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The Etiology of Running Injuries:
A Longitudinal, Prospective Study

by

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ABSTRACT

The purpose of this study was to use a prospective study design to (a) report on boundary conditions which may be associated with running injuries, and (b) to identify kinetic and kinematic movement variables which may be associated with running injuries. Informed written consent was obtained from 146 healthy subjects whose main physical activity was running. A prospective study design was employed such that selected kinematic and kinetic variables were collected prior to the start of each subject's running program. Information regarding the subjects' daily running sessions was obtained from questionnaires which were completed by the participants after each running activity. Subjects were required to participate in the study for a minimum of six months. During the study injuries were diagnosed by a single physician.

Daily questionnaire data were obtained from 95 subjects, 28 of those were diagnosed as having an injury. Patello-femoral syndrome was the most commonly diagnosed injury and found in four subjects. The knee was the most often injured body site and found in eight subjects. The relative frequency of injuries and body sites injured are in agreement with results reported in the literature for studies using runners, however, they disagree with results from studies using patients. The following external factors were found to be significantly related to injuries: surface condition, surface slope, surface level, ambient temperature, surface type and pace.

Stepwise logistic regression yielded a significant prediction of patello-femoral syndrome from variables describing pronation. Eighty percent of trials from legs diagnosed with patello-femoral syndrome could be classified correctly using the pronation variables measured prior to the occurrence of the injury. It was speculated that excessive pronation was associated with excessive internal rotation at the knee joint which may have contributed to patello-femoral syndrome. The injuries of other groups could not be explained mechanically. It was concluded that in order to obtain significant and mechanically meaningful results the injury groups must be homogeneous and larger than those in the present study.

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CHAPTER ONE

INTRODUCTION

Over the past 20 years the number of people that run has increased drastically. In 1980 the estimated number of people running in North America was more than 30 million (Cavanagh, 1980), which meant that more than one in ten North Americans is running. The increased popularity of running is reflected in the number of publications investigating running and jogging. Many of these publications discuss injuries connected with the sport of running. Non-scientific articles in Runner's World (1973, 1977), based on data from a survey, mentioned (probably for the first time) that two out of three runners became injured over a one-year period. Brody et al. (1982) reported that over 70% of all runners sustained injuries severe enough to prevent them from running for seven to ten days over a one-year period. Marti et al. (1988) studied 4,538 male runners over a period of one year and reported an injury rate of 45.8% using a survey questionnaire design.

Schlein (1983) reported that in the 1983 New York City Marathon 1,100 of the 17,000 participants became injured during the race. Five hundred of these injuries occurred in the lower extremities. A questionnaire study of 451 entrants to a 10,000 metre race reported an injury rate of 46.6% (Jacobs et al., 1986).

Injuries may be classified into acute and overuse injuries. An example of an acute injury is a rupture of a ligament due to excessive range of motion caused, for instance, by stepping on an obstacle. An example of an overuse injury is fatigue fracture caused, for instance, by an increase in weekly running distance. The mechanical etiology for an acute injury is often obvious. However, it is usually more difficult to explain the mechanical etiology of overuse injuries. This study concentrates on overuse injuries.

The large number of runners and the high frequency of overuse running injuries suggest that it is important to study the factors contributing to these injuries. Factors which may contribute to an overuse injury may be grouped as *internal* or *external* factors (Figure 1). Internal factors may be subdivided into *anatomy* (e.g., alignment of bones) and *biomaterial* (e.g., material properties of the musculoskeletal system). External factors may be subdivided into *boundary conditions* (e.g., ambient temperature, running shoe, surface) and *dynamic factors* (e.g., number of repetitions or type of movement).

FACTORS INFLUENCING RUNNING INJURIES

INTERNAL	*EXTERNAL*
- ANATOMY	- BOUNDARY CONDITIONS
- BIOMATERIAL	- DYNAMIC FACTORS

Figure 1. Classification of factors leading to an injury.

Several authors studied the association between *anatomical factors* and running injuries (e.g., James *et al.*, 1978; Taunton *et al.*, 1985;

Warren and Jones, 1987). The reviewed reports suggest that the assessment of the anatomical alignment of the lower extremities may help to explain the etiology of certain running injuries. Yamada (1977) reported on material properties of bone, cartilage, tendon, ligament and muscle from cadaver studies. Butler et al. (1978) reviewed material properties of ligaments and tendons. The reviewed reports show that the range of material properties of biomaterial has been determined from cadaver studies. It is generally assumed that the actual material properties in vivo are in a similar order of magnitude. Assessment of the actual forces in a structure of the human body (e.g., tendon, cartilage) and comparing these forces with the critical limits may help to understand the etiology of certain running injuries. The association of boundary conditions with running injuries has been studied by James et al. (1978) (running on hills and hard surfaces), Jacobs and Berson (1986) (stretching and participation in other sports), and by Marti et al. (1988) (history of previous running injuries and characteristics of running shoes). The reviewed reports suggest that certain boundary conditions are associated with running injuries, and that the "thorough" analysis of the effects of these boundary conditions may help to understand the etiology of certain running injuries.

The dynamic factors have mainly been studied in three areas: (1) the general description of kinetics and kinematics in running (Cavanagh and LaFortune, 1980; Nigg, 1986b), (2) the influence of boundary conditions on kinetics and kinematics (Nigg, 1986), and (3) the description of differences between the kinetics and kinematics between injured and healthy subjects (Gehlsen et al., 1980; Bennett et al., 1987).

It has been concluded from studies in the above areas that: (a) it is possible to alter the type of movement with modifications of the boundary conditions, and (b) injured subjects run differently than non-injured subjects. From the above results it has been speculated that certain types of movement are associated with pain and/or injuries in running (Gehlsen et al., 1980; Bennett et al., 1987). However, no evidence has been provided for this speculation, the main reason being that publications discussing running injuries have commonly been designed as retrospective studies. Retrospective studies compare present results with injuries which occurred in the past, i.e., the measurements have been taken after the injury occurred. This type of study design does not allow the determination of whether a specific injury contributes to a specific change in the movement pattern, or if a different movement pattern contributes to a specific injury. However, with a prospective design, the possibility that a change in movement is due to a specific injury may be excluded.

The purpose of this study was to use a prospective study design to (a) report on boundary conditions which may be associated with running injuries, and (b) to identify kinetic and kinematic movement variables which may be associated with running injuries. It is hypothesized that kinetic and/or kinematic variables measured prior to the occurrence of the injury may be associated with specific running injuries.

CHAPTER TWO

REVIEW OF THE LITERATURE

Introduction

The review of the literature will be discussed according to publications referring to (A) the frequency and site of running injuries, (B) possible reasons for the occurrence of these injuries, and (C) study designs in general.

Frequency and Site of Injuries

A 1977 Runner's World survey based on a questionnaire stated that two out of three runners were affected by an injury over the period of one year. This report was not a scientific publication, however, it was one of the first public concerns regarding high injury rates in running and may have initiated subsequent scientific studies. Brody et al. (1982) similarly reported that 70% of people running became injured severely enough to prevent them from running for seven to ten days. Warren and Jones (1987) stated that 50-70% of the 25 to 30 million Americans who run for their aerobic exercise sustained an injury related to their running. Cavanagh et al. (1980) reported that during the years 1973 to 1979 the "percentage of runners getting injured did not change appreciably." Additionally, he reported that leg fractures, heel spur syndromes, shin splints and knee injuries had increased considerably during those six years.

A summary of studies reporting injury with respect to site was presented by Nigg (1986). Questionnaire studies from Runner's World

(1971, 1973) and clinical studies from Brubaker et al. (1974), James et al. (1978), Krissoff et al. (1979), Smith (1979), Cavanagh et al. (1980), and Clement et al. (1981) were summarized. The average frequency of injured sites was 30% for the knee, 15% for the tibia, 10% for the Achilles tendon, 10% for the arch of the foot, and 35% for other sites. Krissoff et al. (1979) also reported that the most frequent site for running injuries was the knee. Knee injuries have increased from less than 20% in 1971 to over 40% in 1981 (Nigg, 1986). DeHaven et al. (1986) stated, based on a clinical study of injuries treated over a period of seven years, that the knee/ankle are the most common sites in sport injuries. In running, which included track, patello-femoral syndrome was the most frequently occurring injury with 16.1% of all sports injuries. In their study, males accounted for 80.3% of all injuries. The second-highest frequency or occurrence was at the tibia. Taunton et al. (1987) reported on 73 injured runners. The two most frequently occurring injuries were patello-femoral pain syndrome (n=42) and ilio-tibial band friction syndrome (n=6). The most frequent etiological factor was reported to be sudden increase in training mileage. There is no information on the occurrence of injuries in the non-running population (Nigg, 1986). It might be that statistics for the non-running population do not differ from the results summarized above. However, it is speculated that some injury sites are typical for running (e.g., knee pain) and that they show a significantly higher relative frequency of occurrence in the running population.

Reasons for Injuries

Introduction

In the past, several attempts have been made to clarify possible reasons for running injuries. James et al. (1978) proposed three factors leading to injuries: (1) training errors, (2) anatomical factors, and (3) running shoes. In his classification, the type of movement (dynamics) which has been assumed to be connected with running injuries is missing. Pagliano (1986) compiled a running injury data bank over a period of ten years. A total of 3,273 injured runners were involved in the study. He identified the ten most commonly occurring running injuries and stated that each one can be traced to one of five major causes: (1) training too much, too fast, too soon; (2) running on surfaces that are too hard, too hilly or uneven; (3) having weak, inflexible muscles; (4) wearing inadequate running shoes; and (5) having faulty foot biomechanics. This classification is very specific, however, possible factors such as weather and type of movement are missing.

In the present study, a general classification is proposed (Figure 1). This classification includes everything which has been proposed by James et al. (1978) and Pagliano (1986), as well as some factors which they did not consider. Figure 2 shows the proposed classification for this study. It is indicated that the classifications of James (J1-J3) and Pagliano (P1-P5) are included in the general classification used in this study. However, it should be pointed out that both classifications (James and Pagliano) are not complete.

INTERNAL	EXTERNAL
- ANATOMY (J2,P5)	- BOUNDARY CONDITIONS (J3,P2,P4)
- BIOMATERIAL (P3)	- DYNAMIC FACTORS (J1,P1)

Figure 2. Proposed classification of factors leading to an injury. The letters "J" and "P" refer to proposed factors of James et al. (1978) and Pagliano (1986) as previously mentioned in the text:

The proposed classification (Figure 1) includes the four factors: anatomy, biomaterial, boundary conditions and dynamic factors. The anatomical factors include the alignment of bones, muscles and/or ligaments. Changes in the alignment have an effect on the magnitude and direction of the internal forces. These changes may be the reason for the development of certain injuries. Mechanical properties of biomaterial describe the resistance of the material against the forces acting upon specific elements of the musculoskeletal system. Injuries may occur if the material properties are in a normal range but the forces are excessive, or if the material properties are below a normal range and the forces are in an acceptable range for normal material properties. Boundary conditions can have an effect on the biomaterial and/or the dynamic factors. Boundary conditions such as ambient temperature or nutrition may influence the mechanical properties of the biomaterial, for example, the ultimate stress of a tendon, and, therefore, affect the resistance of the material against the forces acting upon it. Boundary conditions such as the shoe or running surface may influence the kinematics and, therefore, influence the internal forces acting on elements of the musculoskeletal system. Therefore, boundary conditions are associated with running injuries. Dynamic factors (kinetics and kinematics) can influence the magnitude and/or line of action of the forces acting on the musculoskeletal system. If these internal forces exceed the critical limits of the biomaterial that they act upon, injury may occur. Therefore, dynamic factors may be a possible reason for specific running injuries. In the following the existing knowledge regarding running injuries in these four areas which have been shown to be possibly associated with running injuries will be discussed.

Anatomy

Anatomical factors are assumed to be associated with running injuries. Those anatomical factors associated with knee injuries are reported to be leg length differences, patella alta, and knee joint laxity (Kujala et al., 1986). The importance of the medial collateral ligament and the anterior cruciate ligament on the varus-valgus knee laxity and the kinematics of the knee joint has been reported by Inoue et al. (1987). The results of their study suggest that under normal knee joint motion the functional deficit of the medial collateral ligament in the valgus rotation was compensated by the remaining structures, especially by the anterior cruciate ligament. Yasuda et al. (1986) investigated in vivo dynamic mechanical properties of the knee in valgus loading. Bending elastic and bending damping coefficients of the knee were calculated. Kettlkamp and Chao (1981) concluded that biomechanical principles justify tibial osteotomy for correction of varus deformity of the knee for redistributing knee plateau forces.

Taunton et al. (1985) investigated the influence of corrective running orthotic devices in runners with compensatory overpronation. The authors reported a significant decrease in the total amount of foot eversion during the support phase of running, as well as a significant increase in the amount of plantar flexion occurring after foot strike. No significant differences were found for internal and external rotation plus varus and valgus displacement at the knee.

Olmstead et al. (1986) compared valgus/varus moment-rotation characteristics of the knee obtained with no muscular activity to those obtained with measured flexion and extension torques. The authors suggested that prevention of opening of the lateral side of the joint under varus loading was responsible for increased varus stability with increasing extension and flexion torque. Burkus et al. (1983) investigated a safe and simple procedure for correcting valgus deformities of the ankle in myelodysplastic patients.

Several attempts were made in the past to categorize feet with respect to form and/or function. In an attempt to find a typical foot for a runner, Debrunner (1982) classified feet into different types by their external appearance. However, such external classifications concentrate on external measures of length or volume and do not take into account what the athlete is doing with his foot during actual performance. Stacoff and Luethi (1986) discussed alignment of forces and moment arms acting on the foot. They showed that, for instance, a valgus position of the foot can be corrected by applying inserts or orthotics. They discussed examples regarding different anatomical alignments. For example, a large amount of pronation may be caused, or corrected for, by specific anatomical alignments. They speculated that tibial tendonitis problems and insertion problems of various tendons can be associated with anatomical malalignment. Robbins et al. (1987) concluded, from comparison of populations running barefoot and in shoes, that the anatomy of the foot protects sufficiently from injuries. In his study, changes in the medial-longitudinal arch of the foot in the barefoot running population were assumed to be responsible for increased weight bearing activity. Warren and Jones (1987) examined subjects who were, either presently or previously, suffering from plantar fascitis. It was found that from anatomical measurements it was possible to correctly identify 76% of the non-injured group, but only 63% of the injured group. The authors concluded that the anatomical predictor variables could not be used to correctly predict plantar fascitis injuries.

Anatomical factors have been reported to be associated with injuries. Some of these studies reported that static alignment (Kettlkamp and Chao, 1981; Kujala et al., 1986; Inoue et al., 1987), while others reported that dynamic alignment (Taunton et al., 1985; Olmstead et al., 1986) was associated with the development of running injuries.

Summary

Studies associating anatomical factors with running injuries generally assume that the static alignment of the musculoskeletal system is associated with the dynamic alignment. It is possible, therefore, to explain certain types of injuries with static and/or dynamic anatomical alignment.

Biomaterial

Benedict _et al._ (1968) analyzed the stress-strain characteristics and tensile strength of unembalmed human tendon. They reported average tensile strength values of 92 MPa for extensor tendons while the average values for flexor tendons were reported to be 75 MPa. Yamada _et al._ (1970) reported on modulus of elasticity, elastic limit and ultimate strength for compact bone, long bone, cartilage hyaline, tendon, ligament and muscle tissue for compression (where applicable) and tension. Van Mow _et al._ (1984) reviewed the viscoelastic properties of articular cartilage. The authors summarized the non-linear phenomenon of flow-dependent viscoelastic effects and modeled the compressive viscoelastic properties of articular cartilage mathematically. Material properties of ligaments and tendons have also been reported by Butler _et al._ (1978). The authors showed that the behaviour of ligaments and tendons is significantly influenced by factors such as loading rate, immobilization, exercise, chronic physical activity, steroids, age-related effects, and trauma. Generally, for fresh whole ligament and tendon specimens, an ultimate stress of 50 to 100 MPa and ultimate strain of 4 to 10% may be observed. Fujimoto _et al._ (1970) reported on the effect of nutrition on the material properties of biomaterial. Fascia and tendon properties have been described by Zernicke _et al._ (1977,1984). Safran _et al._ (1988) investigated the role of warm-up in muscular injury prevention and determined that warm-up may reduce the incidence of musculotendinous injury by increasing the length to failure and the elasticity of the muscle-tendon unit. In contrast, from a retrospective study Jacobs and

Berson (1986) reported that injured runners stretched significantly more before running than non-injured runners.

Summary

Factors influencing material properties of biological tissue and limits of material properties of biomaterials have been established. If the internal forces exceed these limits, injuries may be expected.

Boundary Conditions

Andreasson and Peterson (1986) modeled the dynamic behaviour of sport shoes and surfaces and determined that a dynamic spring constant model may be used as a means of predicting potential athletic injuries. Luethi et al. (1986) demonstrated in a prospective study that the occurrence of pain can be influenced by boundary conditions. Nigg (1986b) included in the definition of boundary conditions the running shoe, surface, obstacles, anthropometric facts, and individual fitness level. In the present study boundary conditions are defined as conditions which are imposed from the environment on to the athlete and may be changed by the athlete. The present definition does not include anthropometric factors, which are included in ANATOMY, or fitness level, which is included in BIOMATERIAL.

