EFFECTS OF BANKED-CURVES ON ANKLE AND KNEE KINEMATICS DURING RUNNING

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PREFACE

Contribution of Authors

This study was conducted under the co-supervision of Dr. Sophie J. De Serres and Dr. David J. Pearsall, who contributed intellectually to the conception and design of the study, the analysis and interpretation of the results, and assisted endlessly in the revision of the manuscript. I, Luc De Garie, acted as the principal investigator, responsible for recruiting and screening the runners from the McGill Track and Field Team in order to determine their eligibility into the study, data collection and the subsequent analysis and written presentation of the manuscript.

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Abstract

Given that a greater injury incidence has been shown for indoor versus outdoor running tracks, attention to mechanical differences in curve running is warranted. Hence, the main objective of this study was to compare knee and ankle kinematics of runners while running on an indoor track with a flat curve and a banked-curve in young elite runners. Six elite runners participated in the study. Knee and ankle kinematics were measured while the subjects ran on a flat curve and a 19% banked-curve. No significant differences were observed in left and right knee and ankle peak angular displacements between the two different curves. Angular displacements measured have demonstrated similar profiles to those presented in previous studies. However, significant differences were found in body lean angle between speeds but not between curve inclinations. In conclusion, the results suggest that curve inclination does not perturb lower limb kinematics for elite runners.

Abrégé

Il a été démontré que le taux de blessures causées par la course à pied est plus élevé lors de la pratique de ce sport sur une piste de course intérieure que sur une piste extérieure. Le but de cette étude était d'examiner les effets d'une courbe inclinée intérieure sur la cinématique de la cheville et du genou lors de la course à pied chez de jeunes coureurs compétitifs. Six coureurs de niveau compétitif ont participés à cette étude. La cinématique du genou et de la cheville a été mesurée lors de la course sur une courbe horizontale et sur une courbe inclinée à 19%. Aucune différence significative n'a été observée au niveau des sommets des déplacements angulaires de la cheville et du genou des deux jambes entre les deux types de courbes. Les déplacements angulaires mesurés ont démontré des patrons similaires à ceux présentés dans des études antérieures. Toutefois, en examinant l'inclinaison du tronc des sujets, nous avons observé une différence significative selon la vitesse mais non selon le type de courbe. En conclusion, ces résultats suggèrent qu'une inclinaison de courbe n'a probablement aucune conséquence clinique chez des coureurs élites.

CHAPTER 1

BACKGROUND AND OBJECTIVES

Despite extensive investigation, the etiology, incidence, and prevalence of running injuries is still poorly understood. In part to address these concerns, some researchers have evaluated the biomechanics of running. These studies have been primarily delimited to linear direction contexts, whereas, little attention has been focused on non-linear or even banked-curve conditions that are common in indoor running tracks.

Though, little evidence can be found in the literature on the influence of indoor tracks with or without banked-curves on the biomechanics of running; the rate of running injuries has been shown to be greater in indoor versus outdoor track running and the knee is the most affected joint. There may be a relationship between the configuration of indoor tracks and the prevalence of injuries. To begin to address these concerns, the main objective of this study was to compare knee and ankle kinematics of runners while running on an indoor track with a flat curve and a banked curve.

1.1 BACKGROUND

1.1.1 The importance of having a healthy lifestyle

Physical activity has many positive effects on the human body (Russell et al. 1995). One of these is to decrease the risk of several chronic pathological conditions, including coronary heart disease, hypertension, diabetes, osteoporosis, anxiety and depression (Russell et al. 1995; Powell and Blair 1994). Elvasky et al. (2005) also showed that changes in physical activity over a 4-year period were related to increases in physical self-esteem and positive affect with the latter having a direct improvement in quality of life. Even if a large portion of the population is aware of this, developing regular exercise habits is a lifestyle change that many people find difficult to make (Silverthorn, 1998). It is purported that the earlier in life an individual becomes physically active the greater is the increase in positive health benefits (Kell et al. 2001). One of the most popular forms of recreational physical activity is jogging or running, since it is relatively inexpensive and scheduling is easy. However, this form of physical activity may lead to task specific injuries predominantly to the lower limbs (Macera, 1992). In geographic regions where snow accumulates, this problem is exacerbated by the often slippery conditions. To accommodate for this seasonal barrier, indoor running facilities have been made available, from fitness facilities with running treadmills to various forms of running tracks.

Given the motivations to pursue a healthy lifestyle a number of people choose running as the activity of choice, even though running has inherent risks as seen earlier. Similar to my personal experience as a coach and a physical therapist, most people organize their training regime to maximize the benefits of physical training and at the same time minimize injuries, thus yielding the greatest benefit in terms of quality of life to the individual.

1.1.2 Prevalence and etiology of running injuries

Running injuries have been reported extensively in the literature (Lanese et al. 1990; Lysholm et al. 1987; Beukeboom et al. 2002; Taunton et al. 2002; Fredericson et al. 1999; Brunet et al. 1990; Orchard et al. 1996; Mechelen, 1992; Hoeberigs, 1992; Jones et al. 1994; Wen et al. 1997; Hootman et al. 2002; Taunton et al. 2003). There is some discordance in the rates reported and this is most probably due to the lack of a standard injury definition and the various design and protocols used. These varied from retrospective to prospective design and from medically supervised training to survey sent to a group of runners. The actual reports of the proportion of injured runners in a year vary from 25 to 65% (Mechelen, 1992; Hoeberigs, 1992; Jones et al. 1994; Wen et al. 1997; Hootman et al. 2002; Taunton et al. 2003). For example, in Taunton et al. (2003), some of the participating clinics registered injury rates as high as 48%, whereas other clinics reported rates below 20%. Differences in the rate of injury between outdoor and indoor track running have also been demonstrated (Lanese et al. 1990; Lysholm et al. 1987; Beukeboom et al. 2002), and it is clear that indoor running increases the risk for injury. For example, Lanese et al. (1990) reported an injury rate of 1.65 injuries per 1000 hours for an indoor track season compared to an injury rate of 1.25 injuries per 1000 hours for an outdoor track season. A study by Lysholm et al. (1987) showed the number of injuries per 1000 hours of training to vary between 2.5 in long distance runners and 5.8 in sprinters for outdoor track running. Beukeboom et al. (2002) reported for their part that a large proportion of athletes (68%) were injured during the indoor season. An injury rate of 7.5 injuries per 1000 person-hours of sport exposure was determined. I believe that Beukeboom's study gives a good picture of the reality, mainly because of the controlled environment and also the clearly defined injury definition which were used in the study.

In contrast, there is a consensus in the literature about the sites of injuries. The most common site of injury is the knee, accounting for 20 to 40% of all injuries (Taunton et al. 2002; Fredericson et al. 1999; Brunet et al. 1990; Mechelen, 1992; Wen et al. 1997; Taunton et al. 2003). Within this proportion, the most common injury is the patellofemoral pain syndrome, followed by the iliotibial band friction syndrome, followed by meniscal injuries (Taunton et al. 2002; Fredericson et al. 1999). Injuries may result from a combination of training errors (including lack of specific strength and flexibility), inappropriate surface and terrain, biomechanical lower extremity misalignment (for example rearfoot pronation), and inappropriate footwear (Taunton et al. 2002). The effect of rearfoot pronation has been linked to injuries in runners (Messier et al. 1991, Duffey et al. 2000). They found less pronation and a slower pronation rate during the early stance phase in injured subjects. Another factor that is related to running injuries is the level of impact forces. Hreljac et al. (2000) reported that non-injured runners had lower vertical impact force peak and the maximum vertical loading rates. However, there are also some discrepancies in the results. Brunet et al. (1990) reported a strong correlation between anatomical imbalances (leg length discrepancy) and the incidence of running injuries. For example, Pinshaw et al. (1984) reported that leg length discrepancy was present in 37% of runners with iliotibial band friction syndrome. The association between leg length inequality and increased injury rate should alert the running community to the risk associated with this relatively common condition. Running on cambered roads has been implicated as a possible cause of iliotibial band friction syndrome, mainly because it induces an artificial anatomical imbalance (Messier, 1995).

One of the most common injuries, the iliotibial band friction syndrome, is believed to be caused by excessive rubbing of the band over the lateral epicondyle of the femur during sporting activity when the knee is flexed to approximately 20 to 30 degrees (Fu and Stone 1994). In addition to having increased leg length discrepancy, with the syndrome developing in the shorter leg (Pinshaw et al. 1984), runners with iliotibial band friction syndrome have been shown to have increased forefoot varus, and increased knee Q-angles compared with controls (Schwellnus, 1993). Orchard et al. (1996) also looked at the biomechanics of the iliotibial band friction syndrome. However, their study showed no significant differences between the knee angles of the affected and unaffected legs. Nevertheless, the affected knee was positioned more in extension at foot strike compared with the unaffected knee. This is linked with the fact that runners with leg length discrepancies will extend the knee of the shorter leg to functionally lengthen it. Downhill running and running at slower speeds are conditions which also cause the knee to be less flexed at foot strike, and which predispose the athlete to the development of iliotibial band friction syndrome (Orchard et al. 1996). The postural adaptations to these conditions resembled adaptations for the shorter leg of individuals with a leg length discrepancy of more than 2 cm during walking. More specifically on the short side, the main changes during stance were increases in knee extension and ankle plantarflexion (Walsh et al. 2000).

1.1.3 Running biomechanics

Running biomechanics on flat surfaces has been the most extensively researched condition. Novacheck (1998) gave a very good overview of running biomechanics, where he indicated that: (1) the differentiation between walking and running happens when the double support period gives way to a double float period. This phenomenon is due to a difference in the stance phase duration; (2) In walking, the stance phase period is about 60% of the gait cycle while it is less than 50% in running; (3) The timing of toe-off depends on the speed. There is actually less time spent in stance as the speed increases. So toe-off occurs at 39% of the gait cycle in running and at 36% of the gait cycle in sprinting.

Novachek (1998) also explained that during running, the angular displacement profile of the knee is similar to walking but with a greater range of motion (ROM). The knee will flex on average to 45° during the stance phase of running. It then extends to about 25° of flexion during the propulsion phase. When sprinting, the absorption period of the stance phase is shorter and the knee flexes less. During the propulsion phase, the knee extends more, peaking at 20°. Although the sagittal kinematic profiles are similar for running and sprinting, knee flexion during the swing phase is greater in sprinting than in running. The averaged knee flexion during swing is 90° during running (3.2 m/s) and 105° during sprinting

(9.0 m/s).

Initial contact during walking and running occurs with the heel, but a greater ankle dorsiflexion is required during running. The most typical distinction between running and sprinting is that initial contact goes from the hindfoot to the forefoot, respectively. Maximum dorsiflexion during stance phase in sprinting is less than in running because of the relatively neutral position at initial contact and the shorter duration of the absorption period. Accordingly, maximum plantarflexion during the propulsion phase is greater in sprinting than in running. The timing of maximum plantarflexion/dorsiflexion occurs earlier with increasing speed.

1.1.4 Running on indoor tracks

The direction of track running in a competition has been counter-clockwise for a long time. It is also a rule by the International Association of Athletics Federations which state that the direction of running shall be left-hand inside (IAAF Handbook 2002). Because runners spend a lot of time training, this consistent running direction could lead to muscle imbalance due to changes in force components. Since indoor tracks have a smaller curve radius than outdoor tracks, there is an increase in the centripetal force. Beukeboom et al. (2002) stated that following an indoor running season, the invertor muscles of the left ankle increased in strength significantly more than the invertor muscles of the right ankle. Similarly, the evertor muscles of the right ankle increased in strength significantly more than the evertor muscles of the left ankle.

1.1.5 The effect of slope on walking and running

It is well known that walking on slopes affect the gait pattern (Kuster et al. 1995; Leroux et al. 2002). There are also differences in the adaptation of the lower limb when comparing uphill and downhill walking. Leroux et al. (2002) demonstrated that there was an increased flexion in the hip, knee and ankle joints during the mid-swing to early stance phase of uphill walking gait cycle. This greater joint flexion requirement augmented with increased slope. During uphill walking, the increased hip flexion at the end of the swing phase may contribute to increased stride length. During downslope walking, the main features were observed at the hip and knee (Leroux et al. 2002). At the hip level, a decreased flexion was observed during late swing to early stance. For the knee, an increased flexion was observed during early and late stance (Kuster et al. 1995; Leroux et al. 2002). However, Kuster et al. (1995) found that the ankle position at toe-off was significantly less plantarflexed, but their study was done on level ground and on a negative slope of 19% compared to a -10 to 10% slope in the Leroux study. Another important distinction in their protocols is that the study by Leroux et al. was conducted on a treadmill and the other study was conducted on a walking platform.

As for running, there was a study by Paradisis and Cooke (2001) which looked at the kinematics and postural characteristics associated with sprinting on 3 degree uphill and downhill slopes and on level surface. During downhill running, they found the step length to be significantly longer when compared to level running. Again during downhill running, the leg angle (the angle between the leg and the running surface) was greater (i.e., the ankle was more plantarflexed), the knee was more extended and the hip was less flexed at initial contact when compared to level running. At toe-off, the angles were smaller for the leg (i.e., ankle more plantarflexed) and knee (i.e., more flexed) during downhill compared to level running.

During uphill running, the step length was significantly shorter when compared to horizontal running. The leg angle was also significantly reduced (i.e., ankle more dorsiflexed) and, when combined with a more forward trunk position, it explained the reduction in step length. At toe-off, there was also a reduction in the leg and knee angles, thus a more dorsiflexed ankle and a more flexed knee.

