KNEE TORQUE KINETICS DURING

HIGHLAND DANCING

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Science and the Theory of Coaching

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ABSTRACT

The purpose of the study was to measure torque variations in the knees of malaligned Highland dancers during the early and late stages of a six step Highland Fling. A secondary objective was to measure variations in knee malalignment at impact, maximum flexion and extension.

The most frequently occurring injuries in dance involve the knee (Arnheim, 1980; Schafle, Requa, & Garrick, 1990; Solomon & Micheli, 1986) and develop largely from knee malalignment (Arnheim, 1980; Clarkson & Skrinar, 1988; Clippinger-Robertson, 1987; Ende & Wickstrom, 1982; Reid, 1988; Solomon & Micheli, 1986; Teitz, 1987; Watkins & Clarkson, 1990;). Quantifying knee torque due to malalignment provides a measure to understand why injuries are so prevelant in dance and how potential injuries could be avoided.

Seven subjects, dancing a six step Highland Fling, were video taped from both a frontal and oblique view (45 degrees to the frontal view) while performing on a force platform. Video analysis provided knee displacement measures from both views. Ground reaction forces (GRF) provided the force component for knee torque calculations. Results were analyzed using a single subject baseline design and indicated mixed trends in knee torque, knee malalignment, and knee flexion from early to late stages of the dance. The decrease in knee torque was explained by a decrease in the knee flexion component. Maximum knee malalignment occurred at maximum knee flexion in the last step for all subjects and for five subjects in the first step.

Increased knee malalignment measures, in the oblique plane, demonstrate potential for injury unless the dancer's technique and lower extremity alignment is corrected. The research utilizes Highland dancers, however, the concentration is

on dancing in a turned-out position. Since turnout is common to other dance forms, these results may be applicable to ballet, jazz, and modern dance.

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INTRODUCTION

> There is a desperate need for increased inquiry into the neuromuscular, physiological, and kinesiological aspects of dance to establish appropriate training techniques, to prevent injuries, and to determine the long-range effects of dance training practices on the human body.
>
> (Brennan, 1986, pp 49,53)

Injuries in dance are abundant, but the most frequently occurring injuries involve the knee (Arnheim, 1980; Schafle, Requa, & Garrick, 1990; Solomon & Micheli, 1986). Moreover, knee injuries in dance develop largely from incorrect leg alignment (Arnheim, 1980; Clarkson & Skrinar, 1988; Clippinger-Robertson, 1987; Ende & Wickstrom, 1982; Reid, 1988; Solomon & Micheli, 1986; Teitz, 1987; Watkins & Clarkson, 1990).

The turnout position, so basic to dance (Reid, 1988), describes "the ability of the dancer to stand and move with the legs externally rotated at the hip so the toes are directed diagonally away from the midline of the body" (Solomon, Minton, & Solomon, 1990, p.323). The body weight, represented by the centre of mass, would fall directly through the centre of the knee, then through the base of support, which, in the case of Highland dancing, is the ball of the foot (see Figure 1). This correct alignment is necessary to prevent injury and improve performance during dance movements (Clippinger-Robertson, 1987; Watkins & Clarkson, 1990).

Figure 1
Positioning of Correct Turnout

Malalignment is the result of forced turnout (or poor biomechanical control) and postural limitations. When dancers strive for more turnout, they force the feet beyond the natural line created by the turnout produced at the hip (Figure 2) (Adrian & Cooper, 1989). Postural limitations may also cause some malalignment due to bone structure (Arnheim, 1975) and imbalanced muscles (Lauffenburger, 1987).

Figure 2
Positioning of Incorrect Turnout

The ground reaction force created by the dancer's jumping movements is referred from the foot through the lower extremity, and then absorbed by the soft tissue support structure. Providing there is no malalignment, the forces will be absorbed through the soft tissue. If malalignment does occur, the forces will be magnified at the malaligned joints. Due to the body's continual struggle against gravity, each malaligned body segment will be the focus of the referred forces, causing a dysfunction in optimal joint loading (Solomon & Micheli, 1986).

Knee torque measures are a combination of body weight reaction force and the resultant of knee malalignment and the degree of knee flexion while dancing on one foot. The normal forces occurring within the knee joint, including compression, tension, tearing, shearing, translation, and patellar pressure forces, are compromised due to the malaligned articulating surfaces. In addition, compression forces occurring between the patella and the femur increase as knee flexion increases (Teitz, 1987). This force has been measured as three times body weight while ascending and descending stairs and 7.6 times body weight during deep knee bends (Reilly and Martens, 1972; cited in Teitz, 1987). When malalignment occurs, medial adduction and rotation of the knee results. Consequently, an additional compression force is created along the lateral aspect of the knee joint, while a tension force results along the medial aspect. As a result, the meniscus is compressed on the lateral side and the ligament tensed on the medial side causing damage to the knee joint structure (Arnheim, 1989).

The magnitude of vertical ground reaction force a dancer exerts, when landing from a jump, has been measured at three to four times body weight (Solomon & Micheli, 1986). Similar results were found by Johnstone and Bauer (1993). These measurements do not consider the knee joint forces that may result due to knee malalignment. Since malalignment, and the relationship to correct technique, are a major concern in dance, measurement of the resultant knee joint torque would provide valuable information which would contribute to an understanding of knee joint injuries in Highland dance. Quantification of knee torque would provide better understanding as to why knee injuries are so prevalent in dance and how potential injuries could be avoided (Schafle, et al., 1990; Solomon & Micheli, 1986).

Knee malalignment, and consequently knee torque, may increase from the early to late stages of a dance. In the early minutes of exercise glycogen can be severely lowered causing limitations in the muscle function (McArdle, Katch, & Katch, 1986). Since muscle forces assist joint alignment, muscle fatigue may magnify malalignment and increase the potential for knee injury. However, fatigue levels were not measured in this study.

Purpose

The purpose of the study was to measure torque variations in the knees of malaligned Highland dancers during the early and late stages of a six step Highland Fling. A sub-purpose of the study was to measure the variations in knee malalignment at impact, maximum flexion and extension.

Significance of the Study

The study is significant in quantifying the magnitude of knee torque developed during repetitive landings over the period of a Highland dance. A component of these measures is the degrees of malalignment at the knee. The study could provide an awareness for the prevention of knee injury due to incorrect dance technique during the period of a dance. The available literature provides reasonable information on dance in general, primarily modern and classical ballet, but limited information on Highland dance. All three forms of dance require the dancer to perform movements in a turned-out position. However, Highland dance requires the jumping motion to be performed repeatedly on one foot. The continuous strain on the knee joint may contribute to injury if the dancer is malaligned (Belt, 1990).

The knee is primarily designed to move in the sagittal plane with slight rotation on full extension (Arnheim, 1989). The leg musculature and joint structure is designed to support primarily flexion and extension movements of the leg. Anatomically, the knee retains limited support medially and laterally resulting in potential excessive strain on the medial and lateral collateral ligaments plus increased compression on the lateral meniscus (Arnheim, 1989). In addition, the anatomical shape of the knee joint limits medial and lateral rotations (Arnheim, 1989). The medial rotational forces that occur during landing, with a malaligned knee while Highland dancing, have not been previously investigated. Ground reaction forces, or vertical forces, have been studied in different dance forms, however, the complications due to malalignment have not been investigated (Johnstone & Bauer, 1993; Solomon & Micheli, 1986). Knee torque and malalignment measures will promote an awareness of correct technique and its association with injury prevention in Highland dancers, particularly over prolonged periods of repetitive landing. Comparisons between dance forms emphasize the extreme potential for injury and stress on the soft tissue of the knee, particularly in children. Greater recognition of the injury potential, particularly for young dancers who lack the leg strength and stamina, is a possible outcome of the study.

Limitations

1. The study was delimited to seven advanced or open class Highland dancers from the Thunder Bay region. Dancers were prescreened for malalignment from a previous study, which limited the subject sample to those malaligned based on the definition.
2. Q-angle and internal knee forces were not taken into consideration.
3. It was assumed that the dancer was in balance and the centre of mass was in alignment with the base of support.
4. Image clarity and resolution of the video monitor could effect measurement accuracy.
5. Joint markings placed on joint centres were assumed to represent joint centres.
6. It was assumed that maximum force, measured from the force platform, would occur during maximum degrees of knee flexion.

Chapter II

REVIEW OF LITERATURE

HIGHLAND DANCING

Elwell-Sutton (1990) described Highland dance as a performance either in solo or in formation consisting of a series of rhythmical jumps, leaps, and hops with the fast snapping of legs through straight and bent positions. All movements are completed in a turned-out position, where the dancer stands and moves with the legs externally rotated at the hip so that the toes are directed diagonally away from the midline of the body. The major working step is repetitive jumping on one leg on the ball of that foot (demi-pointe). Many steps involve rapidly brushing the plantar flexed forefoot up and down to the ground (jigging). These repetitive movements require the dancer to be in a state of dynamic balance as the centre of mass must fall through the base of support, where the base of support, the ball of the foot, is very small. The footwear for a Highland dancer consists of thin unlined close-fitting slippers, usually laced along the dorsum, around the ankle and several times around the arch, providing little reinforcement or shock absorption (Elwell-Sutton, 1990).

DANCE AS ATHLETICS

For many years, dance had been considered only an art form resulting in some degree of ignorance with regards to the athletic aspects. An early problem existed in dance involving ignorance on the part of many sports medicine professionals concerning technical demands and training techniques (Cantu & Gillespie, 1982). Dancers are a unique group among the athletic population, because they combine both art and exercise (Schafle, Requa, & Garrick, 1990). They are included within the athletic population because they require the same competition, goal setting, training and dedication, winning and losing, and so forth. In addition, dance offers the additional element of artistry.

Johnstone and Bauer (1993) calculated the average force produced by a Highland dancer and found that force to be comparable, and equivalent, to the forces produced by a marathon runner in a half marathon of 21 km. Consequently, a Highland dancer, on average, exerts as much force as a marathon runner exerts during a competition.

Dancers and other athletes have similar injuries and injury treatments. Runners were found to have similar injury complaints as aerobic dancers (Baitch, 1987). Successful treatment of many problems in runners consisted of realignment of the foot, a concept also applied to aerobic dancers (Baitch, 1987). Excessive rotation of the femur and malalignment of the patella were highly correlated with knee pain in both runners and aerobic dancers. Many dance injuries treated by sports medicine physicians are common to professional athletes, such as the meniscal tear (Silver & Campbell, 1985).

Even though most of the injuries associated with dance are similar to those seen in other athletic activities, the frequency with which certain problems occur seems to reflect the tasks performed in each dance form (Schafle, et al., 1990). Almost 3,500 dance injuries were examined and treated at the Centre for Sports Medicine during the first eight and one-half years of its operation (Schafle, et al., 1990). The population of dancers consisted of ballet, modern, aerobic, and various other dance styles from ethnic and jazz to square and ballroom. Dancers ranged in skill from professional at the very highest caliber, to recreational. Consequently, dance medicine became increasingly popular in the Sports Medicine facility causing the establishment of a separate section in 1984 for the diagnosis and rehabilitation of injured dancers (Schafle, et al., 1990).

For proper care and prevention of dance injuries, it is vital to maintain interactions between physicians, physical therapists, dance teachers, choreographers and the dancers themselves (Cantu & Gillespie, 1982).

ANATOMY OF THE KNEE

The knee is one of the most complex joint structures within the human body and also one of the most traumatized joints (Arnheim, 1989). The knee is designed to provide stability in weight bearing and mobility in locomotion in a sagittal plane. However, it is extremely unstable laterally and medially (Arnheim, 1989).

For the knee to absorb all imposed stresses, it must maintain stability, flexibility, and resilience (Silver & Campbell, 1985). The knee is commonly referred to as a hinge joint, in which only two principal movements occur, flexion and extension. Consequently, medial and lateral rotations are possible, but only to a limited degree. The muscles utilized in knee flexion are the biceps femoris, semitendinosus, semimembranosus, gracilis, sartorius, gastrocnemius, popliteal, and plantaris muscle. The muscles utilized in knee extension are the quadriceps muscles of the thigh, consisting of vastus medialis, lateralis, intermedius, and rectus femoris. The muscles provide support for flexion and extension movements of the leg at the knee, however, muscle plays a lesser role in the support of medial, lateral, or rotational movements. Ligaments and menisci provide soft tissue support for the motions emphasized during knee malalignment. Ligaments have some elastic properties, however, if stretched beyond the elastic limit the ligament does not return to its original shape and becomes permanently stretched, therefore, reducing stability (Kreighbaum & Barthels, 1985). The menisci transmit one half of the contact force in the medial compartment and even a higher percentage of the contact load in the lateral compartment of the knee joint (Arnheim, 1989). The malaligned knee presents as an adducted knee joint, with more than normal valgus, accentuating compression and tension forces. The force (F) has a vertical component (v) and horizontal component (t) causing a compression force of the meniscus on the lateral aspect (b) and a tension force of the medial collateral ligament on the medial aspect (a) (figure 3, Kapandji, 1970). Anterior/posterior shearing forces may also occur across the articulating surfaces as the body centre of mass is displaced anteriorly or posteriorly (Kapandji, 1970).