The first publications suggesting that certain types of surfaces were the origin of running injuries came from physicians (Segesser, 1970; Prokop, 1972; Hess and Hort, 1973) who reported on athletes training on artificial surfaces. Other publications with the same conclusions based on medical observations followed (Hort, 1976; Segesser, 1976; Bolliger, 1979). James et al. (1978) reported that hard running surfaces were connected with the etiology of running injuries while Marti et al. (1988) stated that injuries were not significantly related to training surfaces. However, Marti's surface categories were general (predominantly hard, predominantly natural, or combined), and no information is available on the percentage of subjects using these three categories of surfaces. Jacobs and Berson (1986) also reported that there was no association between injured and non-injured runners with regard to running surfaces on which they trained. However, the majority of their subjects (89%) ran on hard surfaces such as concrete or asphalt.

Other studies considered the construction of the running shoe as a possible factor influencing the occurrence of running injuries. Warren and Jones (1987) speculated that the sensory insulation inherent in modern running shoes appears responsible for the high injury frequency associated with running. A number of authors suggested that the shoe should, in addition to protecting from high-impact forces, provide stability to the foot (Nigg et al., 1977; Subotnik, 1979; Cavanagh, 1980; Smart et al., 1980; Clarke et al., 1983,1984; and Nigg et al., 1984; Stacoff et al., 1988). Numerous publications have suggested that shoe construction and running injuries were connected and that orthotic foot support should help to reduce existing pain and/or injuries (Nigg et al., 1977, 1978, 1982; Segesser et al., 1978; Segesser and Nigg, 1980; Hort, 1979; Cavanagh, 1980; and Clement, 1982). Marti et al. (1988) reported that the characteristics of the running shoes were not significantly related to running injuries. However, the only variables examined in their study were manufacturer and price class. Nigg et al. (1988) found that viscoelastic insoles did not appear to influence kinematic and kinetic variables of the lower extremities in a systematic way during heel-toe running.

Running on hills was reported by James et al. (1978) to be connected with running injuries. However, Jacobs and Berson (1986) found no association between injured and non-injured runners with regard to running on hills, although less than 8% of their population was recorded as running on hills. Jacobs and Berson also found injured runners differed significantly from non-injured runners in that they did not participate regularly in other sports. Previous running injuries and competitive training motivation were reported to be connected with running injuries (Marti et al., 1988).

Summary

There is agreement in the literature that certain boundary conditions are associated with injuries. These include the running shoe and participation in other sports. For other boundary conditions the results in the literature were not consistent. Some authors claimed that the type of surface and/or the type of terrain (hills, slopes) were influencing the occurrence of running injuries, while others disagreed.

Dynamic Factors

James et al. (1978) associated about 60% of all injuries in his study with training errors. These errors were excessive mileage, intense workouts, rapid change in the training routine, and running on hills and hard surfaces. Jacobs and Berson (1986) found that injured runners ran significantly more miles per week, more days per week, at a faster pace, and ran more races during the last year than non-injured runners. No association was found between injured and non-injured runners who ran intervals and sprints. However, less than 8% of their total population (451 subjects) used this form of training.

The discussion of the movement of the lower extremities during ground contact by Root () is used to understand the relative movement of the segments of the lower extremities. In a transverse plane the pelvis and thigh (femur) rotate internally throughout the contact period of the foot. The thigh internally rotates farther and faster than the pelvis, thus producing internal rotation of the thigh with respect to the pelvis. During the midstance and propulsive phases, the thigh rotates externally. The thigh rotates externally farther and faster than the pelvis, thus producing external rotation at the hip joint during midstance and the propulsive period. In a transverse plane the leg (tibia) rotates internally faster than the thigh during the contact period, thus producing <u>internal rotation</u> of the tibia with respect to the femur. During the midstance and propulsion phases, the leg rotates externally with respect to the thigh. In a transverse plane maximal internal rotation of the pelvis in a room-fixed coordinate system is approximately 2°, maximal internal rotation of the thigh approximately 6°, and maximal internal rotation of the leg approximately 10° after heel strike during a walking cycle (Root <u>et al.</u>, 1977). In a sagittal plane the talocrural joint plantarflexes from heel strike to forefoot contact. The trunk and leg then begin to move forward, causing dorsiflexion of the talocrural joint. In this initial plane, motion at the talocrural joint in a transverse plane is only significant when dorsiflexion occurs in the talocrural joint. Then, the foot abducts upon the leg. After the forefoot contacts the ground, however, friction prevents the foot from moving in a transverse plane with the leg and the talus moves with the leg. The leg continues to rotate internally as long as the talocrural joint dorsiflexes. The talus does not rotate internally as far as the leg. In the sagittal plane maximal dorsiflexion (subtalar motion) is approximately 4° during a walking cycle (Root et al., 1977). The subtalar joint provides most of the transverse plane motion which is necessary at the distal extremity of the leg to allow internal leg rotation. In a transverse plane maximal eversion is approximately 4° during a walking cycle (Root et al., 1977). Rotations may influence the magnitude of forces in the tibio-femoral joint, the patello-femoral joint, and the combined ankle joint (talocrural and subtalar joints). As an example, the internal rotation of the tibia with respect to the femur may effect the relative movement of the patella with respect to the femoral condyles. LaFortune and Cavanagh (1987) reported a lateral shift of the patella relative to the femur from heel strike to maximal flexion of the knee joint. On the average, an 8 mm lateral shift has been reported from experiments with 3 subjects. However, due to the small number of subjects, it is not known whether this lateral shift of the patella is representative for a normal walking cycle.

Pronation of the foot consists of eversion, abduction and/or dorsiflexion (Hlavac, 1977; Root et al., 1977; Wright et al., 1964). Pronation is a three-dimensional movement of the foot relative to the body or the leg relative to the foot. Pronation during running is normal and always includes an abduction component. While the forefoot contacts the ground, friction forces prevent the foot from sliding in a transverse plane (abduction). Therefore, the leg is forced to internally rotate during pronation. In addition, the thigh is rotating internally but at a slower rate. Consequently, a difference of 4° of internal rotation at the knee joint has been reported for a walking cycle (Root et al., 1977). Pronation is one of the most frequently cited dynamic factors to be correlated with injuries such as shin splints (Gehlsen et al., 1980; Viitasalo et al., 1983), patello-femoral syndrome (Bennett et al., 1987; Taunton et al., 1987), sacro-iliac joint inflammation (Massey et al., 1978) and microtears in the Achilles tendon (Smart, 1980). In all these studies an injured population (injured subjects or injured legs) was compared with a healthy population (healthy control group or the healthy legs of injured subjects). Significant differences were found between healthy and injured populations. From these results it was then speculated that the significant differences in the amount of pronation was the cause of the injury.

Summary

Dynamic factors have been speculated to be correlated with injuries. Pronation has been speculated to be an important factor in describing running injuries (Clarke, 1984). Pronation is a combined movement of eversion, abduction and dorsiflexion of the foot. While the forefoot contacts the ground, friction forces prevent the foot from sliding in a transverse plane and the leg is forced to internally rotate during pronation. A lateral shift of the patella relative to the femur of 8 mm during a walking cycle has been reported by LaFortune and Cavanagh (1987).

Study Designs

There are different approaches to designing a study. In a retrospective study, observations and measurements are taken after the fact, following the occurrence of an injury. In a prospective study, observations and measurements are taken before the injury occurs. To investigate the effect of boundary conditions on the occurrence of injuries, the study design, whether the study is retro- or prospective, is not crucial. Boundary conditions will not change with time, e.g., the surface or slope will not change during a run. Thus, boundary conditions may be considered as constants over time, and these constants may often be chosen freely by the athlete. However, if the effect of dynamic factors (e.g., type of movement, pronation) on the occurrence of running injuries is to be examined, the time of the measurement is important. If dynamic factors are measured retrospectively, it cannot be distinguished whether the injury caused the movement or whether the movement caused the injury. If the assessment of the movement is taken in a prospective study, it may be hypothesized that the movement leads to the injury since the possibility that the movement is caused by the injury can be excluded. Questionnaire studies examining boundary conditions may, therefore, be set up as retrospective or prospective designs. However, studies examining the possible effect of dynamic factors in the occurrence of injuries should use a prospective study design to eliminate the possibility that results for the measured variables are influenced by the injury. The results of Luethi et al. (1986) suggest that a prospective biomechanical analysis can be used to establish speculations concerning the etiology of pain and injuries in sports-related activities. In Luethi's study, dynamic factors of 229 tennis players were measured prior to a three-month test period. The kinematics of the lower extremities were highly influenced by the type of shoe worn and could be related to the occurrence of pain during the three-month observation period.

Summary

Results reported in the literature associating dynamic factors with running injuries were from studies using a retrospective approach. Such a study design is limited since it cannot be excluded that the movement analyzed after the injury was caused by the injury. However, in a prospective study design this limitation does not exist since the measurement was taken a priori.

Summary of Literature Review

Running injuries occur because of one or a combination of the following four factors: anatomy, biomaterial, boundary conditions and/or dynamic factors. Anatomical factors have been linked to certain running injuries. Ample knowledge of normal biomaterial properties is available from cadaver studies. Some boundary conditions have been shown to be associated with running injuries. Speculations that specific kinematics are associated with a specific running injury have been reported in the literature. However, results on running injuries reported in the literature were from retrospective studies and/or were based on case reports. Such a study design has the limitation that the movement analyzed was caused by the injury since the measurement had been taken a posteriori. In order to exclude this limitation a prospective study design can be used. The reviewed literature suggests that dynamic factors may be significantly involved in the etiology of specific running injuries. However, there is no conclusive evidence for this speculation. A prospective epidemiological study analyzing the dynamic factors and the occurrence of injuries is the appropriate approach to provide the answer to that question.

CHAPTER THREE

METHODOLOGY

Introduction

This chapter explains details about the methodology used in this study in the following order: subject selection, testing protocol (definition of variables, data collection, running sessions), and analyses. The chronological sequence of tests for a subject wishing to participate was:

1. Subject Selection
    - sports screening
    - medical questionnaire about running injury history
2. Laboratory Test
    - explanation of daily questionnaire
    - mark subject shoes
    - practice runs
    - kinetic and kinematic data collection for each leg/shoe
3. Running Sessions for Minimum of 6 Months
    - daily questionnaire reports
    - appointment with medical doctor, if necessary

Subject Selection

Subjects were recruited by using advertisements in running clubs and sport shops specialized for running. The professionals in the clubs and the sales personnel in the stores helped in advertising the present study. The subjects were initially screened to determine the sport activities in which they are and/or were involved. The main sport activity was required to be running. Subjects who were training for competition in sports other than running were not allowed to participate in the study. However, other sports were allowed, with some restrictions, since it was assumed that these activities would not influence the results of the study. Sports allowed with no restrictions included canoeing, cross-country skiing, cycling (recreational and commuting), recreational dancing, hiking, sailing, swimming, limited weightlifting, and wind surfing. Restricted sports that were allowed, if exercised less than four times per month, included aerobics, cycling (training), dancing (performance or competition), downhill skiing, ice hockey, rowing, racquetball, soccer, sprinting, squash, tennis, and triathlon. After meeting the inclusion criteria of the initial screening, a medical questionnaire was completed. This questionnaire included questions regarding the subject's history of joint, muscle and/or tendon injuries of the lower back, thigh, leg, foot or any disabilities which would prevent them from running. Subjects who had no history of running injuries or injuries related to running were allowed to participate in the study. The minimal requirement for participation in the study was that each subject was required to run at least 15 km per week for 6 months.

The sample size for this project was derived using the following assumptions: (1) an injury rate of 70% would be found in the total population sampled (Brody et al., 1982); (2) the most frequently occurring injury should occur on 16% of the injured population (e.g., patello-femoral syndrome; DeHaven, 1986); (3) a minimum of ten subjects would become injured with the most frequently occurring injury; and (4) a valid information and data rate of 65% during the whole study. Marti (1988) reported a non-response rate of questionnaires of 16.4% for questionnaires handed out to participants during a race, and a 20% exclusion rate (e.g., invalid data) was assumed. These assumptions required the total minimal sample size for the project to be 138 subjects. Written consent was obtained from 146 subjects who participated in the study.

Subjects that participated initially in the study were excluded from the analysis if they: (1) did not return all of their daily questionnaires; (2) did not fulfill the total required running distance (15 km/week over 6 months at 30 days/month, 7 days/week with a 10% holiday allowance) of 347 km, unless they had been diagnosed as injured during the study; and (3) did not participate for the minimum time period of 6 months.

Testing Protocol

Markers and Variables

Prior to beginning their individual running programs, film and force data were collected for each subject. Figure 3 illustrates the experimental set-up in the laboratory.

To evaluate kinematic data, markers were placed on the running shoes and on the lower leg of the subject as described by Nigg (1986). Figure 4 illustrates the markers at the rear part of a left leg and shoe. The markers A-D were placed as follows:

A: Located 15 cm above marker B in the centre of the leg (rear view) in the standing position (barefoot)

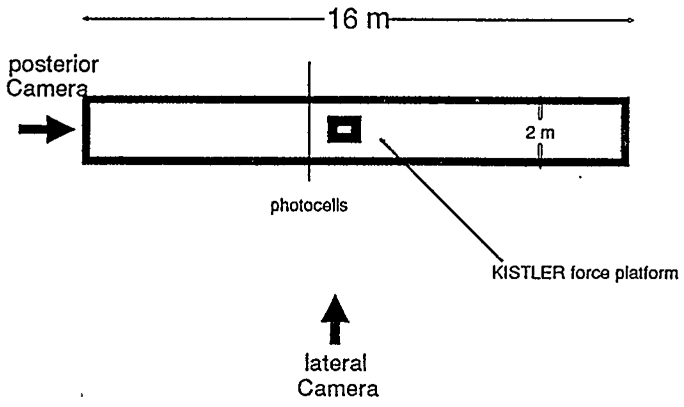

Figure 3. Experimental set-up in laboratory.

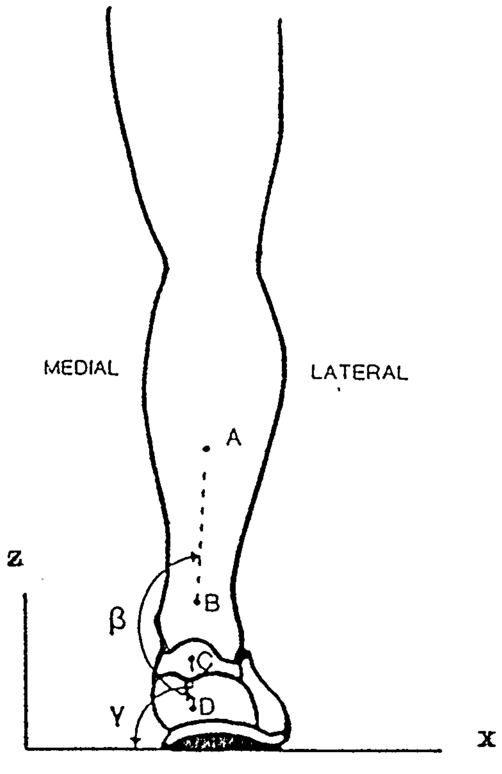

Figure 4. Placing of the markers at the rear part of a left leg and foot.

B: Located on the Achilles tendon just above the heel cap of the shoe

C: Located so that the line between CD and the horizontal form an angle of 90° in the unloaded shoe

D: Located in the centre of the shoe sole (posterior view)

Using the projection of these markers into the x-z plane, the following angles are defined:

ß = <u>Achilles tendon angle</u>

Definition: Angle between AB and CD on the medial side. Comment: The Achilles tendon angle contains information about the relative angular movement between calcaneus and lower leg. It is used to describe pronation and supination.

γ = <u>Rearfoot angle</u>

Definition: Angle between CD and the horizontal line on the medial side. Comment: The rearfoot angle contains information about the shoe. The time history of the Achilles tendon angle and the rear foot may be different.

