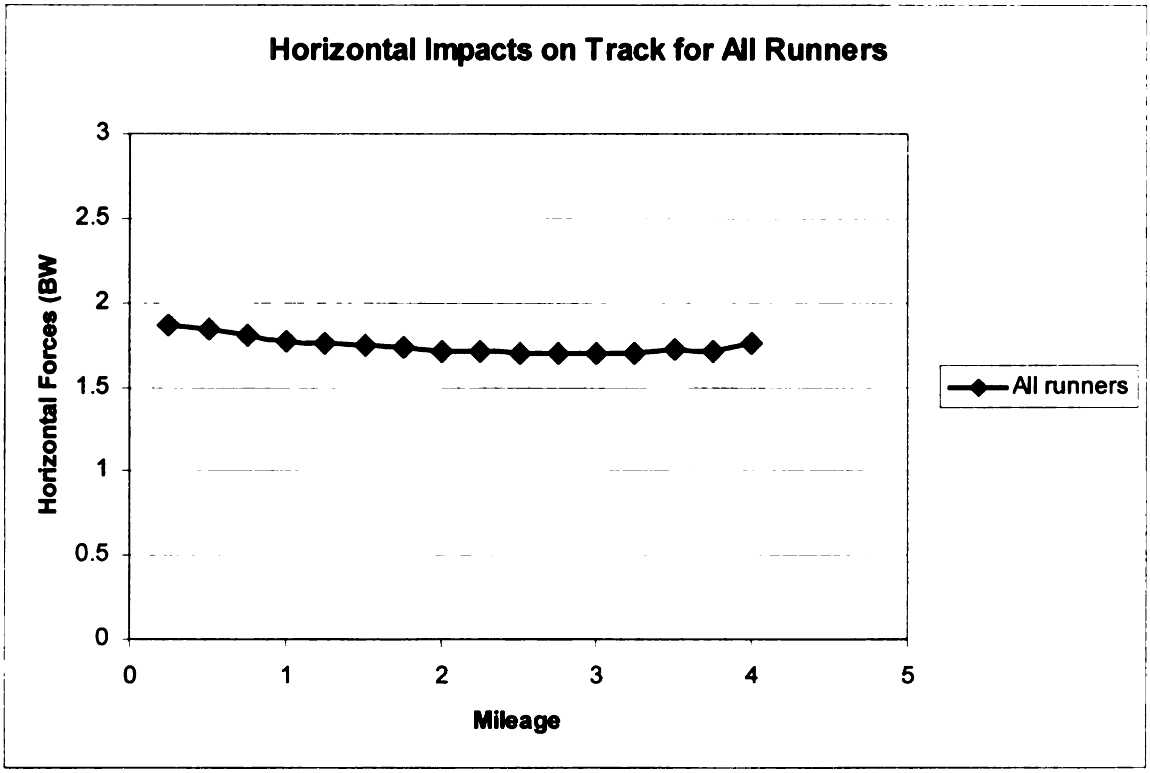

Figure 3.10. This graph shows the horizontal impacts on the track for the entire study population. Error bars indicate the SEM.

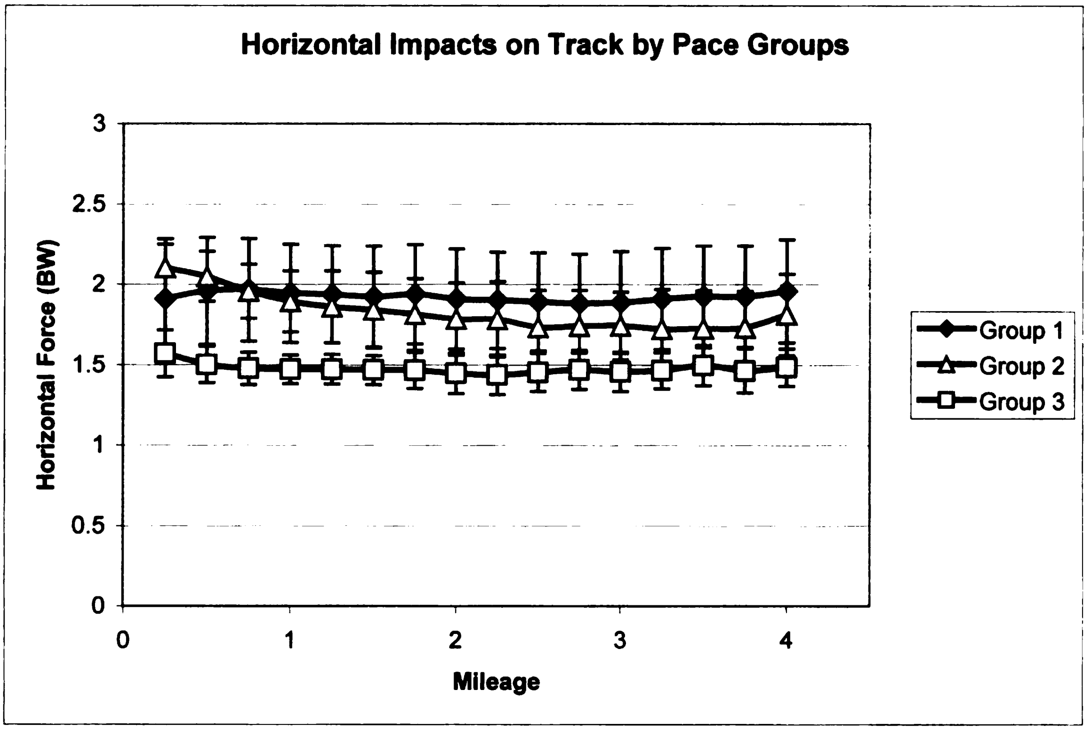

Figure 3.11. A graph showing the horizontal impacts over the course of the track run for the three different pace groups. Error bars indicate the SEM.

Hypothesis 3

In the vertical direction there was a significant difference between impacts with mileage when comparing the impacts in the first quarter mile of the run to the each remaining quarter mile segment when looking at the runners as a whole ($p<0.0001$) as shown in Figure 3.12. Similar differences with group 1 ($p<0.0001$), group 2 ($p<0.0001$) and group 3 ($p<0.0001$) in the vertical direction. Between groups in the vertical direction with mileage on the treadmill there were no significant differences between group 1 and group 2 ($p=0.72$), group 1 and group 3 ($p=0.45$) and group 2 and group 3 ($p=0.27$) as shown in Figure 3.13.