With a greater degree of malalignment or adduction of the knee, a greater horizontal component (t2) results. This causes the force to fall further medially (F2) and further away from the structures of the body, the muscles and ligaments, designed to help absorb this force. A normal degree of adduction of the knee, or knee valgus, would measure at an angle of valgus equal to 170 degrees with a small horizontal force component (t1). With a valgus measurement of 160 degrees, which causes greater adduction of the knee, the horizontal component would be twice as great (t2), causing the force to fall further medially (F2) (figure 4, Kapandji, 1970).

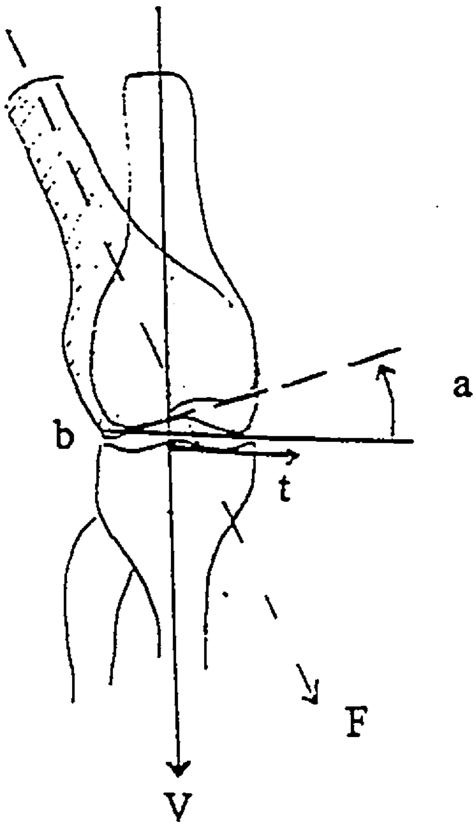

Figure 3
Malalignment of the Knee
Creating Compression and Tension Forces

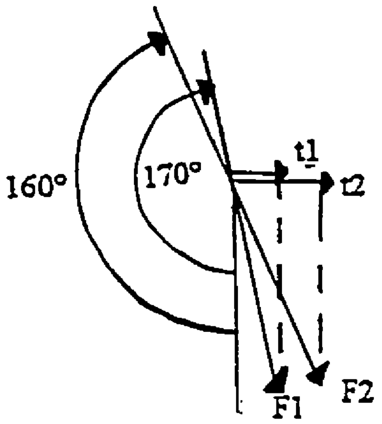

Figure 4
Force Differences with Greater Degrees
of Malalignment at the Knee

IMPACT FORCES, JOINT FORCES, & KNEE TORQUE MEASUREMENTS

Since Highland dancing requires repetitive jumping on one leg while on the ball of the foot (demi-pointe), it is important to understand the impact forces occurring. Johnstone and Bauer (1993) found the average force per jump during a Highland dance to be 1217.6 Newtons per vertical impact. An average force of 2.2 times body weight was found for each impact (Johnstone & Bauer, 1993), with some reports of three to four times body weight (Solomon & Micheli, 1986). If the average dancer weighs 55 kg, the landing force will be equivalent to 1078 Newtons to 2156 Newtons or 110 kg to 220 kg per landing. A Highland dance averages 84 jumps on each foot, which translates to 84 landings of 220 kg or 18,480 kg landed in the period of one dance on one foot.

Compression forces occur between the patella and the femur and increase as knee flexion increases during mala nment. Patellofemoral joint reaction forces have also been found to increase during flexion and are maximized during the full squat (Arno, 1990). Huberti and Hayes (1984) found an increase in patellofemoral contact forces as the angle of flexion increased up to 90 degrees. Hsu, Perry, Gronley, and Hislop (1993) found a significant correlation between knee angle and patellar ligament forces (R^2=0.86, p<0.001). The forces, at the patellar ligament, increased by 4.16% of body weight per degree of knee flexion (between the angles of 0 degrees and 60 degrees). These results are for flexed knee stance, not results from maximum knee flexion during a vertical jump. Increased and decreased Q-angles, which may cause malalignment at the knee, resulted in increased maximum contact pressures (Huberti & Hayes, 1984). Consequently, an increase or decrease in the Q-angle can be an etiological factor in chondromalacia as genu valgum causes malalignment at the knee joint. Patellofemoral forces are not measured in this study, however, they do add additional joint force components to the malaligned knee.

Hsu et al (1993), measured quadricep demands during single limb stance using torque at the knee joint as one of two estimation variables. A significant correlation (R^2=0.91, p<0.001) existed between the length of the moment arm of the body weight about the knee axis and the knee angle. They found the moment arm to increase at a rate of 0.23 centimetres per degree of knee flexion, between 0 and 60 degrees. Maximum knee extension torque occurred most frequently at 45 degrees flexion. Maximum patellar ligament force also occurred at 45 degrees flexion. Johnstone and Bauer (1993) found Highland dancers to have an average maximum flexion angle of 49 degrees, with a range of 38 degrees to 59 degrees. Maximum malalignment occurred at maximum flexion in the same study. Consequently, based on these findings, maximal torque, maximal patellar ligament force, and maximal knee malalignment occur simultaneously, at maximum flexion.

Mularczyk (1990) studied maximum knee torque during the swing phase in running. Marathon runners had extension knee torques of 20.5 Nm to 30.9 Nm, or 0.33 Nm/kg to 0.45 Nm/kg and flexion knee torques of 37.1 Nm to 47.7 Nm, or 0.55 Nm/kg to 0.82 Nm/kg. Shealy, Callister, Dudley, and Fleck (1992) found knee extension torque measurements of 2.7 Nm/kg of body weight and knee flexion torque measurements of 1.47 Nm/kg of body weight in sprinters.

The age factor becomes a consideration as younger children are unable to absorb forces as efficiently as older children. Marino and McDonald (1986), studying the running patterns of children, indicated that younger children demonstrated an average vertical force of 241 percent of body weight, or 2.41 times body weight, and older children demonstrated a vertical force of 209 percent of body weight, or 2.09 times body weight. Younger children may be at greater risks of injury because they land with greater vertical force.

Body weight and speed are also factors related to absorption of ground reaction force. Lower body weight runners running at lesser speeds, demonstrate more efficient absorption of force. Cantu and Gillespie (1982) found the following: light weighted runners (approximately 45 kilograms) had a peak vertical force of 1.3 times body weight at a speed of 3.4 metres per minute and 1.35 times body weight at a speed of 4.5 metres per minute; medium weight runners (approximately 68 kilograms) had a peak vertical force of 1.75 times body weight at 3.4 metres per minute and 1.85 times body weight at 4.5 metres per minute; and heavy weight runners (approximately 91 kilograms) had a peak vertical force of 2.1 times body weight at 3.4 metres per minute and 2.35 times body weight at 4.5 metres per minute.

These ground reaction forces are absorbed through the body segments and musculoskeletal structure. When malalignment occurs, a proportion of the reaction force is not absorbed through the soft tissue but at the malaligned joints. Due to the continual struggle against gravity, each malaligned body segment will be the focus of the referred forces, causing a dysfunction in optimal joint loading (Solomon & Micheli, 1986).

TURNOUT

Turnout is the term describing the "ability of the dancer to stand and move with the legs externally rotated at the hip so that the toes are directed diagonally away from the midline of the body" (Solomon, Minton, & Solomon, 1990, p. 323). Dancers strive to obtain this position, with their feet turned out to 90 degrees or 180 degrees whilst keeping the lower extremity segments in alignment (Meinel & Atwater, 1988). The position is maintained in every position and movement in Highland dance and it is the aim of the dancer to keep the supporting leg, or the hopping leg, and the working leg, or the leg doing the work, turned out at all times. The turnout position is also essential in classical ballet (Reid, 1988). Nevertheless, few dancers actually possess this perfect alignment, but most strive to get as close to this ideal as within their physical limitations (Clippinger-Robertson, 1987). The ideal turnout position occurs with the centre of mass aligned over the thigh and directly through the centre of the knee, ankle, and ball of the foot. This position can be achieved if the external rotation of the lower extremity occurs at the hip (Teitz, 1983). Consequently, the rotation would allow the knees to operate as hinge joints rather than allowing medial and lateral movement (Clippinger-Robertson, 1987). A considerable range of motion is required at the hip joints to achieve the turnout position at all stages of knee flexion while weight bearing.(Clippinger-Robertson, 1987).

Dancers with physical limitations in joint range and muscle control, strive to maintain an ideal turnout position. Forced turnout (limitations in biomechanical and muscular control) and postural limitations (structural limitations controlling limb alignment) are the main causes of knee malalignment in dancers (Clippinger-Robertson, 1987). Unless certain structural problems are recognized and faulty technique corrected, a pattern of injuries is predictable (Elwell-Sutton, 1990).

The term "forced turnout" is demonstrated by dancers trying to achieve turnout beyond what they are capable of. It occurs in several forms of dance, and is especially likely to occur in dancers who do not have a great degree of natural turnout (external rotation) at the hips (Schafle, et al., 1990). The feet are forced beyond the natural line created by the turnout produced at the hip and the "turned-out look" is achieved by rolling the ankles in and over, allowing the knees to sink medially, squeezing the buttocks together, hyper extending the lower back, and anteriorly tilting the pelvis to place the feet at a 180 degree angle (Pruett & Lopez, 1981). This is also known as "screwing the knee" because the adjustment occurs by turning out the feet and then attempting to adjust from the floor upward causing malalignment at the knee (Teitz, 1983). The weight falls medially to the knee and ankle, producing stress on the medial side of the knee and strains at the first metatarsophalangeal joint (Teitz, 1983). Dancers often sacrifice correct alignment because of the benefits of finding a temporary solution to a movement problem. The solution is considered temporary as it leads to muscular inefficiency and eventual injury (Watkins & Clarkson, 1990).

Correct turnout, and therefore, correct alignment is necessary to prevent injury and improve performance as it allows the body to move in agreement with its structural architecture, allowing the muscles to work efficiently (Watkins & Clarkson, 1990). Correct turnout is produced by greater degrees of range of motion at the hip, since turnout should be executed from the hip. Thus, the range of motion at the hip, and therefore, the amount of turnout, is influenced by anatomical or postural factors or bony, ligamentous, and musculotendinous factors (Adrian & Cooper, 1989; Clippinger-Robertson, 1987). Alignment problems in bone structures, the angle of the femoral neck relative to the plane of the femoral condyles at the knee, and imbalanced muscles are factors influencing improper turnout.

Three leg deviations common to dancers are, tibial torsion (a twisting of the lower leg bones), knock-knee or genu valgum, and bowlegs or genu varum, with the most common being the tibial torsion or genu valgum (Arnheim, 1975). Consequently, this causes the outward (external) rotators of the hip and thigh to be weak in comparison to the inward (internal) rotators. This may cause malalignment at the knee in dancers because they do not have the strength in the external rotators to produce ideal turnout. Dancers, with this problem, could be identified early and injury may be prevented by using special shoe orthotics and corrective exercises (Arnheim, 1975).

Femoral anteversion or the angle of the femoral neck relative to the plane of the femoral condyles at the knee must also be considered in correct or incorrect alignment (Teitz, 1987). The average angle is 10 degrees, but some individuals with excess femoral anteversion may demonstrate angles as high as 20 degrees (Teitz, 1987). The 20 degree angle causes an excessive internal rotation of the hip, with the tibia compensating by rotating externally in relation to the femur and the foot pronating at the subtalar joint to get the foot flat on the ground (Teitz, 1987). As femoral anteversion and tibial torsion increases, so does the Q-angle and the lateral vector tending to pull the patella laterally (Teitz, 1987). Consequently, increased Q-angle results in contact pressures within the knee joint (Huberti & Hayes, 1984).

An imbalance of the muscles in the thigh may also cause pain and injury by creating malalignment, and therefore, adding strain to the medial ligaments and lateral meniscus (Lauffenburger, 1987). An overuse in the abductors can create a lateral pull in alignment and add strain to the lateral side of the knee (Lauffenburger, 1987).

Johnstone and Bauer (1993) found that maximum degrees of malalignment usually occurred during the furthest points of knee flexion, which indicates the dancers improved alignment positions when their leg was extended and in the air. The problem of forced turnout could therefore be technique rather than anatomical or postural.

MALALIGNMENT INJURIES

Turnout, so basic to dance, is a source of considerable stress to the lower limb segments (Reid, 1988). Consequently, faulty technique and overuse become the two main causes of chronic injuries in dancers (Baitch, 1987; Clippinger-Robertson, 1986; Solomon & Micheli, 1986). Solomon and Micheli (1986) observed the work of every major modern dance company and class in the greater Boston area. One hundred and sixty four dancers reported 229 injuries with the presumed causes being, overuse/stress/repetition as the highest cause (31 out of 167 chronic injuries) followed closely by faulty technique/incorrect alignment (29 out of 167 chronic injuries). Moreover, there was a dramatic contrast between the prescribed treatment and what the dancers found helpful. Technique and realignment was recommended by doctors in only five cases, but found helpful by dancers in 24 self-help cases. Subtle inaccuracies in technique can place excessive stress on muscles and joints and lead to earlier fatigue resulting in a combination of overuse and faulty technique injuries (Clippinger-Robertson, 1986). Thus, proper technique and appropriate, progressive training are critical for injury prevention in dance (Clippinger-Robertson, 1986). Many overuse injuries related to improper turnout result in stresses at the back, hip, knee, and foot (Clippinger-Robertson, 1987; Reid, 1988; Teitz, 1987). Malalignment may cause weight to be placed toward the front, back, or sides of a joint adding considerable strain to bones, cartilage, and ligaments resulting in chronic pain, and further breakdown and injury (Watkins & Clarkson, 1990).