Figure 5 illustrates the markers used for the filming from the lateral side. The markers E-K were placed as follows:

E: Midsole of forefoot at the head of the 5th metatarsal

F: Midsole of the heel underneath the calcaneus

G: Lateral malleolus

H: Head of the fibula

I: Located above the tibio-femoral joint on a middle line for lateral view in the standing position

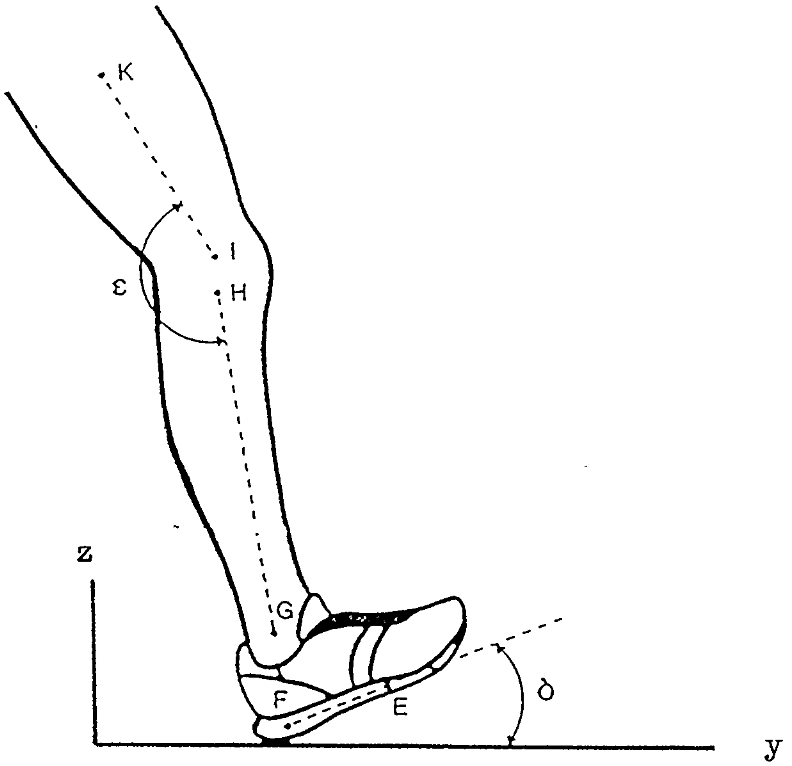

Figure 5. Placing of the markers for the lateral view of a right leg and foot.

K: Same as I but 2/3 of the distance between the tibio-femoral and the hip joint

Using these markers, the following variables were defined, all of them being angles and velocities projected into the y-z plane:

$\varepsilon =$ <u>Knee angle</u>

Definition: Angle between GH and IK on the posterior side of the knee joint. Comment: This angle is important for the determination of the effective mass and internal impact forces.

$\delta =$ <u>Angle of the shoe sole</u>

Definition: Angle between EF and the ground measured at the lateral side. Comment: This angle is connected with the area of contact and the lever arm of the acting force with respect to a specific joint.

One frequent use of these variables is the determination of the initial conditions. They are defined as the values of these variables immediately before first ground contact and are consistently labeled with a subscript "o" (ε_o, δ_o, and, of course, β_o, γ_o).

<u>Kinematic Variables</u>

$\Delta\beta_{10}$	Initial pronation (°). Change of the Achilles tendon angle in the first tenth of foot contact.
$\Delta\beta_{pro}$	Total pronation (°). Total change of the Achilles tendon angle during the pronation part of foot contact.
β_{end}	Take-off Achilles tendon angle (°). Achilles tendon angle one-tenth of the total foot contact before last foot contact.
$\Delta\gamma_{10}$	Initial change of rear foot angle (°). Change of the rear foot angle in the first tenth of foot contact.
$\Delta\gamma_{pro}$	Total pronation of rear foot angle (°). Total change of the rear foot angle during the pronation part of foot contact.
δ_o	Shoe angle (°) at touch-down.
ε_o	Knee angle (°) at touch-down.
v_o	Velocity of the heel at touch-down (marker G).

The kinematic variables used in this study were derived from positions of surface markers on the skin and on the shoes of the subjects. For instance, markers A and B on the leg were positioned on the skin above the Achilles tendon. The connection between these markers was used to represent the orientation of the leg at any point in time during movement. However, during this movement the skin, and with the skin the markers attached to it, may have moved relative to the bony structure (e.g., the tibia) and the Achilles tendon under these markers. Markers C and D were positioned on heel of the shoe. However, any movement between the shoe and the foot affected the position of these markers relative to the calcaneus. Therefore, surface markers often do not represent the true positions of the bony segments of the musculoskeletal system which define the true three-dimensional movement.

In this study two-dimensional kinematic variables were used. However, during ground contact the posterior aspects of the calcaneus and leg were not always in a plane parallel to the film plane. The largest deviation for the calcaneus and the leg from this plane occurred before the landing and during the take-off phase as soon as the heel left the ground. This two-dimensional method from the posterior underestimated the three-dimensional angular changes for the Achilles tendon angle during foot contact (Engsberg, 1987). The same is true for the lateral view, however, deviations from the lateral film plane are insignificant. Since the kinematic variables used in this study described projections of a three-dimensional movement into a frontal or sagittal plane viewed from the posterior or lateral view, respectively, any movement in a transverse plane (i.e., abduction and adduction) was not detected.

Furthermore, with the above definitions of kinematic variables, it was not possible to detect movement around only the subtalar joint or around only the talocrural joint. All movement measured between the leg and foot consisted of combined movement around the subtalar joint and the talocrural joint. The angles defined above (i.e., Achilles tendon angle, rearfoot angle and knee angle) were not anatomical angles. Any terms and variables derived from these angles were simplifications of the three-dimensional anatomical movement (Engsberg and Andrews, 1987). However, if any variables defined from the simplified two-dimensional data collection will show a significant association with running injuries, they may yield a powerful tool to understand these injuries since these variables are easy to assess. Since results from the two-dimensional definitions have indicated large variations in observed angles between runners, and these results have since brought about significant changes in running shoe design (Engsberg and Andrews, 1987), it may be speculated that these variables may be appropriate for the present study.

Kinetic Variables

F_{zi}	vertical impact force peak (N), occurring before 50 ms of contact time.
t_{zi}	time of occurrence (ms) of vertical impact for peak, F_{zi}.
G_{zi}	maximum vertical loading rate (N/ms) of vertical force curve.
F_{x-}	minimal medio-lateral ground reaction force (N); medial direction is positive.
F_{x+}	maximal medio-lateral ground reaction force (N); medial direction is positive.
I_x	absolute integral of medio-lateral ground reaction force-time curve (N/ms).
F_{y-}	minimal anterior-posterior ground reaction force (N); anterior direction is positive.

F_{y+} maximal anterior-posterior ground reaction force (N); anterior direction is positive.

Data Collection

After marking the left and right legs and shoes, the subjects were asked to run over a KISTLER (Type 9287 SN) force platform placed in the middle of a 16 m long runway, contacting the platform with one foot during a stride. Subjects were asked to run at their "normal" running speed. Ample opportunity was given to adjust to the laboratory conditions and to different running shoes. A minimum of five test runs per shoe were performed prior to any data collection. The ground reaction forces were measured at a sampling frequency of 1,020 Hz per channel. The platform measurements were triggered by photocells which were mounted 1 m before the platform at a height of 1.5 m above the ground. Three valid force trials were recorded for each unique subject-leg-shoe combination. A retest in the laboratory was required for each new shoe that a subject used during their running program.

Each subject-leg-shoe combination was filmed during contact with the force platform from the lateral and posterior view with two stationary LOCAM II cameras operating at a nominal film rate of 100 frames per second. The field of view contained the lower limb from the hip to the floor. The film data was digitized (Hewlett Packard 9874A) to obtain time histories of kinematic variables of the movement.

Running Sessions

After the initial laboratory testing, each subject was required to run at least 15 km per week for a minimum of six months or until an injury was diagnosed by a medical doctor. Following each running session the participants were required to complete a "daily questionnaire." The daily questionnaire was used to examine the influence of boundary conditions on the occurrence of injuries during running. The questionnaire included questions regarding ambient temperature, distance of run, length (time) of run, pace (steady, variable), surface type (grade-dirt, asphalt-concrete, mixed, synthetic, wood, other), surface conditions (wet, dry, snowy-icy), surface smoothness (bumpy-uneven, smooth-even), surface grade (level, uphill/stairs, downhill/stairs, up and down), surface slope (no slope, right slope, left slope), running shoe used during the run, participation in other sports and experience of pain during the run. Reported distances and times where the average speed was below 5 km/h or greater than 30 km/h were assumed to be erroneous and ignored during the analysis. If a subject experienced "pain" during or after a running session the subject was required to state in the daily questionnaire whether the pain was assumed to be due to running, the site of pain/injury, the side (right, left, both) and a short description of the pain. Pain was defined as (a) problems which persisted after exercise ceased and which lasted for three consecutive runs, (b) problems which prevented running, (c) problems which did not respond to simple measures (rest, ice, wrapping), and (d) problems which increased with running. Problems due to blisters, splinters, falls or any other external direct trauma were excluded from the definition of "pain." The subject was required to have a medical doctor diagnose an injury within one week of its occurrence. To maintain consistency throughout the study, all medical examinations and diagnoses were done by the same medical doctor. If the diagnosis was positive, the subject was no longer required to run.

Analysis

This project was part of a larger project involving subjects continuously following the same methodology. Therefore, it was possible to include additional data from injured subjects at a later stage in the analysis if the first group of selected subjects did not provide enough injured cases for one specific group. This could be done without including additional healthy subjects since it was assumed that the "healthy" group was large enough and representative. Small injury groups may, therefore, have been enlarged by adding data from injured subjects which have followed the identical methodology and thus, increased the knowledge of a particular injury group. For the selected subjects (Chapter 3, Subject Selection) and additional subjects as described above, the analysis was done in the following three steps.

Medical Diagnoses

A definition of each diagnosed injury occurring more than once was given. Injuries occurring only once during the study were grouped together and classified as "other." A descriptive summary of the medical diagnoses occurring during the study was given. Descriptive statistics of

(a) the number of occurrences of specific injuries, and (b) the sites of occurrence of the injuries, were listed.

Grouping of Subjects

All data from subjects with no diagnosed injury were grouped into the "healthy" category. Kinetic and kinematic data from the injured leg of subjects diagnosed with an injury were grouped into one of the following injury groups. Groups may be classified according to different selection criteria. The possibilities of a basic selection unit, referred to as "case," are:

a. selection according to subjects as cases,
b. selection according to legs as cases, and
c. selection according to subject/leg/shoe cases.

If selecting according to (a), all data recorded for one subject should describe the subject's running style, i.e., an injured subject has to have a particular running style for all shoes used in both, injured and non-injured, legs. Since there is no causal or functional connection between measurements from an injured leg and a non-injured leg of one subject, possibilities of selection (a) have been rejected. A case selection according to (b) satisfies the condition of functional connection of the variables measured at this leg and the injury occurring at the same leg. However, the influence of the shoe has not been taken into account. For example, a subject running with two shoes might have a "healthy" running style in shoe #1, but not in shoe #2. However, the occurrence of an injury may not be positively identified to one specific shoe since, for example, an injury today might have recurred due to wearing shoe

#1 yesterday or due to wearing shoe #2 today. Therefore, case selection (c) was rejected and case selection (b) was chosen. Hence, all kinetic and kinematic data from non-injured legs of subjects diagnosed as injured were disregarded.

It should be pointed out that with case selection (b) in which a leg is defined as a case for grouping, all subjects were weighted in analytical procedures according to the number of shoes used in this study. Other possibilities included (a) weighting according to distance run, or (b) equal weight for each subject, regardless of the number of shoes used or distance run. For the healthy group, weighting considerations were not crucial since the group consisted of a "large" number of subjects. Most subjects used an average of two pairs of running shoes in the study. The injury groups, however, consisted of "few" subjects. Therefore, a non-average subject with a large number of shoes would be weighted more and would influence the analysis.

At the same time, it was assumed that more serious runners were represented with a greater number of shoes. Using the equal weight possibility (b) for each subject is assumed to be not representative for the average running population, since runners with the assignment of one (dominant) shoe per subject is totally arbitrary and subjective. Furthermore, it might be impossible to identify the exact shoe causing the injury. All analyses in this study were, therefore, weighted towards runners with more than the average number of shoes, or the more "serious" runner.

All data from the subjects were grouped according to:

(1) Diagnosis. All subjects with the same diagnosis were classified in the same group if there were a minimum of three subjects in the particular group. If less than three subjects could be classified into a specific injury group, the classification was established using functional criteria (2) of the injured elements of the human musculoskeletal system.

(2) Functional criteria. Functional grouping was performed in two classifications: (a) all subjects having problems with hamstrings were grouped into the "hamstring" injury group, including the diagnoses hamstring strain, hamstring tear and hamstring tendonitis; and (b) all subjects with injuries involving elements of the musculoskeletal system performing plantarflexion of the foot were grouped into the "plantarflexion" injury group. Diagnoses in the "plantarflexion" injury group included Achilles tendonitis, peroneal tendonitis, and posterior tibialis tendonitis.

Daily Questionnaire

The boundary conditions mentioned in "Running Sessions" were analyzed using chi-square tests (level of significance $\alpha=0.05$). Subjects were grouped into two groups, (1) healthy and (2) injured. Subjects who were never reported and/or diagnosed as injured were grouped into the "healthy" group. All subjects with a diagnosis of injury were grouped into the "injured" group. Frequencies of boundary conditions were compared between the healthy and injured subjects. Significant differences in the boundary conditions between those two subject groups were reported.

In order to count frequencies for continuous variables, ranges were established for average distance (0 to 5.0 km; 5.1 to 10.0 km; 10.1+ km), ambient temperature (0 to 10°C; 10.1 to 15.0°C; 15.1 to 20.0°C, 20.1+°C), average time (0 to 40 min; 40.1 to 60.0 min; 60.1+ min) and average speed (0 to 10.0 km/h; 10.1 to 12.5 km/h; 12.6 to 15.0 km/h; 15.1+ km/h). In order for distance and time entries to be accepted, the average speed (distance/time) had to be between 5 and 30 km/h.

Dynamic Factors

Kinematic and kinetic data variables related to one of the above defined injury groups were identified by statistical analysis using stepwise logistic regression procedures. Through logistic regression, independent predictor variables were selected in a stepwise manner and the coefficients for a logistic regression were estimated. The dependent response variable is a binary variable coded as 0 (healthy) or 1 (injured). The predicted proportion of successes (s/n; where s = the number of successes (healthy) and n = the number of the population) follows the logistic model:

$$P(s) = P(\text{healthy}) = e^u/(1 + e^u)$$

where u is a linear function of one or more independent variables.

$$u = c + \Sigma\, c_i \cdot \text{var}_i$$

where c and c_i are constants and var_i is the independent variable i. The independent variables can be categorical or continuous.

In the comparison between healthy and injured cases, variables were found which significantly (α=0.05) described dynamic differences between healthy and injured cases according to the function(s) of the injured musculoskeletal elements.

CHAPTER FOUR

RESULTS

Subject and Injury Profiles

One hundred and forty-six subjects passed the initial medical screening and provided informed written consent to participate in this study. Fifty-one subjects were excluded from the analysis of the external factors for the following reasons: 37 subjects did not return their daily questionnaires, 13 uninjured subjects did not meet the minimum total running requirement of 347 km and one subject was injured while participating in an excluded sport. The remaining **95 subjects**, referred to as the "**external factor group**," were analyzed further to determine the influence of external factors on the occurrence of running injuries based on information from the daily questionnaires. Sixty-eight percent of the subjects in the external factor group were male and 32% were female (mean mass = 67.3 kg, SD=10.4 kg). The accepted "external factor group" reported a total of 8,279 valid single runs.

Of the 95 subjects in the external factor group, 28 (29%) were diagnosed as injured with a total of 18 different injuries (Table 1). The most commonly diagnosed injury was patello-femoral syndrome. Seven injuries were diagnosed twice (Table 1). In addition, the following injuries (classified as "Other" in Table 1) were diagnosed only once in the study: Achilles tendonitis, costochondritis, hamstring tendonitis, low back pain, patellar tendonitis, peroneal tendonitis, posterior tibial tendonitis, rotator cuff tendonitis, lateral collateral ligament strain, and synovitis.

Table 1.--Diagnoses and frequencies from subjects included in the external factor group (n=95)

Diagnosis Name	Frequency [# of subjects]
patello-femoral syndrome	4
anterior tibial stress syndrome	2
hamstring strain, medial	2
hamstring tear, 1st degree	2
ilio-tibial band syndrome	2
meniscus tear, medial	2
plantar fascitis	2
retinaculitis	2
Other	10
Total	28

The diagnoses of injuries occurring more than once in this study were defined by the medical doctor as:

1. Patello-femoral syndrome. A clinical syndrome characterized by a pain in the retropatellar and peripatellar structures. Typically the discomfort is aggravated by ascending and descending stairs, as well as prolonged sitting and squatting. It is a diagnosis of clinical exclusion confirmed by the absence of other significant knee pathology and aided by the clinical signs of discomfort when palpating the peripatellar structures, compressing the patella, and displacing the patella medially and laterally.
2. Hamstring strain and tear. Hamstring strain or tear is an acute injury to the posterior thigh muscles/hamstrings characterized by a specific initiating incident in a previously well musculotendinous unit. Clinically there is painful palpation to the injured muscle

area made worse with active contraction of the muscle group through functional activity or against resistance.