For the horizontal direction on the treadmill, there was no significant difference in impacts over time in the entire group (Figure 3.14) or in group 1, group 2 or group 3 (Figure 3.15). Comparisons between groups show no significant change in impacts with

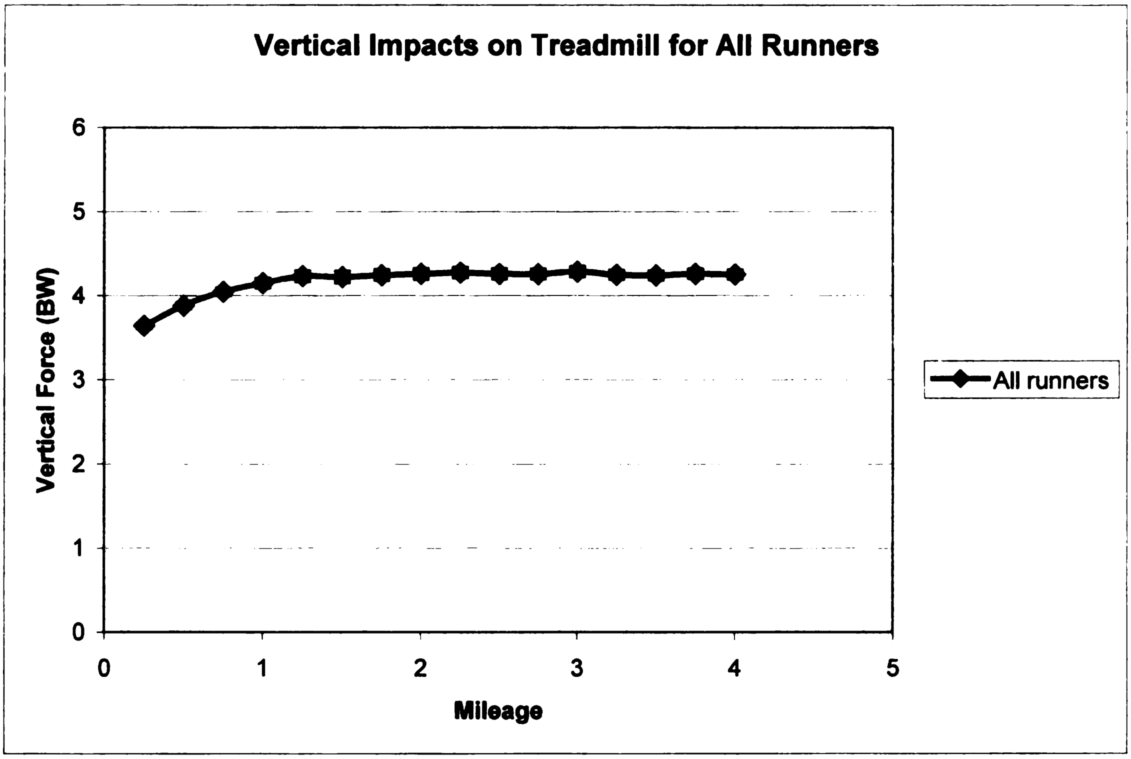

Figure 3.12. A line graph showing the mean vertical impacts over the treadmill run for the entire study population. Error bars represent the SEM.

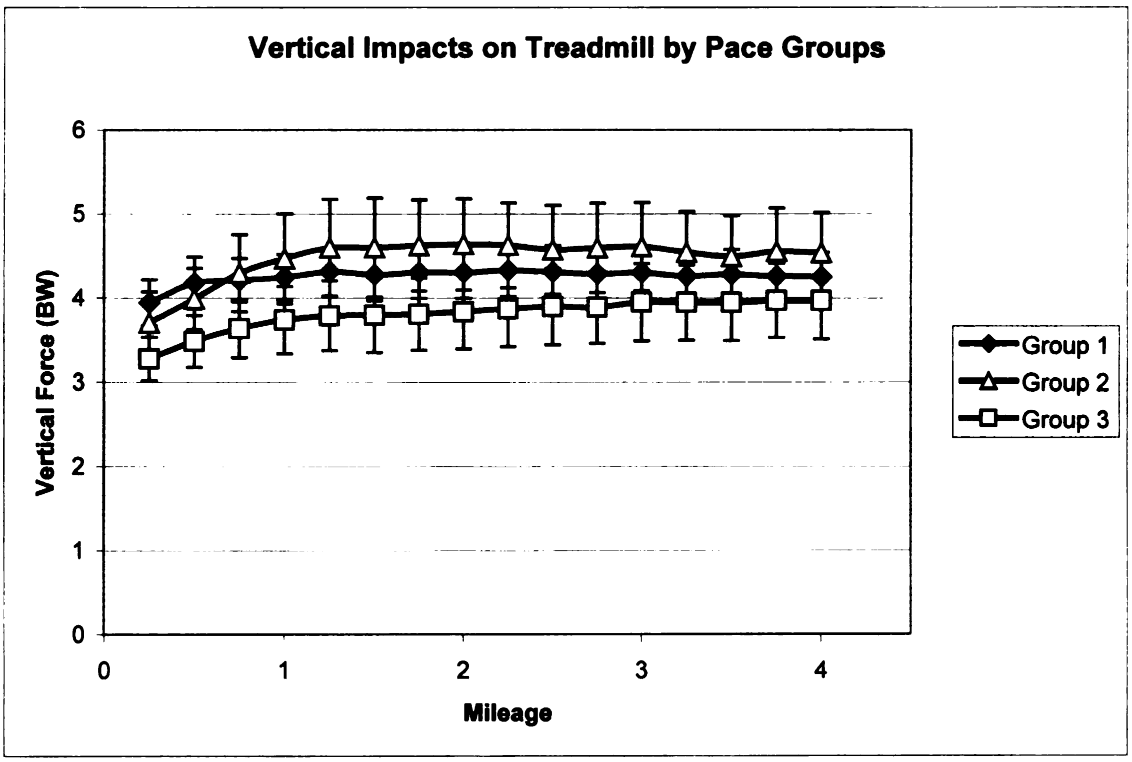

Figure 3.13. This line graph shows the vertical impacts on the treadmill run by pace group. Error bars indicate the SEM.

mileage on the treadmill in the horizontal direction. Group 1 compared to group 2 (p=0.50), group 1 compared to group 3 (p=0.65) and group 2 compared to group 3 (p=0.83).