Malalignment may result in stress and tearing of ligaments. A study by Miller (1975) found several dancers who began performing dance at an older age to have significant laxity of the knee ligaments thought to be caused by compensation for a satisfactory turnout in the absence of sufficient hip external rotation. Moreover, stress on ligaments is the first step to the more serious weakening and tearing of these ligaments (Lauffenburger, 1987; Reid, 1988).

Menisci function to absorb impact and control motion at the knee (Teitz, 1990). Malalignment may cause meniscal compression resulting in meniscal shearing. Quirk (1983) analyzed 2113 consecutive ballet injuries and found the operation most often performed on dancers was meniscectomy. He found that poor turnout and incorrect placement of the foot created excessive torque through the knee that could cause repeated meniscal shearing. Proper turnout and foot placement would alleviate the cause of most of these meniscal tears (Quirk, 1983). Moreover, menisci are most susceptible to injury in the acutely flexed position, particularly with associated rotation while weight bearing (Clarkson & Skrinar, 1988). The menisci of the knee are extremely important in the impact forces of the knee.

Malalignment may result in knee strains. Data presented by Chambers (cited in Teitz, 1983), who studied orthopedic injuries in athletes ages six to 17, confirmed medial knee strains by simply asking the child to do a plie. An imaginary line was to drop from the knee over the second toe (to equal correct alignment), but in those cases of knee strains, the child's imaginary line fell medial to the foot during the plie (Teitz, 1983). Chambers found that because plies are prerequisites to initiating jumps and landings, the incorrect technique allowed for the chance of musculoskeletal problems (Teitz, 1983).

Changes in biomechanical structure, muscular control, and consequently, leg alignment from the early to the late stages of a dance may be attributable to fatigue. When a dancer begins to experience fatigue, rehearsing new, unfamiliar, or advanced steps can become a real danger (Kravitz, 1990). After intense exercise, the glycogen in the liver and specific muscles may become severely lowered (McArdle, Katch, & Katch, 1986). Since stored muscle glycogen is one of the prime contributors of energy in the early minutes of exercise, its depletion causes fatiguing factors in the functioning of the muscles (McArdle, et al., 1986). The fatiguing factors may include effects in motor unit recruitment, in their firing characteristics and possibly in the transfer of mechanical energy from the eccentric to the concentric phase of contact (Viitasalo, J.T., Hamalainen, K., Salo, A., Lahtinen, J., 1993). When a dancer continues to perform, mechanical deterioration may result due to inadequate functioning of the muscles needed to stabilize the joint, causing improper body mechanics (Fitt, 1990). Thus, the dancer is left in improper alignment as he/she no longer has the capabilities of the soft tissue support structure in maintaining proper body mechanics. Although it is beyond the scope of the present study to measure muscular fatigue, it may however, be a contributing factor to knee malalignment and lack of limb control, particularly in young dancers over long periods of time.

With the structural weaknesses of the knee, especially those restricting medial and lateral movement, there is a concern for potential injury with respect to malalignment. Malalignment occurs frequently in dance, whether it be from postural limitations or poor biomechanical control. This condition is further aggravated by those dancers required to perform with the legs in a turned out position. With a small base of support, the ball of the foot, high forces, two to four times body weight, are absorbed through a very small area. A second force, or torque, develops with malalignment and flexion, and consequently, creates compression and tension forces at the knee. During a dance, performance, or practice, dancers may become more susceptible to malalignment due to a combination of factors, including joint range of motion and muscular control. With the limited education available to dance instructors, potential injuries and the causes thereof, are often overlooked. Thus, the need arises to develop awareness, which may be accomplished by developing a technique for standardized measurement of knee torque. Awareness is thus created, and consequently, prevention can be addressed.

> There are many single research efforts that offer promise but too often there is no follow-up. Without persistent in-depth study there will be no new knowledge from which we can discover new theories and new questions - and some answers.
>
> (Brennan, 1986, p. 53)

Chapter III

METHODS AND PROCEDURES

PURPOSE

The purpose of the study was to measure torque variations in the knees of malaligned Highland dancers during the early and late stages of a six step Highland Fling. A sub-purpose of the study was to measure the variations in knee malalignment for impact, maximum flexion, and extension.

METHODS

SUBJECTS

All suitable, available subjects were asked to participate on a volunteer basis. The dancer was considered suitable, if she was an Open or Advanced-Intermediate class competitor, and therefore, could maintain a consistently balanced position, aligning the centre of mass with the base of support. Since Open and Advanced-Intermediate are the highest class competitors, a balanced position could be better maintained by these dancers as compared to less experienced dancers. The dancers were prescreened for knee malalignment from a previous study (Johnstone & Bauer, 1993).

MEASUREMENT DESCRIPTION

A spatial referencing system including frontal, sagittal, transverse, and oblique planes was used for measurement purposes. Three planes of motion, frontal, sagittal, and transverse were defined based on vertical direction (y), anterior-posterior (x), and medial-lateral (z) (Figure 5). The two planes in consideration were: a two-dimensional frontal plane view (yz) and a two-dimensional sagittal plane view (xy). Three dimensional measurement combined a frontal plane (yz) and an oblique plane taken 45 degrees from the frontal plane. The oblique angle of 45 degrees was selected based on the plane of motion of the supporting leg which is turned out approximately 45 degrees, with the hip, knee, and ankle ideally aligned over the ball of the foot and in alignment in the oblique plane.

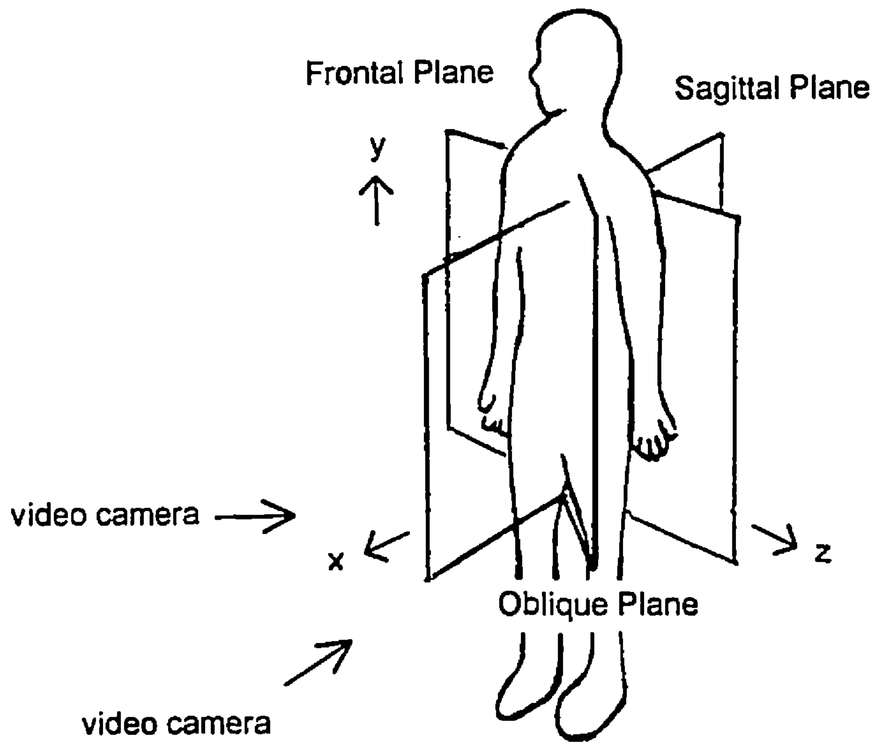

Figure 5
Spatial Coordinate System

The centres of the three joints, of the lower limb (Figure 6), the hip (H), knee (O), and ankle (C), lie on a line(HOC), which is the mechanical axis of the lower limb (Kapandji, 1970) creating a correctly aligned system in the lower limb segments. If any lower limb segment moved outside this mechanical axis it would be considered malaligned and/or flexed. The motion of the knee joint centre away from the mechanical axis produces a torque resulting from the body weight reaction force and the perpendicular distance from the mechanical axis to the joint centre.

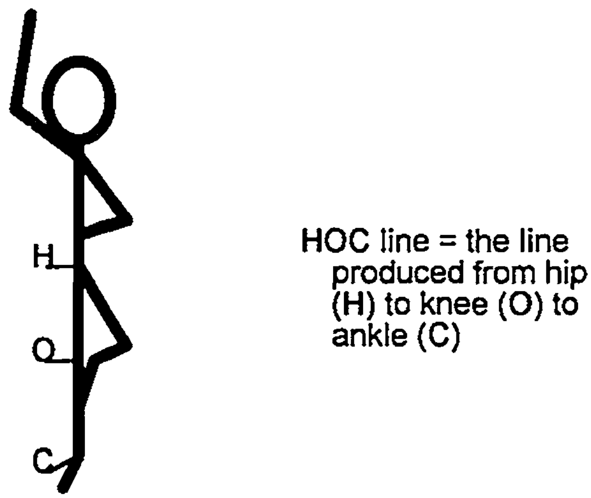

Figure 6
Lower Limb Alignment

Movements that occur about the knee include rotation about the transverse and long axis (Kapandji, 1970). Rotation about the transverse axis of the knee includes flexion and extension in the frontal plane camera view (yz). Additional motion relates to malalignment with movement of the joint centre medial to the long axis while the knee is in a flexed position, in the oblique plane camera view.

MEASUREMENT SYSTEM

To synchronize the force platform landings with the two plane video recordings, a system was designed to illuminate a light with each impact. A sensor switch was attached to the bottom of the dance shoe, which caused the light to eluminate upon contact with the force platform. Cameras were set up in the frontal plane (yz) and the oblique plane (45 degrees to the frontal plane, to the right of the subject). The two views were video taped using Panasonic cameras running at 30 Hz. The light, attached to the sensor switch on the bottom of the subject's shoe, was placed in a position to the right of the dancer to be recorded by both video camera views during the dance. Consequently, force platform data and video data were calculated simultaneously and synchronized by the light system.

TEST PROCEDURES

Each dancer performed a six step Highland Fling consisting of a three minute dance, standard to Highland dancers. Each step is a combination of movements. The movements consisted of hops on one foot or the other while the non-support leg completed extensions and movements around the calf of the jumping leg. The dancer completed the dance on the force platform while being video taped using two video cameras in both a frontal and a 45 degree oblique angle to the right of the dancer.

Ten hops were chosen toward the beginning of the dance, within the first step, and ten hops were chosen at the end of the dance, within the last step, to indicate changes in knee torque between the early and late stages of a six step Highland Fling. Ten hops for each phase were video taped in two planes to demonstrate knee alignment changes over the period of a dance.

VIDEO ANALYSIS

All joint centres were marked with black marker to aid in the digitization of the joint centres on the PEAK 2D system. Images from the two camera views were analyzed using the PEAK 2D video analysis system (PEAK Performance Technologies Inc.) to provide x, y coordinates for body segmental end points in both planes. A PEAK 2D spatial model was utilized (see Appendix C).

The maximum flexion frame of each hop was digitized on the PEAK 2D system from the frontal view to provide vector measures for the calculation of knee torque. Impact, maximum flexion, and full extension frames for each hop were digitized from the oblique view to provide vector measures for the calculation of knee torque at maximum flexion and to measure variations in malalignment at impact, maximum flexion, and extension. The video analysis calculated the body's centre of mass positioning, along with the positioning of each marked joint centre. When in correct alignment the x-coordinate, or horizontal coordinate, of the knee falls in alignment with the x-coordinate, or horizontal coordinate, of the centre of mass, creating a line called the mechanical axis or HOC line (figure 7). When these horizontal coordinates are equal malalignment is minimal. However, when the x coordinates of the centre of mass and the knee joint centre increase, the degree of malalignment increases.