3. Hamstring tendonitis. A clinical syndrome characterized by pain or discomfort in the tendon of hamstring muscle. It is confirmed by palpation of the tendon showing swelling, tenderness or attenuation of the tendon.
4. Achilles strain. An acute injury to the gastrocnemius/soleus musculotendinous unit, characterized on physical examination by tenderness to palpation within the muscle bellies or at the musculotendinous junction and associated with discomfort upon active plantar flexion or resisted muscle activity.
5. Achilles tendonitis. A clinical syndrome characterized by pain and discomfort within the Achilles tendon. On physical examination there is evidence of tenderness to palpation of the tendon, thickening of the tendon or attenuation, occasionally a gritty sensation of the tendon and the surrounding peritenon. Plantar flexion, appropriate activities, and resisted muscle activities reproduce the discomfort.
6. Peroneal tendonitis. A clinical syndrome characterized by pain and inflammation of the peroneal tendons. Palpation of the tendons elicits tenderness, as does resisted foot eversion.
7. Posterior tibialis tendonitis. A clinical syndrome characterized by inflammation of the tibialis posterior tendon. Physical examination reveals tenderness along the distribution of the tibialis posterior tendon, as well as on resisted plantar flexion with inversion. This diagnosis is made in exclusion of other signs of an historical

evidence of periostitis, compartment syndrome, stress fracture and myofascitis.

The injuries reported occurred in nine different body parts (Table 2). The most common injury location was the knee (29% of all injured subjects) followed by the thigh (25%) and the foot (21%).

In addition to the 28 injured subjects 23 subjects reported discomfort during 64 runs. Therefore, a total of 51 subjects reported injuries and/or discomfort which corresponds to 54% of the external factor group.

Table 2.--Sites of injury occurrence.

Body Part	Frequency [# of subjects]
knee	8
thigh	7
foot	6
ankle	2
calf	2
chest	1
low back	1
shoulder	1
Total	28

External Factors

Based on the results of the completed daily questionnaires, subjects reported a total of 74,674 km run. The average time of participation in the study was 200 days per subject (SD = 75 days), the average distance per run was 9 km (SD = 5 km), and the average weekly distance was 28 km per subject (SD = 19 km). The maximum distance for one single run was 42 km, the minimum distance 1 km. The duration of a single run ranged from 3 to 240 minutes. The average speed ranged from 5 to 25 km/h. Forty-one distance and time entries were excluded because the average speed was outside the accepted range of 5 to 30 km/h.

The results for the healthy and injured subjects in the external factor group were compared for the following eleven variables: ambient temperature, average distance, average time, average speed, pace, surface type, surface condition, surface smoothness, surface level, surface slope, and participation in other sports. Table 3 summarizes the probabilities of the null hypothesis that the analyzed variables were the same for the injured subjects as for the healthy subjects. The following six external factors were found to show a significant difference between injured and non-injured runners: ambient temperature, pace during the run, surface type, surface condition, surface level, and surface slope. No significant differences were found between the injured and healthy subjects for: average distance run (mileage), average time per run, average speed per run, surface smoothness, and participation in other sports.

The significant differences in the external factors between healthy and injured subject groups showed the following trends. Subjects who became injured were running at higher ambient temperatures than subjects who did not suffer from injury. Subjects running at a steady pace showed fewer injuries than those running at a variable pace (e.g.,

Table 3.--P-values for chi-square tests of healthy and injured subject groups for eleven variables from the daily questionnaire
*significant at $\alpha=0.05$

VARIABLE	P
Surface Condition*	0.000
Surface Slope*	0.000
Surface Level*	0.000
Ambient Temperature*	0.002
Surface Type*	0.003
Pace*	0.024
Distance	0.177
Surface Smoothness	0.218
Other Sports	0.348
Time	0.741
Speed	0.900

Table 4.--Percentage values of single runs for healthy and injured subjects on different surface types
*significant difference between the injured and healthy group (chi-square test) at $\alpha=0.05$.

Surface Type	% injured	% healthy
Grass/Dirt	9.8	9.1
Asphalt/Concrete	60.5	60.5
Mixed (1/2 and 1/2)	23.9	22.2
Synthetic	1.1	1.9
Wood*	1.2	0.7
Other*	2.8	4.1
not reported	0.7	1.5
Total	100.0%	100.0%

interval training). The results for different surface types are listed in Table 4. The majority of surface types used was not statistically different between injured and healthy subjects. However, significant differences were found for wood surfaces and those classified as "other" surface types. Subjects who ran on wet and/or dry surface conditions reported more injuries than subjects who ran on snowy and/or icy surface conditions. The healthy group ran more on level surfaces while the injured subjects ran more on right- or left-sloped surfaces. Subjects running on a sloped surface were injured more often than subjects running on flat surfaces. The injured group ran more on a right slope (right foot lower) than the healthy group and more than twice as much on the left slope (left foot lower) as the healthy group.

Dynamic Factors

In the analysis of the kinetic/kinematic variables seventeen additional subjects were excluded from the external factor group. Twelve subjects were excluded for not completing the full six months of participation, and five subjects were excluded for missing data due to technical problems in the data collection. The remaining **78 subjects,** referred to as the "**dynamic factor group,**" were analyzed further for dynamic factors. Force platform data and film data of 373 trials were collected from these 78 subjects.

From the 78 accepted subjects in the dynamic factor group, four subjects were diagnosed with **patello-femoral syndrome.** One additional subject diagnosed with patello-femoral syndrome was added to this group as described in Chapter 3, Analysis. These five subjects were referred to as the patello-femoral syndrome injury group. A total of ten trials from the injured legs of these subjects were collected for the patello-femoral syndrome injury group.

Stepwise logistic regression was used to predict the observed proportion of trials of injured legs from the kinetic and kinematic variables measured. The stepwise logistic regression procedure yielded the following four significant variables improving the prediction of patello-femoral syndrome:

1. the total pronation, $\Delta\beta_{pro}$;
2. the initial leg pronation, $\Delta\gamma_{10}$;
3. the initial shoe angle, δ_o; and
4. the total pronation of the rear foot, $\Delta\gamma_{pro}$.

Table 5.--Mean values (S.D.) for significant variables improving the prediction of patello-femoral syndrome

VARIABLES	healthy N=225	patello-femoral syndrome N=10
$\Delta\beta_{pro}$	14.8 (4.5)	18.1 (6.6)
$\Delta\gamma_{10}$	-5.8 (3.5)	-4.5 (3.9)
δ_o	22.6 (6.5)	22.7 (4.5)
$\Delta\gamma_{pro}$	-12.1 (3.9)	-13.7 (6.6)

Choosing the cut-point at P_c(healthy) = .975 the following correct classifications of trials can be made: 72% healthy, 80% patello-femoral syndrome, and 72% total (healthy + patello-femoral syndrome). Table 6 illustrates four different models with four (model 4) to one (model 1) variables included in the equation (in order of significance).

Table 6.--Constants and coefficients for four different patello-femoral syndrome models describing the probability P of being classified as healthy as a function of kinematic variables

i	var_i	model 4 c_i	model 3 c_i	model 2 c_i	model 1 c_i
0	constant	12.5	10.3	6.03	5.12
1	$\Delta\beta pro$	-.820	-.337	-.304	-.123
2	$\Delta\gamma_{10}$	-.395	-.446	-.399	
3	δ_o	-.205	-.159		
4	$\Delta\gamma_{pro}$	-.562			
cut-point		.975	.908	.958	.975
correct trial classifications:					
healthy (n=225)		72%	92%	74%	24%
injured (n=10)		80%	70%	90%	100%
total (n=235)		72%	91%	75%	27%

Note: blank entries mean that the variable is not included in the model. The model including four variables (model 4) is significant at the α=0.05 level.

The cut-points in the above summary table were chosen according to the rule of a maximal sum of correct percentage classifications of healthy trials plus injured trials with at least, arbitrarily chosen, two--thirds correct patello-femoral syndrome classifications. Tables 7 to 10 summarize the correct and incorrect classifications as a function of the cut-point for each model.

Figures 6 to 9 illustrate the sensitivity of each variable included in the patello-femoral syndrome model 4 (four significant variables at $\alpha=0.05$) while maintaining the three other variables constant. The values for the constant variables were chosen to be the mean of the patello-femoral syndrome group while the range of the variable in question was from the minimal observed value to the maximal observed value in the patello-femoral syndrome group.

Table 7.--Predictions of trials as healthy or injured as a function of the cut-point for the patello-femoral syndrome (PFS) model 4

	PERCENT CORRECT		
Cut-Point	Healthy N=225	PFS N=10	Total N=235
0.292	100.0	10	96.17
0.308	100.0	10	96.17
0.325	100.0	10	96.17
0.342	100.0	10	96.17
0.358	100.0	10	96.17
0.375	100.0	10	96.17
0.392	100.0	10	96.17
0.408	100.0	10	96.17
0.425	100.0	10	96.17
0.442	100.0	20	96.60
0.458	99.56	20	96.17
0.475	99.56	20	96.17
0.492	99.56	20	96.17
0.508	99.56	20	96.17
0.525	99.56	20	96.17
0.542	99.56	20	96.17
0.558	99.56	20	96.17
0.575	99.56	20	96.17
0.592	99.56	30	96.60
0.608	99.56	40	97.02
0.625	99.56	40	97.02
0.642	99.56	40	97.02
0.658	99.56	40	97.02
0.675	99.56	40	97.02
0.692	99.56	40	97.02
0.708	99.56	40	97.02
0.725	99.11	40	96.60
0.742	98.67	40	96.17
0.758	98.22	60	96.60
0.775	98.22	60	96.60
0.792	97.33	60	95.74
0.808	96.89	60	95.32
0.825	95.56	60	94.04
0.842	95.56	60	94.04
0.858	94.22	60	92.77
0.875	92.89	60	91.49
0.892	91.11	60	89.79
0.908	89.78	60	88.51
0.925	86.67	60	85.53
0.942	83.11	60	82.13
0.958	80.89	70	80.43
0.975	71.56	80	71.91
0.992	46.67	100	48.94

Table 8.--Predictions of trials as healthy or injured as a function of the cut-point for the patello-femoral syndrome (PFS) model 3

	PERCENT CORRECT		
Cut-Point	Healthy N=225	PFS N=10	Total N=235
0.392	100.0	10	96.17
0.408	100.0	10	96.17
0.425	100.0	10	96.17
0.442	00.0	10	96.17
0.458	99.56	10	95.74
0.475	99.56	10	95.74
0.492	99.56	10	95.74
0.508	99.56	10	95.74
0.525	99.56	10	95.74
0.542	99.56	10	95.74
0.558	99.56	10	95.74
0.575	99.11	10	95.32
0.592	99.11	20	95.74
0.608	99.11	20	95.74
0.625	99.11	30	96.17
0.642	98.67	30	95.74
0.658	98.67	30	95.74
0.675	98.67	30	95.74
0.692	98.67	30	95.74
0.708	98.67	40	96.17
0.725	98.67	40	96.17
0.742	98.22	40	95.74
0.758	98.22	40	95.74
0.775	97.78	40	95.32
0.792	97.78	40	95.32
0.808	96.89	40	94.47
0.825	96.44	40	94.04
0.842	96.00	50	94.04
0.858	94.67	50	92.77
0.875	94.67	60	93.19
0.892	94.22	60	92.77
0.908	92.44	70	91.49
0.925	88.89	70	88.09
0.942	86.22	70	85.53
0.958	78.67	70	78.30
0.975	65.78	80	66.38
0.992	35.56	90	37.87

Table 9.--Predictions of trials as healthy or injured as a function of the cut-point for the patello-femoral syndrome (PFS) model 2

Cut-Point	PERCENT CORRECT Healthy N=225	 PFS N=10	 Total N=235
0.592	99.56	0	95.32
0.608	99.56	0	95.32
0.625	99.56	0	95.32
0.642	99.11	10	95.32
0.675	99.11	20	95.74
0.692	99.11	20	95.74
0.708	99.11	20	95.74
0.725	99.11	30	96.17
0.742	98.67	40	96.17
0.758	97.78	40	95.32
0.775	97.78	40	95.32
0.792	97.33	40	94.89
0.808	97.33	40	94.89
0.825	97.33	40	94.89
0.842	96.44	40	94.04
0.858	95.56	40	93.19
0.875	94.22	40	91.91
0.892	92.89	40	90.64
0.908	92.44	40	90.21
0.925	88.44	40	86.38
0.942	84.00	60	82.98
0.958	74.22	90	74.89
0.975	57.78	90	59.15
0.992	24.00	90	26.81

Table 10.--Predictions of trials as healthy or injured as a function of the cut-point for the patello-femoral syndrome (PFS) model 1

Cut-Point	PERCENT CORRECT Healthy N=225	 PFS N=10	 Total N=235
0.708	100.0	10	96.17
0.725	100.0	10	96.17
0.742	100.0	10	96.17
0.758	100.0	10	96.17
0.775	100.0	10	96.17
0.792	100.0	10	96.17
0.808	100.0	10	96.17
0.825	99.56	10	95.74
0.842	98.22	10	94.47
0.858	97.33	10	93.62
0.875	96.89	10	93.19
0.892	96.44	10	92.77
0.908	95.11	10	91.49
0.925	93.78	20	90.64
0.942	85.33	40	83.40
0.958	67.56	40	66.38
0.975	23.56	100	26.81
0.992	0.44	100	4.68

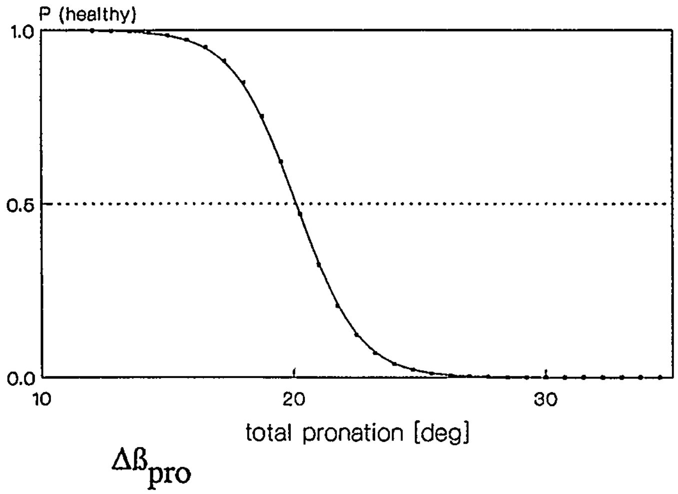

Figure 6. The probability of being healthy, P(healthy), as a function of $\Delta\beta_{pro}$ in the patello-femoral syndrome model 4. The variables $\Delta\gamma_{10}$, δ_o, and $\Delta\gamma_{pro}$ are constant and are mean values of the patello-femoral syndrome injury group.

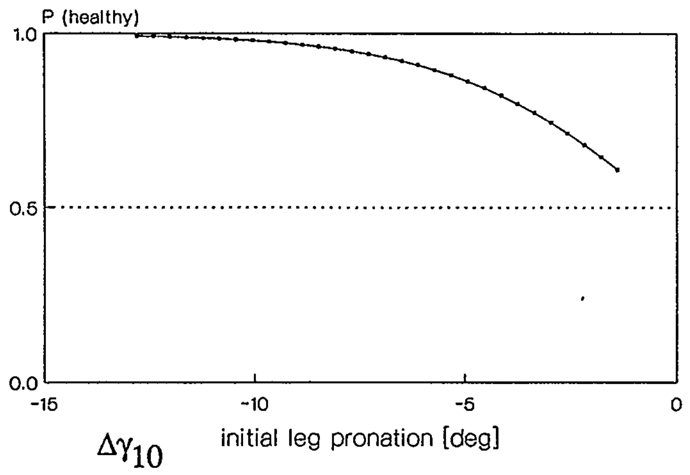

Figure 7. The probability of being healthy, P(healthy), as a function of $\Delta\gamma_{10}$ in the patello-femoral syndrome model 4. The variables $\Delta\beta_{pro}$, δ_o, and $\Delta\gamma_{pro}$ are constant and are mean values of the patello-femoral syndrome injury group.

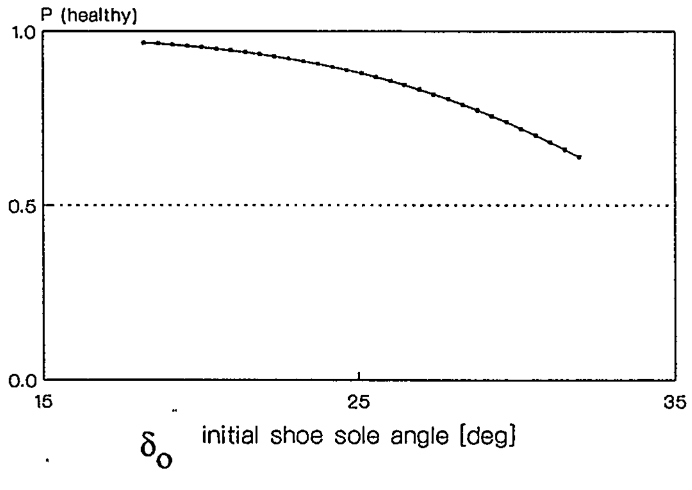

Figure 8. The probability of being healthy, P(healthy), as a function of δ_o in the patello-femoral syndrome model 4. The variables $\Delta\beta_{pro}$, $\Delta\gamma_{10}$, and $\Delta\gamma_{pro}$ are constant and are mean values of the patello-femoral syndrome injury group.