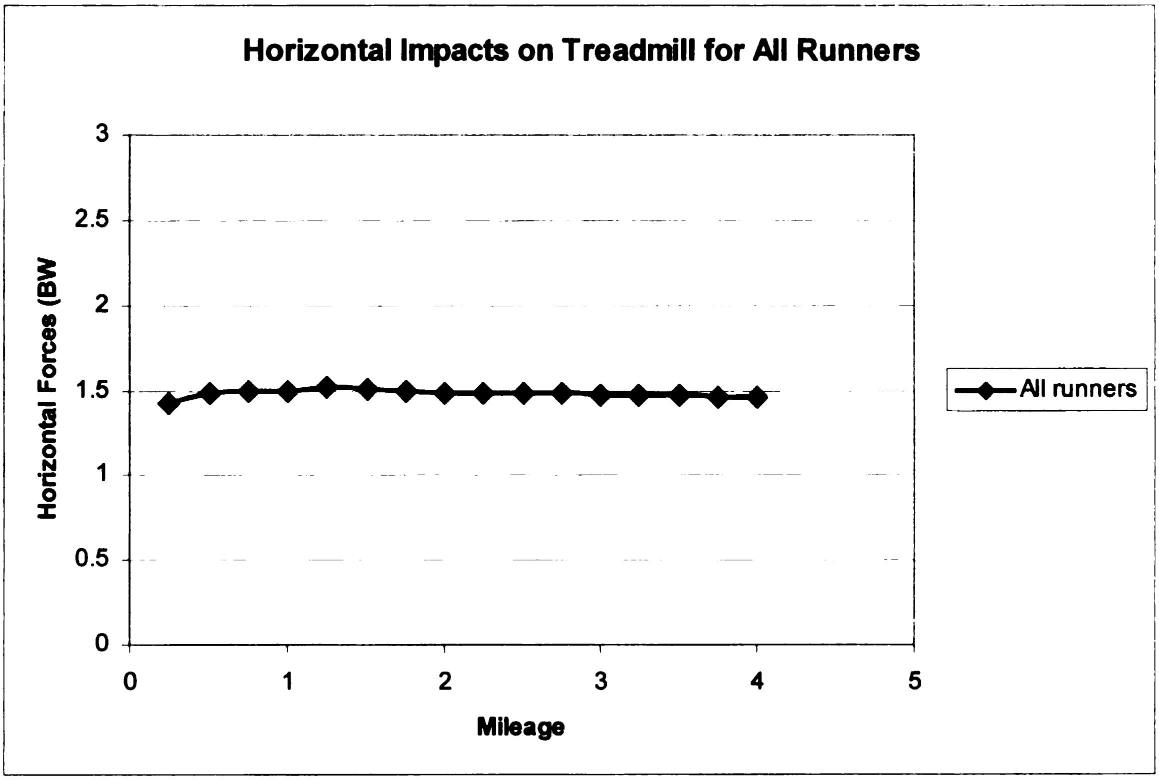

Figure 3.14. This graph shows the mean horizontal impacts on the treadmill run for the entire study population. Error bars indicate the SEM.

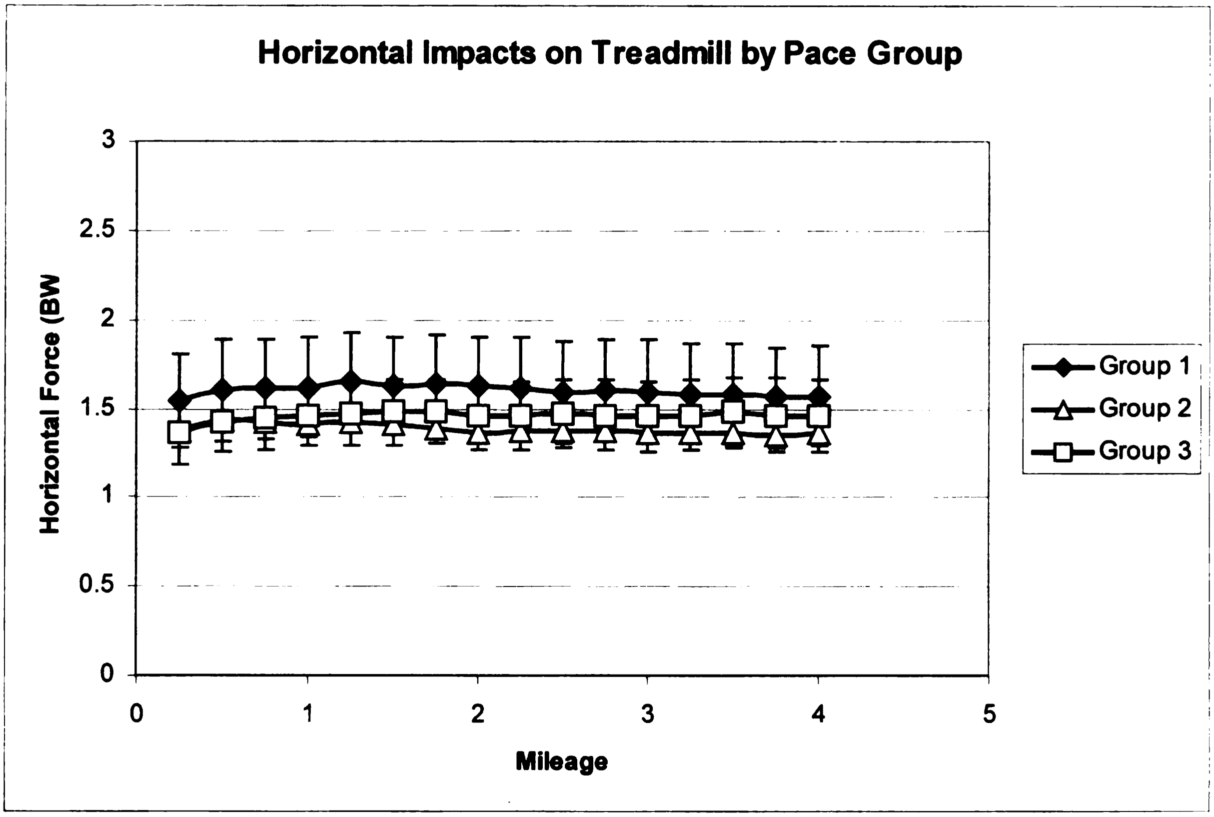

Figure 3.15. A line graph illustrating the mean horizontal impacts during the treadmill run divided up into three pace groups. Error bars indicate one the SEM.

Discussion

There was a significant difference between impact accelerations on the track compared to the treadmill as hypothesized. However, the statistical differences were in the horizontal plane, not the vertical one as had been theorized. It may be the difference in the peak horizontal impact accelerations that creates the different feeling that runners experience when running on the track and on the treadmill. The hypothesis that the peak impact accelerations would change over time on the track was shown in both the vertical and horizontal directions. That the peak impact accelerations would be significantly different over time on the treadmill was not fully supported, with significant changes in the vertical plane, but not in the horizontal one. A more detailed discussion about this follows later in this section.

Track Versus Treadmill

The hypothesis that the peak vertical impact accelerations would be greater on the track compared to the treadmill was not supported by the results from this study. It was thought that the difference runners claim to feel in running on a track compared to a treadmill was due to the peak vertical accelerations. This study found no significant difference on vertical impacts between the track and treadmill runs for the study population as a whole or by pace groups. These findings are not in agreement with a walking study that compared treadmill and overground walking and found that vertical ground reaction forces were significantly higher in overground walking compared to treadmill walking (White et al 1998). However, the 1998 White et al. study was only looking at walking, not running. The aforementioned study also looked at a limited distance, having the subjects walk less than 10 meters for each trial, which may not be enough time for the walkers to establish a normal gait pattern as is discussed later. Other studies look at the changes in vertical ground reaction forces and are difficult to directly compare to peak vertical impact accelerations (Hreljac et al 2000, Gerlach et al 2005).