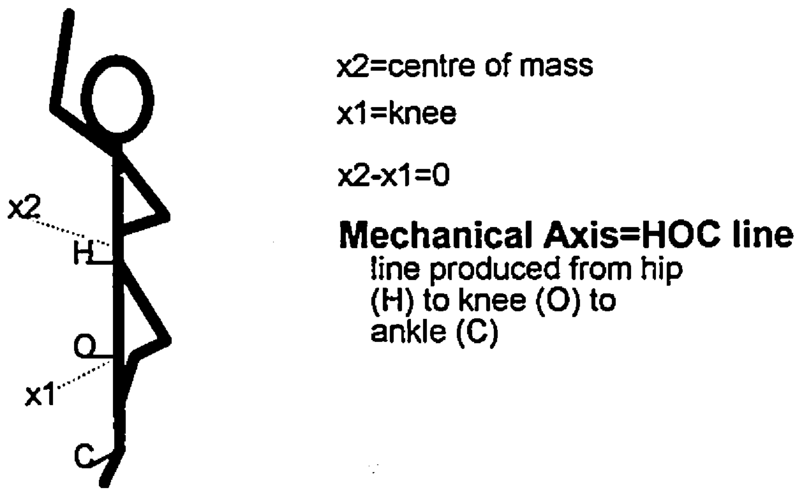

Figure 7
Balanced Knee and Centre of Mass Alignment

In both malalignment and flexion motions in the frontal and oblique planes, the knee is displaced from the mechanical axis creating a resultant displacement value for the calculation of torque (x1≠x2; see figure 8). The horizontal x-coordinates of the knee and centre of mass are used to calculate a two-dimensional knee joint centre displacement by subtracting the centre of mass horizontal coordinate from the knee horizontal coordinate.

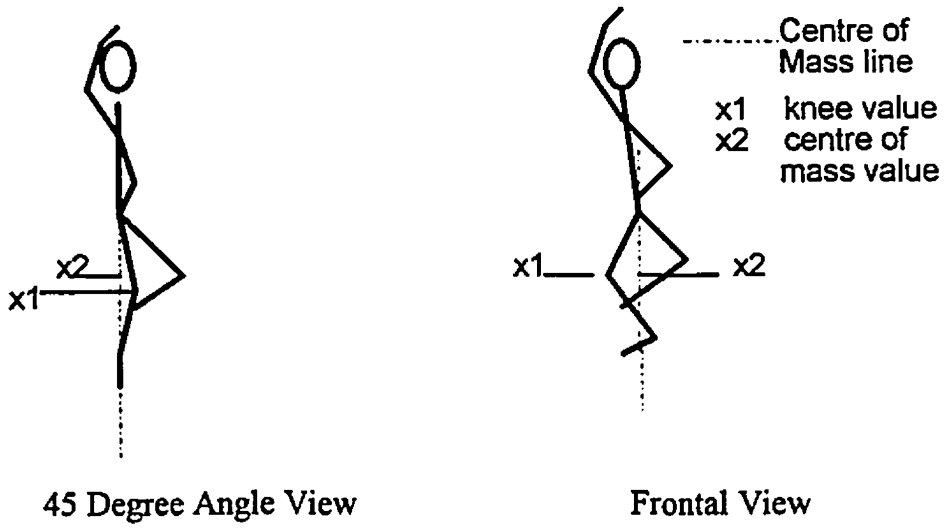

Figure 8
Displacement of Knee X-Coordinate from
Centre of Mass X-Coordinate

Three-Dimensional Knee Displacement Calculations

A values were calculated for the frontal camera view (yz) by subtracting the horizontal coordinates of the centre of mass from the horizontal coordinates of the knee for each frontal view frame analyzed. ***B*** values were calculated for the oblique view using the same method, resulting in two-dimensional knee joint centre displacements in both views for ten hops during the early and late stages of the Highland Fling. *A* values and ***B*** values were then represented as displacement vectors aligned at 45 degrees. A resultant *C*, was calculated, using the COS rule, formula $C^2=A^2+B^2-2AB\cos\varnothing$ (figure 9).

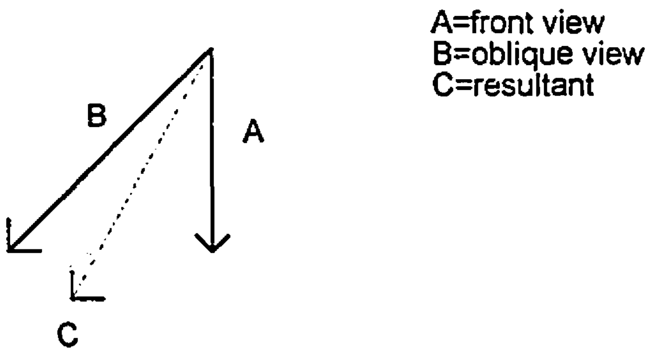

Figure 9
Three-Dimensional Resultant Vector
for Knee Torque

The resultants were calculated for maximum flexion for each of the 20 hops. From the 45 degree oblique view, two-dimensional knee joint centre displacements were calculated for impact and extension, as well as maximum flexion.

FORCE MEASUREMENT PROCEDURES

Ground reaction force measurements (GRF) for each impact during the beginning of the dance (first step) and end of the dance (last or sixth step) were measured using an A.M.T.I. (Advanced Mechanical Technology Inc.) force platform and the Gait Analysis package. A GRF average for the first step was measured for 10 seconds. The procedure was repeated for the last step. The first and last step force measurements were matched with the resultant knee joint centre displacements, calculated for the beginning of the dance and the end of the dance.

KNEE TORQUE MEASUREMENT PROCEDURES

Torque (T) equals vertical GRF multiplied by the displacement of the knee from the centre of mass projection line (T = GRF x Resultant Knee Displacement). Torque measurements for each maximum flexion frame were calculated for the beginning of the dance and the end of the dance.

RESEARCH DESIGN AND STATISTICAL MEASURES

A Multiple Baseline Single Subject Design was utilized to measure differences between individual dancer's malalignment. Results were presented based on trend, mean, level, and variability for knee torque, maximum malalignment, maximum flexion, and GRF's during the early and late stages of the dance. Trends were discussed to provide similarities amongst subjects. Means of all measures were presented to provide an average number to compare differences in the early and late stages of the dance for each subject. Ranges for all measures were presented to provide the difference between the lowest and highest scores. Standard deviations were presented to demonstrate the average of the deviations of each score from the mean.

Chapter IV

RESULTS

The purpose of the study was to measure torque variations in the knees of malaligned Highland dancers during the early and late stages of a six step Highland Fling. A sub-purpose was to measure the variations in knee malalignment for impact, maximum flexion, and extension.

Seven Highland dancers performed a six step Highland fling on a force platform while being video taped from both frontal and oblique views. Ten hops were analyzed in the first step and 10 in the last step to show variations in knee torque and knee malalignment for the early and late stages of the dance. By subtracting the x-coordinate, or horizontal coordinate, of the centre of mass from the horizontal coordinate of the knee, knee displacement values were calculated for both frontal (*A*) and oblique (*B*) views for each hop analyzed. Knee torque was calculated using vertical ground reaction forces (GRF) and the resultant displacement (*C*) calculated from the two views.

A Multiple Baseline Single Subject Design was utilized. Results are presented statistically for the dependent variables: knee torque, ground reaction force (GRF) and knee displacement (knee malalignment and knee flexion). Statistical measures include mean and variability. Trends in means are presented for the dependent variables. Results are also presented graphically for the dependent variables: knee malalignment, knee flexion, and knee torque. Graphical measures demonstrate different levels in the first and last steps for the dependent variables. Raw data for the seven subjects is presented in Appendix A.

MEAN MEASURES

Mean scores for knee torque, GRF, knee malalignment, and knee flexion over the duration of the dance period are as follows. Knee torque means ranged from 89.55 Nm to 149.35 Nm (or 1.7 Nm/kg to 2.7 Nm/kg), in the beginning of the dance, and 94.4 Nm to 127.6 Nm (or 1.7 Nm/kg to 2.1 Nm/kg), at the end. Increases in knee torque during the dance occurred in subject 6 only, whereas, decreases in knee torque occurred in all other subjects.

GRF means ranged from 1216.9 N to 1759.1 N and 1130 N to 1672.6 N from early to late stages of the dance. This is equivalent to approximately two to three times body weight per impact. GRF means increased in subjects 3, 4, and 5 and decreased in subjects 1, 2, 6, and 7 over the dance period.

Knee malalignment displacement means ranged from 0.0105 metres to 0.0439 metres and 0.0188 metres to 0.0697 metres, for the first and last steps, respectively. Knee malalignment means during the dance period increased in all seven subjects.

Knee flexion displacement means ranged from 0.0227 metres to 0.0734 metres, for the first step, and 0.0183 metres to 0.067 metres, for the last step. Knee flexion means during the dance period decreased in all seven subjects.

Table 1 - Knee Torque Statistics for Subjects 1, 2, and 7

	Knee Torque (Nm)	
Subject 1	**First Step**	**Last Step**
mean	149.35	114.16
range	97.66-227.3	98.62-127.03
std. dev.	35.716	10.092
Subject 2		
mean	108.43	99.7
range	81.13-171.2	87.72-123.05
std. dev.	25.598	14.363
Subject 7		
mean	119.73	112.9
range	47.5-177.67	65.23-157.22
std. dev	40.749	36.925

Table 2 - Knee Displacement Statistics for Frontal Oblique Views for Subjects 1, 2, and 7

	Knee Displacement Measure			
	First Step		**Last Step**	
	Malalignment	Flexion	Malalignment	Flexion
Subject 1	Oblique View	Frontal View	Oblique View	Frontal View
mean	0.0192	0.0734	0.0342	0.0374
range	0-0.048	0.027-0.125	0.001-0.051	0.017-0.077
std. dev.	0.016	0.029	0.0197	0.0201
Subject 2				
mean	0.0168	0.0692	0.0188	0.067
range	0.001-0.022	0.046-0.113	0.007-0.037	0.049-0.094
std. dev.	0.0118	0.0203	0.0113	0.0168
Subject 7				
mean	0.0207	0.0515	0.0443	0.0264
range	0.006-0.044	0.022-0.091	0.011-0.093	0.002-0.059
std. dev	0.0126	0.0224	0.0321	0.0184

VARIABILITY

Variability of the measures for knee torque, GRF, knee malalignment, and knee flexion over the duration of the dance period are as follows.

Knee torque variability for subjects 1, 2, and 7 demonstrated ranges of 97.66 Nm to 227.3 Nm, 81.13 Nm to 171.2 Nm, and 47.55 Nm to 177.67 Nm; and standard deviations of 35.716, 25.598, and 40.749, respectively for the beginning of the dance. The end of the dance demonstrated less variability for subjects 1, 2, and 7 with ranges of 98.62 Nm to 127.03 Nm, 87.72 Nm to 123.05 Nm, and 65.23 Nm to 157.22 Nm; and standard deviations of 10.092, 14.363, and 36.925, respectively (table 1).

Knee malalignment variability for subjects 1, 2, and 7 demonstrated ranges of 0 metres to 0.048 metres, 0.001 metres to 0.022 metres, and 0.006 metres to 0.044 metres; and standard deviations of 0.016, 0.0118, and 0.0126, respectively. Increases in variability occurred for subjects 1, 2, and 7 at the end of the dance, except for the standard deviation for subject 2. Ranges were 0.001 metres to 0.051 metres, 0.007 metres to 0.037 metres, and 0.011 metres to 0.093 metres, respectively. Standard deviations were 0.0197, 0.0113, and 0.0321, respectively (table 2).

Knee flexion variability for subjects 1, 2, and 7 demonstrated ranges of 0.027 metres to 0.125 metres, 0.046 metres to 0.113 metres, and 0.022 metres to 0.091 metres; and standard deviations of 0.029, 0.0203, and 0.0224, respectively. The last step demonstrated less variability for subjects 1, 2, and 7 with ranges of 0.017 metres to 0.077 metres, 0.049 metres to 0.094 metres, and 0.002 metres to 0.059 metres; and standard deviations of 0.021, 0.0168, and 0.0184, respectively (table 2).

Table 3 - Knee Torque Statistics for Subjects 3, 4, and 5

	Knee Torque (Nm)	
Subject 3	**First Step**	**Last Step**
mean	111.44	98.04
range	82.55-133.7	69.51-121.6
std. dev.	18.302	16.93
Subject 4		
mean	97.72	94.4
range	80.32-155.7	78.66-116.6
std. dev.	34.77	16.057
Subject 5		
mean	136.78	127.6
range	85.39-173.8	41.78-162.3
std. dev	30.165	38.927

Table 4 - Knee Displacement Statistics for Frontal Oblique Views for Subjects 3, 4, and 5

	Knee Displacement Measure			
	First Step		Last Step	
	Malalignment	Flexion	Malalignment	Flexion
Subject 3	Oblique View	Frontal View	Oblique View	Frontal View
mean	0.0297	0.0535	0.0332	0.0392
range	0.003-0.053	0.03-0.096	0.005-0.054	0.026-0.058
std. dev.	0.0164	0.0211	0.0177	0.011
Subject 4				
mean	0.0252	0.0595	0.0445	0.0318
range	0.009-0.058	0.021-0.111	0.009-0.064	0.008-0.078
std. dev.	0.0141	0.033	0.0173	0.0234
Subject 5				
mean	0.0414	0.055	0.0588	0.0241
range	0.016-0.065	0.031-0.096	0.026-0.085	0-0.053
std. dev	0.0195	0.0231	0.0216	0.0282

Knee torque variability for subjects 3, 4, and 5 demonstrated ranges of 82.55 Nm to 133.7 Nm, 80.32 Nm to 155.7 Nm, and 85.39 Nm to 173.8 Nm; and standard deviations of 18.302, 34.77, and 30.165, respectively, in the first step. The last step demonstrated less variability for subject 4 with a range of 78.66 Nm to 116.6 Nm and a standard deviation of 16.057. Subject 3 also showed less variability in the standard deviation with 16.93 and an increase in variability for the range with 69.51 Nm to 121.6 Nm. Subject 5 demonstrated an increase in variability with a range of 41.78 Nm to 162.31 Nm and a standard deviation of 38.927 (table 3).