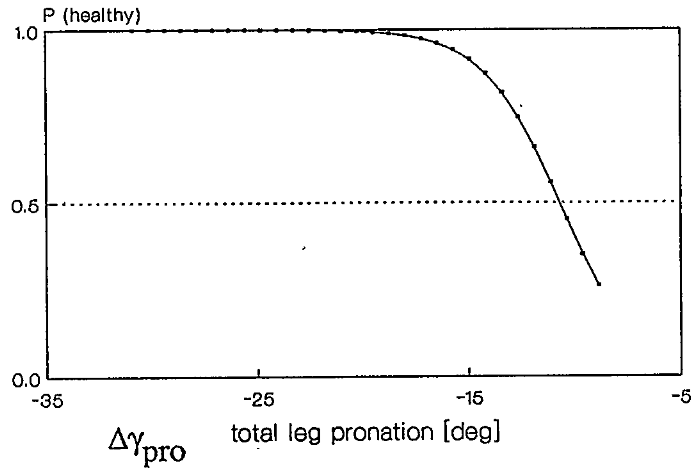

Figure 9. The probability of being healthy, P(healthy), as a function of $\Delta\gamma_{pro}$ in the patello-femoral syndrome model 4. The variables $\Delta\beta_{pro}$, $\Delta\gamma_{10}$, and δ_o are constant and are mean values of the patello-femoral syndrome injury group.

Four subjects were diagnosed with **hamstring injuries.** These four subjects were referred to as the hamstring injury group. A total of twelve trials from the injured legs of these subjects were collected for the hamstring injury group.

Stepwise logistic regression yielded the following two significant variables improving the prediction of hamstring injuries:

1. the time of occurrence of the impact peak, t_{zi}, and
2. the shoe angle, δ_o.

Table 11.--Mean values (S.D.) for significant variables improving the prediction of hamstring injuries

VARIABLES	healthy N=225	hamstring N=12
t_{zi}	30.0 (7.5)	24.9 (3.4)
δ_o	22.6 (6.5)	25.9 (4.9)

Choosing the cut-point at P_c(healthy) = .958 the following correct classifications of trials can be made: 63% healthy, 83% hamstring injuries, and 64% total (healthy + hamstring injuries). Table 12 shows two different models with two to one variables included in the model (in order of significance).

The cut-points in Table 12 were chosen according to the rule of a maximal sum of correct percentage classifications of healthy trials plus injured trials with at least two-thirds (arbitrarily chosen) correct hamstring injuries classifications and at least two-thirds correct healthy classification. Tables 13 and 14 summarize the correct and incorrect classifications as a function of the cut-point for each model. Figures 10 and 11 illustrate the sensitivity of each variable included in the hamstring model 2 (two significant variables at α=0.05) while maintaining the other variable constant. The value for the constant variable was chosen to be the mean of the hamstring injury group while the range of the variable in question was from the minimal observed value to the maximal observed value in the hamstring injury group.

Table 12.--Constants and coefficients for two different hamstring models describing the probability P of being classified healthy as a function of kinematic variables

i	var_i	model 2 c_i	model 1 c_i
0	constant	.719	-.815
1	t_{zi}	.185	.138
2	δ_o	-.115	
	cut-point	.958	.942
	<u>correct trial classifications</u>:		
	healthy (n=225)	63%	64%
	injured (n=12)	83%	83%
	total (n=237)	64%	65%

Note: Blank entries mean that the variable is not included in the model. The model including two variables is significant at the α=0.05 level.

Table 13.--Predictions of trials as healthy or injured as a function of the cut-point for the hamstring model 2

Cut-Point	PERCENT CORRECT Healthy N=225	 Hamstring N=12	 Total N=237
0.592	99.56	0	94.51
0.608	99.56	0	94.51
0.625	99.56	0	94.51
0.642	99.56	0	94.51
0.658	99.56	0	94.51
0.675	99.11	0	94.09
0.692	99.11	0	94.09
0.708	99.11	0	94.09
0.725	98.67	0	93.67
0.742	97.78	0	92.83
0.758	97.78	0	92.83
0.775	97.78	0	92.83
0.792	97.78	0	92.83
0.808	96.89	0	91.98
0.825	96.00	0	91.14
0.842	95.11	25.00	91.56
0.858	94.67	25.00	91.14
0.875	94.22	25.00	90.72
0.892	91.56	58.33	89.87
0.908	87.11	58.33	85.65
0.925	80.44	58.33	79.32
0.942	72.89	66.67	72.57
0.958	62.67	83.33	63.71
0.975	41.78	91.67	44.30
0.992	16.00	100.0	20.25

Table 14.--Predictions of trials as healthy or injured as a function of the cut-point for the hamstring model 1.

Cut-Point	PERCENT CORRECT Healthy N=225	Hamstring N=12	Total N=237
0.758	99.11	0	94.09
0.775	99.11	0	94.09
0.792	99.11	0	94.09
0.808	99.11	0	94.09
0.825	97.78	0	92.83
0.858	96.89	0	91.98
0.875	96.89	0	91.98
0.892	92.44	16.67	88.61
0.908	88.44	25.00	85.23
0.925	78.67	33.33	76.37
0.942	64.00	83.33	64.98
0.958	51.11	91.67	53.16
0.975	24.89	91.67	28.27
0.992	11.11	100.0	15.61

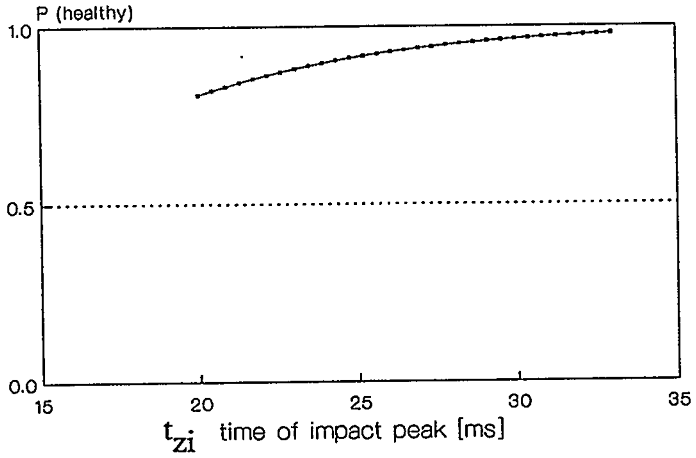

Figure 10. The probability of being healthy, P(healthy), as a function of t_{zi} in the hamstring model 2. The variable δ_o is constant and is the mean value of the hamstring injury group.

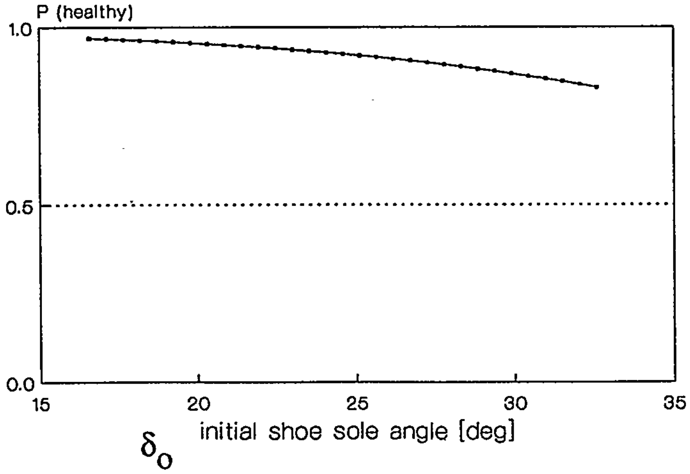

Figure 11. The probability of being healthy, P(healthy), as a function of δ_o in the hamstring model 2. The variable t_{zi} is constant and is the mean value of the hamstring injury group.

Three subjects were diagnosed with **plantar-flexor injuries.** These three subjects were referred to as the plantar-flexor injury group. A total of nine trials from the injured legs of these subjects were collected for the plantar-flexor injury group.

Stepwise logistic regression yielded the following four significant variables improving the prediction of plantar-flexor injuries:

1. the maximum vertical loading rate, G_{zi},
2. the take-off Achilles tendon angle, $ß_{end}$,
3. the total pronation, $\Delta ß_{pro}$, and
4. the absolute touch down velocity of the heel, v_o.

Choosing the cut-point at P_c(healthy) = .975 the following correct classifications of trials can be made: 84% healthy, 89% plantar-flexor

Table 15.--Mean values (S.D.) for significant variables improving the prediction of plantar-flexor injuries

VARIABLES	healthy N=225	plantar-flexor N=9
G_{zi}	80.4 (26.0)	50.6 (13.2)
$ß_{end}$	175.9 (7.1)	183.9 (7.9)
$\Delta ß_{pro}$	14.8 (4.5)	19.0 (3.1)
v_o	2.5 (0.6)	3.0 (0.4)

injuries, and 84% total (healthy + plantar-flexor injuries). Table 16 shows four different models with four (model 4) to one (model 1) variables included in the model (in order of significance).

The cut-points in the above summary table were chosen according to the rule of a maximal sum of correct percentage classifications of healthy plus injured trials with at least, arbitrarily chosen, two-thirds correct plantar-flexor injuries classifications and at least two-thirds correct healthy classification. Tables 17 to 20 summarize the correct classifications as a function of the cut-point for each model.

Figures 12 to 15 illustrate the sensitivity of each variable included in model 4 (four significant variables at α =0.05) while maintaining the other variables constant. The values for the constant variables were chosen to be the mean of the plantar-flexor injury group while the range of the variable in question was from the minimal observed value to the maximal observed value in the plantar-flexor injury group.

Tables 21a,b,c summarize all single results for the significant variables of the patello-femoral syndrome injury group, hamstring injury group, and plantar-flexor injury group, respectively. Only data from injured legs are presented.

Table 16.--Constants and coefficients for four different plantar-flexor models describing the probability of being classified as healthy as a function of kinematic variables

i	var_i	model 4 c_i	model 3 c_i	model 2 c_i	model 1 c_i
0	constant	48.0	41.9	25.4	-3.79
1	G_{zi}	.096	.084	.089	.115
2	β_{end}	-.218	-.220	-.155	
3	$\Delta\beta_{pro}$	-.318	-.254		
4	v_o	-2.17			
cut-point		.975	.992	.975	.975
correct trial classifications:					
healthy (n=225)		84%	89%	74%	67%
injured (n=12)		89%	100%	78%	89%
total (n=237)		84%	70%	74%	68%

Note: Blank entries mean that the variable is not included in the model. The model including four variables, model 4, is significance at the α=0.05 level.

Table 17.--Predictions of trials as healthy or injured as a function of the cut-point for the plantar-flexor model 4

Cut-Point		PERCENT CORRECT	
	Healthy N=225	Plantar-Flexor N=9	Total N=234
0.042	100.0	11.11	96.58
0.058	100.0	22.22	97.01
0.075	100.0	22.22	97.01
0.208	100.0	22.22	97.01
0.225	100.0	33.33	97.44
0.242	100.0	33.33	97.44
0.258	100.0	44.44	97.86
0.275	100.0	44.44	97.86
0.292	100.0	44.44	97.86
0.308	99.56	55.56	97.86
0.325	99.56	55.56	97.86
0.508	99.56	55.56	97.86
0.525	99.56	55.56	97.86
0.542	99.56	55.56	97.86
0.558	99.56	55.56	97.86
0.575	99.56	55.56	97.86
0.592	99.56	66.67	98.29
0.608	99.56	66.67	98.29
0.625	99.56	66.67	98.29
0.642	99.56	66.67	98.29
0.658	99.56	66.67	98.29
0.675	99.56	66.67	98.29
0.708	99.56	66.67	98.29
0.725	99.56	66.67	98.29
0.742	99.11	66.67	97.86
0.758	99.11	66.67	97.86
0.775	99.11	66.67	97.86
0.792	99.11	66.67	97.86
0.808	99.11	66.67	97.86
0.825	99.11	66.67	97.86
0.842	98.22	66.67	97.01
0.858	97.33	66.67	96.15
0.875	95.56	66.67	94.44
0.892	93.78	66.67	92.74
0.908	93.33	66.67	92.31
0.925	92.00	66.67	91.03
0.942	90.67	77.78	90.17
0.958	88.44	77.78	88.03
0.975	84.00	88.89	84.19
0.992	71.11	100.0	72.22

Table 18.--Predictions of trials as healthy or injured as a function of the cut-point for the plantar-flexor model 3

Cut-Point	PERCENT CORRECT		
	Healthy N=225	Plantar-Flexor N=9	Total N=234
0.175	100.0	22.22	97.01
0.192	100.0	22.22	97.01
0.208	100.0	22.22	97.01
0.225	100.0	22.22	97.01
0.242	100.0	33.33	97.44
0.425	100.0	33.33	97.44
0.442	100.0	33.33	97.44
0.458	100.0	44.44	97.86
0.475	100.0	44.44	97.86
0.492	100.0	44.44	97.86
0.508	100.0	44.44	97.86
0.525	100.0	44.44	97.86
0.542	100.0	55.56	98.29
0.558	100.0	55.56	98.29
0.575	99.56	55.56	97.86
0.592	99.56	55.56	97.86
0.608	99.56	55.56	97.86
0.625	99.56	55.56	97.86
0.625	99.56	55.56	97.86
0.642	99.56	55.56	97.86
0.658	99.11	55.56	97.44
0.675	99.11	55.56	97.44
0.692	98.67	55.56	97.01
0.708	98.67	55.56	97.01
0.725	98.22	55.56	96.58
0.742	97.78	55.56	96.15
0.758	97.78	55.56	96.15
0.792	97.33	55.56	95.73
0.808	96.89	66.67	95.73
0.825	96.89	66.67	95.73
0.842	95.56	66.67	94.44
0.858	95.56	66.67	94.44
0.875	95.11	66.67	94.02
0.892	94.67	66.67	93.59
0.908	92.44	66.67	91.45
0.925	92.44	66.67	91.45
0.942	89.78	66.67	88.89
0.958	86.22	66.67	85.47
0.975	80.89	77.78	80.77
0.992	68.89	100.0	70.09

Table 19.--Predictions of trials as healthy or injured as a function of the cut-point for the plantar-flexor model 2

Cut-Point	PERCENT CORRECT Healthy N=225	Plantar-Flexor N=9	Total N=234
0.208	100.0	11.11	96.58
0.225	100.0	11.11	96.58
0.242	100.0	11.11	96.58
0.258	100.0	11.11	96.58
0.275	100.0	22.22	97.01
0.292	100.0	22.22	97.01
0.308	100.0	22.22	97.01
0.325	100.0	22.22	97.01
0.342	100.0	22.22	97.01
0.358	100.0	22.22	97.01
0.375	100.0	33.33	97.44
0.392	100.0	33.33	97.44
0.408	100.0	33.33	97.44
0.425	100.0	33.33	97.44
0.442	100.0	33.33	97.44
0.458	100.0	33.33	97.44
0.475	100.0	33.33	97.44
0.492	100.0	33.33	97.44
0.508	100.0	33.33	97.44
0.525	100.0	33.33	97.44
0.542	100.0	33.33	97.44
0.558	100.0	33.33	97.44
0.575	100.0	44.44	97.86
0.592	100.0	44.44	97.86
0.608	100.0	44.44	97.86
0.625	100.0	44.44	97.86
0.658	100.0	44.44	97.86
0.675	99.56	44.44	97.44
0.692	99.56	44.44	97.44
0.708	99.56	44.44	97.44
0.725	99.11	44.44	97.01
0.742	99.11	44.44	97.01
0.758	98.67	44.44	96.58
0.792	97.33	44.44	95.30
0.808	97.33	44.44	95.30
0.825	96.89	55.56	95.30
0.842	96.00	55.56	94.44
0.875	94.22	55.56	92.74
0.892	93.78	55.56	92.31
0.908	92.44	55.56	91.03
0.925	90.22	55.56	88.89
0.942	86.22	66.67	85.47
0.958	84.00	66.67	83.33
0.975	73.78	77.78	73.93
0.992	53.78	100.0	55.56

Table 20.--Predictions of trials as healthy or injured as a function of the cut-point for the plantar-flexor model 1

Cut-Point	PERCENT CORRECT Healthy N=225	 Plantar-Flexor N=9	 Total N=234
0.592	100.0	11.11	96.58
0.608	100.0	11.11	96.58
0.625	100.0	33.33	97.44
0.642	100.0	33.33	97.44
0.658	100.0	33.33	97.44
0.675	100.0	44.44	97.86
0.692	100.0	44.44	97.86
0.708	100.0	44.44	97.86
0.725	99.56	44.44	97.44
0.742	99.11	44.44	97.01
0.758	98.67	44.44	96.58
0.775	98.67	44.44	96.58
0.792	96.89	44.44	94.87
0.808	95.56	44.44	93.59
0.825	95.56	44.44	93.59
0.842	95.11	44.44	93.16
0.858	95.11	44.44	93.16
0.875	92.44	44.44	90.60
0.892	91.11	44.44	89.32
0.908	87.56	55.56	86.32
0.925	85.78	55.56	84.62
0.942	80.44	55.56	79.49
0.958	76.89	66.67	76.50
0.975	67.11	88.89	67.95
0.992	53.33	100.0	55.13

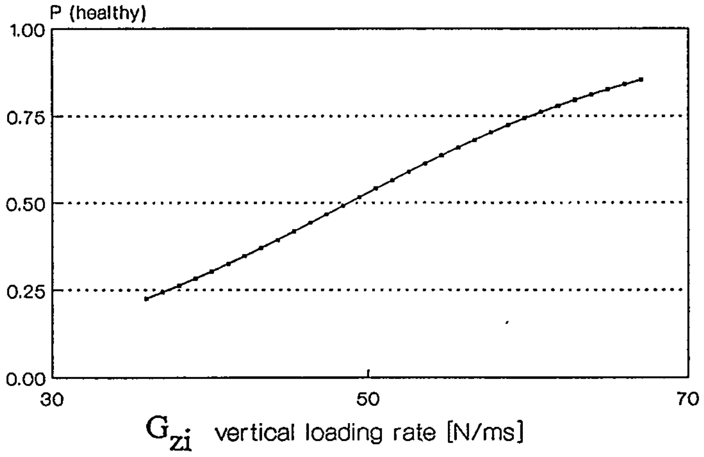

Figure 12. The probability of being healthy, P(healthy), as a function of G_{zi} in the plantar-flexor model 4. The variables $ß_{end}$, $\Delta ß_{pro}$ and v_o are constant and are mean values of the plantar-flexor injury group.