The hypothesis that there would be no significant difference in the peak horizontal acceleration impacts between the track and treadmill runs was not supported by the data. Among runners in this study there was a significant difference between the horizontal impacts on the track compared to the treadmill, with the impacts being higher on the track than the treadmill. These findings are in agreement with a walking study that looked at the difference between treadmill and overground walking and found that while there is not a significant difference in propulsion, that there is a difference in the braking peak, which this study refers to as the horizontal impact (Goldberg et al 2008). This study also showed a decreased braking peak on the treadmill when compared to overground (Goldberg et al 2008). The greater horizontal impact on the track compared to the treadmill could be due to a change in running mechanics where runners reach out further with the leading foot and allow the treadmill belt to pull the foot back under them (Nelson et al 1972). Another possible explanation for the difference is that females have greater hip flexion angles on the treadmill compared to the track, which could alter the way the body moves during the braking part of the running stance (Alton et al 1998, Ferber et al 2003). It is also possible that some of this difference between the peak horizontal impacts on the track compared to the treadmill is due to a difference in friction of the two surfaces. Testing of the friction of the two surface was beyond the scope of the project.

Track Over Time

The present study found that there was an increase in the peak vertical impact accelerations over time on the track for the overall running population as well as for each pace group. These findings agree with a study that found that leg impact accelerations increased to the middle and end of a run when compared to the beginning (Derrick et al 2002). The same study found that this change in impact accelerations was accompanied by greater shock attenuation, greater knee flexion angle and a more inverted subtalar joint at the end of the run (Derrick et al 2002). While these changes were noted as possible reasons for the change in leg impact accelerations, it should be noted that unlike the current study, the aforementioned study had the subjects run until exhaustion prevented them from running further. The present study required subjects to run only four miles, which was not to exhaustion for any of the runners, thus some of the changes seen in the Derrick et al (2002) study may be greater than the present study, although it is clear that these changes in vertical impact accelerations begin early in the run and continue throughout, regardless of how long the run is. When we asked the subjects in the study how they felt about the track run right after completion many said that it took them about a mile to achieve a consistent stride. When the data were analyzed it was clear that while there was significant difference in the peak vertical accelerations throughout the run, the greatest change occurred in the first mile, which would be consistent with the runners acquiring a steady gait pattern.

Horizontal impact accelerations have also been shown to change over time on the track. While many studies look at vertical impacts while running, very few concentrate on the horizontal impact aspect of running. This lack of research makes it difficult to compare the results of the present study to others, but reasons for the changes in the horizontal impact accelerations could be the same as those responsible for changes in the vertical impact accelerations; greater shock attenuation and changes in body angles over the course of the run (Derrick et al 2002). Another factor that may play into the peak impact accelerations changing over time on the track run is fatigue. While the runners are becoming physically tired which can lead to changes in running style it could be that the runners are also becoming mentally tired (Mizrahi et al 2000). As the run continues, the runner may be concentrating less on the run, which could contribute to the deterioration of running form and the increased peak vertical and peak horizontal impact accelerations that are seen in this study. Further work should be done in this area to determine if this change is due to physical or mental fatigue, or a combination of the two. Having runners complete several runs, some with running form reminders, others without, might be of assistance in resolving this issue.

Treadmill Over Time

The current study showed that there was an increase from the beginning of the run to the end in the vertical impacts during the treadmill run. These findings are consistent with other studies, including the aforementioned Derrick et al. (2002) study that demonstrated that impact accelerations increase over the course of a run. However, another study showed that vertical impact decreased significantly on the treadmill with fatigue (Gerlach et al 2005). Unlike the Gerlach et al. (2005) study, the current study was not looking at changes with fatigue, only with differences after four miles of running. It may be that the difference in fatigue definitions between the Derrick et al. (2002) and Gerlach et al. (2005) studies is part of the cause for the disagreement between impact behaviors over time. Mental fatigue could again be playing a role in the change in peak vertical impact accelerations over the course of the treadmill run.

Unlike the track run, horizontal impacts did not change significantly over time on the treadmill. This could be due to the more controlled method of the treadmill, which would not allow runners to drastically change horizontal impacts without risking falling off the treadmill (Milgrom et al 2003). As the treadmill belt is moving at a constant speed through the run, the runner has to maintain a constant speed in order to remain on. Maintaining a constant speed means that the runner will likely push off and brake with a consistent force, keeping the peak horizontal acceleration consistent over time.

There are several problems when trying to make direct comparisons between the present study and other running studies. The first issue when comparing these results is that most of the studies used for comparison are comprised of male subjects or a mix of male and female runners. These studies, therefore, may not be as applicable for comparison because of the differences between the genders while running (Ferber et al 2003). There were no studies that looked at the difference between track and treadmill running for only female runners.

Also a problem is that many running studies only examine runners for short distances, often less than 50 m, and use these results to make generalizations about running patterns as a whole (Hreljac et al 2000, Bus 2003, Zifchock et al 2006, Milner et al 2006). The runners in the present study often said that it took them about a mile before they felt like they were at a normal, steady gait. Therefore, the results from studies that only measure short distances may not be collecting a true representative running gait.

Those studies that have compared treadmill and overground running generally use short distances as well (Nelson et al 1972, Elliot and Blanksby 1976, Wank et al 1998).

Many of the studies that compare treadmill and overground running are done in conditions that do not resemble the current study, as the speed at which the subject runs is already pre-determined before the study, rather than allowing the runner to move at a comfortable self-selected pace. Some of these studies will test the same runners at several different speeds, which can allow direct comparison between runners at different speeds, but the running mechanics may vary greatly from a normal run under forced pace circumstances. For the present study it was decided that it was preferable to measure the accelerations on the natural running gait of the subjects rather than require all the runners to run at a specific pace.

Looking at the results of the overall study it is interesting to see that while there is no statistical difference between the peak vertical accelerations, the peak horizontal acceleration is smaller on the treadmill and stays constant throughout a four mile run. These lower impacts could be beneficial especially as it has been theorized by several studies that there is a link between higher impacts and injury in recreational runners (Hreljac et al 2000, Mizrahi et al 2000, Ferber et al 2002, Hreljac 2004). The results of the present study validate the use of treadmills for rehabilitation. Lower impacts on the treadmill would mean less chance of reinjury during rehabilitation. This information is especially useful to recreational runners who are prone to running injuries, especially ones like stress fractures that may be linked to increased impacts during running.

Another area for further study would be to compare the peak lateral accelerations during runs on the track and treadmill. While the differences that runners report feeling between the two running surfaces could be explained by the difference in the peak horizontal impacts, there may also be differences in the lateral accelerations between track and treadmill runs. Differences in lateral accelerations while training on the two surfaces may contribute to runners reporting that they feel different while distance training on a track compared to the treadmill. The peak lateral accelerations may be very small on the treadmill, where the runner has a very limited amount of lateral movement when compared to the track.