Knee malalignment variability for subjects 3, 4, and 5 demonstrated ranges of 0.003 metres to 0.053 metres, 0.009 metres to 0.058 metres, and 0.016 metres to 0.065 metres; and standard deviations of 0.0164, 0.0141, and 0.0195 respectively. The last step demonstrated increases in variability for subjects 3, 4, and 5 except for a decrease in range for subject 3. Ranges for the last step were 0.005 metres to 0.054 metres, 0.009 metres to 0.064 metres, and 0.026 metres to 0.085 metres, respectively. Standard deviations were 0.0177, 0.0173, and 0.0216, respectively (table 4).

Knee flexion variability for subjects 3, 4, and 5 demonstrated ranges of 0.03 metres to 0.096 metres, 0.021 metres to 0.111 metres, and 0.031 metres to 0.096 metres; and standard deviations of 0.0211, 0.033, and 0.0231, respectively. The last step demonstrated less variability for subjects 3, 4, and 5 except for an increase in standard deviation for subject 5. Ranges for the last step were 0.026 metres to 0.058 metres, 0.008 metres to 0.078 metres, and 0 metres to 0.053 metres. Standard deviations were 0.011, 0.0234, and 0.0282, respectively (table 4).

Table 5 - Knee Torque Statistics for Subject 6

	Knee Torque (Nm)	
Subject 6	First Step	Last Step
mean	89.55	94.92
range	45.41-146.1	42.94-150.2
std. dev.	32.732	32.441

Table 6 - Knee Displacement Statistics for Frontal Oblique Views for Subject 6

	Knee Displacement Measure			
	First Step		Last Step	
	Malalignment	Flexion	Malalignment	Flexion
Subject 6	Oblique View	Frontal View	Oblique View	Frontal View
mean	0.0439	0.0227	0.0697	0.0183
range	0.005-0.087	0.001-0.056	0.016-0.11	0.003-0.038
std. dev.	0.0238	0.0182	0.0287	0.0114

Knee torque variability at the beginning of the dance for subject 6 demonstrated a range of 45.41 Nm to 146.1 Nm; and a standard deviation of 32.732. The end demonstrated less variability for the standard deviation, with 32.441 and greater variability for the range, with 42.94 Nm to 150.2 Nm (table 5).

Knee malalignment variability for subject 6 demonstrated a range of 0.005 metres to 0.087 metres; and a standard deviation of 0.0238. Greater variability occurred at the end of the dance with a range of 0.016 metres to 0.11 metres and a standard deviation of 0.0287 (table 6).

Knee flexion variability for subject 6 demonstrated a range of 0.001 metres to 0.056 metres; and a standard deviation of 0.0182. The end of the dance demonstrated less variability with a range of 0.003 metres to 0.038 metres; and a standard deviation of 0.0114 (table 6).

Table 7 - Knee Displacement Statistics for Oblique View for Subjects 1 and 7

	Knee Displacement Measure			Knee Displacement Measure		
		First Step			Last Step	
	Full Ext	Impact	Max Flex	Full Ext	Impact	Max Flex
Subject 1	(m)	(m)	(m)	(m)	(m)	(m)
mean	0.0421	0.0105	0.0192	0.02	0.0121	0.0342
range	0.009-0.107	0.001-0.022	0-0.048	0.002-0.056	0.001-0.029	0.001-0.053
std. dev.	0.0356	0.0065	0.016	0.0178	0.0085	0.0197
Subject 7						
mean	0.0216	0.01	0.0207	0.0217	0.0166	0.0443
range	0.011-0.068	0-0.022	0.006-0.044	0.001-0.074	0.001-0.035	0.011-0.093
std. dev.	0.0194	0.0075	0.0126	0.0238	0.0118	0.0321

Table 8 - Knee Displacement Statistics for Oblique View for Subjects 2, 3, 4, 5, and 6

	Knee Displacement Measure			Knee Displacement Measure		
		First Step			Last Step	
	Full Ext	Impact	Max Flex	Full Ext	Impact	Max Flex
Subject 2	(m)	(m)	(m)	(m)	(m)	(m)
mean	0.0162	0.0115	0.0168	0.011	0.008	0.019
range	0-0.042	0-0.037	0.001-0.035	0.002-0.027	0.004-0.019	0.01-0.037
std. dev.	0.0169	0.0103	0.0118	0.0097	0.0056	0.0113
Subject 3						
mean	0.0069	0.0179	0.0297	0.006	0.0126	0.0332
range	0-0.015	0.007-0.028	0.003-0.053	0.001-0.016	0.002-0.022	0.005-0.054
std. dev.	0.0094	0.007	0.0164	0.005	0.0078	0.0177
Subject 4						
mean	0.0181	0.0171	0.0252	0.0103	0.0216	0.0445
range	0.001-0.062	0-0.035	0.009-0.058	0-0.029	0.005-0.037	0.009-0.064
std. dev.	0.0204	0.0101	0.0141	0.0082	0.0107	0.0173
Subject 5						
mean	0.016	0.0277	0.0414	0.0338	0.0507	0.0588
range	0.001-0.053	0.014-0.046	0.016-0.065	0.013-0.049	0.026-0.075	0.026-0.085
std. dev.	0.0153	0.0109	0.0195	0.0172	0.0156	0.0216
Subject 6						
mean	0.0165	0.0197	0.0439	0.0223	0.0317	0.0697
range	0.001-0.044	0.001-0.038	0.005-0.087	0.002-0.089	0.003-0.057	0.016-0.11
std. dev.	0.0149	0.0175	0.0238	0.0281	0.0169	0.0287

KNEE MALALIGNMENT

Greatest knee malalignment, in the first step, occurred at extension for subjects 1 and 7 with 0.0421 and 0.0216 metres, respectively (table 7). Subjects 2, 3, 4, 5, and 6 demonstrated greatest knee malalignment at maximum flexion with 0.0168, 0.0297, 0.0252, 0.0414, and 0.0439 metres, respectively (table 8). In the last step greatest knee malalignment occurred at maximum flexion for subjects 1 through 7 with 0.0342, 0.019, 0.0332, 0.0445, 0.0588, 0.0697, and 0.0443 metres, respectively.

GRAPHICAL KNEE TORQUE DATA

Knee torque levels from early to late stages of the dance decreased slightly for subjects 1 to 5 and 7, and are demonstrated in figure 10 and 11. Subject 6 demonstrated a knee torque level increase and is demonstrated in figure12.

Figure 10 - Knee Torque Measures for the First & Last Steps of the Highland Fling

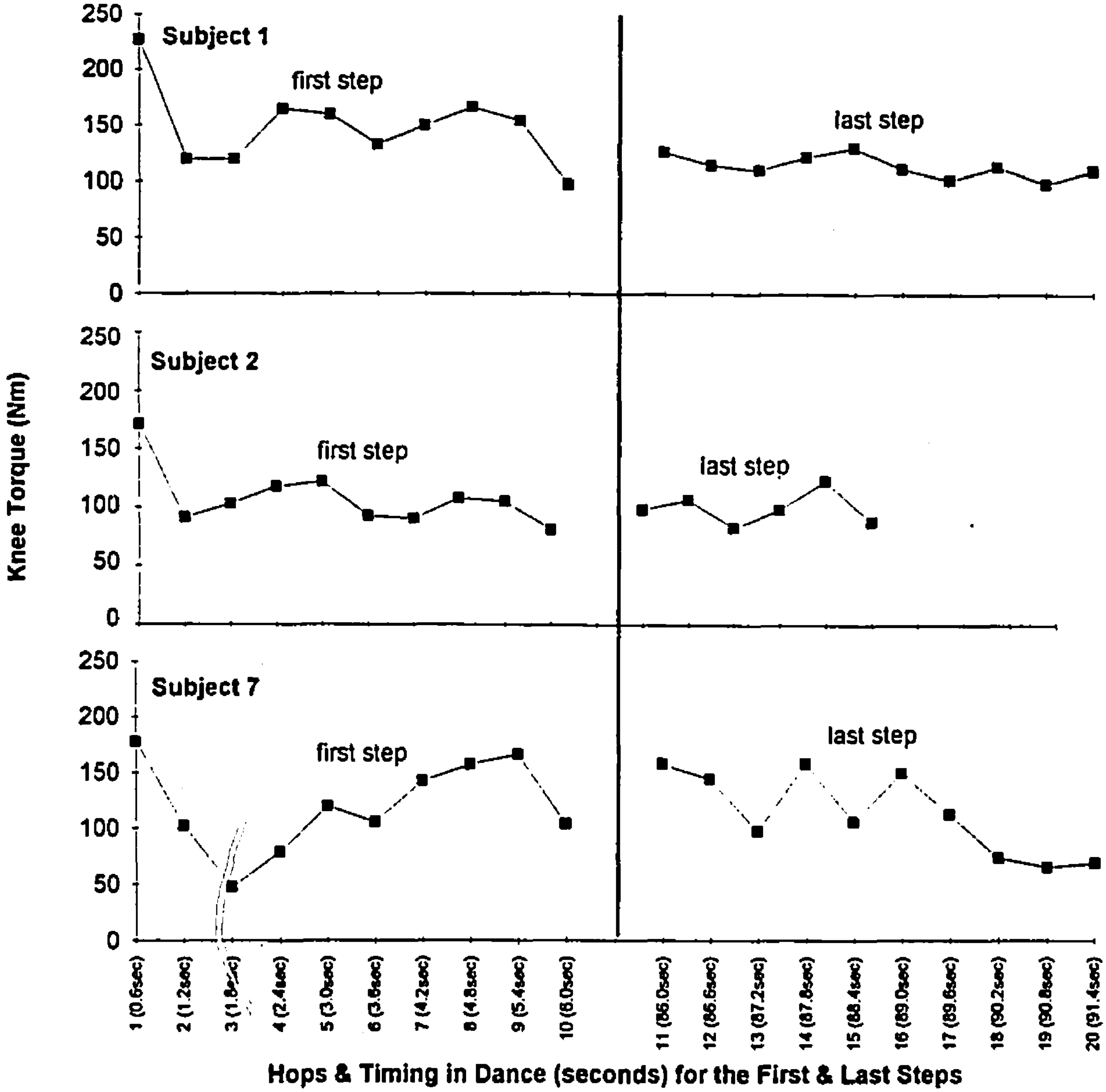

Figure 10 demonstrates a slight decrease in levels from early to late stages for subjects 1, 2, and 7 in knee torque.

Figure 11 - Knee Torque Measures for the First & Last Steps of the Highland Fling

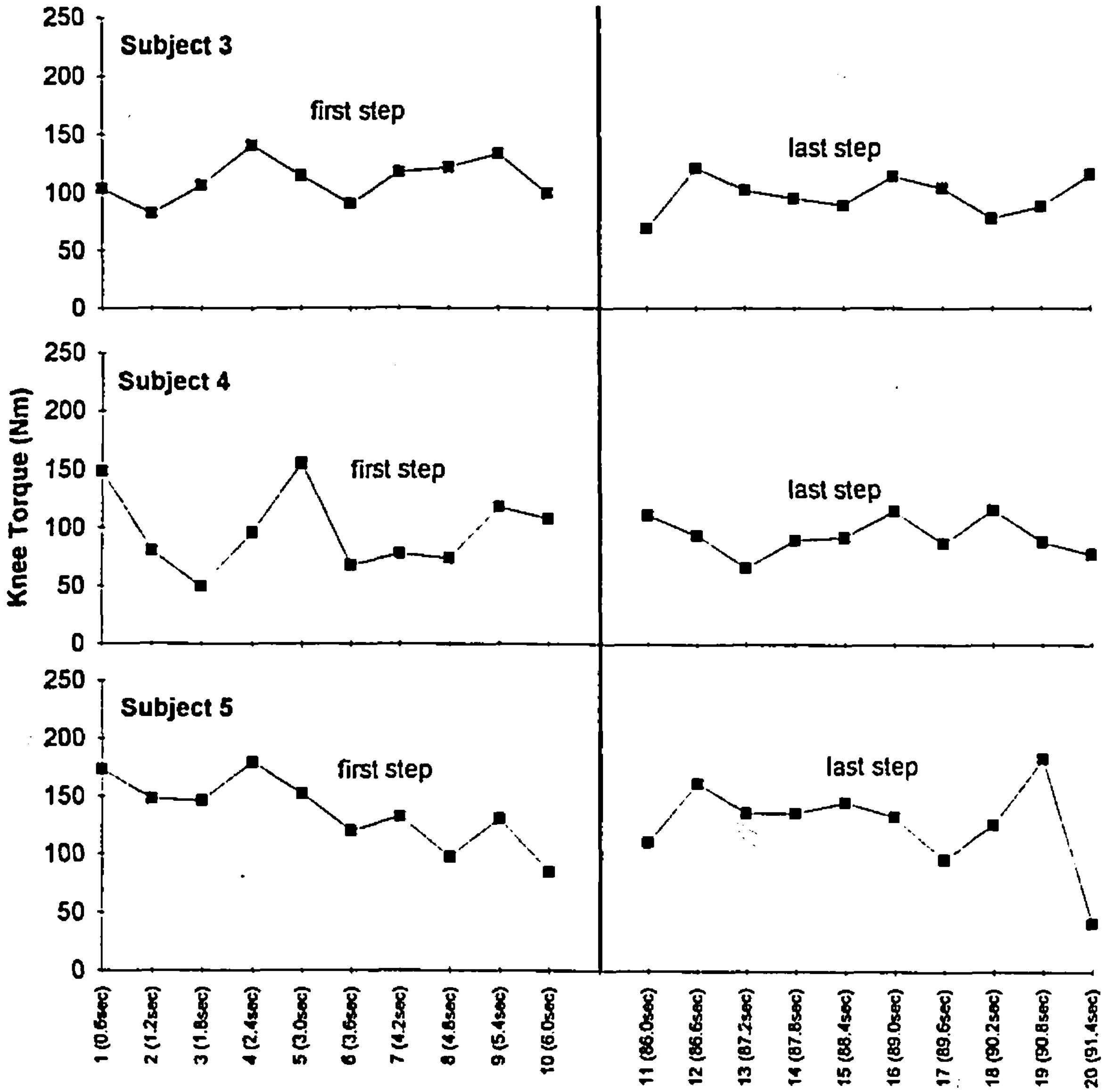

Figure 11 demonstrates a slight decrease in levels from the beginning to the end of the dance for subjects 3, 4, and 5 in knee torque.