1.1.6 The effect of sideslope on walking and running

A minimal amount of information about gait on sideslope is available in the literature. In 2000, with subjects walking on a straight walkway with a right to left down slope (or roll), we found significant differences in the range of motion between the uphill and downhill knees and confirmed the hypothesis that there were asymmetries produced in gait when walking on a transversely inclined surface (20% and 40%; De Garie and Pearsall, 2000). It was a pilot study that led to the present study. During the swing phase, uphill knee flexion increased steadily as the slope increased, while downhill knee flexion decreased. Peak knee flexion during stance in the uphill knee increased with slope. For the downhill knee, peak knee flexion during stance phase increased from 0 to 20% inclination, and then decreased from 20 to 40%. In addition, on a 20% slope, there was a tendency for the downhill knee to be more flexed than the uphill knee during the stance phase. Averaged knee angle measures are shown in Table 1.1. This trend suggests that we have different adaptation techniques for different slopes. Further studies with greater sample sizes are required to confirm these results and look at the adaptation at the ankle level. Post-hoc analysis (Tukey HSD) identified significant differences in the peak knee flexion of the uphill knee between slopes of 0 and 20%, and between 20 and 40%. The difference between the ROM of the uphill knee and the downhill knee were nearly significant ($p=0.07$). Near significant differences in minimum stance phase knee flexion were also seen with the uphill knee between slopes of 0 and 40%.

Table 1.1 Grouped knee flexion averages in degrees

	INCLINE (% SLOPE)		
VARIABLES	0%	20%	40%
UH MAX ST	15.4	16.1	22.1
UH MIN ST (TO)	7.1	7.6	11.8
UH MAX SW	54.9	60.9	65.6
DH MAX ST	15.4	18.8	17.1
DH MIN ST (TO)	7.1	9.5	8.0
DH MAX SW	54.9	51.6	47.9

(UH) uphill, (DH) downhill, (MAX ST) peak knee flexion in stance, (MIN ST) minimum knee flexion at toe-off, (MAX SW) peak knee flexion in swing

Nicolaou and Pearsall (2002) also found significant joint angle differences in both lower limbs. More specifically, the knee positioned on the lowest side of the platform was more extended for both 5 and 10% slope when compared to a levelled surface. Urry et al. (2002) demonstrated that walking on sideslopes significantly altered the pressure distribution beneath the foot. In the lower limb positioned on the highest side of the platform, pressure increased significantly beneath the lateral structures of the foot and decreased significantly under the first metatarsal head and big toe. In the lower limb positioned on the lowest side of the platform, pressure increased beneath the first metatarsal head. It is important to note that these significant increases occurred for sideslopes as little as 2 degrees.

Sussman et al. (2001) reported that running on a treadmill at 6 or 7 mph with a lateral inclination of 2.5 and 5 degrees significantly affected the knee range of motion during running. A greater knee flexion at initial contact and toe-off for the uphill leg, and a greater knee extension for the downhill leg at all conditions and velocities were observed.

1.1.7 Running on banked and non-banked curves

Regarding running on a curved track, early work was done by Peter Greene during the mid-nineteen eighties. His concerns were mainly related to the effects of running on flat curves on the maximal running speed. In his first study, he concluded that the reduction in speed associated with running on curves with a smaller radius was due to an increased foot contact time (Greene 1985). This means that when racing on oval tracks, the outermost lanes will have a speed advantage over the innermost lanes with smaller curve radius (Greene 1985; Ryan et al. 2003).

In a second study (Greene 1987), he studied the effect of banked-curve running on maximum speed and heel-over angle of the runner. Running along a flat curve is, at the same speed and radius, more demanding than running on a banked turn. The most efficient reduction in forces put on the runner is when the heel-over angle of that runner is equal to the banking angle of the track (Greene 1987). Greene used the term heel-over angle to mention that a runner inclines his body from a vertical position. The optimal bank angle is dependent on the running speed and on the radius of the curve. According to these conditions the track may be underbanked, optimally banked, or overbanked (Greene 1987). He investigated the effects of running on four different bank angles and with three different curve radii. He showed that bank angle effects can produce a 10% difference in the speed of the runner. A mismatch between the bank and the heel-over angle of 30 degrees will produce a decrease in speed of 11%.

Regarding the kinematics of running on a curve banked and non-banked, rare are the studies that have been published. Ryan et al. (2003) examined the effect of bend radius on lower limb kinematics. Thirteen competitive sprinters (eight men and five women) were included in this study. The subjects were required to sprint at maximum speed over a 70 m section of track including a curved section of at least 33 m. Those sprints were accomplished on four different bend radii: indoor lanes 1 and 4 (r=10.5 m and 13.5 m respectively) and outdoor lanes 1 and 8 (r=36.5 m and 45.04 m respectively). The indoor lanes were banked on the curves, but the amount of banking was not given. Kinematics was calculated from video analysis with the subjects wearing circular retro-reflective tape markers for identification of joint centers.

Their data showed a general trend towards greater knee flexion during the stance phase in the indoor lane 1 compared with the outdoor lane 8 conditions. It actually accounts for a 35m difference between the radii of the 2 lanes. These differences could be linked to the fact that indoor banked-curves increase ground reaction forces (due to centrifugal forces) causing greater flexion in the knee. This trend was also greater in the left knee compared with the right, which could suggest an asymmetrical effect of bend radius on limb kinematics. However, the statistical analysis of the joint amplitude data found no significant main effect for the bend radius. On the other hand, the statistical analysis demonstrated significant bend-related and not banking effects on all the other variables: stride length, stride frequency, stance phase duration and running speed. More specifically, running speed and stride length increased progressively as radius increased. Stance phase duration decreased as bend radius increased up to a radius of 36.5 m and then remained constant.

1.1.8 Leg length discrepancy

Running on a curve, banked or non-banked, is likely to mimic the effects of running with a leg length discrepancy when the speed is not optimal for the inclination of the surface (either too fast or too slow). On a banked-curve, the inside leg would be analogous to the short leg and the outside leg would be similar to the long leg when the runner is going too slowly. When the runner is going too fast, the inside leg would be analogous to the long leg and the outside leg would be similar to the short leg on both banked and non-banked curves. In his review of the literature on leg length discrepancy, Gurney (2002) stated that the discrepancy needed to be in excess of 19 mm before running parameters are affected. For example, Bloedel et al. (1995) found no significant differences in the maximum amount of calcaneal inversion and eversion ranges of motion for subjects with a leg length discrepancy between 12.7 and 19 mm. Gurney (2002) also reported that persons with long standing true leg length discrepancies are able to cope with larger leg length discrepancy than those who are subjected to artificial or induced leg length discrepancy. Artificial leg length discrepancy refers to a leg length that is not induced by anthropometric differences between both lower extremities (for example shoe insert or sideslope).

Walsh et al. (2000) examined the main compensatory mechanisms of a normal population in response to an artificially imposed leg length discrepancy of using a motion analysis system. The discrepancy was induced by inserting a raise under one of the shoes. The raises were from 0 to 50 mm increasing by 10 mm increment. During the stance phase of walking, the long side hip and knee became more flexed while the ankle became more dorsiflexed. On the short side, the main changes during stance were increased knee extension and ankle plantarflexion. The most common mechanism for dealing with minor degrees of limb length discrepancy was the induction of pelvic obliquity. This pelvic obliquity appeared to be the common manner for dealing with small amounts of leg length discrepancy up to about 20 mm. With discrepancies above 20 mm, significant changes in knee flexion occurred. While pelvic obliquity does not require substantial energy expenditure for short time duration, muscle recruitment will most likely be different. Nevertheless, the maintenance of knee flexion may put considerable extra pressure on the knee extensor mechanism. The combination of these changes have the effect of shortening the long limb both in the stance and swing phases while lengthening the shorter limb during the stance phase.

1.2 RATIONALE FOR THE PRESENT STUDY

The biomechanics of running on level surfaces have been extensively researched, but little evidence can be found in the literature on the biomechanical influence of running on indoor tracks with or without banked-curves and running on lateral inclines (Beukeboom et al. 2002, Fujii et al. 1999, Sussman et al. 2001, Ryan et al. 2003). With the emergence of indoor running tracks, more and more runners move their winter training to these warm and dry environments.

1.3 OBJECTIVES AND HYPOTHESES

The first objective of this study was to determine the effects of an indoor-banked curve on running kinematics at the knee and ankle, and on body lean angle in young healthy elite runners. These effects were quantified by comparing the knee and ankle angular displacements and body lean angle when running on an indoor track with or without curve inclinations.

The second objective of this study was to examine whether these effects were altered by the running speed.

The first hypothesis was that knee and ankle kinematics of banked-curve running are expected to resemble running kinematics of individuals with leg length discrepancies. More specifically, the knee should be more extended during the stance phase on the inside leg (downhill leg analogous to the short leg in leg length discrepancy) to functionally lengthen the limb. The knee should be more flexed during stance phase on the outside leg (uphill leg analogous to the long leg) to functionally shorten the limb. The inside ankle should be less everted and the outside ankle should be less inverted throughout the stance phase. For the plantarflexion and dorsiflexion movements, we expected to see an increased plantarflexion at push-off for the inside leg and an increased dorsiflexion in stance phase as well as a decreased plantarflexion at push-off for the outside leg. More specifically, the null hypothesis stated that no changes in kinematics are observed between running on a levelled curve and a banked-curve.

The second hypothesis is that we expected to see a greater similarity in kinematics between leg length discrepancy and slower running speed than with faster running speed. In addition, we expected the runners to keep their body perpendicular to the track at 3.8 m/s on the levelled curve and at 7.0 m/s on the 19% banked curve. In contrast, we expected the runners to incline their body inward during running at 7.0 m/s on the levelled curve and to keep their body vertically aligned at 3.8 m/s on the 19% banked curve. The null hypothesis stated that no changes in body lean angle are observed between running on a levelled curve and a banked-curve.

CHAPTER 2

METHODS AND PROCEDURES

2.1 Subjects

Six males were included in the study after the completion of a written informed consent (Appendix I). All were elite runners from the McGill Track and Field Team with no recent history of injury to the pelvis, trunk, or lower leg nor leg length inequality greater than 5 mm. Each participant was required to complete a medical history questionnaire on injury and training history prior to participation to account for experience (APPENDIX II). The questionnaire was used as a screening process. The mean (± SD) age, height, body mass, and leg lengths of the participants were: 19.3 ± 1.1 years, 177.3 ± 5.4 cm, 67.2 ± 4.2 kg, 92.1 ± 3.1 cm for the right leg, and 91.7 ± 3.0 cm for the left leg, respectively (see Table IV.1 in Appendix IV). For subjects training history see Table IV.2. The subjects included in the study suited the following criteria: (1) they had to be elite runners between the ages of 18 to 35 years, and (2) free of any injury to the lower limbs, pelvis and trunk. Subjects who had any previous lower limb surgery or leg length discrepancy greater than 5mm were excluded from the study.

The target population for this study was the group of individuals who run on a banked-curve indoor running track as part of their exercise regimen or sports training program. Hence elite runners were the target group of interest.

To control for the inclusion and exclusion criteria, an injury definition (adapted from Beukeboom et al., 2002) was created and leg length was measured before the subjects were included in the study. Injury was defined using an adaptation of the definition created by and was: any physical incident reported to a trainer, or a medical clinic, that resulted in cessation, reduction, or alteration in training. We used this definition because it included any incident, even if it was not related to running. This definition was also operational and clear.

Given the specialized environmental context of our research project, discriminating our target population was still warranted. Elite runners were individuals who train regularly for mid to long distance running competition (800 m, 1500 m, and 3000 m). Knowing the substantial amount of time required by this group of individuals to train within this environment, addressing the mechanics of indoor track running is relevant to them.

2.1.1 Sample Size

The primary outcome used for sample size calculation was stance phase knee flexion, as measured during running in the two different conditions (banked and unbanked curves). Some indication of the expected magnitude of joint angular changes may be inferred from De Garie et al. (2000), who reported changes of the order of 3-7 degrees for peak knee flexion during stance phase in walking. Since joint ROM in running is greater than in walking, we expected a difference between knee flexion at mid-stance of 5-10 degrees. Using the Power/Sample Size Calculator (http://www.univie.ac.at/medstat/n2.html) to make inference for means comparing two independent samples or conditions, the sample size required was five subjects. Sample size has been calculated with a smaller effect size to provide us with enough statistical power (80%) if the change in the outcome was smaller than we expected. Therefore, using 6 subjects allowed us to make significant inference with three standard deviations or when the effect size was greater than 4 degrees.

2.2 Experimental Procedure

Following the presentation of the project, subjects were asked to read and sign the consent form (Appendix I). Following this, the pre-study medical history questionnaire was administered, a copy of which is included in Appendix II. Anthropometric measurements including height, weight and leg length were collected. Height was measured using a wall-mounted tape measure to the nearest 0.1 cm. Subjects were barefoot. Body mass was measured using the Tanita BF 350 scale (Tanita Corp., Tokyo, Japan) and recorded to the nearest 0.1 kg. With regards to leg length discrepancy, Gurney (2002) stated that although imaging techniques (Magnetic Resonance Imaging, Computer Tomography, radiography, and three-dimensional ultrasonography) are considered to be the most accurate method for determining leg length discrepancy, they are costly, time consuming, and in the case of radiographs and CT, the patient is exposed to radiation. Therefore direct tape measurement was used as the technique of choice in this study. Leg length was measured while each subject was standing with their shoes on. A tape measure was used to measure from the ASIS of each leg to the medial malleolus and recorded to the nearest 0.1 cm. A digital picture was also taken of each subject with reflective markers placed on each ASIS using a Cannon Power Shot S30 (Cannon Inc., Tokyo, Japan). Preparation time was approximately thirty minutes.