Limitations

There were several limitations with the current study that should be noted. While every effort was made to eliminate variables between the two testing conditions, there were certain factors that may influence the results, including the surface of the track and the treadmill. Testing the surface elasticity of the two surfaces was not a feasible option for this study because it would have destroyed the surfaces. One surface may depress more under the runner, which could influence the results. Another potential issue with the design of the study is that the runners always performed the track run before the treadmill with a week between the two runs. It is possible that the runners, especially those not as established in running, may have improved in running, or conversely, gotten worse in the time between the two runs which may effect the results of the study. However, having the track run before the treadmill run was necessary in order to determine the pace of the runner with which to set the treadmill to. Other limitations include a small study population, which may not be representative of the general population of female recreational runners. Efforts were made to recruit runners with a wide variety of pace and age so that these would not be factors in the current study.

Future Directions

Further studies in this area may yield even more applicable knowledge in the running patterns of female recreational runners. Future studies could compare treadmill running to overground running or road runs, which are much more common among this running population. Comparing longer runs on the track and treadmill surfaces would also be valuable, to look at the effects of fatigue on peak impact accelerations. A third study could examine the link between impacts and injury by splitting a population of female recreational runners into a group that trains solely on the treadmill and a group that runs on the track only, to determine if one group is more likely develop running related injuries.

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APPENDICES

Appendix A

INFORMED CONSENT

Department of Civil and Environmental Engineering

Principle Investigator: Steven P. Arnoczky, DVM

(517) 353-8964

MEASUREMENT OF BIOMECHANICAL PARAMETERS DURING FOUR MILE RUN ON A TRACK AND TREADMILL

Your written consent is required before you may participate in this research study. Your participation is voluntary. Please read this document carefully. If you are willing to participate, please sign in the space provided.

Purpose of Study:

The purpose of this research study is to test the validity of novel sensor for measuring accelerations during running. The goal of this research study is to compare the accelerations measured by the accelerometers and force plate data to draw correlations. The study is being done as part of a master's thesis.

Procedure:

We wish to collect acceleration data using a novel sensor while you participate in several 30m runs over a force plate. The total weight of each device will be less than 2 oz. One accelerometer will be worn on your lower back after being attached to a triathlon belt, the second will be mounted on a soft knee support. After a warm-up, which could include jogging, running and stretching, you will run 30m over a runway with the force plate in it. You will be given a minute to rest between 30m runs. After you have completed several runs, the sensor data will be downloaded to a computer for analysis.

Your participation in this study is strictly voluntary and you can discard the sensor during the run if you believe that they hinder you in any way.

Expected Benefits:

As a subject in this study, you may benefit from understanding more about your own personal running performance and knowing that your participation may benefit others in the prevention of injuries. Over the long term, this study may provide answers to how and why some athletes develop injuries during running. By monitoring the loads during running, it might be possible to predict athletes that are at risk of injury and to provide them with specific exercises to reduce the chances of injury.

Expected Discomforts:

There are minimal risks associated with this study. The weight and size of the devices are significantly less than the weight of water carried by many runners during long-distance running and marathons. It is possible that you will feel some skin irritation from the triathlon belt. To avoid possible irritation, it is suggested that you wear a belt carrying an equivalent weight (or water-bottle) while training.

Contact Information:

If you have questions about the study, contact Steven Arnoczky, DVM, Wade O. Brinker Endowed Professor of Veterinary Surgery, (517) 353-8964, email: arnoczky@cvm.msu.edu, mail: College of Veterinary Medicine, G-387, Michigan State University, East Lansing 48824.

In case you have questions or concerns about your rights as a research participant, please feel free to contact Peter Vasilenko, Ph.D., Director of Human Research Protections, (517)355-2180, fax (517)432-4503, e-mail irb@msu.edu, mail: 202 Olds Hall, Michigan State University, East Lansing, MI 48824-1047.

Withdrawal:

As a participant, you are free to withdraw from the testing session at anytime without risk or prejudice.

Injury:

If you are injured as a result of your participation in this research project, Michigan State University will assist you in obtaining emergency care, if necessary, for your research related injuries. If you have insurance for medical care, your insurance carrier will be billed in the ordinary manner. As with any medical insurance, any costs that are not covered or in excess of what are paid by your insurance, including deductibles, will be your responsibility. The University's policy is not to provide financial compensation for lost wages, disability, pain or discomfort, unless required by law to do so. This does not mean that you are giving up any legal rights you may have. You may contact Steven P. Arnoczky at telephone number (517) 353-8964 with any questions or to report an injury.

Compensation:

You will not be compensated for participating in this study.

Confidentiality:

Your privacy will be protected to the maximum extent allowable by law. All data obtained will remain confidential. You will not be identified by name in any data summaries, publications, or reports that result from this study without your written permission. Although the data is confidential, the Institutional Review Board may inspect our records to verify that the study is following safe protocols.

STATEMENT OF CONSENT

You must be 18 years or older to participate in this study. You must be actively fit and run for at least 3 hours per week for no less than the 6 weeks prior to the date of participating in this research study.

I am running on my own volition.

I have read the above informed consent form, and I agree to participate in this research study.

PARTICPANT'S NAME: ______________________________
ADDRESS: ______________________________
TELEPHONE: ______________________________

PARTICIPANT'S SIGNATURE: ______________________________
DATE: ______________________________

WITNESS'S SIGNATURE: ______________________________
DATE: ______________________________

Appendix B

Table B.1. This table shows all the raw data collected in the study. Group denotes the pace group the runner was in. Subject is the random subject number assigned to the runner. Mileage shows which quarter mile the impacts have been averaged over. RX$ denotes whether the run was a track or treadmill run. VerticalF and HorizontalF stand for the vertical impact and horizontal impact, respectively.