Figure 12 - Knee Torque Measures for the First & Last Steps of the Highland Fling

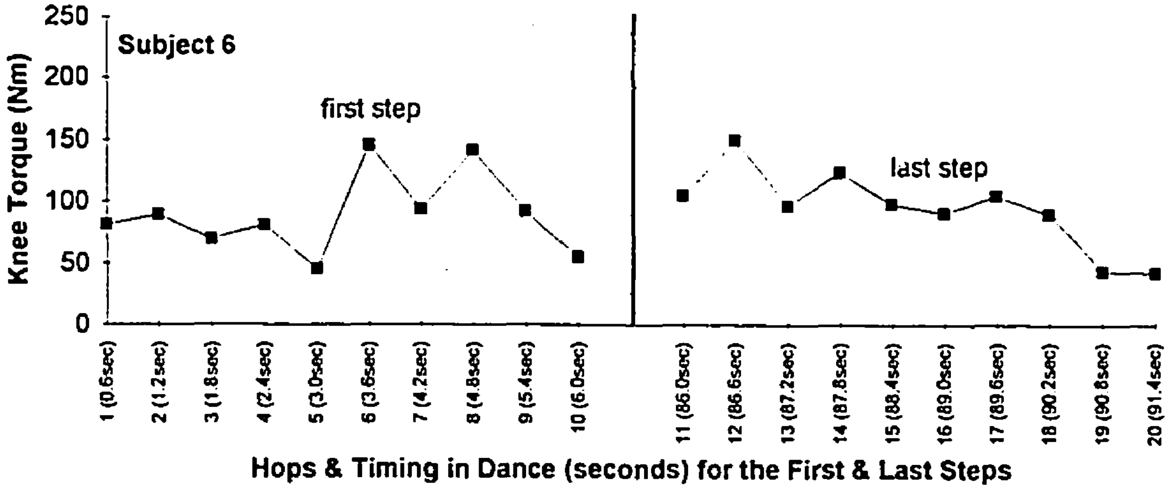

Figure 12 demonstrates an increase in level from early to late stages for subject 6 in knee torque.

GRAPHICAL KNEE MALALIGNMENT DATA

Knee malalignment levels from the beginning to the end of the dance increase for all subjects and are demonstrated in the following graphs (figure 13, 14 and 15).

Figure 13 - Knee Malalignment Measures from an Oblique View for the First & Last Steps of the Highland Fling

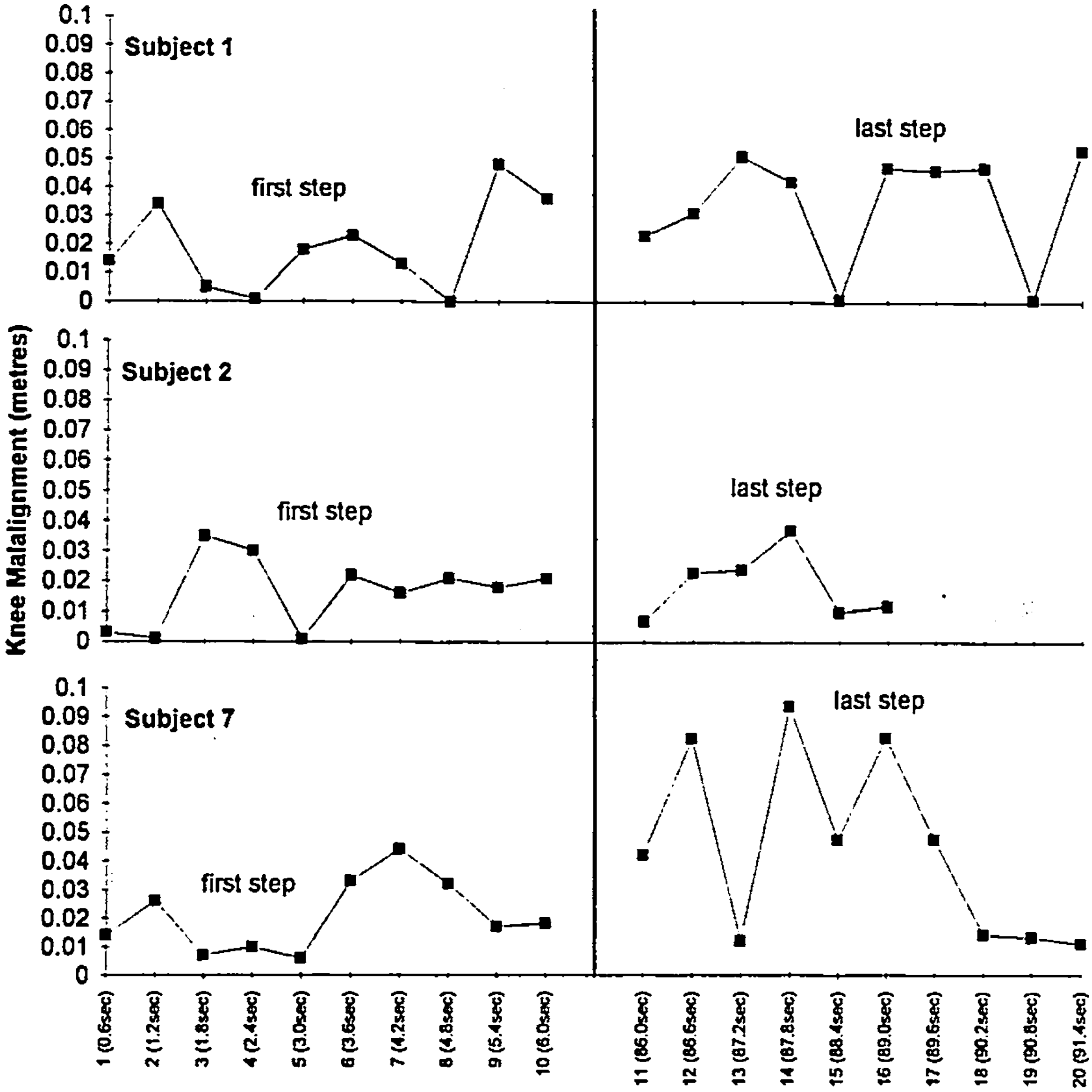

Figure 13 demonstrates an increase in levels from the early to late stages for subjects 1, 2, and 7 in knee malalignment.

Figure 14 - Knee Malalignment Measures from an Oblique View for the First & Last Steps of the Highland Fling

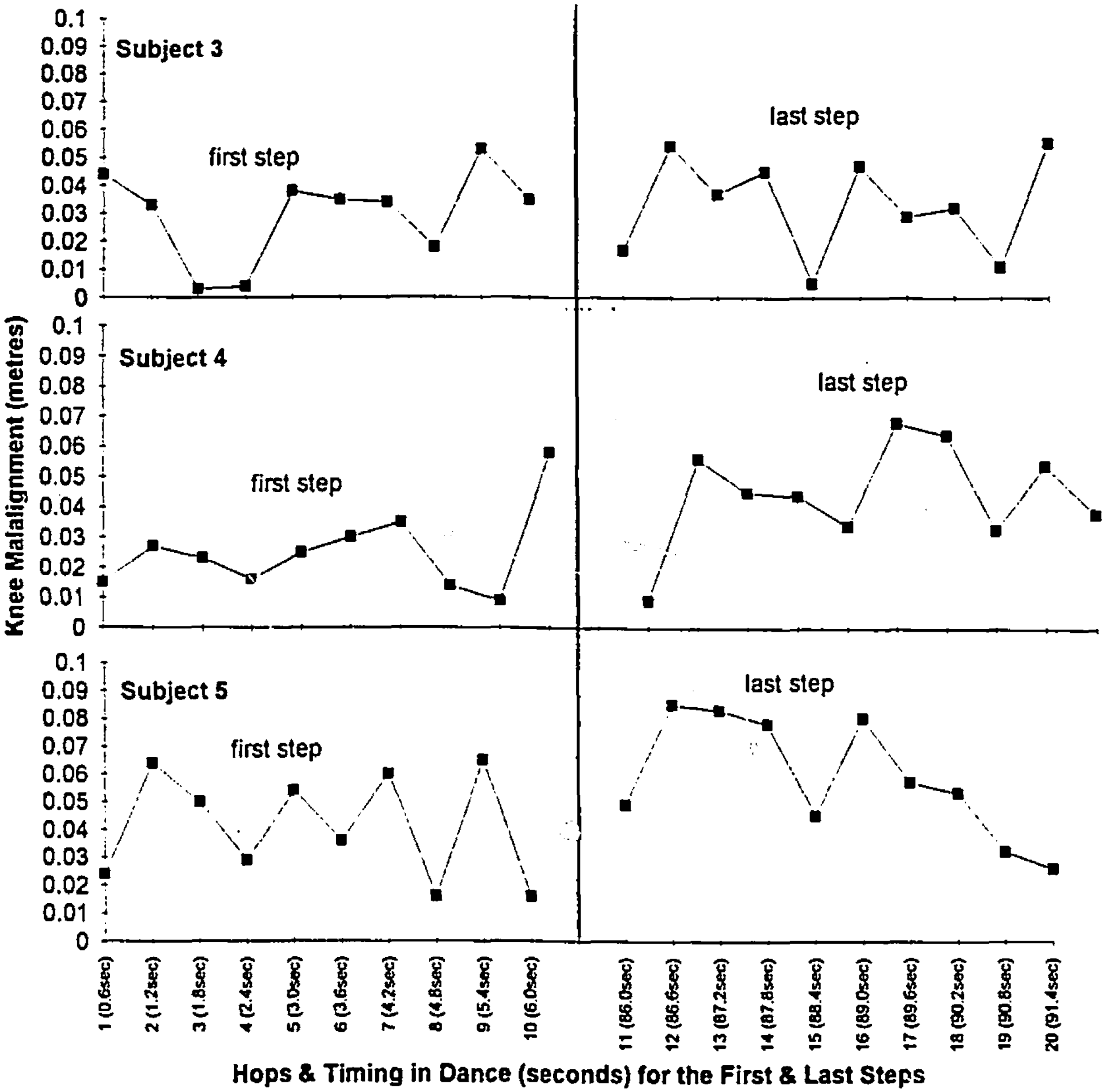

Figure 14 demonstrates an increase in levels from the beginning to the end of the dance for subjects 3, 4, and 5 in knee malalignment.

Figure 15 - Knee Malalignment Measures from an Oblique View for the First & Last Steps of the Highland Fling

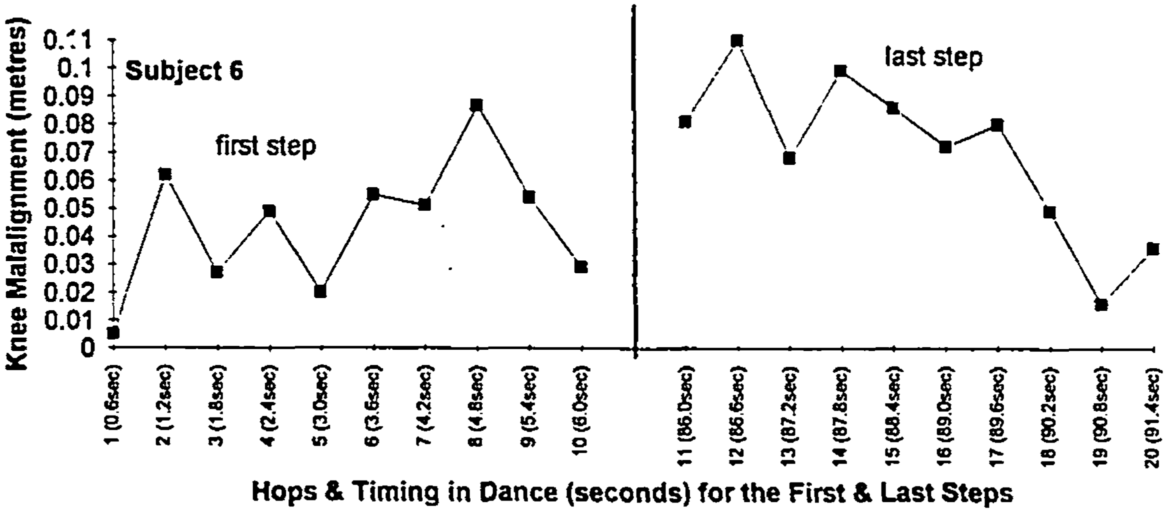

Figure 15 demonstrates an increase in level from early to late stages for subject 6 in knee malalignment.