The study used a within subject design with repeated measures. Knee and ankle kinematics were measured for all subjects while running on levelled and banked curves at controlled speeds. Block randomization was used to control for the effect of slope adaptation and the order effect of the different speeds. Six different blocks were used; 2 speeds and 3 conditions (Table 2.1). Speed was randomized first, then the inclination. Changing the speed after every inclination would be greatly impractical and confusing for the subjects because practice trials would have to be allowed each time. The blocks were determined by computer randomization and were inserted in envelopes prior to the beginning of the study. Each subject performed 5 running trials for each condition and speed.

Table 2.1 Randomization blocks

Running Speed	Condition
Running (3.8 m/s)	0% slope curve
	19% slope curve
	Straight
Sprinting (7.0 m/s)	0% slope curve
	19% slope curve
	Straight

Subjects were asked to perform their usual stretching and warm-up before the testing time. Once on the track, each subject was allowed a pre-trial to get accustomed to the backpack and cables during running. There was a warm-up period of 10 minutes. Any necessary adjustments to the cables were made prior to testing. Before each new speed, the subject was asked to perform 2 to 3 trials to get comfortable with that specific running speed. For each slope condition and speed, two 20 m trials were performed. The 10 m testing zone was marked clearly on the track using colour-contrasting tape. Subjects began running approximately 10 m before the testing zone in order to allow sufficient time to reach the desired speed prior to entering the zone. If runners exceeded 0.5 m/s above or below the required speed, the trial was repeated. At the beginning of each trial, runners were asked to heel strike two times with the right foot in order to trigger the inshoe footswitch to clearly mark the start of each trial within the datalogger recordings to aid subsequent data processing. At the end of each trial, subjects were instructed to slowly jog back to the starting position in order to avoid fatigue. A total of 30 trials were performed, which took approximately 10-12 minutes.

The main independent variable was the environment: it was the inclination of the curve of the indoor running track at the McGill Fieldhouse facilities. The other two independent factors were running speed and body side of measurement.

There were two inclinations, 0% and 19% for the curve and no inclination for the straight condition. The inclination of the curve is given in ratio of the rise over the run, so the inclination of 11° gives a slope ratio of 0.19 or 19%. The first condition, 0% inclination, was performed on lane A, just inside of lane 1. The second condition, 19% inclination, was performed on lane 1. The straight running condition was performed on lane 1 (see Appendix III for an illustration of the track). By using two adjacent lanes, we limited the effect of radius on the outcome. The radius for the line between lane one and the lane A (inside of lane one) was 25.25 m and the width of each lane was 0.917 m. So the radius of the midline portion of lane A was 24.79 m and of lane 1 was 25.70 m. This resulted in a difference of radius dimension of 3.5%. In addition to construction plans of the track, the curve radius and the inclination were verified by direct linear and inclinometer measures.

All conditions were performed at the two different speeds and subjects wore their own running shoes. The subjects ran at 3.8 m/s and sprinted at the optimal speed. The optimal speed (v_{opt}) was a theoretical speed at which the body should have leaned in order to keep the trunk perpendicular to the track when attacking the curve. It was calculated as follows:

$$v_{opt} = \sqrt{\tan\theta * r * g} = \sqrt{\tan 11 * 25.708 * 9.81} = 7.0 \text{ m/s}$$

where θ was the banking of the curve in degrees, r was the radius of the curve in meters and g was gravity in m/s^2 (based on the work from Greene, 1987). For lane 1, θ was 11 degrees, r

was 25.7 m and g was 9.81 m/s^2, thus we had an optimal running speed of 7.0 m/s. This formula calculated the optimal speed for the body's longitudinal axis to remain perpendicular to the ground surface. As the slope approaches 0% (i.e. a flat surface) the optimal speed would approach 0 m/s. Hypothetically, if lane A was to be banked at the same angle, the optimal running speed would have been 6.88 m/s. This resulted in a 2% speed difference. Speed was determined by time interval divided by standard distances using a stop watch. The error on the running speed was restricted to ± 0.5 m/s (14%) and with no overlap in the speed ranges.

The side of the body, whether it was the inside or the outside leg, was also considered as an exposure. Since subjects ran in the counter-clockwise direction (as viewed from above), hereafter the inside and outside legs were referred to as the left and right sides of the body, respectively. Accordingly, the right lower limb of the body was more likely to be elevated when compared to the left lower limb when running on the banked-curve, but it was always at the same level for flat running.

2.3 Data acquisition and processing

The main outcome measures were knee flexion/extension and ankle plantarflexion/dorsiflexion and inversion/eversion angles during running on the flat and banked curve. Angular displacements were measured with electrogoniometers (XM 110 Penny & Giles, UK). The knee flexion/extension was determined from the movement between the thigh and the leg. The electrogoniometer was positioned on the lateral aspect of the knee. The proximal segment was aligned with the lateral condyle of the femur. The distal segment of the electrogoniometer was positioned over the head of the fibula.

At the ankle level, plantarflexion/dorsiflexion and inversion/eversion was determined from the movement between the leg and the rear foot segments (calcaneus). For each ankle, the electrogoniometer was positioned with the proximal segment in line with the Achilles tendon on the posterior leg and the distal segment positioned on the posterior calcaneus inside the shoe. It was determined, from pilot testing, that there was no discomfort related to the placement of the electrogoniometer inside the shoe.

The electrogoniometers were held in place with adhesive Tuff-Skin tape adherent (Cramer Products Inc., Kansas, USA) and Transpore transparent medical tape (3M Corp., Minnesota, USA) and elastic stretch tape. The cables were secured to the leg using Transpore transparent medical tape and elastic stretch tape. Furthermore, the electrogoniometer cables and footswitch cables were held in place by lycra-spandex tights worn by each runner (Under Armor, Baltimore, USA). The cables from the footswitches and electrogoniometers were passed through a hole made at the bottom of a polyester backpack (Infinity Sports Imports Inc., Langley, Canada) and attached to the datalogger (Biometrics DataLOGII no.P3X8, Biometrics Ltd., Gwent, UK). The dimension of the datalogger was 158 mm by 95 mm by 33 mm with a mass of 350 g. Prior to testing on the track, each subject was asked to perform deep bends, squats and lunges to verify that the length of the cables was sufficient as to not impede regular movement during running. Before the actual testing started, static posture measurements from the electrogoniometers were collected to provide the necessary offset to adjust subsequent measures with relation to neutral. Data were recorded on a 512 MB MMC flash card (Multimedia Card ATP, Taiwan) in the DATALOGII and then downloaded to a Toshiba Portage M200 laptop computer (Toshiba Corp., China).

Subjects were also filmed running on the curve using a Sony DCR-TRV17 mini DV Camcorder (Sony Corp., Tokyo, Japan) to later determine the degree of body lean and step width for the different conditions. The subjects were filmed from the rear at a distance of 15 m from the center point of the testing zone.

2.4 Data analysis

The dependant and independent variables along with their respective type and scale are presented in Table 2.2 which includes a list of the dependent and independent variables along with their type and scale. For offline analysis, the data were downloaded in the DataLogII (Biometrics Ltd) program and then exported as binary text files for importing into MATLAB® (The MathWorks, Inc., Natick, MA) scripted processing modules. Once the data was imported, the joint angles were derived by applying predetermined calibration factor and amplitudes offset to account for the neutral positions.

The data from every trial was segmented in stride cycles (based on initial contact of one foot to the next initial contact of the same foot from foot switches and marked toe-off events). Five to ten stride cycles were selected from every trial. Valid stride cycles were selected after the acceleration phase was completed. This was determined from the actual angular displacement profiles and it usually lasted from three to five strides. This provided a total of 9 to 15 strides per condition per subject for ensemble averaging. During stance, the angles per stride cycle used for evaluation were:

- peak knee flexion and extension
- peak ankle plantarflexion and dorsiflexion
- peak ankle inversion and eversion

Table 2.2 Summary of independent and dependent variables included in the data analysis

Variables: Independent (Exposure)	Variables: Dependent (Outcome)	Definition	Scale
Condition (banked-curve, straight)	---------------	Inclination of the track in the curve 1. 0% 2. 19% Straight 1. 0%	Polychotomous
Body side	---------------	In relation to the side of the body that is closer to the center of the track 1. Inside leg 2. Outside leg	Dichotomous
Speed	---------------	Running speeds 1. run at 3.8 ± 0.5m/s 2. sprint at 7.0 ± 0.5 m/s i.e. v_{opt}	Polychotomous
---------------	Knee and ankle kinematics	Angular displacement between body segments 1. knee – flexion/extension 2. ankle – plantarflexion/ dorsiflexion and inversion/eversion	Continuous
---------------	Body lean angle	Inclination of the trunk in relation to the track	Continuous

For the conditions ran on the curve at 0% and 19%, runners were filmed from the posterior position. Three running trials for each curve condition and speed were selected using Pinnacle Studio Version 8 (Pinnacle Systems Inc., Mountain View, CA, USA) and partitioned into two strides such that it consisted of one stance phase for each leg. This was exported to Hu-m-an (HMA Technology Inc., King City, Ontario, Canada) whereby the absolute angle was calculated from the midline of the ankle when the supporting foot was in middle of stance to middle of head position (Figure 2.1). The mean value from the three captured trials was used as the body's lean angle for that condition. The body lean angle measurements were expressed relative to global vertical reference points. Since the camera was placed on the exterior side of the curve a slight leaning from the perpendicular was expected. In order to diminish error in body's lean angle calculation the results obtained were corrected by using two fixed vertical structures. The values obtained for the absolute angle from those structures were averaged and subtracted or added to the body's lean angle (Figure 2.1).

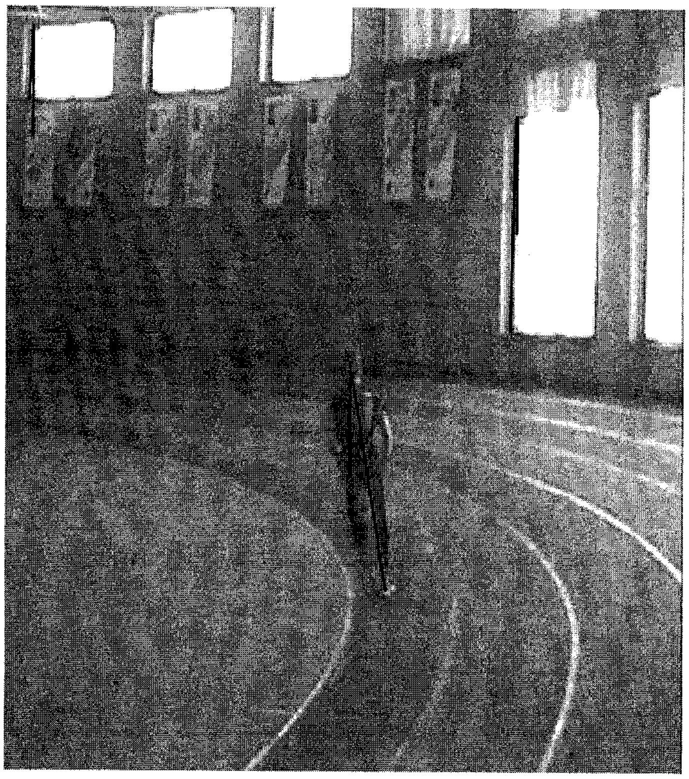


Figure 2.1 Body lean angle measurements for right leg

2.5 Statistical analysis

The analysis addressed the two objectives which were to compare knee and ankle kinematics of runners while running on an indoor track with different curve inclinations, at 2 different speeds. A 2-way ANOVA for the effect of side and condition on angular displacement with the following 2 factors was used: inclination of track and body side. The significance level was set at $\alpha = 0.05$. The Analyse-it^{TM} for Microsoft Excel (General + Clinical Laboratory statistics version 1.73) software was used.

CHAPTER 3

RESULTS

3.1 Knee and ankle kinematics

Despite consistent intrasubject knee and ankle kinematics during the stance phase, we failed to discern any differences between the left and right sides (p-values between 0.1826 and 0.9895). The averaged knee flexion angular displacement profiles for one subject are shown in Figure 3.1. The analysis of the knee and ankle kinematics revealed similar profiles for both joints on the 0% curve and the 19% banked-curve, under both speeds.