Group	Subject	Mileage	RX$	VerticalF	HorizontalF
1	1	0.25	Track	3.7704	-2.7166
1	1	0.5	Track	3.7338	-2.7554
1	1	0.75	Track	3.8743	-2.7217
1	1	1	Track	3.9911	-2.6712
1	1	1.25	Track	4.1104	-2.6464
1	1	1.5	Track	4.2002	-2.6527
1	1	1.75	Track	4.247	-2.6527
1	1	2	Track	4.3127	-2.5879
1	1	2.25	Track	4.3291	-2.549
1	1	2.5	Track	4.3363	-2.5663
1	1	2.75	Track	4.3078	-2.5738
1	1	3	Track	4.3227	-2.5897
1	1	3.25	Track	4.3448	-2.6043
1	1	3.5	Track	4.4406	-2.6095
1	1	3.75	Track	4.3894	-2.6142
1	1	4	Track	4.3901	-2.6543
1	1	0.25	Treadmill	3.8023	-2.241
1	1	0.5	Treadmill	4.1099	-2.3856
1	1	0.75	Treadmill	4.2484	-2.376
1	1	1	Treadmill	4.2872	-2.3679
1	1	1.25	Treadmill	4.3953	-2.3636
1	1	1.5	Treadmill	4.4076	-2.3519
1	1	1.75	Treadmill	4.4335	-2.3751
1	1	2	Treadmill	4.4597	-2.362
1	1	2.25	Treadmill	4.4853	-2.3718
1	1	2.5	Treadmill	4.422	-2.3261
1	1	2.75	Treadmill	4.4173	-2.3503
1	1	3	Treadmill	4.4507	-2.3457
1	1	3.25	Treadmill	4.3951	-2.3137
1	1	3.5	Treadmill	4.4224	-2.3269
1	1	3.75	Treadmill	4.3606	-2.299
1	1	4	Treadmill	4.34	-2.2849
1	2	0.25	Track	3.8875	-1.5344
1	2	0.5	Track	3.9982	-1.5589
1	2	0.75	Track	4.0056	-1.5602
1	2	1	Track	4.038	-1.5189
1	2	1.25	Track	4.0933	-1.4966
1	2	1.5	Track	4.1627	-1.4325
1	2	1.75	Track	4.2089	-1.4536
1	2	2	Track	4.2469	-1.3566

1	2	2.25 Track	4.2338	-1.3564
1	2	2.5 Track	4.266	-1.316
1	2	2.75 Track	4.2383	-1.3
1	2	3 Track	4.215	-1.2798
1	2	3.25 Track	4.203	-1.3023
1	2	3.5 Track	4.2214	-1.3188
1	2	3.75 Track	4.1692	-1.3257
1	2	4 Track	4.2524	-1.3543
1	2	0.25 Treadmill	3.7791	-1.249
1	2	0.5 Treadmill	4.0376	-1.1802
1	2	0.75 Treadmill	4.0953	-1.1558
1	2	1 Treadmill	4.067	-1.1304
1	2	1.25 Treadmill	4.1478	-1.1776
1	2	1.5 Treadmill	4.1145	-1.1501
1	2	1.75 Treadmill	4.1473	-1.1
1	2	2 Treadmill	4.1561	-1.1084
1	2	2.25 Treadmill	4.2317	-1.077
1	2	2.5 Treadmill	4.1847	-1.0332
1	2	2.75 Treadmill	4.2077	-1.0366
1	2	3 Treadmill	4.1877	-1.0038
1	2	3.25 Treadmill	4.1852	-1.0152
1	2	3.5 Treadmill	4.2256	-1.0202
1	2	3.75 Treadmill	4.2686	-1.0322
1	2	4 Treadmill	4.27	-1.0246
1	3	0.25 Track	5.3147	-2.1969
1	3	0.5 Track	5.6464	-2.2362
1	3	0.75 Track	5.5132	-2.2532
1	3	1 Track	5.4144	-2.2244
1	3	1.25 Track	5.3329	-2.228
1	3	1.5 Track	5.3654	-2.2417
1	3	1.75 Track	5.275	-2.2555
1	3	2 Track	5.3124	-2.2852
1	3	2.25 Track	5.2572	-2.27
1	3	2.5 Track	5.2498	-2.2447
1	3	2.75 Track	5.2038	-2.2142
1	3	3 Track	5.2401	-2.2469
1	3	3.25 Track	5.1855	-2.2713
1	3	3.5 Track	5.1706	-2.306
1	3	3.75 Track	5.1189	-2.3016
1	3	4 Track	5.0532	-2.3495
1	3	0.25 Treadmill	4.728	-1.6117
1	3	0.5 Treadmill	5.0131	-1.6897
1	3	0.75 Treadmill	4.8758	-1.6951
1	3	1 Treadmill	4.9568	-1.731
1	3	1.25 Treadmill	5.0345	-1.7634
1	3	1.5 Treadmill	5.008	-1.7567
1	3	1.75 Treadmill	5.0566	-1.7585
1	3	2 Treadmill	5.0203	-1.7276

1	3	2.25 Treadmill	5.033	-1.7395
1	3	2.5 Treadmill	5.0715	-1.7175
1	3	2.75 Treadmill	4.9851	-1.7308
1	3	3 Treadmill	5.0162	-1.7046
1	3	3.25 Treadmill	4.9347	-1.7151
1	3	3.5 Treadmill	4.945	-1.6817
1	3	3.75 Treadmill	4.8976	-1.6876
1	3	4 Treadmill	4.9046	-1.7151
1	4	0.25 Track	3.3628	-1.1851
1	4	0.5 Track	3.4266	-1.2833
1	4	0.75 Track	3.4717	-1.3269
1	4	1 Track	3.5251	-1.36
1	4	1.25 Track	3.5131	-1.3777
1	4	1.5 Track	3.4569	-1.3672
1	4	1.75 Track	3.4415	-1.3922
1	4	2 Track	3.4334	-1.4053
1	4	2.25 Track	3.4116	-1.4312
1	4	2.5 Track	3.4001	-1.4381
1	4	2.75 Track	3.3677	-1.4342
1	4	3 Track	3.3993	-1.4331
1	4	3.25 Track	3.2984	-1.4599
1	4	3.5 Track	3.3185	-1.4631
1	4	3.75 Track	3.3222	-1.4574
1	4	4 Track	3.294	-1.4757
1	4	0.25 Treadmill	3.4564	-1.0578
1	4	0.5 Treadmill	3.537	-1.1664
1	4	0.75 Treadmill	3.6167	-1.2154
1	4	1 Treadmill	3.655	-1.2444
1	4	1.25 Treadmill	3.655	-1.2887
1	4	1.5 Treadmill	3.5514	-1.2594
1	4	1.75 Treadmill	3.5692	-1.3
1	4	2 Treadmill	3.5616	-1.3088
1	4	2.25 Treadmill	3.5446	-1.267
1	4	2.5 Treadmill	3.5441	-1.2805
1	4	2.75 Treadmill	3.5287	-1.311
1	4	3 Treadmill	3.5343	-1.3239
1	4	3.25 Treadmill	3.5182	-1.2831
1	4	3.5 Treadmill	3.5173	-1.2658
1	4	3.75 Treadmill	3.4936	-1.2336
1	4	4 Treadmill	3.4768	-1.2477
2	5	0.25 Track	3.7923	-2.1258
2	5	0.5 Track	3.9943	-2.125
2	5	0.75 Track	4.0826	-2.276
2	5	1 Track	4.3861	-2.3442
2	5	1.25 Track	4.5197	-2.3992
2	5	1.5 Track	4.7116	-2.3575
2	5	1.75 Track	4.7735	-2.3626
2	5	2 Track	4.7942	-2.3278