GRAPHICAL KNEE FLEXION DATA

Knee flexion levels from the beginning to the end of the dance decreased for all subjects and are demonstrated in the following graphs (figure 16, 17, and 18).

Figure 16 - Knee Flexion Measures from a Frontal View for the First & Last Steps of the Highland Fling

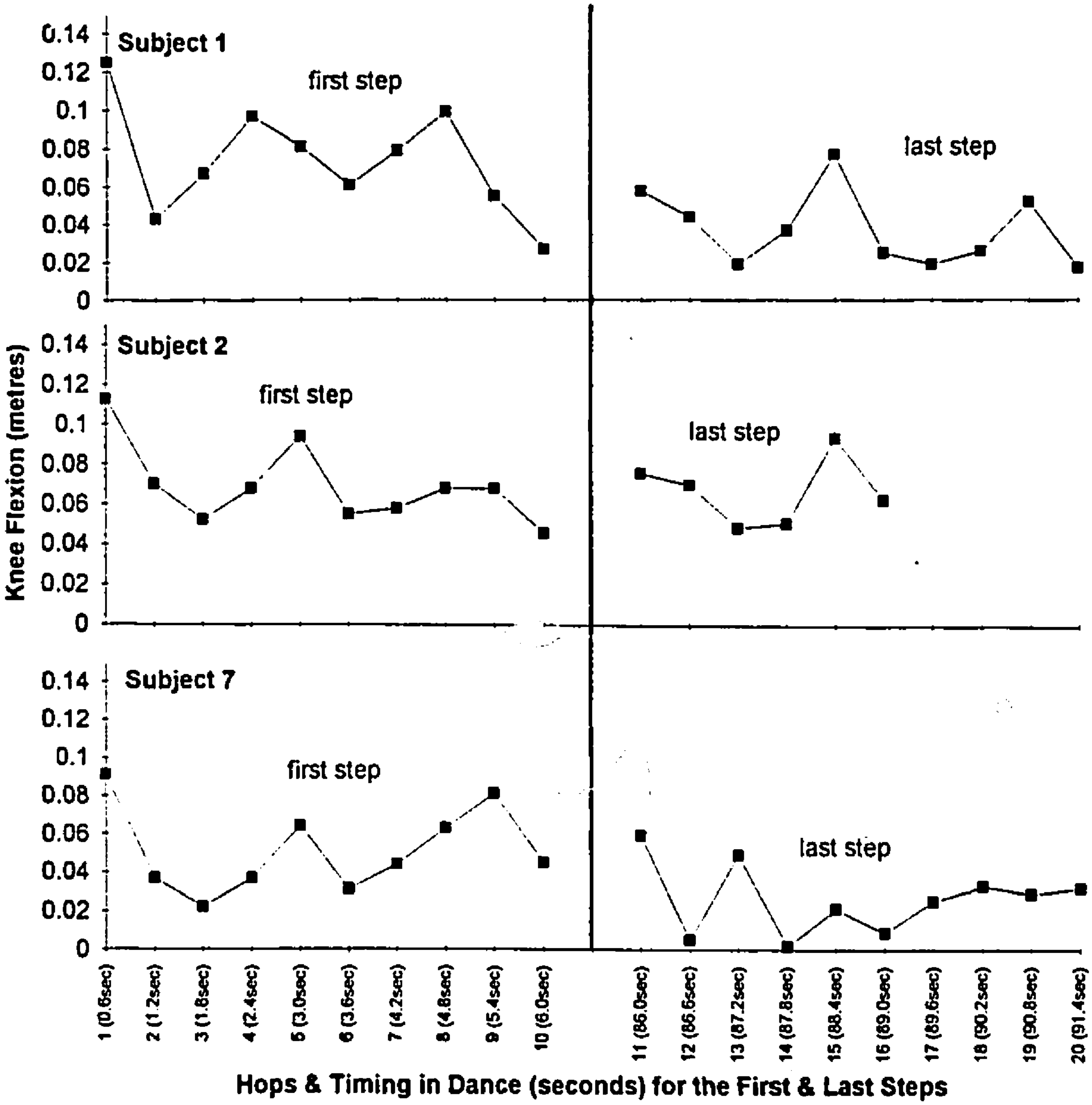

Figure 16 demonstrates a decrease in levels from early to late stages for subjects 1, 2, and 7 in knee flexion.

Figure 17 - Knee Flexion Measures from a Frontal View for the First & Last Steps of the Highland Fling

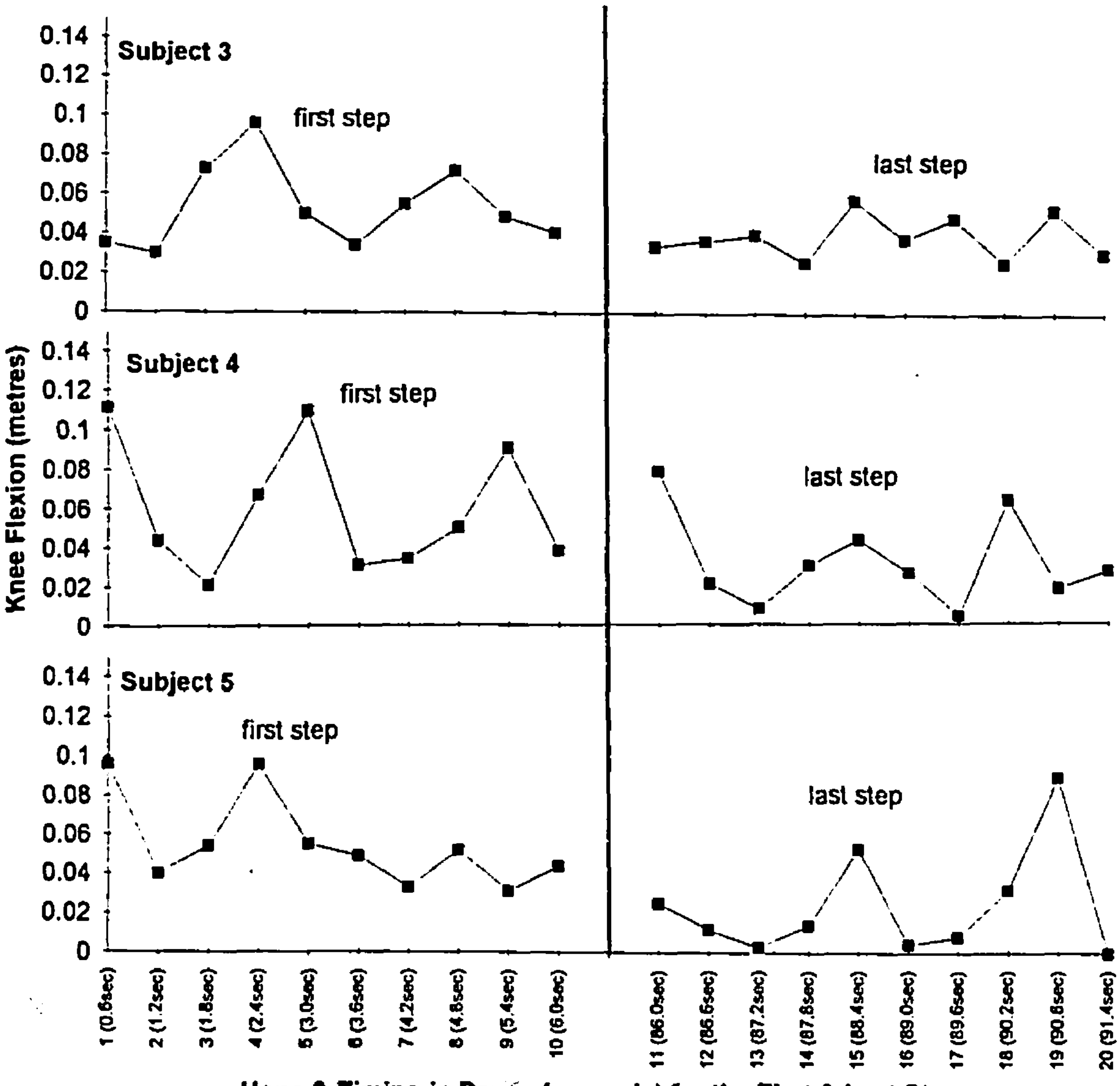

Figure 17 demonstrates a decrease in levels from the beginning to the end of the dance for subjects 3, 4, and 5 in knee flexion.

Figure 18 - Knee Flexion Measures from a Frontal View for the First & Last Steps of the Highland Fling

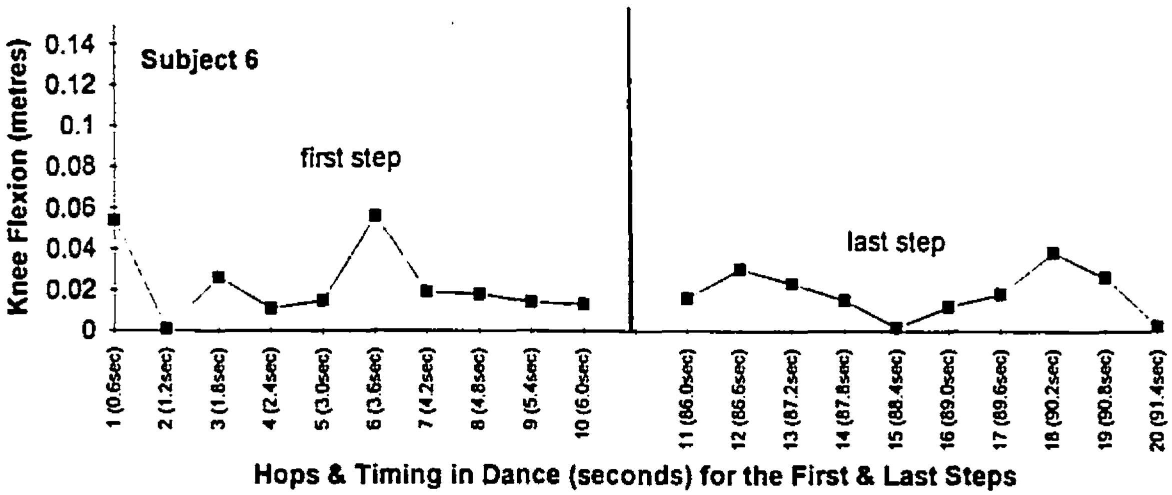

Figure 18 demonstrates a decrease in level from early to late stages for subject 6 in knee flexion.

Chapter V

DISCUSSION

Knee torque variations during Highland dancing are discussed in relation to the components: knee malalignment, knee flexion, and ground reaction force (GRF). Maximum knee malalignment is discussed relative to the degrees of knee flexion. Trends exist in both components, knee torque and maximum knee malalignment, within the seven subjects.

TORQUE & GROUND REACTION FORCES

Knee torque is measured in the present study as it combines ground reaction forces and knee alignment.[1] Previous studies have investigated ground reaction forces (GRF) in dancers (Johnstone & Bauer, 1993; Solomon & Micheli, 1986), but these measurements do not consider torque at the knee resulting in knee malalignment. Although, GRF is essential to an understanding of the potential for knee injury in dance, the malalignment of the knee joint is also a consideration for potential injury (Arnheim, 1989). Knee injuries occur frequently in dance due to the turnout required and the related knee malalignment (Arnheim, 1989; Solomon & Micheli, 1986). Since malalignment, and the relationship to correct technique, are a major concern in dance, measurement of knee torque provides valuable information and contributes to a better understanding of knee joint injuries in Highland dance.