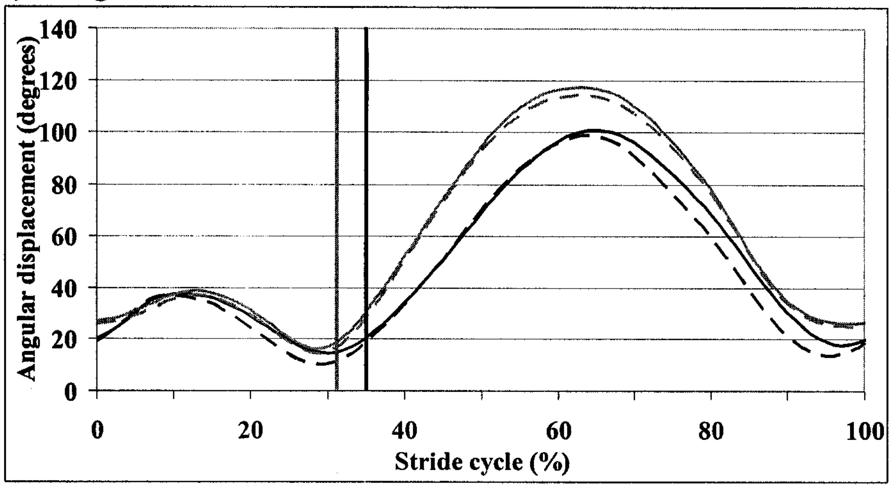
These profiles were, in general, similar for all subjects. Figures 3.2 to 3.4 show group kinematic profiles for the knee and ankle joints. These profiles resemble the patterns seen in the literature for the knee flexion/extension (Novacheck 1998), the ankle dorsiflexion/plantarflexion (Novacheck 1998) and the ankle inversion/eversion (McClay et al. 1998, Reinschmidt et al. 1997).

The knee angular displacement profile was in agreement with the literature for straight running at slow and fast speeds (Novachek 1998). Peak knee flexion happened at midstance and minimum knee flexion happened around toe-off. The angular displacement profile of the ankle plantar/dorsiflexion also reflected the profile observed in the literature. The ankle was in a relatively plantarflexed position just before initial contact. This was consistent with a midfoot striking running profile (Novachek 1998). In addition, a foot slap condition was observed just after initial contact in two of the subjects. This foot slap was a quick plantarflexion movement as the ankle went from a dorsiflexed position with the rearfoot in contact with the ground to a position where the whole foot was on the ground. Peak dorsiflexion occurred around midstance while peak stance phase plantarflexion occurred at toe-off. When looking at the inversion/eversion patterns of the ankle, the profiles are again similar to the literature although the magnitudes are different (McClay et al. 1998, Reinschmidt et al. 1997). Our results demonstrated a smaller inversion/eversion ROM than previously seen in the literature. The peak ankle eversion happened around the first third of the stance phase and peak inversion happened at toe-off.

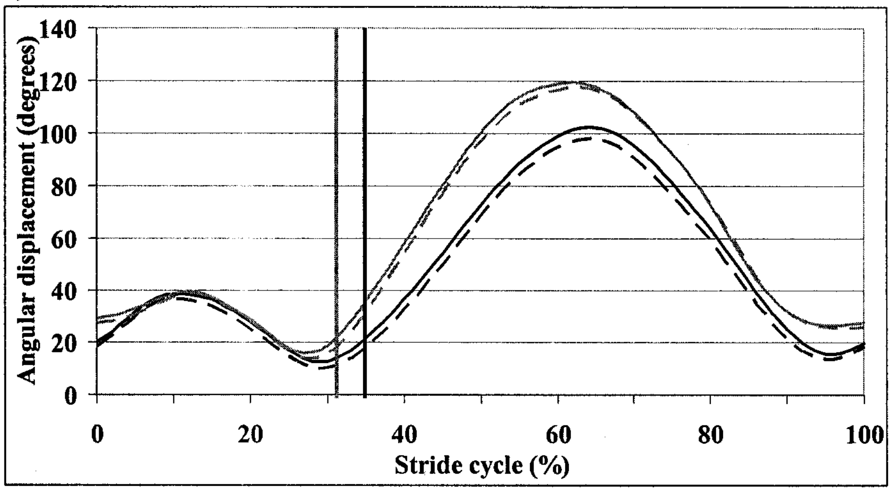
Group averages for the maximum and minimum knee flexion, peak ankle dorsiflexion, plantarflexion, inversion and eversion during the stance phase are shown in Figures 3.5 to 3.10 (data with standard deviation and p-values are shown in Appendix IV, Tables IV.3 to IV.9). When looking at peak knee flexion across speeds and conditions (Figure 3.5), we noticed that there were no statistical differences. At 7.0 m/s, the knee was slightly less flexed than at 3.8 m/s (34.4 degrees at 7.0 m/s and 36.9 degrees at 3.8 m/s). The minimum knee flexion results (Figure 3.6) showed that again the knee was a little more extended at toe off when running at faster speeds (6.5 degrees at 7.0 m/s and 8.4 degrees at 3.8 m/s). Slightly larger differences were observed for peak ankle dorsiflexion (21.1 degrees at 7.0 m/s and 18.6 degrees at 3.8 m/s) (Figure 3.7) and on the opposite, plantarflexion was slightly less at a faster speed (15.8 degrees at 7.0 m/s and 17.1 degrees at 3.8 m/s) (Figure 3.8), although not statistically significant. When running on the curves (flat and banked), the left ankle had a tendency to be more dorsiflexed than the right ankle ($p = 0.53$ at 3.8 m/s and $p = 0.258$ at 7.0 m/s) and the right ankle had a tendency to be more plantarflexed than the left ankle ($p = 0.317$ at 3.8 m/s and $p = 0.364$ at 7.0 m/s). Peak ankle eversion (Figure 3.9) also showed some differences though not significant. When running on the curve, the left and right ankle had a smaller peak eversion when running on the 0% banked-curve compared to the 19% banked-curve, a difference which was more prominent at 7.0 m/s with a p-value of 0.183.

Figure 3.1 Average knee flexion for a complete stride cycle for one subject

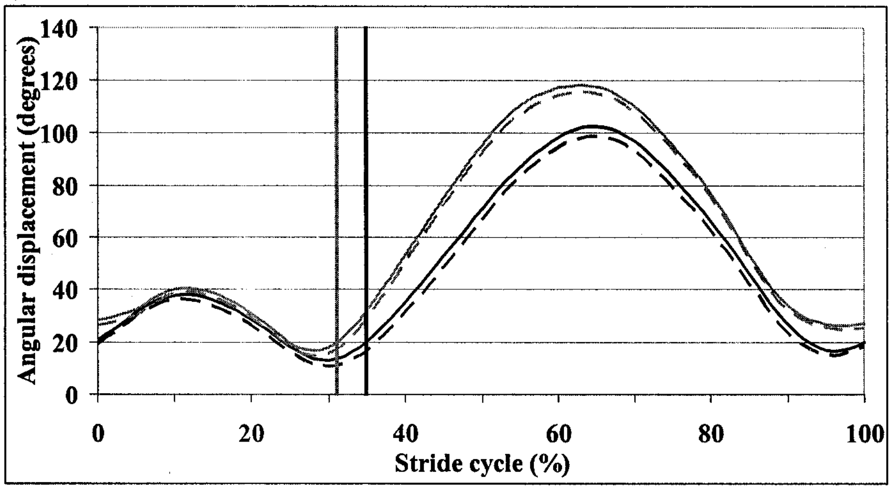
a) Straight condition



b) 0% banked-curve condition



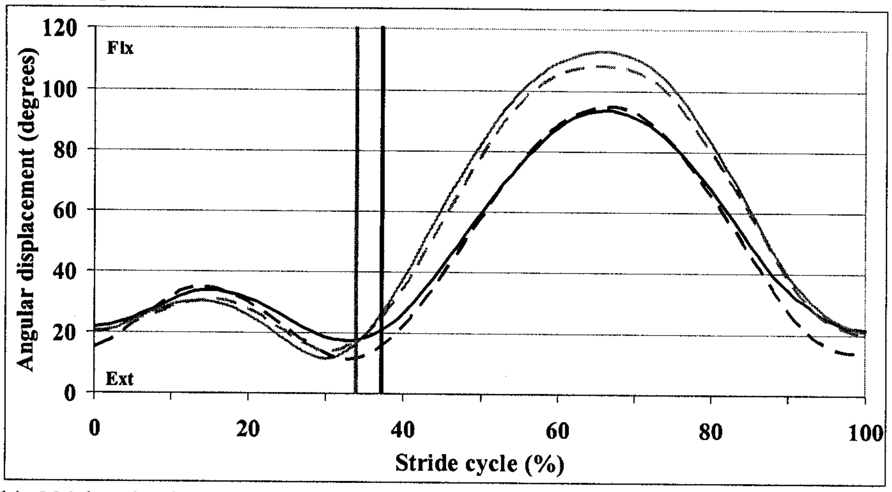
c) 19% banked-curve condition



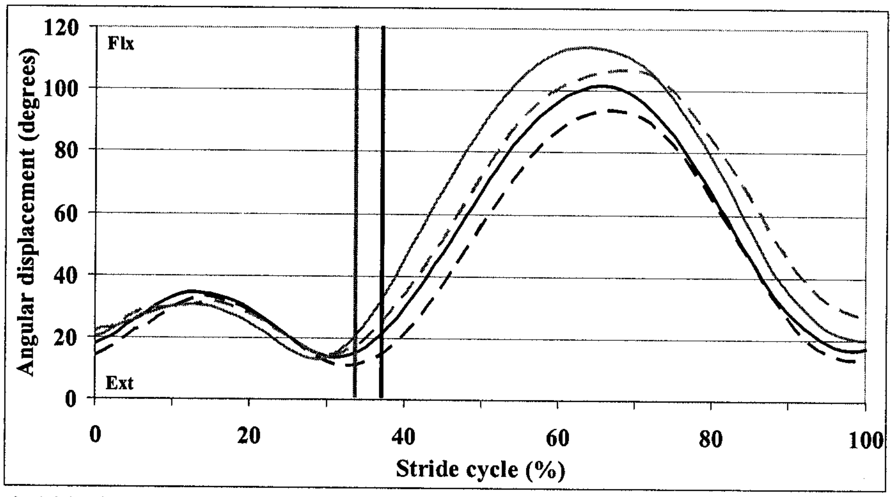
The solid lines represent the left leg and the dashed lines represent the right leg. The 3.8 m/s speed is shown in black and the 7.0 m/s speed in grey. The vertical lines represent the toe-off events at 3.8 m/s (black) and 7.0 m/s (grey).

Figure 3.2 Group average (n = 6) knee flexion for a complete stride cycle

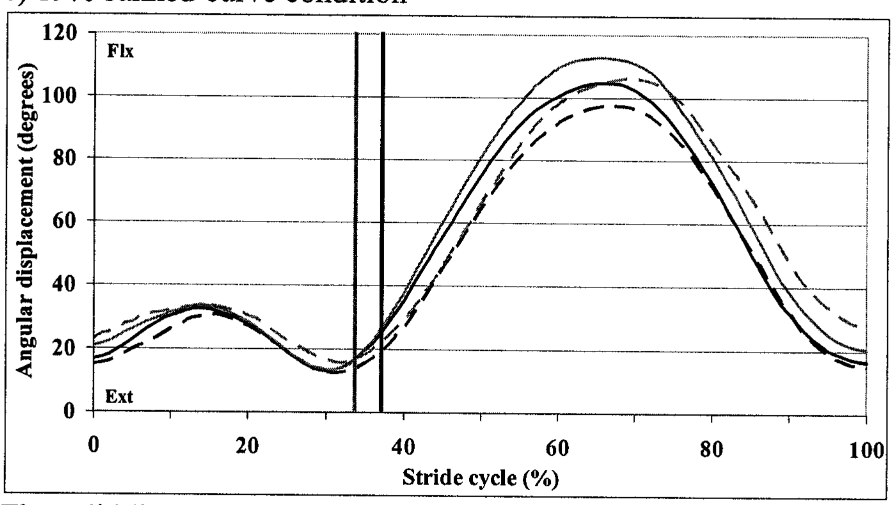
a) Straight condition



b) 0% banked-curve condition



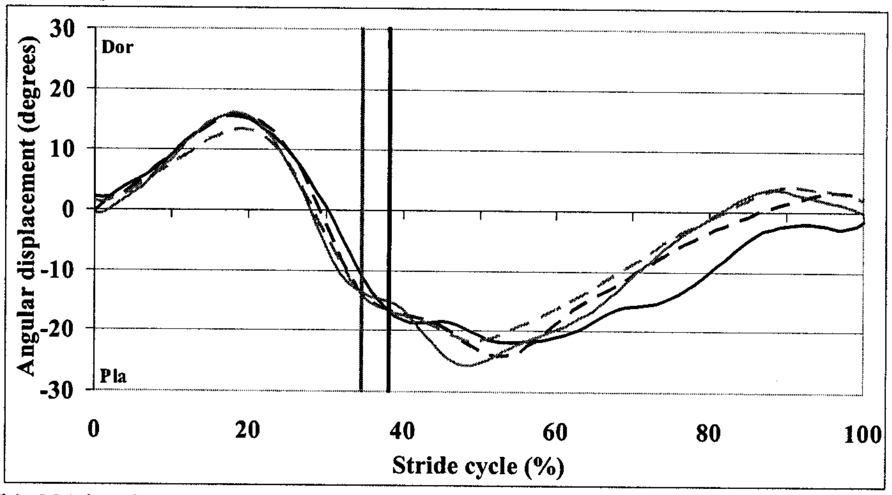
c) 19% banked-curve condition



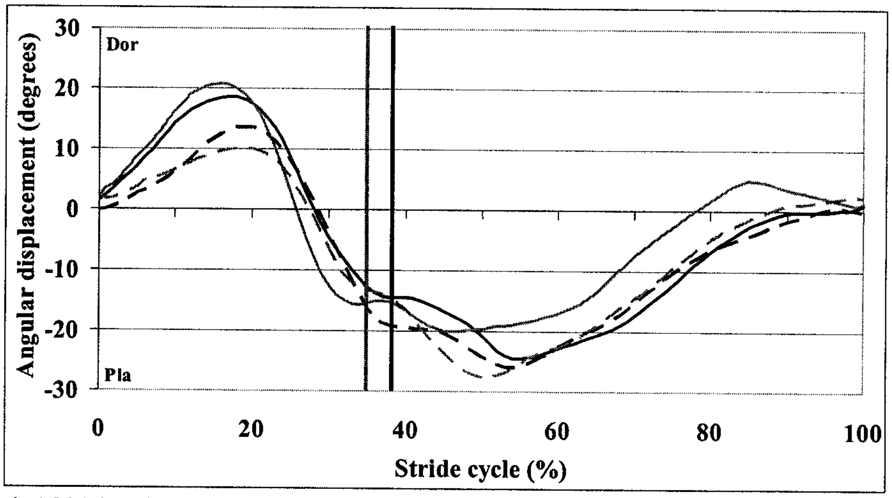
The solid lines represent the left leg and the dashed lines represent the right leg. The 3.8 m/s speed is shown in black and the 7.0 m/s speed in grey. The vertical lines represent the toe-off events at 3.8 m/s (black) and 7.0 m/s (grey). The positive angles represent flexion and the negative angles represent extension.