2	5	2.25 Track	4.758	-2.3456
2	5	2.5 Track	4.8401	-2.2823
2	5	2.75 Track	4.7586	-2.2847
2	5	3 Track	4.753	-2.2361
2	5	3.25 Track	4.6931	-2.3223
2	5	3.5 Track	4.7939	-2.2133
2	5	3.75 Track	4.7182	-2.1917
2	5	4 Track	4.5201	-2.2764
2	5	0.25 Treadmill	4.101	-1.5402
2	5	0.5 Treadmill	4.1125	-1.682
2	5	0.75 Treadmill	4.2216	-1.7861
2	5	1 Treadmill	4.3695	-1.7951
2	5	1.25 Treadmill	4.3891	-1.7762
2	5	1.5 Treadmill	4.3902	-1.7973
2	5	1.75 Treadmill	4.5154	-1.754
2	5	2 Treadmill	4.4976	-1.7052
2	5	2.25 Treadmill	4.3874	-1.7115
2	5	2.5 Treadmill	4.3612	-1.7328
2	5	2.75 Treadmill	4.357	-1.7533
2	5	3 Treadmill	4.3735	-1.7511
2	5	3.25 Treadmill	4.3773	-1.73
2	5	3.5 Treadmill	4.3614	-1.6924
2	5	3.75 Treadmill	4.4344	-1.6976
2	5	4 Treadmill	4.2846	-1.7068
2	6	0.25 Track	2.9719	-1.9611
2	6	0.5 Track	3.1697	-1.7557
2	6	0.75 Track	3.3436	-1.589
2	6	1 Track	3.3216	-1.5946
2	6	1.25 Track	3.4407	-1.5311
2	6	1.5 Track	3.3873	-1.5011
2	6	1.75 Track	3.3731	-1.4971
2	6	2 Track	3.403	-1.4785
2	6	2.25 Track	3.4154	-1.4645
2	6	2.5 Track	3.3778	-1.4224
2	6	2.75 Track	3.3397	-1.4671
2	6	3 Track	3.3963	-1.4886
2	6	3.25 Track	3.3701	-1.4521
2	6	3.5 Track	3.4184	-1.4135
2	6	3.75 Track	3.411	-1.3989
2	6	4 Track	3.3842	-1.4108
2	6	0.25 Treadmill	2.756	-1.227
2	6	0.5 Treadmill	3.0052	-1.1924
2	6	0.75 Treadmill	3.0788	-1.0935
2	6	1 Treadmill	3.145	-1.078
2	6	1.25 Treadmill	3.2148	-1.0858
2	6	1.5 Treadmill	3.1771	-1.0815
2	6	1.75 Treadmill	3.2912	-1.0614
2	6	2 Treadmill	3.3344	-1.052

2	6	2.25	Treadmill	3.4798	-1.0743
2	6	2.5	Treadmill	3.4031	-1.0517
2	6	2.75	Treadmill	3.3739	-1.0692
2	6	3	Treadmill	3.4152	-1.0758
2	6	3.25	Treadmill	3.4321	-1.0592
2	6	3.5	Treadmill	3.4845	-1.068
2	6	3.75	Treadmill	3.4692	-1.0727
2	6	4	Treadmill	3.6065	-1.0447
2	7	0.25	Track	3.6569	-1.7391
2	7	0.5	Track	3.8203	-1.8604
2	7	0.75	Track	4.0016	-1.7567
2	7	1	Track	4.128	-1.5611
2	7	1.25	Track	4.3747	-1.4514
2	7	1.5	Track	4.3201	-1.3833
2	7	1.75	Track	4.3771	-1.4075
2	7	2	Track	4.629	-1.3528
2	7	2.25	Track	4.568	-1.3338
2	7	2.5	Track	4.5057	-1.2871
2	7	2.75	Track	4.5278	-1.3078
2	7	3	Track	4.3741	-1.3055
2	7	3.25	Track	4.5143	-1.2121
2	7	3.5	Track	4.5158	-1.2436
2	7	3.75	Track	4.3725	-1.2961
2	7	4	Track	4.2639	-1.3363
2	7	0.25	Treadmill	3.5125	-1.1246
2	7	0.5	Treadmill	4.0558	-1.1944
2	7	0.75	Treadmill	4.6054	-1.1913
2	7	1	Treadmill	4.581	-1.2111
2	7	1.25	Treadmill	4.7285	-1.3006
2	7	1.5	Treadmill	4.7734	-1.2832
2	7	1.75	Treadmill	4.7392	-1.238
2	7	2	Treadmill	4.7234	-1.2319
2	7	2.25	Treadmill	4.6958	-1.221
2	7	2.5	Treadmill	4.5539	-1.2615
2	7	2.75	Treadmill	4.6829	-1.2208
2	7	3	Treadmill	4.6781	-1.1672
2	7	3.25	Treadmill	4.5614	-1.2082
2	7	3.5	Treadmill	4.2906	-1.1906
2	7	3.75	Treadmill	4.3514	-1.2024
2	7	4	Treadmill	4.3786	-1.2111
2	8	0.25	Track	4.6476	-2.5864
2	8	0.5	Track	4.859	-2.4513
2	8	0.75	Track	4.8694	-2.2054
2	8	1	Track	5.2393	-2.0719
2	8	1.25	Track	5.3669	-2.0564
2	8	1.5	Track	5.4219	-2.1185
2	8	1.75	Track	5.4119	-1.9863
2	8	2	Track	5.3147	-1.9764

2	8	2.25	Track	5.3541	-1.9856
2	8	2.5	Track	5.2753	-1.9376
2	8	2.75	Track	5.4163	-1.9064
2	8	3	Track	5.3611	-1.9363
2	8	3.25	Track	5.3037	-1.9012
2	8	3.5	Track	5.3528	-2.0307
2	8	3.75	Track	5.189	-2.038
2	8	4	Track	5.2048	-2.225
2	8	0.25	Treadmill	4.4444	-1.6201
2	8	0.5	Treadmill	4.7668	-1.6535
2	8	0.75	Treadmill	5.2624	-1.6192
2	8	1	Treadmill	5.7611	-1.5786
2	8	1.25	Treadmill	6.0328	-1.5266
2	8	1.5	Treadmill	6.0432	-1.481
2	8	1.75	Treadmill	5.9349	-1.4767
2	8	2	Treadmill	5.985	-1.4568
2	8	2.25	Treadmill	5.9239	-1.4769
2	8	2.5	Treadmill	5.9661	-1.4634
2	8	2.75	Treadmill	5.9515	-1.4764
2	8	3	Treadmill	5.9595	-1.4567
2	8	3.25	Treadmill	5.7922	-1.4765
2	8	3.5	Treadmill	5.8244	-1.493
2	8	3.75	Treadmill	5.9541	-1.447
2	8	4	Treadmill	5.8743	-1.478
3	9	0.25	Track	3.8216	-1.7378
3	9	0.5	Track	4.2088	-1.5942
3	9	0.75	Track	4.4461	-1.6063
3	9	1	Track	4.4399	-1.6246
3	9	1.25	Track	4.5198	-1.647
3	9	1.5	Track	4.5847	-1.6623
3	9	1.75	Track	4.5563	-1.7436
3	9	2	Track	4.5514	-1.7709
3	9	2.25	Track	4.5325	-1.7479
3	9	2.5	Track	4.5027	-1.7492
3	9	2.75	Track	4.5778	-1.7693
3	9	3	Track	4.6111	-1.7615
3	9	3.25	Track	4.6078	-1.7339
3	9	3.5	Track	4.6453	-1.7834
3	9	3.75	Track	4.6148	-1.7476
3	9	4	Track	4.5739	-1.6995
3	9	0.25	Treadmill	3.4068	-1.2682
3	9	0.5	Treadmill	3.9224	-1.3481
3	9	0.75	Treadmill	4.1289	-1.4098
3	9	1	Treadmill	4.4088	-1.4866
3	9	1.25	Treadmill	4.5675	-1.5481
3	9	1.5	Treadmill	4.6165	-1.5576
3	9	1.75	Treadmill	4.5976	-1.5624
3	9	2	Treadmill	4.6468	-1.5776