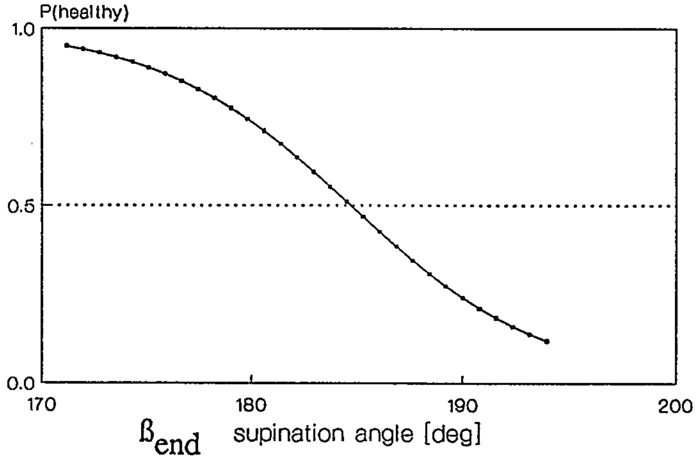

Figure 13. The probability of being healthy, P(healthy), as a function of $ß_{end}$ in the plantar-flexor model 4. The variables G_{zi}, $\Delta ß_{pro}$ and v_o are constant and are mean values of the plantar-flexor injury group.

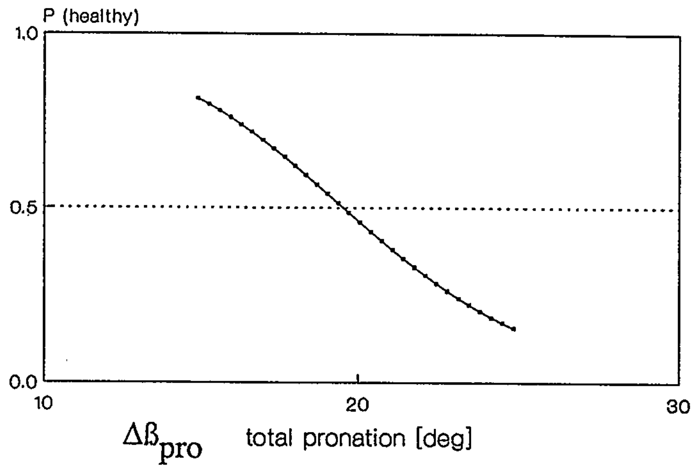

Figure 14. The probability of being healthy, P(healthy), as a function of $\Delta ß_{pro}$, in the plantar-flexor model 4. The variables G_{zi}, $ß_{end}$ and v_o are constant and are mean values of the plantar-flexor injury group.

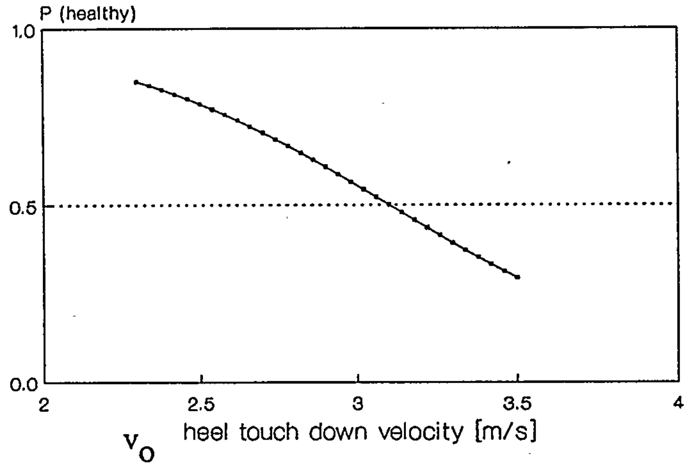

Figure 15. The probability of being healthy, P(healthy), as a function of v_o in the plantar-flexor model 4. The variables $ß_{ene}$, G_{zi}, and $\Delta ß_{pro}$ are constant and are mean values of the plantar-flexor injury group.

Table 21a.--Single results of injured subjects for significant variables in the patello-femoral syndrome model 4

subject #	gender	shoe	leg	$\Delta\beta_{pro}$ [°]	$\Delta\gamma_{10}$ [°]	δ_o [°]	$\Delta\gamma_{pro}$ [°]
87	M	1	R	15.7	-10.5	30.6	-9.8
87	M	2	R	14.6	-3.8	18.2	-11.1
95	F	1	L	19.3	-1.0	24.6	-12.5
95	F	1	R	20.5	-3.1	24.3	-15.0
95	F	2	L	21.5	-3.5	26.0	-15.7
95	F	2	R	14.9	-2.9	30.9	-14.8
121	F	1	L	12.0	-1.8	21.7	-8.9
133	M	1	L	13.5	-2.1	27.8	-8.1
133	M	1	L	14.3	-3.3	32.0	-9.9
220	M	1	R	34.5	-12.8	30.6	-30.9

Table 21b.--Single results of injured subjects for significant variables in the hamstring injury model 2

subject #	gender	shoe	leg	t_{zi} [ms]	δ_o [°]
22	M	1	L	25	18.6
22	M	2	L	33	24.6
22	M	3	L	26	23.2
28	M	1	R	23	25.9
28	M	2	R	21	26.6
28	M	3	R	22	16.6
71	M	1	L	26	26.6
71	M	2	L	25	32.6
71	M	3	L	26	30.2
71	M	4	L	25	29.4
101	M	1	L	20	25.0
101	M	2	L	27	31.9

Table 21c.--Single results of injured subjects for significant variables in the plantar-flexor model 4

subject #	gender	shoe	leg	G_{zi} [N/ms]	ß_{end} [°]	$\Delta\text{ß}_{pro}$ [°]	v_o [m/s]
40	M	1	L	37	194.7	14.9	3.5
40	M	2	L	39	185.2	18.4	3.1
40	M	3	L	36	191.7	15.6	3.5
40	M	4	L	37	189.0	20.1	2.3
40	M	5	L	53	184.9	17.0	3.2
78	M	1	L	62	177.2	19.2	2.4
78	M	2	L	67	186.5	25.2	3.0
107	M	1	L	60	171.2	21.0	2.9
107	M	2	L	64	174.9	19.5	3.3

CHAPTER FIVE

DISCUSSION

Subject and Injury Profile

In the present study, 29% of the external factor group became injured. This percentage of **injury frequency** is much lower than results previously presented in the literature. Typical injury rates have been reported to be between 46% and 70% as illustrated in Table 22. One possible reason for this difference may be that most of the studies presented in the literature were conducted over the period of one year while the present study was conducted over a period of six months. Theoretically, if the results of the present study were extended to a one year period, the predicted injury rate would be 50% as illustrated in Figure 16. This calculation assumes (1) the observed injury rate of 29% per six months is constant over time, and (2) the remaining healthy subjects will become injured at a rate of 29% per six months. The corrected injury rate of 50% per year is closer to the reported results in the literature, however, slightly lower than the average of the reported injury rate (Table 22).

Possible explanations which may cause these differences are:

(a) There is a slight trend of decreasing frequency of injuries as reported for the years from 1977 to 1988. This trend may be a result of (1) equipment improvements, such as better running shoes and surfaces and/or (2) the improvements in training techniques and/or (3) increased public knowledge regarding injury prevention.

Table 22.--Reported injury rate in the literature from 1977 to 1988.
Injury Rate = reported injury rate during the study;
Time = time period of study;
Corrected Injury Rate = injury rate per one year.

Year	Author	Injury Rate [%]	Time [Years]	Corrected Injury Rate [%]
1977	Runner's World	67	1	67
1982	Brody	70	1	70
1986	Jacobs	47	2	27
1987	Warren	50-70	1	50-70
1988	Marti	46	1	46
1988	present	29	0.5	50
	average	54	1.0	54

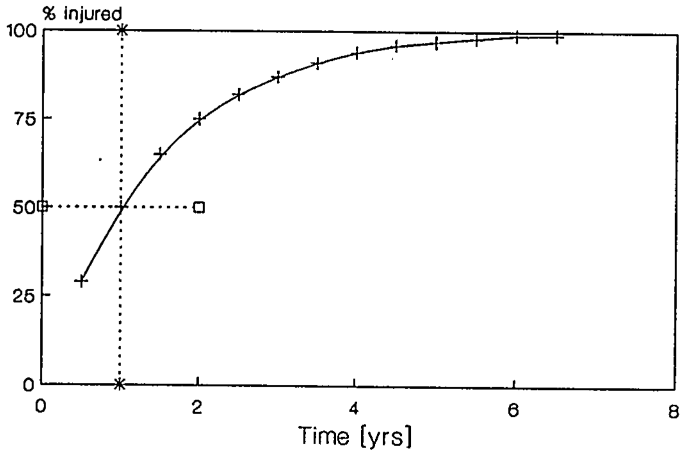

Figure 16. Expected injury rate of a population with a constant injury rate of 29% per six months as a function of time.

(b) The definition of "injury" is often used in different ways. In this study every injury was medically diagnosed by a single physician. If cases where discomfort was reported by the subjects are included in the definition of injury, the percentage of subjects who reported discomfort and/or injury would be 53% per six months. This corresponds to 78% per year, assuming (1) a constant observed injury rate of 53% per six months and (2) the remaining healthy subjects will become injured at a rate of 53% per six months.

(c) There are differences in the study designs (prospective versus retrospective) and the population samples used in the various studies. This study included only initially healthy subjects whose main physical activity was running. This restriction is assumed to exclude a significant number of injuries due to other sport activities.

The most commonly diagnosed injury was **patello-femoral syndrome** which occurred in 14% of the injured population. Clement et al. (1981) reported that patello-femoral syndrome was the most common injury occurring in 25% of their patients, with tibial stress syndrome as the second most common injury with a frequency of 13%. A frequency of 13% for posterior-tibial syndrome was also reported by James et al. (1978). McKenzie et al. (1985) stated that Clement's tibial stress syndrome and James' posterior-tibial stress syndrome are comparable. These syndromes, commonly called "shin splints," were diagnosed as anterior-tibial-stress syndrome for 7% of the injured subjects in this study. The relative occurrence of patello-femoral syndrome and anterior-tibial-stress syndrome is consistently lower in this study than in James' and Clement's studies, and the injuries have the same ranking. However, the frequencies of patello-femoral syndrome and anterior-tibial-stress syndrome in this study and in the study of Clement et al. were not found to be statistically different (chi-square test) because of the difference in the number of injured subjects (28 in this study compared to 1,650 patients in the study of Clement et al.).

The **knee** is generally reported to be the most commonly injured body site (Table 23). The next most common injury site is the thigh, followed by the foot, ankle, and calf. It is difficult to compare the relative occurrence of injury sites in different studies due to different definitions of the site categories or grouping of the injured sites. Thus, the following discussion will focus on the knee as it is classified consistently between studies. Clement et al. (1981) and Newell et al. (1984) reported a higher number of knee injuries, however, in these studies the population consisted of all injured subjects. The remaining studies presented in Table 23 examined "healthy" running populations and the relative occurrence of injuries.

Figure 17 illustrates the differences in knee injury frequency for studies with patients and with runners as subjects. It can be seen that studies using a patient population show an increasing trend over the years, while studies examining a runner population show little change in knee injury frequency over the years. A possible explanation for the higher ratio of knee injuries in populations with patients as subjects

Table 23.--Percentage of reported knee injuries in the literature in order of year of occurrence. N = number of subjects in population.

RW^1=<u>Runner's World</u> (in Cavanagh, 1980)
RW^2=<u>Runner's World</u> (in Cavanagh, 1980)
RW^3=<u>Runner's World</u> (in Krissoff, 1979)

MAIN AUTHOR	YEAR	KNEE INJURIES [%]	N	POPULATION
RW^1	1971	18	800	runners
RW^2	1973	23	1600	runners
RW^3	1977	25		runners
James	1978	29	180	patients
Gudas	1980	31	224	runners
Clement	1981	41	1650	patients
Newell	1984	50	658	patients
Jacobs	1986	21	451	race
Marti	1988	28	4358	race
present study		29	28	runners

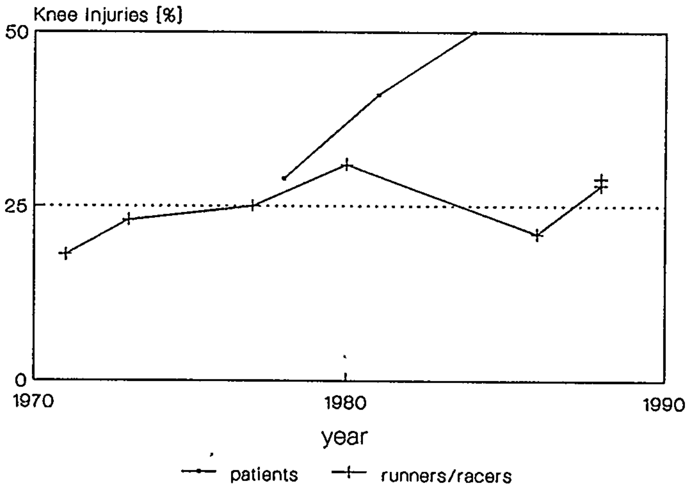

Figure 17. Relative occurrence of knee injuries over the years for studies involving (a) patients as subjects and (b) runners as subjects.

may be that clinical studies are biased towards a special group of injuries, depending on the hospital where the clinical investigation is performed. The reason for this bias may be that certain clinical specialists attract injuries of their specialization. In addition, the studies of Clement and Newell did not seem to exclude or account for other sports.

External Factors

In this study, the distance run did not have a significant effect on reported injuries. This finding is supported by examining the results of James et al. (1978), Clement et al. (1981), and Newell and Bramwell (1984) as illustrated in Table 24. Although the relative knee injury frequency increased from 1978 to 1984 the, weekly distance decreased in the same period of time. The findings of the present study contradicted those of Jacobs et al. (1986) who reported that the injured group ran a greater weekly distance and more days per week than the healthy group. It was stated that weekly distance in excess of 30 miles was significantly correlated with injuries. However, these different results may be attributed to the differences in study designs and populations used for the studies. Jacobs et al. (1986) conducted a retrospective questionnaire study of randomly chosen entrants of a 10 000 metre race in which injuries were defined by the participant and not diagnosed by a medical doctor. James et al. (1978) reported that excessive distance (mileage) was associated with 60% of the injuries.

Table 24.--Summary of studies reporting the relative occurrence of knee injuries, the weekly distance reported, and the population sampled.

MAIN AUTHOR	YEAR	KNEE INJURIES [%]	AVERAGE WEEKLY DISTANCE [km]	POPULATION
James	1978	29	81	patients
Clement	1981	41	45	patients
Newell	1984	50	40	patients
Jacobs	1986	21	63	race
present	1988	29	28	runners

Different running populations run different average weekly distances (M_{Pi}). It may be assumed that there is a critical absolute weekly distance limit for the occurrence of injuries (M_c). If a population runs at a weekly distance well below the critical limit, i.e., $M_{Pi} << M_c$, an increase of the distance will not be above the critical limit M_c. In this situation distance would not be correlated with injuries. If, however, the population was competitive, racing or training for a race, the population distance mean would be closer to the critical distance mean, i.e., $M_{Pi} < M_c$. A small increase in distance would then bring the subject above the critical limit M_c, and injury would occur. The results presented in Table 24 and the finding of Jacobs et al. (1986) support the above explained speculation. As reported by Jacobs et al. a weekly distance of 50 km would be the critical limit, M_c. The two studies in Table 24 with an average weekly distance (M_{Pi}) of greater than 50 km report a relationship between distance and injuries, and the three studies in Table 24 with an average weekly distance (M_{Pi}) of less than 50 km report no relationship between distance and injuries. Since the present study had a weekly distance of 28 km it is understandable that distance had no significant effect on injuries.