Figure 3.3 Group average (n = 6) ankle plantar/dorsiflexion for a complete stride cycle

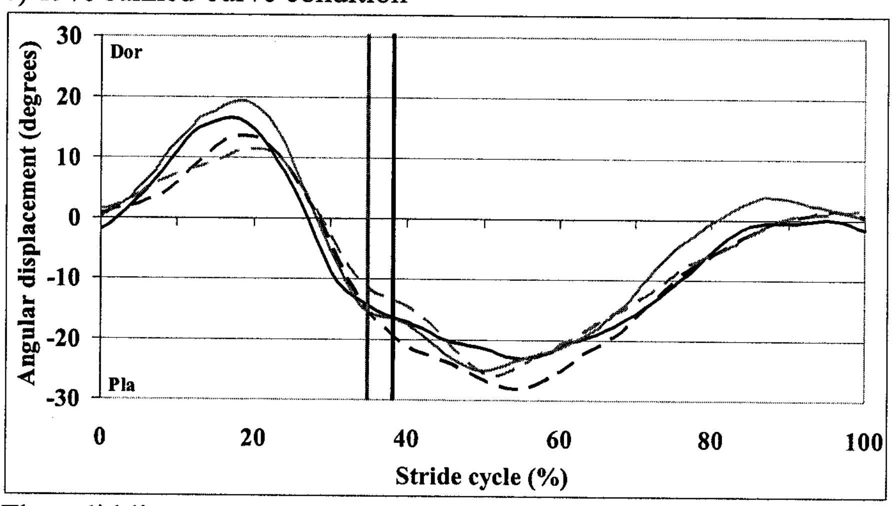
a) Straight condition



b) 0% banked-curve condition



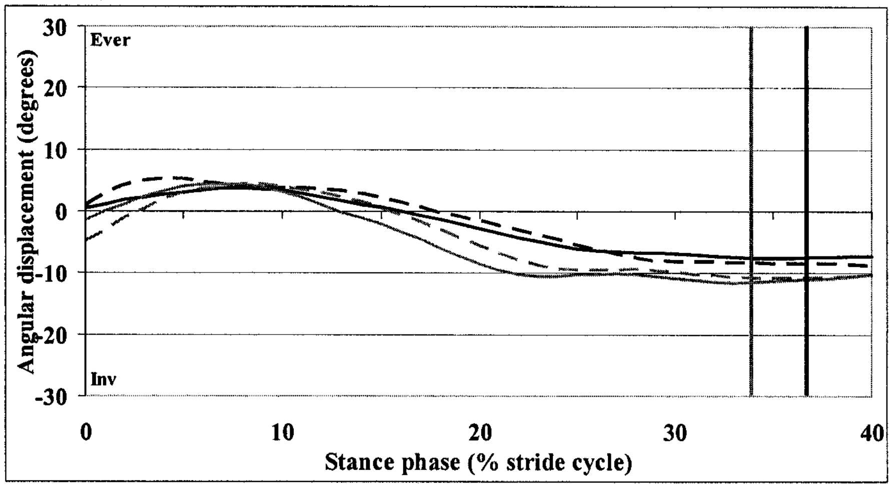
c) 19% banked-curve condition



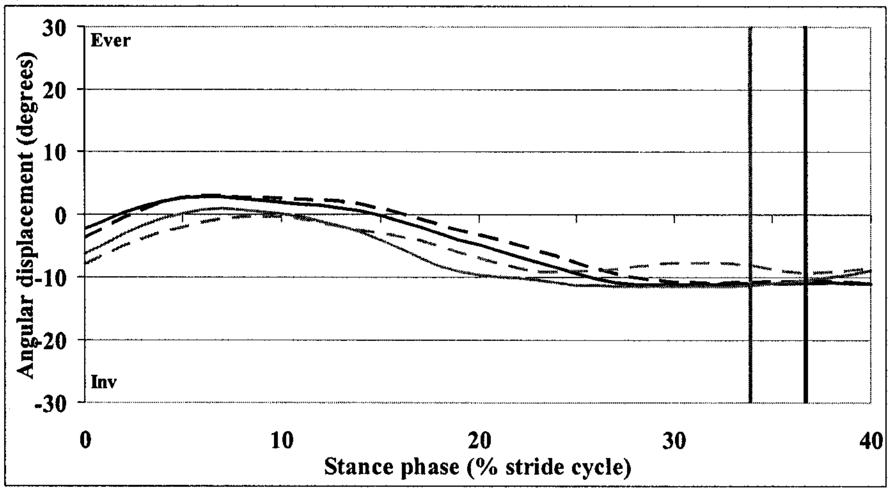
The solid lines represent the left leg and the dashed lines represent the right leg. The 3.8 m/s speed is shown in black and the 7.0 m/s speed in grey. The vertical lines represent the toe-off events at 3.8 m/s (black) and 7.0 m/s (grey). The positive angles represent dorsiflexion and negative angles represent plantarflexion.

Figure 3.4 Group average (n = 6) ankle inversion/eversion for a complete stride cycle

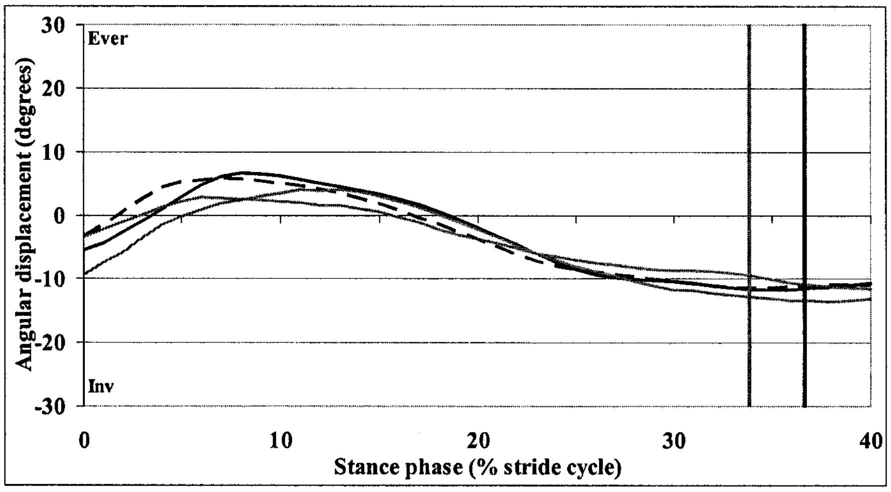
a) Straight condition



b) 0% banked-curve condition



c) 19% banked-curve condition



The solid lines represent the left leg and the dashed lines represent the right leg. The 3.8 m/s speed is shown in black and the 7.0 m/s speed is in grey. The vertical lines represent the toe-off events at 3.8 m/s in black and 7.0 m/s in grey. The positive angles represent eversion and negative angles represent inversion.

Figure 3.5 Group averages and standard deviations for peak knee flexion during the stance phase shown for left and right sides for both speeds (3.8 and 7.0 m/s). The white bars represent the straight condition, the black bars represent the 0% banked-curve condition and the hatched bars represent the 19% banked-curve.

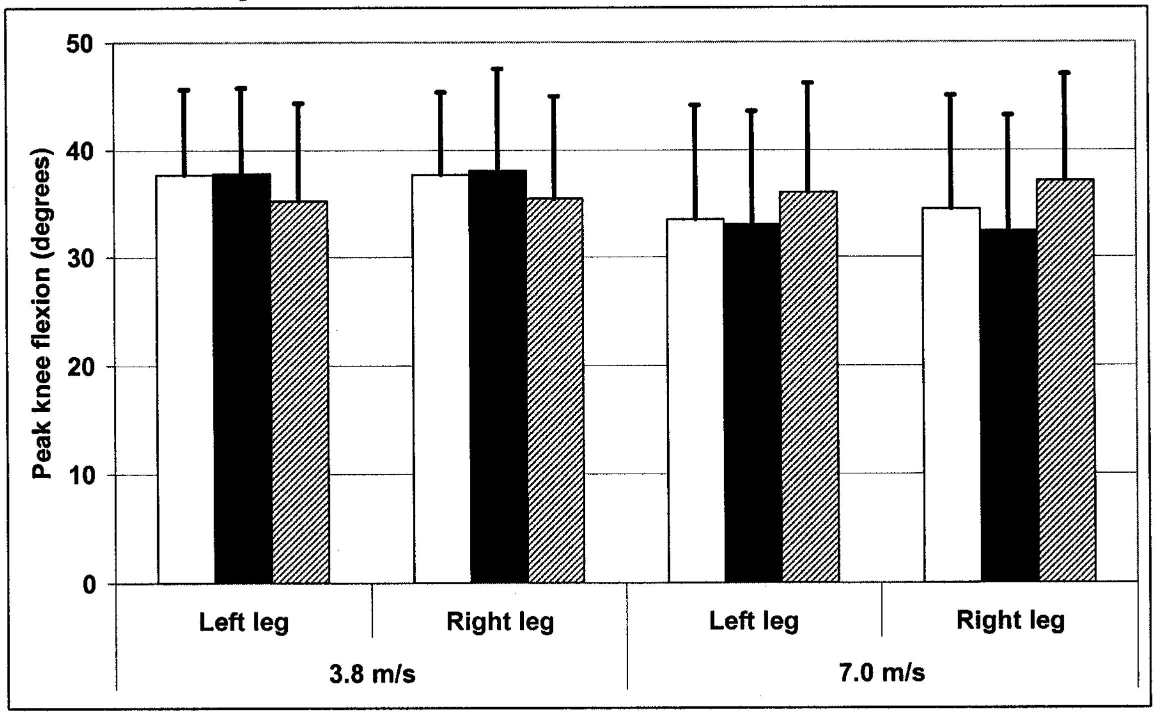


Figure 3.6 Group averages and standard deviations for minimum knee flexion during the stance phase shown for left and right sides for both speeds (3.8 and 7.0 m/s). The white bars represent the straight condition, the black bars represent the 0% banked-curve condition and the hatched bars represent the 19% banked-curve.

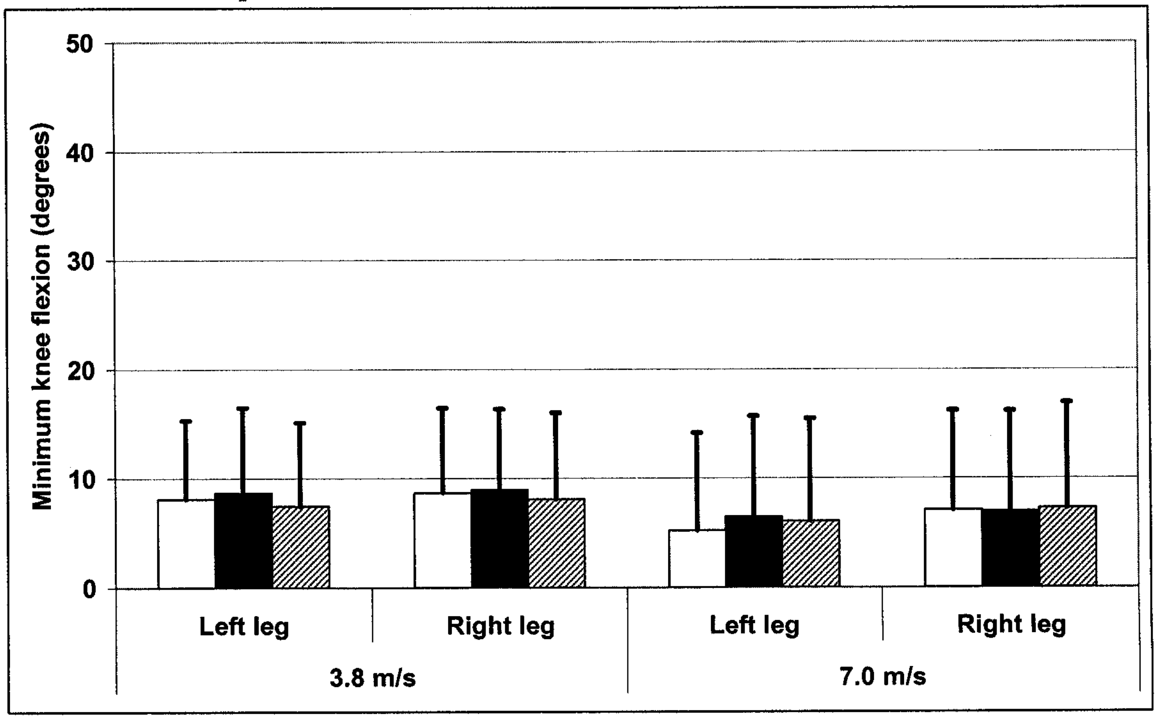


Figure 3.7 Group averages and standard deviations for peak ankle dorsiflexion during the stance phase shown for left and right sides for both speeds (3.8 and 7.0 m/s). The white bars represent the straight condition, the black bars represent the 0% banked-curve condition and the hatched bars represent the 19% banked-curve.