3	9	2.25	Treadmill	4.7327	-1.6031
3	9	2.5	Treadmill	4.7868	-1.6133
3	9	2.75	Treadmill	4.684	-1.5945
3	9	3	Treadmill	4.7726	-1.5867
3	9	3.25	Treadmill	4.7405	-1.5873
3	9	3.5	Treadmill	4.8	-1.6526
3	9	3.75	Treadmill	4.8518	-1.6439
3	9	4	Treadmill	4.9141	-1.6259
3	10	0.25	Track	3.8817	-1.1385
3	10	0.5	Track	3.8148	-1.1632
3	10	0.75	Track	4.0054	-1.1769
3	10	1	Track	4.1812	-1.2153
3	10	1.25	Track	4.3099	-1.2152
3	10	1.5	Track	4.3551	-1.2337
3	10	1.75	Track	4.207	-1.2067
3	10	2	Track	4.2765	-1.1837
3	10	2.25	Track	4.3219	-1.1669
3	10	2.5	Track	4.4259	-1.2049
3	10	2.75	Track	4.4619	-1.2176
3	10	3	Track	4.4862	-1.2237
3	10	3.25	Track	4.7081	-1.2627
3	10	3.5	Track	4.6182	-1.2805
3	10	3.75	Track	4.4168	-1.2499
3	10	4	Track	4.6732	-1.2956
3	10	0.25	Treadmill	3.811	-0.9307
3	10	0.5	Treadmill	3.9296	-1.0012
3	10	0.75	Treadmill	4.1044	-1.0237
3	10	1	Treadmill	4.1496	-1.0254
3	10	1.25	Treadmill	4.1664	-0.9889
3	10	1.5	Treadmill	4.2625	-1.0148
3	10	1.75	Treadmill	4.2117	-1.0319
3	10	2	Treadmill	4.2659	-0.9758
3	10	2.25	Treadmill	4.2908	-0.9803
3	10	2.5	Treadmill	4.2583	-0.9747
3	10	2.75	Treadmill	4.3176	-0.9558
3	10	3	Treadmill	4.4614	-0.9553
3	10	3.25	Treadmill	4.4656	-0.9605
3	10	3.5	Treadmill	4.4569	-0.9569
3	10	3.75	Treadmill	4.3421	-0.9328
3	10	4	Treadmill	4.3208	-0.9496
3	11	0.25	Track	3.0238	-1.751
3	11	0.5	Track	2.9984	-1.6268
3	11	0.75	Track	3.0935	-1.5539
3	11	1	Track	3.1708	-1.5136
3	11	1.25	Track	3.1656	-1.4982
3	11	1.5	Track	3.2331	-1.4417
3	11	1.75	Track	3.2387	-1.3975
3	11	2	Track	3.323	-1.3409

3	11	2.25	Track	3.4299	-1.3477
3	11	2.5	Track	3.3963	-1.3292
3	11	2.75	Track	3.3194	-1.3432
3	11	3	Track	3.3243	-1.2969
3	11	3.25	Track	3.4652	-1.299
3	11	3.5	Track	3.481	-1.2967
3	11	3.75	Track	3.3799	-1.207
3	11	4	Track	3.4858	-1.275
3	11	0.25	Treadmill	3.3019	-1.4867
3	11	0.5	Treadmill	3.4541	-1.5144
3	11	0.75	Treadmill	3.6488	-1.4724
3	11	1	Treadmill	3.7763	-1.4783
3	11	1.25	Treadmill	3.7658	-1.4807
3	11	1.5	Treadmill	3.7024	-1.4448
3	11	1.75	Treadmill	3.7822	-1.4226
3	11	2	Treadmill	3.8002	-1.4059
3	11	2.25	Treadmill	3.8182	-1.3784
3	11	2.5	Treadmill	3.8722	-1.3931
3	11	2.75	Treadmill	3.8488	-1.4069
3	11	3	Treadmill	3.8602	-1.391
3	11	3.25	Treadmill	3.8356	-1.3956
3	11	3.5	Treadmill	3.7895	-1.4251
3	11	3.75	Treadmill	3.8829	-1.3706
3	11	4	Treadmill	3.8681	-1.3512
3	12	0.25	Track	2.6923	-1.6503
3	12	0.5	Track	2.7174	-1.6195
3	12	0.75	Track	2.7324	-1.5704
3	12	1	Track	2.8462	-1.5348
3	12	1.25	Track	2.9197	-1.5276
3	12	1.5	Track	2.8469	-1.5278
3	12	1.75	Track	2.8593	-1.5098
3	12	2	Track	2.8944	-1.4908
3	12	2.25	Track	2.9459	-1.4911
3	12	2.5	Track	2.9117	-1.5316
3	12	2.75	Track	2.8739	-1.5474
3	12	3	Track	2.8369	-1.5465
3	12	3.25	Track	2.8388	-1.5627
3	12	3.5	Track	2.8162	-1.6261
3	12	3.75	Track	2.8204	-1.6525
3	12	4	Track	2.8159	-1.6678
3	12	0.25	Treadmill	2.5762	-1.7544
3	12	0.5	Treadmill	2.6196	-1.8111
3	12	0.75	Treadmill	2.6569	-1.8683
3	12	1	Treadmill	2.6013	-1.8491
3	12	1.25	Treadmill	2.6457	-1.8759
3	12	1.5	Treadmill	2.5954	-1.8901
3	12	1.75	Treadmill	2.6216	-1.8988
3	12	2	Treadmill	2.6215	-1.8677

3	12	2.25	Treadmill	2.6375	-1.8843
3	12	2.5	Treadmill	2.656	-1.8949
3	12	2.75	Treadmill	2.701	-1.8869
3	12	3	Treadmill	2.692	-1.8798
3	12	3.25	Treadmill	2.7255	-1.8981
3	12	3.5	Treadmill	2.731	-1.8843
3	12	3.75	Treadmill	2.7938	-1.9002
3	12	4	Treadmill	2.759	-1.9114