The interpretation of results analyzing the correlation of external factors with running injuries is not always obvious. Significant differences were found between the healthy and injured group regarding surface conditions and ambient temperatures. A possible explanation for this may be that subjects anticipating snow, ice or cold temperatures were better prepared, both mentally and physically (i.e. warm-up), for a run with increased injury potential.

Excessive pronation has been shown to be correlated with injuries (Clement et al., 1981). An uneven surface may force a subject to have greater amount of pronation or supination compared to an even surface. Thus, it may be explained why greater amounts of surface slope were found to be correlated to injuries.

Right- or left-sloped terrain has been reported to be connected with injuries by James et al., (1978) and McKenzie at al. (1985). The results of this study also illustrated that subjects running on right- or left-sloped terrain became injured more frequently.

Dynamic Factors

The significant kinematic variables found to be associated with **patello-femoral syndrome** are variables which describe pronation. Pronation of the foot in an anatomical sense is defined as the simultaneous movement of eversion, dorsiflexion, and abduction in the combined talocrural and subtalar joint and is associated with internal rotation of the leg (Wolpa, 1982; Stacoff and Luethi, 1986).

The variables $\Delta\beta_{pro}$, $\Delta\gamma_{10}$, and $\Delta\gamma_{pro}$ are related to the eversion of the foot. The variable δ_o, the initial shoe sole angle, describes the dorsiflexion of the foot. Therefore, a combination of the four variables found to be significant may be used to describe anatomical pronation. A negative coefficient in the logistic regression model means that a higher variable value is connected with a higher probability of becoming injured. All pronation variables have a negative coefficient in the logistic regression model. Therefore, according to the model, a large amount of pronation would predict a high probability of patello-femoral syndrome.

Patello-femoral syndrome (also called chondromalacia patellae or runner's knee) has been reported to be caused by various factors. An anatomical factor that has been associated with patello-femoral syndrome is patella alta. Dynamically, patello-femoral syndrome has been associated with an abnormal motion in the knee resulting from a problem within the foot (Wolpa, 1982). Suggested treatment is to "control the pronation problems occurring at the ankle joint." In order to understand the influence of pronation on the knee joint, one has to examine the functional anatomy of the combined ankle joint. Figure 18 illustrates a schematic representation of the talocrural joint and the subtalar (talocalcanean) joint. Based on its definition, pronation can occur at the talocrural joint and/or the subtalar joint. The talocrural joint is usually considered to act as a simple hinge joint allowing dorsiflexion

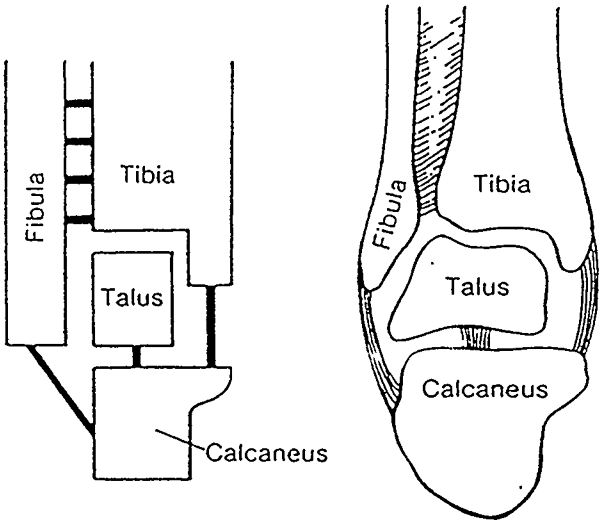

Figure 18. Schematic representation of the talocrural joint and the subtalar (talocalcanean) joint (Basmajian, 1982).

and plantar flexion (Inman, 1976), "but any subsidiary movement that may occur. . .is undesirable and a sign of weakness in the joint" (Basmajian, 1982). The movement occurs about an axis which passes more or less transversely through the talus (Figure 19). The range of motion possible is about 35° in plantar flexion and 25° in dorsiflexion (Lanz and Wachsmuth, 1972). The subtalar joint is located between the talus and calcaneus (Figure 18).

The oblique axis through the subtalar joint passes from the lateral inferior part of the calcaneus to the medial side of the talus. Motion is primarily that of inversion and eversion of the calcaneus relative to the talus (Stacoff and Luethi, 1986). Both of these axes, the subtalar joint axis and the talocrural joint axis, are not fixed with respect to the foot during movement. Considering the obliqueness of these joint axes, any rotation around these axes results in a rotation of the foot in the

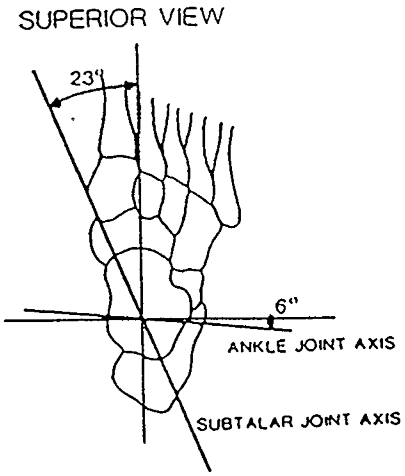

Figure 19. Schematic representation of the orientations of the axes of the talocrural joint and subtalar joint (Inman, 1976). Average values for six cadavers (reported range = 15°).

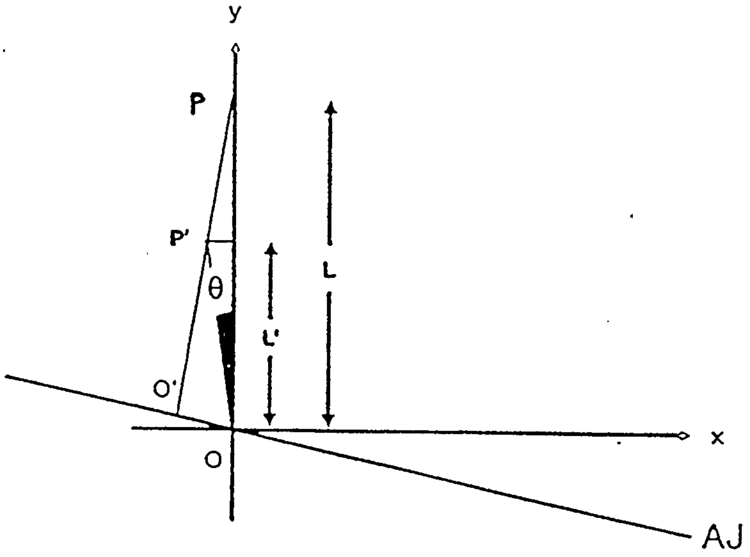

Figure 20a. Geometrical consideration of the talocrural joint to estimate leg rotation as a function of pronation (see text for nomenclature). Top view.

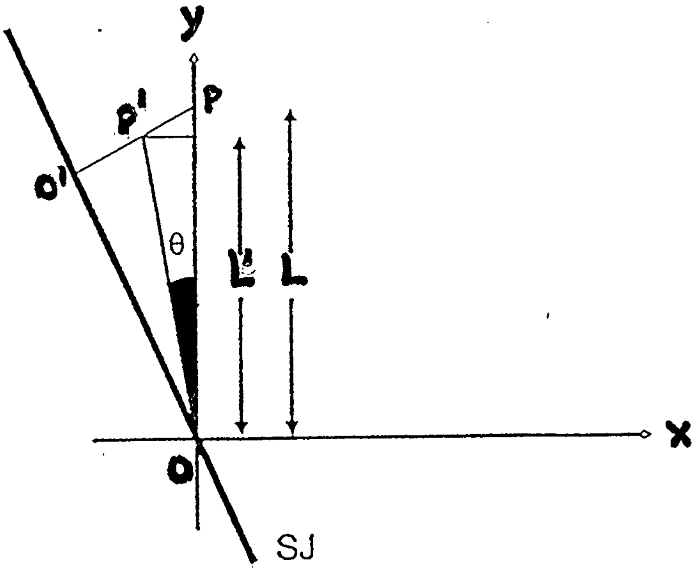

Figure 20b: Geometrical consideration of the subtalar joint to estimate leg rotation as a function of pronation (see text for nomenclature). Top view.

transverse plane. A geometrical model (Figures 20a,b) is used to illustrate the amount of rotation in the transverse plane as a function of pronation. The origin O of an x-y coordinate system is placed at the intersection of the projection of the talocrural joint axis AJ and the subtalar joint axis SJ into a transverse plane. The y-coordinate axis is placed along the center line of the foot, positive in the direction of movement. The length of the forefoot is OP, in the following labeled as L, with P being a point at the anterior end of the foot.

In a first step, plantarflexion, a movement around the talocrural joint axis AJ, is considered (Figure 20a). Point P will move to a new position, labeled P'. The projection of the distance traveled, PP', depends on the amount of plantarflexion. Let us assume a maximal value of 35° plantar flexion. Therefore,

$$PP' = L \cdot \sin(x,AJ) \cdot \sin(35°) \qquad (1)$$

The new orientation of the foot, OP', and the old y-axis define the angle of rotation, θ, due to the amount of plantar flexion assumed.

$$\theta = \arctan [L' / \{(OP')^2 - (L')^2\}^{1/2}]. \qquad (2)$$

The amount of foot rotation, θ, due to a maximum of 35° plantar flexion yields a maximal rotational value in the transverse plane of 1.2° (equation 2).

In a second step, eversion, a movement around the subtalar joint axis SJ, is discussed (Figure 20b). The same considerations as above apply, however, equation 1 becomes

$$PP' = L \cdot \sin(x,SJ) \cdot \sin(35°) \qquad (3)$$

The amount of foot rotation, θ, due to a maximum of 35° eversion yields a maximal value in the transverse plane of 7.3°.

If the foot is fixed the rotation, θ, may be transmitted to the tibia and may occur at the knee joint (Root et al., 1977). No variables in the present study measured internal rotation of the leg. However, it is possible to estimate roughly the internal rotation of the leg, θ, from the posterior kinematic data. Figure 21 illustrates a thigh, leg and foot at the moment of maximal pronation during touch-down viewed from the posterior. Markers A and D were initially placed in the posterior centre of the leg and shoe sole, respectively, while the subject was standing (Figure 4). Marker A was initially placed at a distance (d_A) equal to 50% of the diameter (D_A) of the tibia from the medial border and

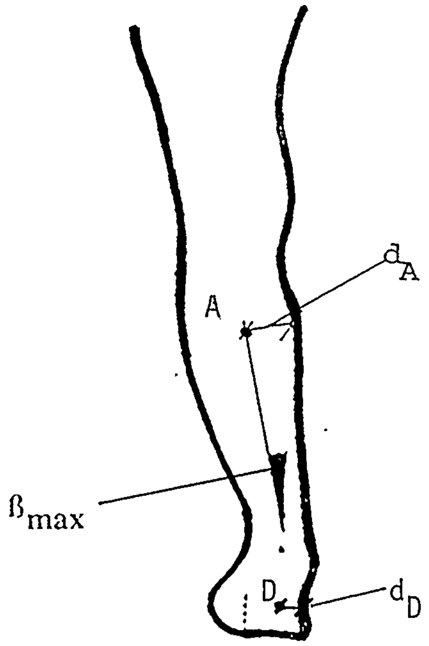

Figure 21. Posterior view for a thigh, leg and foot at maximal pronation, $ß_{max}$ (see text for notations).

marker D was initially placed at a distance (d_D) equal to 50% of the diameter (D_D) of the shoe from the medial border. In order to estimate internal leg rotation, θ, the lateral displacement of markers A and D (equation 4) were used as follows.

$$\theta = \arcsin [\{d_A/D_A - d_D/D_D\} \cdot 2] \qquad (4)$$

where d_D/D_D corrects for the lateral displacement of marker D at maximal pronation if the direction of the movement is not perpendicular to the film plane and d_A/D_A estimates the lateral displacement of marker A at maximal pronation as compared to the position of the subject when being marked.

The internal leg rotation for one trial of each of the patello-femoral subjects calculated from experimental data according to equation 4 (Table 25) shows that all patello-femoral injured subjects demonstrated internal leg rotation during maximal pronation. An arbitrary example of a healthy subject is listed in Table 25 (denoted by an * behind the subject number). This healthy subject demonstrated external leg rotation during maximal pronation. The data from this experiment support the earlier speculation that the subjects with patello-femoral syndrome have excessive pronation associated with internal leg rotation. Figure 22 summarizes the rotation of the foot in the transverse plane as a function of the amount of rotation around the talocrural joint axis and around the subtalar joint axis according to the geometrical model described above (equation 2). According to these theoretical considerations excessive pronation may be connected with excessive rotation between tibia and femur at the knee joint. This is supported in the literature by Wolpa (1982) who defines pronation as

Table 25.--Total internal leg rotation, θ, according to equation 4 from marker measurements d_A and d_D from the medial side of the tibia and shoe, respectively, for all patello-femoral subjects and one healthy subject (*). D_A (tibia diameter) and D_D (shoe diameter) at maximal pronation, $ß_{max}$ (Figure 21). Assuming an error of ± 1 mm to estimate distances d and D from the film, the error in θ will be ± 4°.

Subject #	$ß_{max}$ [°]	d_A/D_A	d_D/D_D	θ [°]
87	10	.52	.42	12
95	12	.46	.39	8
121	5	.42	.41	1
133	17	.48	.44	5
220	21	.58	.50	9
mean	13	.49	.43	7
SD	6.2	.06	.04	4.2
96*	15	.47	.50	-3

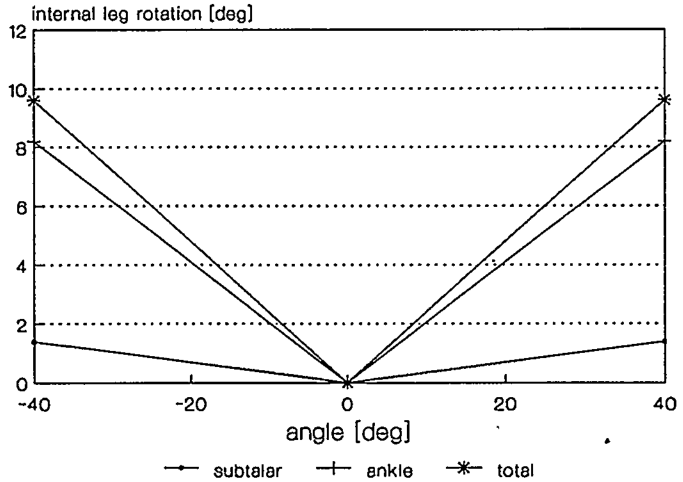

Figure 22. Rotation of the foot in the transverse plane as a function of pronation according to the geometrical setup illustrated in Figures 20a,b. Angle=angle of rotation about a joint axis, either the talocrural joint axis, AJ, or the subtalar joint axis, SJ. Internal rotation angle (equation 2) θ=rotation about an axis trough O perpendicular to the x-y plane.

"the foot rolls in, the arch lowers, and the leg internally rotates." However, no quantification of internal rotation of the leg at the knee joint due to pronation has been found in the literature. Movement around the talocrural joint, dorsiflexion and plantar flexion described by δ_o, has little effect on the internal rotation of the leg (Figure 22). Movement around the subtalar joint, mainly eversion and inversion, has more than four times the effect on internal leg rotation than movement around the talocrural joint (Figure 22). Variables describing the movement around the subtalar joint are $\Delta\beta_{pro}$, $\Delta\gamma_{10}$, and $\Delta\gamma_{pro}$.

Internal rotation of the leg at the knee joint in the transverse plane will influence the position of the patella between the condyles of the femur. The insertion of the patellar tendon is on the tibial tuberosity, therefore, any internal rotation of the tibia will tend to slide the patella towards the medial femoral condyle. This medial movement of the patella causes the contact surface area between the condyles and the patella to decrease since the patella is no longer evenly situated between both femoral condyles. Figure 23 illustrates the influence of 10° internal rotation of the leg. For a force of 1 000 N in the quadriceps muscles the line of action of the patellar tendon would be deviated by an estimated .43 cm which would be responsible for a 90 N medial force acting on the patella. For a given force in the quadriceps muscles and, therefore, the patellar tendon, this amount of internal rotation will cause an increased stress between the patella and the femoral surface due to a decreased area of contact. Figure 24 depicts

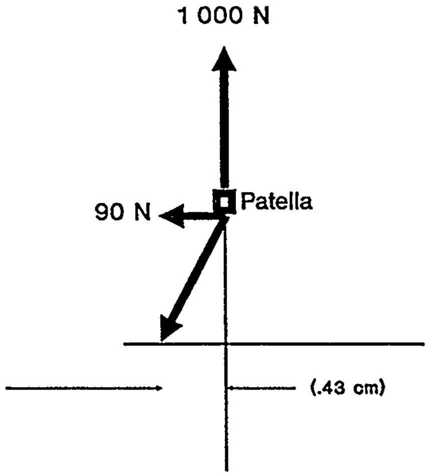

Figure 23: Geometrical model for a 10° internal rotation of the leg. Assumptions: static equilibrium and a force of 1 000 N in the patellar tendon. Diameter of tibia = 5 cm.