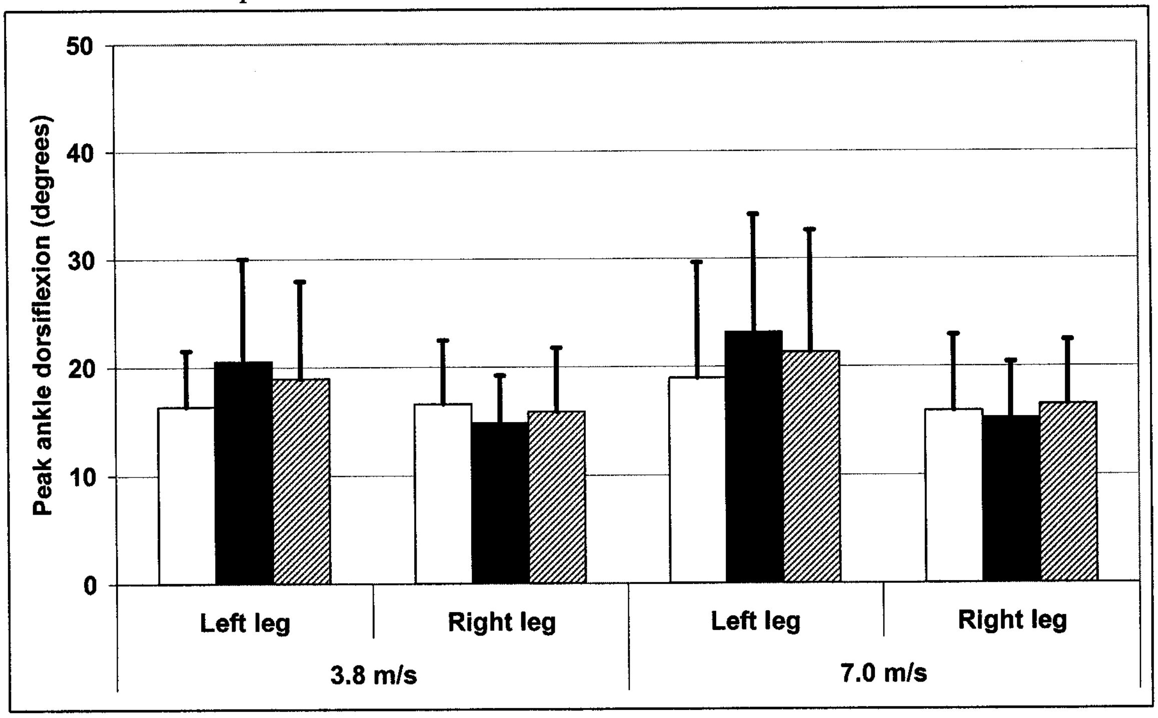


Figure 3.8 Group averages and standard deviations for peak ankle plantarflexion during the stance phase shown for left and right sides for both speeds (3.8 and 7.0 m/s). The white bars represent the straight condition, the black bars represent the 0% banked-curve condition and the hatched bars represent the 19% banked-curve.

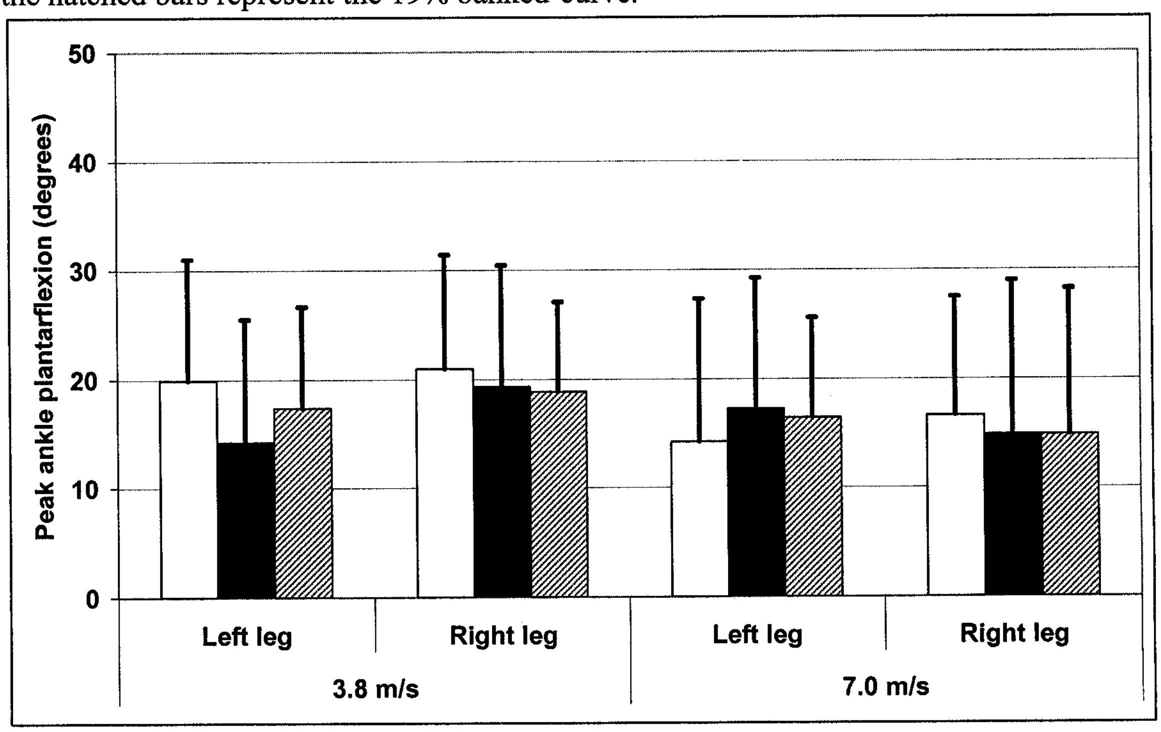


Figure 3.9 Group averages and standard deviations for peak ankle eversion during the stance phase shown for left and right sides for both speeds (3.8 and 7.0 m/s). The white bars represent the straight condition, the black bars represent the 0% banked-curve condition and the hatched bars represent the 19% banked-curve.

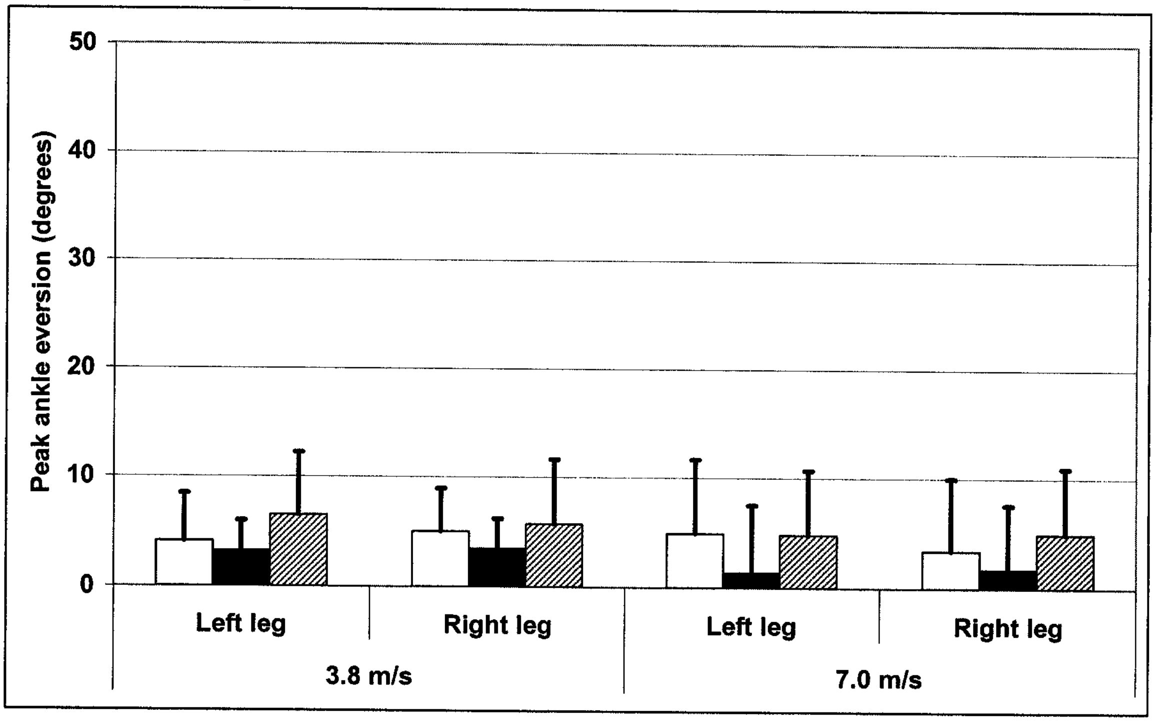
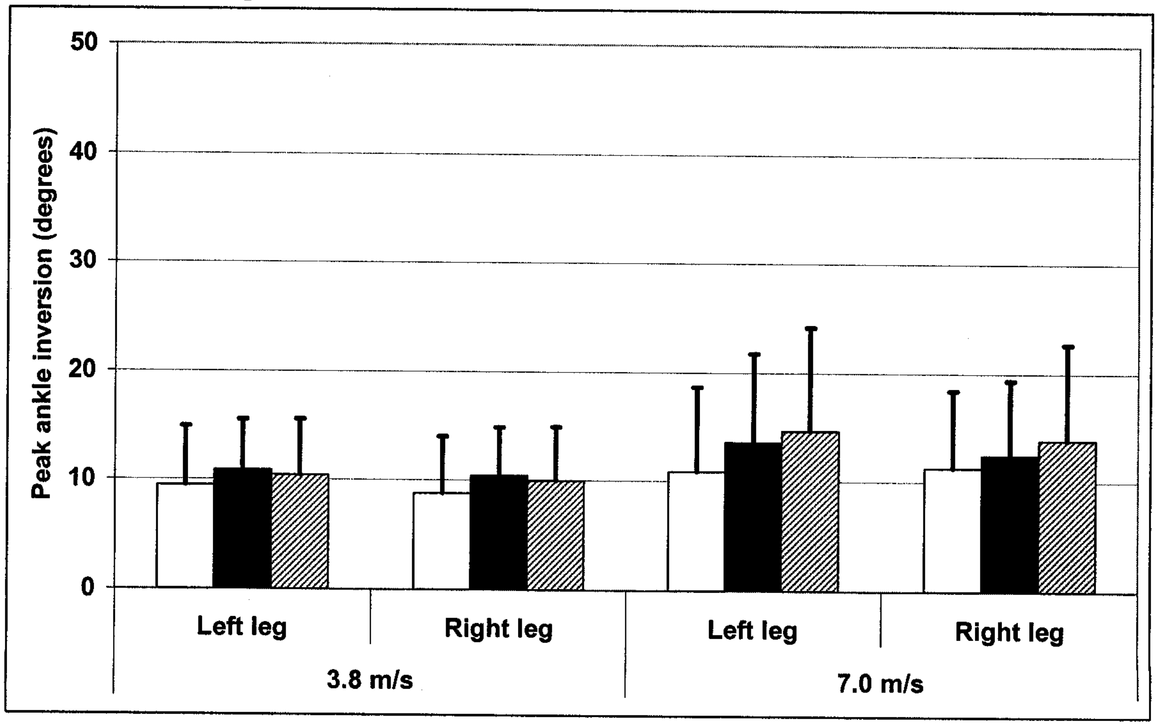


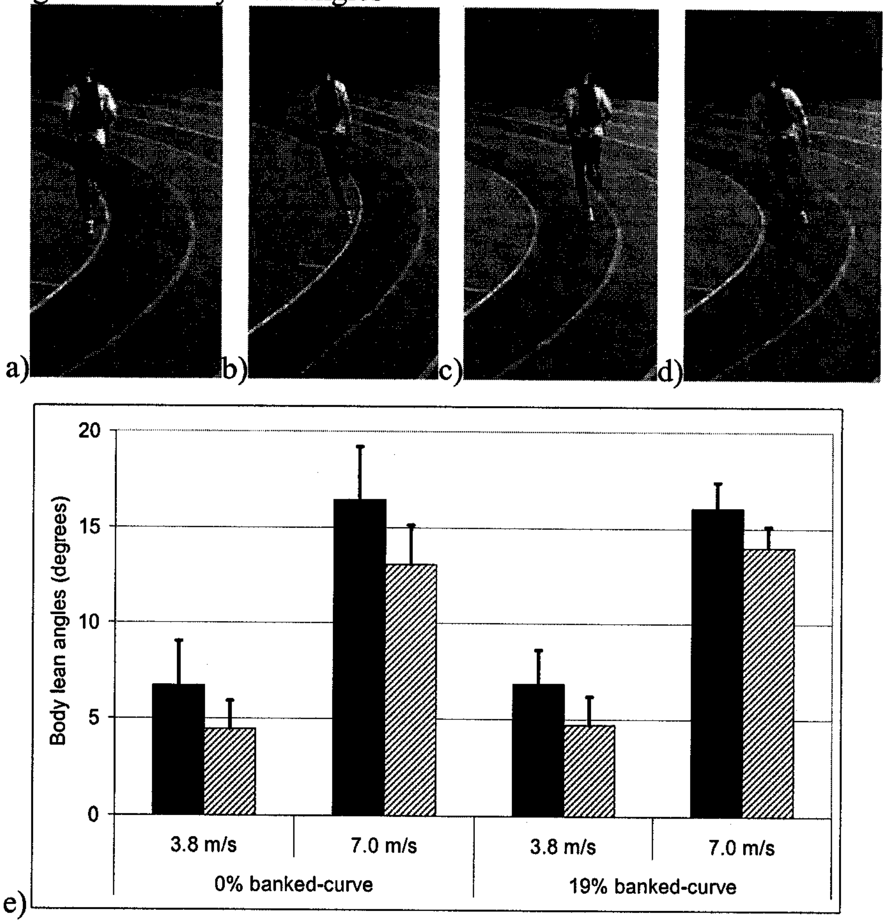
Figure 3.10 Group averages and standard deviations for peak ankle inversion during the stance phase shown for left and right sides for both speeds (3.8 and 7.0 m/s). The white bars represent the straight condition, the black bars represent the 0% banked-curve condition and the hatched bars represent the 19% banked-curve.