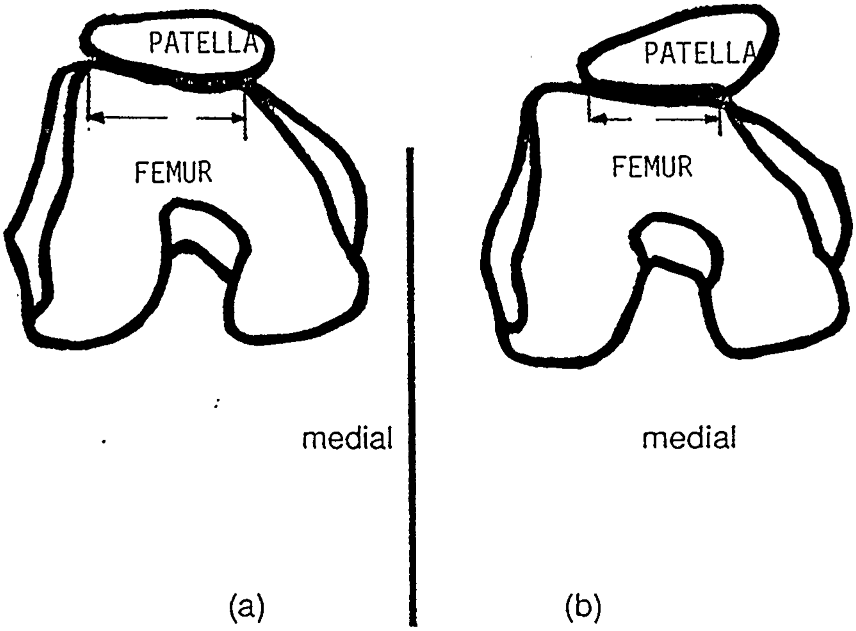

Figure 24: Area of contact of the patella with the femur in (a) a centre position and (b) a medially rotated position, viewed from below.

the position of the patella (a) in the centered position between the condyles of the femur, and (b) in a medially rotated position between the condyles. It may be estimated that the area of contact due to internal rotation of the leg is reduced up to 50% which would increase the stress in the patella by a factor of two. Using a critical stress of 5 MPa for cartilage, an estimated 4 cm^2 for the area of contact in the patello-femoral joint and a patello-femoral joint force equal to the force in the quadriceps muscles (Nordin and Frankel, 1980), the stress in the patello-femoral joint would be 2.5 MPa or 50% of the critical limit. A 50% reduction of the area of contact increases the stress in the patello-femoral joint to the critical limit of 5 MPa. This increase in stress on the patella would explain the increased injury occurrence. The above assumptions are supported by Hehne (1983), who applied a force of 500 to 2 500 N to the patellar tendon and measured area of contact and pressure in the patello-femoral joint for knee angles ranging from 40° to 150°. He reported an area of contact in the patello-femoral joint in the range of 1-4 cm^2, depending on the knee angle, and an average pressure in the patello-femoral joint in the range of 1.2-3.0 MPa from these cadaver studies.

The medial sliding of the patella due to internal rotation of the tibia may explain the injury at the medial side of the patella. Clinical experience, however, suggests that often pain is evident on the lateral side of the patella. It is than often argued that this type of pain is accompanied by internal rotation of the leg and a valgus position of the leg. Genum valgus stresses the patella on the <u>lateral</u> side, since the patella contacts the femoral condyles dominantly on the lateral side.

However, the data from the present study do not support the explanation of the occurrence of patello-femoral syndrome on the lateral side. Tracings of the thighs and legs of the five patello-femoral syndrome subjects viewed from the posterior at the time of maximal pronation show (Figure 25) that all patello-femoral syndrome subjects had a genum varum position at the time of maximal pronation. The average varus angle, Ω, was 5.2° (SD = 1.8°) for the patello-femoral syndrome group.

There is, however, another possibility to explain possible lateral patella-femoral syndrome. Increased acitvity of the vastus lateralis may prevent the medial sliding of the patella due to excessive internal rotation of the leg. The vastus lateralis inserts into the lateral side of the rectus tendon and attaches to the lateral side of the patella (Basmajian, 1982; Figure 26). This muscle is, therefore, capable of exerting a laterally oriented force onto the patella. The additional force in the vastus lateralis will increase the force acting in the patello-femoral joint and/or pull the patella to the lateral side.

In summary, the following factors are associated with patello-femoral syndrome:

1. Excessive pronation was statistically linked with patello-femoral syndrome in the present study.
2. Pronation has been reported to be associated with internal leg rotation. Internal leg rotation was experimentally demonstrated for all patello-femoral syndrome subjects in the present study.

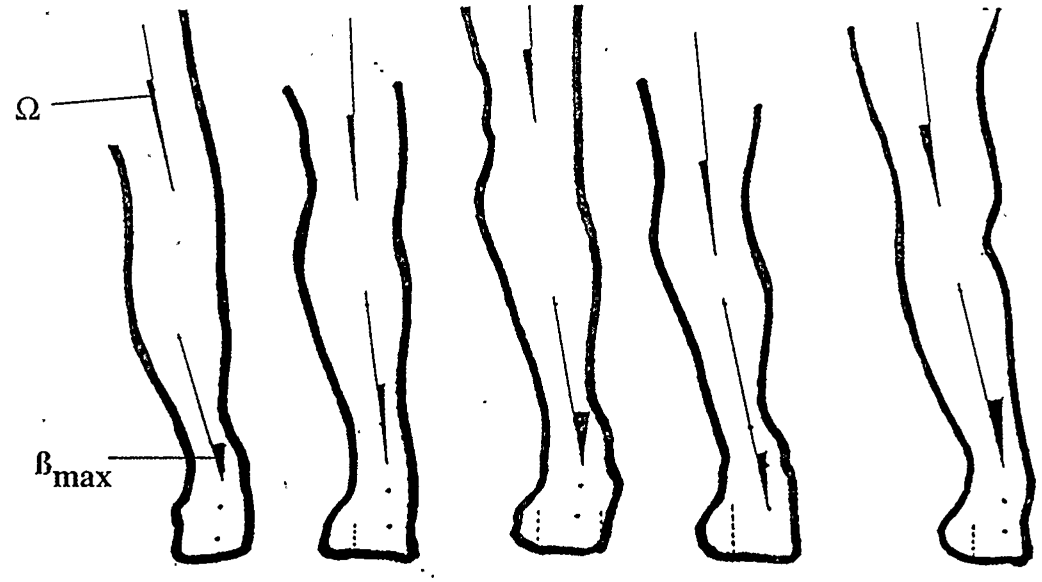

Figure 25. Posterior view of one trial for each patello-femoral syndrome subject. Ω = varus angle; β_{max} = angle of maximal pronation.

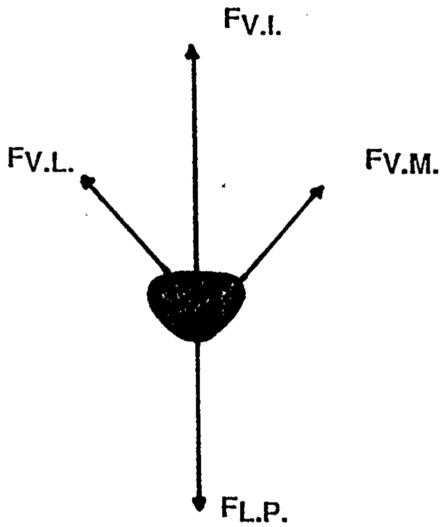

Figure 26. Free body diagram of the patella (gravity neglected), anterior view. $F_{V.L.}$ = force of the vastus lateralis acting on the patella; $F_{V.I.}$ = forces of the vastus intermedius and rectus femoris on the patella; $F_{V.M.}$ = force of the vastus medialis acting on the patella; $F_{L.P.}$ = force of the ligamentum patellae acting on the patella.

3. Excessive internal leg rotation may lead to three possible mechanisms. (a) A medial sliding of the patella relative to the femur. This may decrease the area of contact between the patella and the femur and, therefore, increase the patello-femoral joint pressure. Medial patella pain will result. (b) The medial sliding of the patella is prevented by an increased activity of the vastus lateralis. Since the vastus lateralis inserts into the patella, the force in the patello-femoral joint will be increased and the patella will be pulled to the lateral side. Lateral patella pain will result. (c) The excessive internal leg rotation and/or the medial sliding of the patella is prevented by genum valgus position of the leg. This may decrease the area of contact between the patella and the femur and, therefore, increase the patello-femoral joint pressure. Lateral patella pain will result. Kinematic data from the present study do not support possibility (c) for the subjects examined in the present study. All patello-femoral syndrome subjects demonstrated genum varus during maximal pronation. However, explanations (a) and (b) may not be excluded from data in the present study.

The logistic regression equations describing patello-femoral syndrome are models detecting excessive pronation while running. The pronation model was tested on subjects which were not included in the analysis when deriving the coefficients. Two subjects who were diagnosed with patello-femoral syndrome but were excluded from the analysis due to an incomplete daily questionnaire were evaluated by the model. The patello-femoral syndrome model 2, which yielded the highest sum of percentage values for injured and healthy classifications, was used on all three trials with the injured legs of these two subjects. All three trials were classified as patello-femoral syndrome injured by the model. This result provides some evidence for the appropriateness of the model used and its interpretation.

In the **hamstring equation** the coefficients for the two significant variables have different numerical signs. The time of occurrence of the impact peak, t_{zi}, has a positive coefficient and the initial shoe sole angle, δ_o, has a negative coefficient. Therefore, if the impact force peak occurs late and the initial shoe sole angle is low the probability of being classified as healthy is high. It is speculated that (a) a slow loading rate (late occurrence of the impact peak) and a small shoe sole angle at landing is a "more stable" and a "lower loading" position for the foot and leg as compared to (b) a high loading rate at a large shoe sole angle.

No functional explanations for this result can be given at this point in time. However, possible explanations for the lack of functional explanations may be (a) the result is of statistical nature and has no mechanical bearing, or (b) the injury group analyzed has no common functional variables. This injury group included all subjects with hamstring problems, namely hamstring tear, hamstring strain and hamstring tendonitis. Also, there was a small number of subjects in this group (4). Since hamstring tear and hamstring strain are medically similar this left an average of two subjects per diagnosis. It was concluded that there were too many different diagnoses and too few subjects in this group to yield mechanically meaningful results.

According to the **plantar-flexor** equation, a high (positive coefficient) loading rate, G_{zi}, low (negative coefficients) pronation values, $\Delta\beta_{end}$ and $\Delta\beta_{pro}$, and a low (negative coefficient) touch down velocity, v_o, significantly describe a high probability of being classified as healthy.

As with the results of the hamstring group, no functional explanations are available at this point in time. Possible explanations for the lack of functional explanations may be (a) the result was of statistical nature and had no mechanical bearing or (b) the injury group analyzed had no common functional variables. This injury group included all subjects with problems related to structures of the musculoskeletal system which plantarflex, namely, Achilles tendonitis, peroneal tendonitis, and posterior tibialis tendonitis. Also, the number of subjects in this group was small (3), which left an average of one subject per diagnosis. It was concluded that there were too many different diagnoses and too few subjects in this group to yield mechanically meaningful results.

The **use and relevance of the pronation model** developed for the patello-femoral syndrome injury group was tested on subjects which were not included in the derivation of this model. From the 28 diagnosed subjects, 149 trials were recorded. Thirteen trials were from four subjects diagnosed with patello-femoral syndrome. Two subjects were deleted due to technical problems. The remaining 136 trials from 22 subjects were classified by the pronation model 4 as 71 trials injured (52%) and 65 trials healthy (48%). This result may be interpreted as half of the "other than patello-femoral syndrome" injured subjects having pronation problems, and the other half of the injured subjects having no pronation problems. Furthermore, the model predicts most of these 136 trials (average of 80%) into a dominant group for one subject, either injured or healthy. That is, a subject's specific running style is either classified as dominantly pronation dependent or dominantly pronation independent for 80% of all trials. It is further speculated that the remaining 20% of trials classified differently are caused by different shoe wear. A small percentage of subjects wore different shoes influencing their running style significantly in pronation values, whereas the majority of subjects chose shoes which did not influence their running style. It is speculated that most subjects chose their running shoes according to pronation values. Most of the subjects chose shoes which allowed their running style to be consistent, at least for their pronation values.

A small percentage of subjects chose their different shoes so their pronation values differed between different shoes. It is interesting to note that the following seven diagnoses were dominantly classified as injured, i.e., as problems being dominantly connected with pronation problems (Table 26): Achilles tendonitis, posterior tibial tendonitis, ilio-tibial band syndrome, medial meniscus tear, patellar tendonitis, retinaculitis, and synovitis.

Table 26.--Classification of different diagnoses
by the pronation model.

DIAGNOSIS	N	N_o	N_h	N_i
I-T-B syndrome	2	0	0	2
medial meniscus tear	2	0	0	2
retinaculitis	2	0	0	2
Achilles tendonitis	1	0	0	1
patellar tendonitis	1	0	0	1
posterior tibial tendonitis	1	0	0	1
synovitis	1	0	0	1
hamstring tear/strain	3	0	2	1
anterior tibial stress syndrome	2	1	1	0
costochondritis	1	1	0	0
hamstring tendonitis	1	1	0	0
low back pain	1	1	0	0
peroneal tendonitis	1	0	1	0
peroneal tendonitis	1	0	1	0
plantar fascitis	2	0	2	0
rotator cuff tendonitis	1	0	1	0

Note: N=total number of diagnosis, N_o=number of times trials of diagnosis were classified as 50% healthy and 50% injured, N_h=number of times diagnosis was classified as dominantly healthy, N_i=number of times diagnosis was classified as dominantly injured.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to (a) report on boundary conditions which may be associated with running injuries, and (b) identify kinetic and kinematic variables which may be associated with running injuries. Results from the present study answer the purpose in the following way.

(a) Boundary conditions (surface condition, surface slope, surface level, ambient temperature, surface type and pace) were found to be significantly different between the healthy and injured subject groups. No significant differences were found for the distance run, surface smoothness, participation in other sports, time used for the running session, and speed of the run.

Except for participation in other sports, there were no controls for any of the above factors. The reported results reflect a profile of factors used by the population of this study.

(b) Two out of the eight analyzed <u>kinetic variables</u> were identified by stepwise logistic regression analysis to be significantly associated with injuries. The time of occurrence of the impact peak, t_{zi}, was correlated with hamstring injuries and the vertical loading rate, G_{zi}, was correlated with plantar/flexor injuries. However, no mechanical explanation could be given for these statistical results.

Six out of the eight analyzed <u>kinematic variables</u> were identified by stepwise logistic regression analysis to be significantly associated with injuries. The total pronation, $\Delta\beta_{pro}$, the initial change of rearfoot angle, $\Delta\gamma_{10}$, the initial shoe sole angle, δ_o, and the total pronation of the rearfoot, $\Delta\gamma_{pro}$, were significantly associated with patello-femoral syndrome. These variables were used to mechanically explain the etiology of patello-femoral syndrome. The shoe sole angle at touch-down was significantly associated with hamstring injuries and the take-off Achilles tendon angle and the total pronation were significantly associated with plantar/flexor injuries. However, no mechanical explanation could be found for these statistical results.

In addition, a large data base for kinetic and kinematic variables of healthy runners was established which may be used in the future to compare results from injured subjects who were tested according to the same methodology. The main limitation of the study was the small number of subjects in each injury group. It was concluded that the hamstring and plantar/flexor injury groups were too small and had too many different diagnoses within each injury group to explain the statistical results mechanically. However, the patello-femoral syndrome group was larger and consisted of only one type of injury. Therefore, it was possible to present a mechanical understanding of potential mechanisms for patello-femoral syndrome.

The pronation model developed for patello-femoral syndrome is considered to be a powerful tool which may be used in the future to select healthy subjects who have a high probability of developing a specific injury. This is the first model presented in the literature which may be used on healthy subjects and which predicts the probability of developing patello-femoral syndrome. This model may be used to select groups of subjects who may later be analyzed using conventional statistical analysis (e.g., analysis of variance) to detect differences in variables of interest.

The developed pronation model should be tested further and then expanded to include a larger number of injured subjects. This should be done in two steps:

(a) Additional healthy subjects should be tested. If the model predicts a high probability of injury with patello-femoral syndrome, the subject should be followed over time and the prediction of the model can be verified.

(b) If injury occurs as predicted by the model, the subject should be included in the derivation of the coefficients of the model.

It is further suggested that models for other injuries (e.g., ilio-tibial band syndrome) should be developed in a similar way. This requires a continuation of the study, including and analyzing subjects who became injured with a specific diagnosis. In the future these models may be used to aid in choosing running equipment (e.g., shoes) on an individual basis before using or purchasing them. Running equipment may be matched to personal running style and the risk of the occurrence of an injury may be reduced by applying the statistical injury models.

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