3.2 Body lean angle

The body lean angle was also examined and significant main effects were found for speed ($p < 0.0001$) and side ($p < 0.0001$) (Figure 3.11). The analysis showed that at 3.8 m/s the mean body lean angle was 5.7 degrees and at 7.0 m/s it was 14.9 degrees. It also revealed a significantly greater lean of the body when the left foot was in the support phase with a mean angle of 11.5 degrees compared to an angle of 9.0 degrees when the right foot was in the support phase ($p< 0.01$). On the other hand, there were no significant differences found for condition, as the mean body lean angle was 10.2 degrees for the 0% curve and 10.4 degrees for 19% banked-curve. Step width was measured from video data for a few subjects and was 5.2 cm on average.

Figure 3.11 Body lean angles



a) 0% curve at 3.8 m/s, b) 0% curve at 7.0 m/s, c) 19% curve at 3.8 m/s, d) 19% curve at 7.0 m/s, e) body lean angles for the stance phase (black bar is for the left side and the hatched bar is for the right side).

CHAPTER 4

DISCUSSION AND CONCLUSION

4.1 DISCUSSION

This study was the first attempt to examine the effects of an indoor-banked curve on angular kinematics at the knee and ankle, and on body lean angle in young elite runners. It was hypothesized that the knee and ankle kinematics of banked-curve running would resemble the kinematics observed when individuals with leg length discrepancies are running. Counter to expectations, the results from the present study showed no significant differences (p-values between 0.1826 and 0.9895) in knee and ankle angular displacements whether the individuals were running on a track with or without an inclination of the curve. The following text will explore the possible reasons for the stability of knee and ankle kinematics despite the substantial surface incline of 19% and discuss the implications of these observations.

4.1.1 Lack of effect of banked curve

The lack of differences in the knee and ankle angular displacements across the different conditions (straight, 0% banked-curve and 19% banked-curve) may be explained by several factors. First, it is important to remember that a clear distinction between walking and running is the step width. As the speed of locomotion increases, the step width decreases to create a more efficient pattern (i.e. less medial-lateral shift necessitated by the body's center of mass). During walking, Grabiner and Troy (2005) demonstrated a step width of 15.2 cm and during straight running, Pohl et al. (2006) demonstrated a step width of 5 cm. This functional adaptation would directly mitigate the effect of the banking thereby avoiding gait asymmetries associated with leg length discrepancy. That is, by reducing the medio-lateral distance between the left-right placements of the feet, the difference in the height of the foot stance width on the banked curve is directly decreased. This could explain why we did not observe the same effects of the sideslope on the knee and ankle kinematics as was previously described in walking studies (De Garie and Pearsall, 2000, Nicolaou and Pearsall, 2001).

Also, an important component of gait that is found in walking and not in running is the double-support phase during stance. This double support is associated with a wider base of support than that of alternate single leg support during running. In a study looking at the coupling relationship at the midfoot and subtalar joints during running at different step width, Pohl et al. (2006) demonstrated that rearfoot kinematics were only significantly different in cross-over running (when the medial aspect of the foot crosses the midline during stance) when compared to normal (running on the midline) and wide running (when the medial aspect of the foot is at 10 cm from the midline during stance). In our study, the step width was on average 5.2 cm and as with Pohl et al. study (2006), no significant differences were found in peak rearfoot eversion. However, our results showed smaller peak eversion ranging from 3.4 to 5.1 degrees during straight running compared to the results from Pohl et al. (2006) with a peak inversion average of 11.1 degrees. Second, by leaning inward in the curve and keeping their body relatively perpendicular to the ground, the subjects decreased the effect of the bank which would, otherwise, have most likely produced increased peak rearfoot eversion.

The population of interest in this study was the athletes who spend a lot of time training in the winter on the indoor track. This population was chosen mainly because we expected them to be the most familiar to the banking of the curve. These athletes were thus recruited from the McGill Track and Field Team. Our results might suggest that these subjects had already adapted their running technique to the banking of the curve, minimizing the effect size. As reported by Novacheck (1998), the peak angular displacement was dependent on the training experience, most likely due to a more careful placement of the foot on the ground. Although we expected a significant difference in ankle inversion/eversion angular displacements across the conditions, this expectation may not be present because of the level of experience of the subjects. This is supported by the p-values that are high for almost all the different conditions (p-values between 0.1826 and 0.9895).

A third and most compelling factor to consider in explaining the lack of significant differences in angular kinematics across conditions is that experienced runners who are training for short distances use a midfoot to forefoot pattern for initial contact. Since whole foot inversion/eversion movement involves a substantial contribution from the intertarsal joints, the electrogoniometer position used would only account for rearfoot inversion/eversion movements at the ankle alone. In addition, this running style would directly affect the amplitude of the eversion range of motion observed at the rearfoot. Indeed, Laughton et al. (2004) demonstrated that individuals with a forefoot strike pattern exhibited greater inversion at footstrike, which implied a greater total range of motion of the rearfoot. This means that even though the total amount of movement at the rearfoot is increased, the actual peak eversion during stance would be decreased. In our study, we expected the right foot to display a greater peak eversion during stance but it was not the case. This may be explained by the observations from Laughton et al. (2004).

A fourth factor to mention is the environment. The radii chosen in our study were the radii of the McGill University indoor running track dimensions. We used this same track because it is the environment where our subjects trained during the winter. Our main objective was to examine the effects of the banking of the curve, not a change in radius. Therefore it was important to choose two radii that were similar. The radii used in our study were 24.79 m for lane A and 25.7 m for lane 1 leading to a difference in radius of 0.917 m. Our findings are consistent with a study by Ryan et al. (2003) where they examined knee kinematics for several radii. Their data only showed a general trend towards greater knee flexion during the stance phase in the indoor lane 1 ($r = 10.5$ m) compared with the outdoor lane 8 ($r = 45.04$ m) conditions. This actually accounted for a 35 m difference between the radii of the 2 lanes. On the other hand, there were no differences in knee flexion when comparing indoor lane 1 (10.5 m) to indoor lane 4 (13.5 m) or to outdoor lane 1 (36.5 m). In addition, the indoor lanes were banked. Thus finding no differences in knee angular displacement between the two radii in our study is not surprising.

A fifth factor, the sample size, is also to be considered. The sample size used in this study was small ($n = 6$). This is likely to create a lack of power when using two-way ANOVA for statistical analysis. As for the power analysis, we had anticipated greater differences in ROM between the conditions. Nevertheless, with the high p-values observed (0.1826 to 0.9895), a larger sample may not change the results. In addition, finding significant subtle differences in angular displacements across conditions and sides may not be meaningful clinically.

4.1.2 Knee and ankle kinematics during straight running

There were however, differences when comparing the amplitudes of the current angular displacement profiles with those reported in a previous study for straight running. Novacheck (1998) reported an averaged knee flexion during stance of 45 degrees for running and less during sprinting. He reported that the knee then extends to 25 degrees at toe-off in running and 20 degrees in sprinting. We found the knee flexion during stance to be 37.7 degrees for the left and right side, and at toe-off to be 8.1 degrees for the left side and 8.7 degrees for the right side. Our runners were thus using less knee flexion when compared to the values reported by Novacheck (1998). On the other hand, Cavanagh (1990) reported, from an extensive review, that at 3.83 m/s, maximum knee flexion during stance was 41 degrees and at toe-off, 10.7 degrees, results which are closer to the ones we obtained. Differences in the review protocols from Novacheck and Cavanagh may account for the differences in the magnitude of knee and ankle angular displacements.

The angular displacement profiles yielded by our study are very similar to profiles found in the literature for ankle plantar/dorsiflexion. However, for ankle plantar/dorsiflexion, we found the magnitudes to be less than reported by Novacheck (1998). From a visual inspection of the profiles included in his review, peak ankle dorsiflexion during running was approximately 30 degrees and it was approximately 18 degrees during sprinting. From our study, peak ankle dorsiflexion was 16.4 degrees for the left foot and 16.6 degrees for the right foot at 3.8 m/s and 19.0 degrees for the left and 15.9 degrees for the right at 7.0 m/s. Cavanagh (1990) reported that ankle dorsiflexion after initial contact was 10 degrees. Our results are thus within the range found in the literature for ankle dorsiflexion.

At toe-off, ankle plantarflexion was similar between the different speeds, whereas Novacheck's profiles demonstrated that the ankle was more plantarflexed at higher speeds. When looking at the angular displacement profile included in his review, peak plantarflexion at toe-off was approximately 18 degrees during running and 28 degrees during sprinting. In our study, peak ankle plantarflexion at toe-off was 19.9 degrees for the left foot and 21.0 degrees for the right foot at 3.8 m/s and 14.2 degrees for the left and 16.6 degrees for the right at 7.0 m/s. Finally, the profiles and peak for ankle inversion/eversion are consistent with the literature (McClay et al. 1998, Reinschmidt et al. 1997), although the magnitudes are slightly different (the magnitudes being smaller in our study). This is most probably due to our equipment which only looked at the movement of the calcaneus in relation to the tibia. The electrogoniometers were fixed to the calcaneus inside the shoe whereas McClay et al.

(1998) and Reinschmidt et al. (1997) used external markers which may have overestimated angular displacement (Reinschmidt et al. 1997).

4.1.3 Effect of running speed on body lean angle

While running on the curve, the body lean angles increased with speed (14.9 degrees at 7.0 m/s compared to 5.7 degrees at 3.8 m/s). This result fits with Greene's theory (Green, 1985) which states that a runner must tilt his body when running into a curve to balance the centrifugal acceleration, thus making an angle between the centreline of the body and the vertical. Therefore, as speed of gait increases, the body must lean more into the inside of the curve to counteract greater centripetal forces, which draw the runner away from the curve.

On the other hand, the body lean angles on the flat curve and banked curve were not statistically significant. Runners assumed lean angles of 10.2 degrees and 10.4 degrees for the 0% curve and the 19% curve respectively. At 7.0 m/s, which was calculated to be the optimal speed at which the trunk would be perpendicular to the track (as proposed by Greene, 1985), the 14.9 degrees of body lean was 3.9 degrees greater than the expected 11 degrees of the 19% banked curve. Therefore, the runners ran on the banked curve at an angle slightly greater than expected to maintain the body perpendicular to the track. In addition, the lean angle measures differed but not significantly, depending on which foot was in stance. Specifically, the lean angle was greater when support was on the left (inside) leg compared to the right.

4.1.4 Limitations of the study

The present study had some inherent limitations. To begin with, there is the reduced generalisabilty to other populations. By using elite runners, it is difficult to estimate how inexperienced runners would adapt to the curve inclination. Also, the sample size was also small. The environment is also a limitation to the generalisabilty of the results. It is difficult to estimate the implication of different curvature and inclination on knee and ankle kinematics. As mentioned earlier, the position of the electrogoniometer at the ankle prevented us from measuring forefoot motion. This would have been of great interest, mainly because our subjects used a forefoot strike pattern and thus it is suspected that most of the adaptation to the curve occurred at the forefoot.

4.2 CONCLUSION

In conclusion, our results demonstrate that the use of banked curves on an indoor track caused no significant differences in the knee and ankle kinematics when compared with flat curves. Thus, I suspect that the use of such banked curves is less likely to be responsible for increased injury rate reported for indoor running. Other possibilities may be the differences in frequency and duration of the training sessions, running shoes or running surfaces.

One question raised from this project is how the recreational runners actually adapt their running pattern to the banked curves. Unfortunately, our results do not allow us to extrapolate to other population seeing the degree of experience observed in our subjects. Further research should be conducted to look at a broader population and should probably include a larger sample size because more variability across subjects is to be expected in a broader population.

CHAPTER 5

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APPENDIX I

Information and Consent document

The Effect of Banked-Curves on Knee and Ankle Kinematics during Running

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Introduction

Extensive research has been conducted to evaluate running patterns on levelled surfaces, but little is known about how we adapt to inclined or irregular terrains and its potential association to injury. Furthermore, the rate of running injuries has been shown to be different in indoor versus outdoor track running, so there may be a relationship with the configuration of indoor tracks and the prevalence of injuries.

Purpose of the Study

The purpose of this study is to compare the knee and ankle range of motion when running on an indoor track with different curve inclinations.

Your participation in this study involves:

1. Providing informed consent prior to the experimental session.
2. Completing a brief medical history and training habits questionnaire.
3. Perform the following tasks during the experimental session:
   a. Walk at 1.4 m/s, run at 3.8 m/s, and sprint at 7.0 m/s on a 60-meter distance. Once on a levelled curve and than on an inclined curve.
   b. Each condition will be performed twice. First for ankle measurements and a second time for knee measurements. Three trials will be performed for each condition. A total of 36 trials will be required.
   c. The electrogoniometers will be held in place at the level of your knees and ankles with adhesive Tuff-Skin spray, 3M surgical tape and/or athletic tape.
   d. Foot switches will be taped on the insoles of your shoes to measure foot contact on the ground.
   e. Two reflective markers will be secured on your back and neck to measure trunk inclination.
   f. During the running trials, a fanny pack will be secured around your waist to carry the data acquisition box.

Potential Risks

This research project involves no greater risks than present in your everyday life, mainly because you are already comfortable with the testing environment and the electrogoniometers will not interfere with your normal running technique. The track will be free from any obstacles and the number of trials performed should not take you to exhaustion.

Benefits

There are no personal benefits to be derived from participating in this study. The information that we will obtain will help us increase our understanding of the effects of curved inclination on running gait patterns.

Subject Rights

Your participation in this study is voluntary. You are free to withdraw from the study at anytime and for any reason without prejudice with regards to your training involvement with the McGill Track and Field Team. You are also free to ask questions to the experimenter at any time.

Privacy and Confidentiality

The confidentiality of your results will be maintained by substituting your name by a number assigned to this particular research project. This list of subject names and coordinates will be locked in the physical education biomechanics laboratory of McGill University and only the main investigator and his supervisors will have access to this list. Also, subject's face will be hidden if they happen to be seen on the video images.

Contacts

In the event of adverse effects or if you need additional information, you can contact the investigator's supervisors:

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Consent

I, ______________________________, AGREE TO VOLUNTARILY PARTICIPATE IN THE STUDY DESCRIBED ABOVE ABOUT THE EFFECTS OF BANKED-CURVES ON KNEE AND ANKLE KINEMATICS DURING RUNNING.

I have received and read a detailed description of the experimental protocol. I am fully satisfied with the explanations that were given to me regarding the nature of this research project, including the potential risks and discomforts related to my participation in this study.

I am aware that I have the right to withdraw my consent and discontinue my participation at any time without any prejudices.

Signatures

<u>SUBJECT</u>

____
(Signature)

<u>WITNESS</u>

______________________________ ______________________________
(Signature) (Print name)

Date: ______________________

APPENDIX II

Subject Information and Medical History Questionnaire

SUBJECT IDENTIFICATION

Name: ______________________________ ID code: ____________

Age: ______ years Sex: M or F Telephone number: ____________

MEDICAL HISTORY

1. Have you ever been affected by joint disorders? Yes or No
   If yes, specify ______________________________
2. Have you recently complained of pain in the lower limbs, hips, or back? Yes or No
   If yes, specify ______________________________
3. Are you currently taking any medication? Yes or No
   If yes, specify ______________________________
4. Do you have other medical conditions that should be mentioned? Yes or No
   If yes, specify ______________________________

TRAINING HISTORY

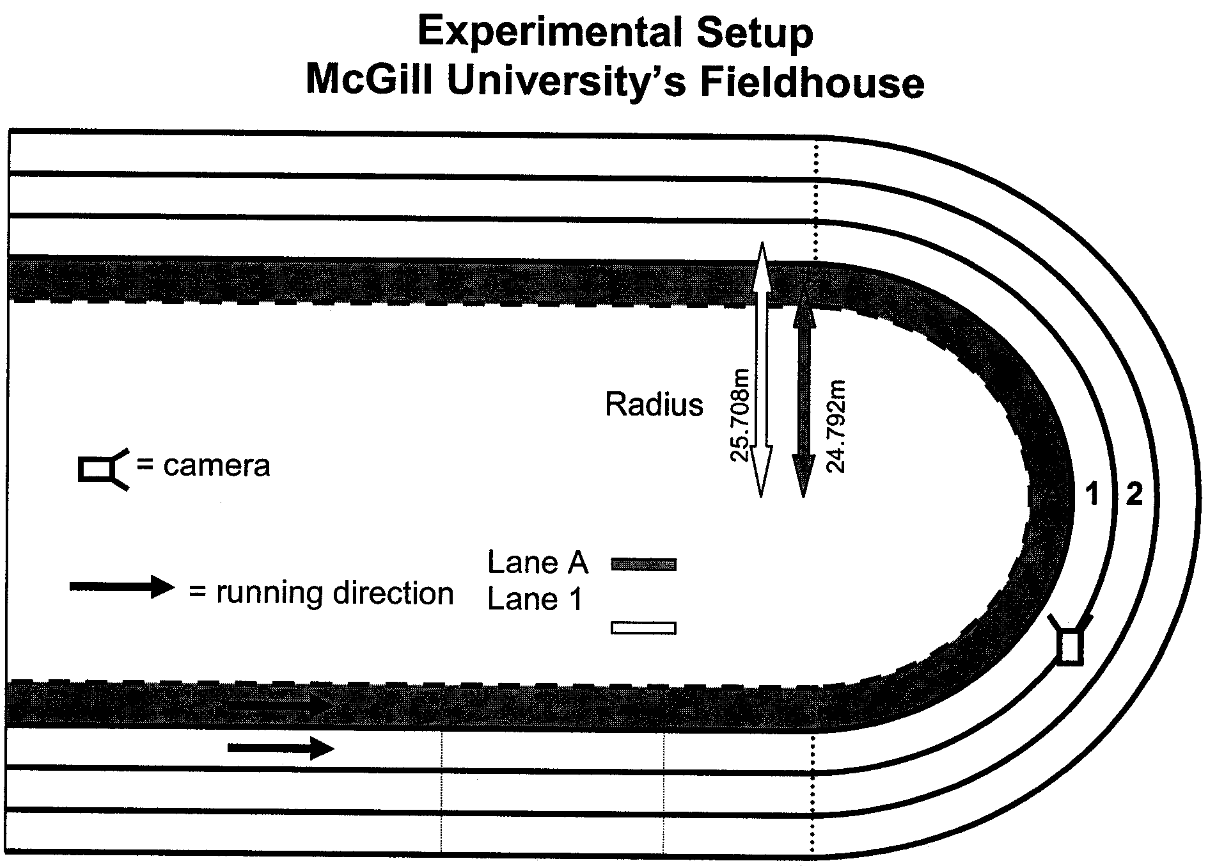
1. How often do you run each week? ______
2. For how long do you normally run? ______ hours
3. On average, in a training session, what is the distance that you run? ______ km
4. How many years have you been running for? ______ years
5. How many years have you been running indoors? ______ years

ANTHROPOMETRIC MEASUREMENTS

Height: ______ m Weight: ______ kg

Leg length: Right ______ cm Left: ______ cm

APPENDIX III



APPENDIX IV

Table IV.1 Anthropometric measurements and leg length

Subject Number	Age (years)	Height (cm)	Weight (kg)	Leg length (R) (cm)	Leg length (L) (cm)
1	18	177.8	67.7	95.0	95.0
2	21	185.4	75.0	91.0	90.5
3	18	171.5	63.6	92.0	90.5
4	19	175.3	68.0	92.5	93.0
5	20	180.3	65.9	93.0	93.0
6	19	180.3	68.2	95.0	94.0
Mean	19.3	177.3	67.2	92.1	91.7
Standard deviation	1.1	5.4	4.2	3.1	3.0

Table IV.2 Subject training history

Subject Number	Shoe size	Shoe Model	Training Frequency per week	Distance run per session (km)	Running experience indoors (years)	Running experience (years)
1	10.5	Muzion Wave Raider	6	14	1	6
2	11	Saucony 2530	3	5	1	3
3	-	Asics	6	15	4	5
4	10	Saucony	6	15	4	6
5	11	Asics	4	15	5	4
6	-	-	5	8	5	5
Mean			4,7	12,4	3,4	4,9
SD			1,4	4,2	1,7	1,1

- not recorded

Table IV.3 Group averages for peak knee flexion during stance

Condition	Speed (m/s)	Side	Mean (degrees)	Std (degrees)	2-way ANOVA for speed		
					Speed (m/s)	**Source of variation**	**p**
straight	3.8	left	37.7	8.0	3.8	side	0.631
		right	37.7	7.7			
	7.0	left	33.5	10.6		condition	0.874
		right	34.5	10.6			
0% curve	3.8	left	37.8	8.0		side x condition	0.989
		right	38.1	9.5			
	7.0	left	33.0	10.6	7.0	side	0.808
		right	32.4	10.8			
19% banked-curve	3.8	left	35.3	9.1		condition	0.936
		right	35.5	9.5			
	7.0	left	36.0	10.2		side x condition	0.921
		right	37.1	9.9			

Table IV.4 Group averages for minimal knee flexion during stance

Condition	Speed (m/s)	Side	Mean (degrees)	Std (degrees)	2-way ANOVA for speed		
					Speed (m/s)	**Source of variation**	**p**
straight	3.8	left	8.1	7.2	3.8	side	0.587
		right	8.7	7.8			
	7.0	left	5.2	9.0		condition	0.933
		right	7.1	9.2			
0% curve	3.8	left	8.7	7.8		side x condition	0.993
		right	9.0	7.4			
	7.0	left	6.5	9.2	7.0	side	0.980
		right	7.0	9.2			
19% banked-curve	3.8	left	7.5	7.7		condition	0.713
		right	8.1	8.0			
	7.0	left	6.1	9.4		side x condition	0.988
		right	7.3	9.7			

Table IV.5 Group averages for peak ankle dorsiflexion during stance

Condition	Speed (m/s)	Side	Mean (degrees)	Std (degrees)	2-way ANOVA for speed		
					Speed (m/s)	Source of variation	p
straight	3.8	left	16.4	5.1	3.8	side	0.530
		right	16.6	5.8			
	7.0	left	19.0	10.7		condition	0.982
		right	15.9	7.0			
0% curve	3.8	left	20.5	9.5		side x condition	0.907
		right	14.9	4.3			
	7.0	left	23.1	10.9	7.0	side	0.258
		right	15.2	5.2			
19% banked-curve	3.8	left	18.9	9.0		condition	0.972
		right	15.9	5.8			
	7.0	left	21.3	11.3		side x condition	0.828
		right	16.5	5.9			

Table IV.6 Group averages for peak ankle plantarflexion during stance

Condition	Speed (m/s)	Side	Mean (degrees)	Std (degrees)	2-way ANOVA for speed		
					Speed (m/s)	Source of variation	p
straight	3.8	left	19.9	11.1	3.8	side	0.317
		right	21.0	10.4			
	7.0	left	14.2	13.1		condition	0.921
		right	16.6	10.9			
0% curve	3.8	left	14.2	11.3		side x condition	0.819
		right	19.3	11.1			
	7.0	left	17.2	12.0	7.0	side	0.364
		right	14.8	14.1			
19% banked-curve	3.8	left	17.4	9.3		condition	0.914
		right	18.9	8.2			
	7.0	left	16.4	9.1		side x condition	0.775
		right	14.8	13.4			

Table IV.7 Group averages for peak ankle eversion during stance

Condition	**Speed (m/s)**	**Side**	**Mean (degrees)**	**Std (degrees)**	**2-way ANOVA for speed**		
					Speed (m/s)	**Source of variation**	**p**
straight	3.8	left	4.1	4.3	3.8	side	0.612
		right	5.1	3.9			
	7.0	left	4.9	6.7		condition	0.985
		right	3.4	6.6			
0% curve	3.8	left	3.2	2.8		side x condition	0.938
		right	3.5	2.7			
	7.0	left	1.4	6.2	7.0	side	0.656
		right	1.7	5.9			
19% banked-curve	3.8	left	6.5	5.7		condition	0.183
		right	5.7	5.9			
	7.0	left	4.8	5.9		side x condition	0.533
		right	4.9	6.0			

Table IV.8 Group averages for peak ankle inversion during stance

Condition	**Speed (m/s)**	**Side**	**Mean (degrees)**	**Std (degrees)**	**2-way ANOVA for speed**		
					Speed (m/s)	**Source of variation**	**p**
straight	3.8	left	9.5	5.4	3.8	side	0.317
		right	8.8	5.2			
	7.0	left	10.9	7.8		condition	0.921
		right	11.3	7.1			
0% curve	3.8	left	10.9	4.7		side x condition	0.819
		right	10.4	4.4			
	7.0	left	13.6	8.1	7.0	side	0.364
		right	12.5	6.9			
19% banked-curve	3.8	left	10.4	5.2		condition	0.914
		right	10.0	4.9			
	7.0	left	14.7	9.5		side x condition	0.775
		right	13.8	8.8			