The mean knee torque measures calculated from the sample group (N=7) ranged from 1.7 Nm/kg to 2.7 Nm/kg in the first step and 1.7 Nm/kg to 2.1 Nm/kg in the last step. Knee torque values are considerably higher than those found by Mularczyk in marathon runners (Mularczyk, 1990). The runners, analyzed at the

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[1]Knee torque (T) is the combination of the 3-dimensional displacement measure of the knee (*C*) (a combination of knee flexion displacement measures(*A*) and knee malalignment measures (*B*)) and the ground reaction force (GRF). $T = C \times GRF$; $C^2 = A^2 + B^2 - 2AB\cos Ø$

38 km point, were reported to have extension and flexion knee torque values of 0.33 Nm/kg to 0.45 Nm/kg and 0.55 Nm/kg to 0.82 Nm/kg, respectively. The knee torque values in the present study were comparable to knee torque values in sprinters in a study by Shealy et al (1992). Results indicated 2.7 Nm/kg and 1.47 Nm/kg for extension and flexion knee torque, respectively. Based on this comparison and the referenced literature, knee torque measures in Highland dancers are more comparable to sprinters than to marathon runners.[2]

One might expect torque to increase as a result of muscular fatigue and lack of support at the joints. Over the period of a dance, torque increases result from the combination of changes in knee malalignment and knee flexion. The general trend was that knee flexion decreased, causing the vertical height of the jumps to decrease. Consequently, the quality of the dance can generally be effected.

Knee torque values indicated a decrease from early to late stages of the dance. Subjects 1, 2, 3, 4, 5, and 7 all demonstrated decreases in knee torque (see Results - Table 1 and 3). Consequently, a definite trend in torque exists for 6 of the 7 subjects.

The combination of malalignment increases and knee flexion decreases provided the dominant trend in knee torque results. All seven subjects demonstrated increases in knee malalignment (Table 2 and 4). The degree of knee flexion decreased in all seven subjects, and therefore, influenced the knee torque measures. In addition, GRF's decreased slightly for subjects 1, 2, and 7, and compounded the knee torque decreases. GRF's increased slightly for subjects 3, 4, and 5, and therefore, do not support decreases in knee torque.

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[2]Both Mularczyk (1990) and Shealy et al (1992) measured flexion and extension knee torque using a horizontal force; whereas, the present study uses a vertical ground reaction force (GRF) in the measurement of knee torque. Both torque measurements are comparable, as they both deal with force and displacement measurements for the knee joint.

Subject 6 did not follow the same trend in knee torque and indicated an increase from 89.55 Nm to 94.92 Nm (Table 5). Large increases in knee malalignment resulted in an increase in torque at the knee. Decreases in knee flexion occurred, similar to all other subjects. GRF's decreased, and therefore, did not contribute to the increased knee torque.

The general trend indicating increases in knee malalignment and decreases in knee flexion could be explained by a failure in soft tissue support due to muscular fatigue. Fatigue, however, was not measured in the present study, but could be considered a possible explanation for the result. If muscles fatigue toward the end of the dance, the dancer may not have the muscular support and strength to flex as the dance progresses. To compensate, the dancer decreases the level of knee flexion or ankle flexion, and therefore, malalignment increases, aiding in the natural force absorption process.

The results indicate a possible relationship between knee malalignment and knee flexion with one compensating for the other with decreases in knee flexion and increases in knee malalignment. This may be a fatigue controlling mechanism. Less knee flexion may result in less shock absorption in the lower limb segments, and therefore, an increase in the malaligned position. The potential for knee injury increases with knee malalignment, as well as the potential for hindering performance. The dancer will not obtain the optimal height between jumps and since jumping height is one of the criteria judged in competition for a Highland dancer, the quality of the performance is effected (Nichols, 1987). Although not measured in this study, there may be possible increases in ankle flexion to aid in absorption. Dropping the ankle also hinders a Highland dancer's performance, as the dancer is instructed to "lock" the ankle in a high arched position and allow only the knee to flex on impact, not the ankle (Nichols, 1987). Marks are deducted for both errors, less vertical height and dropping of the ankle.

One Highland Fling may not cause fatigue, however, knee malalignment may increase during longer dance periods. During the average practice or competition, several dances are performed in a one to four hour time span. Muscular endurance may become a factor, especially in non-conditioned dancers. Increasing the endurance fitness levels of dancers could be enhanced using alternate cross-training activities combined with resistance training and leg strengthening.

KNEE MALALIGNMENT AT EXTENSION, IMPACT & MAXIMUM FLEXION

Knee malalignment at extension, impact, and maximum flexion[3] was measured to demonstrate the variations of displacement at extreme degrees of flexion. The measurement of knee flexion at different stages of weight bearing could aid in an understanding of the mechanics of knee malalignment. Knee malalignment may result due to faulty technique or postural problems[4]. Postural malalignment, however, was not measured in this study.

The majority of subjects (subjects 2, 3, 4, 5, and 6) experienced increases in knee malalignment at maximum flexion (Table 7 and 8). Subjects 1 and 7 produced maximum knee malalignment at extension early in the dance (Table 7), suggesting potential postural malalignment while in a non-weight bearing position. Nonetheless, the subjects compensated at impact and maximum flexion with initial, correct technique. At the end of the dance, however, maximal malalignment developed at maximum flexion.

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[3]**extension** - frame measuring fullest knee extension; **impact** - frame measuring the supporting leg's first contact with the force platform; **maximum flexion** - frame measuring greatest degrees of knee flexion
[4] Postural limitations and faulty technique incorporate forced turnout and malalignment of the lower limb segment. Postural is structural limitations, whereas, faulty technique is limitations from technique requirements (i.e. turnout).

Instructional technique provides a critical correction factor for malaligned dancers. Dancers may need to be encouraged to turn the feet within the range of hip rotation while increasing the flexibility of the hip rotators and strengthening the legs. An early screening program would demonstrate postural limitations. All the subjects in the present study, were previously screened for malalignment. Highland dancers, as well as other dancers, may benefit from a preliminary screening to set appropriate training programs. Recommendations for a suitable training program may include strengthening imbalanced muscles, increasing flexibility in the hip rotators, and decreasing percent body fat. Prevention of injuries was the reason for the instigation of the dance screening program at the University of California, Irvine. The screening resulted in a decline of injuries due to alignment and a decline in the amount of lost time due to injury (Plastino, 1987).

Because so many problems in dance are either partly or wholly related to overuse/fatigue and faulty technique, analyzing the techniques responsible and altering them where feasible, are essential steps in preventing recurrence of injury (Schafle et al., 1990). These essential steps apply to Highland dancers in the present study and include; establishing alignment through education, adequate strength and balance of muscles, flexibility in the hip rotators, and screening programs for postural limitations.

Chapter VI

CONCLUSIONS & RECOMMENDATIONS

The results of the present study indicate trends in knee torque, knee malalignment, and knee flexion from early to late stages of a Highland Fling. Knee torque values decreased from early to late stages of the dance due to the dancer adjusting the level of knee flexion on landing. Knee flexion decreased from early to late stages, and probably had a major effect on knee torque values. Consequently, if the decrease in knee flexion is great enough it may cause a decrease in knee torque even though knee malalignment increased.

The study has quantified knee torque, knee malalignment, and knee flexion measurements in Highland dancing. Based on the available literature this is the first study to do so. The research utilizes Highland dancers, however, the concentration is on dancing in a turned-out position. Since turnout is common to other dance forms, these results may be applicable to ballet, jazz, and modern dance.

The present study provides a basis for the following recommendations:

1. A future study of Highland dance practices or competitions could produce drastic changes in knee torque from early to late stages of the performance as the soft tissue support structure may not be able to offer the necessary support throughout practices or competitions. Consequently, greater differences may exist in knee malalignment during longer periods of dance.
2. Measuring fatigue during a dance, competition, or practice could provide information on the possible causes of knee malalignment.
3. A future study of different dance forms may produce different knee torque results in early and late stages of dances, performances, and competitions. It could demonstrate differences or similarities in other sports and different dance forms.

4. Measuring the hip flexors, Q-angle, and anthropometric data in dancers could provide a relationship between forced turnout/malalignment and the dancers' ideal turnout capabilities.
5. A three-dimensional measurement system to analyze displacements and force would produce a more accurate and complete picture for knee torque measurements.
6. A larger sample size may confirm similar results or possibly demonstrate cases of more severe malalignment resulting in increases in knee torque from early to late stages of a Highland Fling.

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APPENDIX A

Definitions

Turnout is the ability of the dancer to stand and move with the legs externally rotated at the hip so that the toes are directed diagonally away from the midline of the body.

Ground reaction force is the reaction force resulting from a gravitational force produced by the weight of an object against the surface on which the object impacts.

Alignment is the arrangement of a straight line or bringing into a line.

Hop is considered, in this study, a movement of elevation begun on the ball of one foot landing on the ball of either foot.

Step is considered, in this study, a series of movements (including hops) in combination.

Ground Reaction Force (GRF) is the reaction force acting at the joint due to the weight force of the body impacting on a force plate.

Torque is a force that produces rotation (Torque = Force x Perpindicular Distance (or the perpindicular displacement from the force arm)).

Plie is a bending or flexing movement of the knee or knees.

Flexion is the decreasing of the angle of a joint.

Chondromalacia is the degeneration or softening of cartilage, found most commonly on the under surface of the patella.

Medial is an anatomical position describing a part of the body that is closest to the midline of the body (i.e. the inside of the knee).

Lateral is an anatomical position describing a part of the body that is away from the midline of the body (i.e. the outside of the knee).

Adduction is the movement of a body part toward the axis or midline of the body (the adductors are the muscles which move the body part away from the midline).

Abduction is the movement of a body part away from the axis or midline of the body (the abductors are the muscles which move the body part away from the midline).

Genu Valgum is indicated by the knee cap rotating inward while the foot is pointed straight ahead (often referred to as "knock-knee").

Genu Varum is indicated by the knee cap rotating outward while the foot is pointed straight ahead (often referred to as "bowlegs").

Q-Angle is the relationship of the patella to the alignment of the anterior superior iliac spine and the tibia.

Knee Malalignment is a displacement of the x-coordinate (or horizontal coordinate) of the knee from the x-coordinate (or horizontal coordinate) of the centre of mass. The knee is considered malaligned if the x-coordinate of the centre of mass subtracted from the x-coordinate of the knee is greater than zero.

APPENDIX B

Table 9 - Resultant Displacements for Frontal and Oblique Views - Subject 1

		Knee Displacement Measure		
		Frontal	Oblique	Resultant
STEP	HOP	View (m)	View (m)	(m)
		A	B	C
1	1 (0.6sec)	0.125	0.014	0.135
1	2 (1.2sec)	0.043	0.034	0.071
1	3 (1.8sec)	0.067	0.005	0.071
1	4 (2.4sec)	0.097	0.001	0.098
1	5 (3.0sec)	0.081	0.018	0.095
1	6 (3.6sec)	0.061	0.023	0.079
1	7 (4.2sec)	0.079	0.013	0.089
1	8 (4.8sec)	0.099	0	0.099
1	9 (5.4sec)	0.055	0.048	0.092
1	10 (6.0sec)	0.027	0.036	0.058
Mean		0.0734	0.0192	0.0887
Range		0.027-0.125	0-0.048	0.058-0.135
Std. Dev.		0.02901	0.016033	0.021213
6	11 (86.0sec)	0.058	0.023	0.076
6	12 (86.6sec)	0.044	0.031	0.069
6	13 (87.2sec)	0.019	0.051	0.066
6	14 (87.8sec)	0.037	0.042	0.073
6	15 (88.4sec)	0.077	0.001	0.078
6	16 (89.0sec)	0.025	0.047	0.067
6	17 (89.6sec)	0.019	0.046	0.061
6	18 (90.2sec)	0.026	0.047	0.068
6	19 (90.8sec)	0.052	0.001	0.059
6	20 (91.4sec)	0.017	0.053	0.066
Mean		0.0374	0.0342	0.0683
Range		0.017-0.077	0.001-0.061	0.059-0.078
Std. Dev.		0.020073	0.01973	0.006038

Table 10 - Resultant, Force, and Knee Torque Results - Subject 1

		Resultant	Force	Torque
STEP	HOP	(m)	N	Nm
		C		C x Force
1	1 (0.6sec)	0.135	1683.8	227.30
1	2 (1.2sec)	0.071	1683.8	119.55
1	3 (1.8sec)	0.071	1683.8	119.55
1	4 (2.4sec)	0.098	1683.8	165.01
1	5 (3.0sec)	0.095	1683.8	159.96
1	6 (3.6sec)	0.079	1683.8	133.02
1	7 (4.2sec)	0.089	1683.8	149.86
1	8 (4.8sec)	0.099	1683.8	166.70
1	9 (5.4sec)	0.092	1683.8	154.91
1	10 (6.0sec)	0.058	1683.8	97.66
Mean		0.0887	1683.8	149.35
Range		0.058-0.135		97.66-227.3
Std. Dev.		0.021213	0	35.71618
6	11 (86.0sec)	0.076	1671.5	127.03
6	12 (86.6sec)	0.069	1671.5	115.33
6	13 (87.2sec)	0.066	1671.5	110.32
6	14 (87.8sec)	0.073	1671.5	122.02
6	15 (88.4sec)	0.078	1671.5	130.38
6	16 (89.0sec)	0.067	1671.5	111.99
6	17 (89.6sec)	0.061	1671.5	101.96
6	18 (90.2sec)	0.068	1671.5	113.66
6	19 (90.8sec)	0.059	1671.5	98.62
6	20 (91.4sec)	0.066	1671.5	110.32
Mean		0.0683	1671.5	114.16
Range		0.059-0.078		98.62-127.03
Std. Dev.		0.006038	0	10.09211

Table 11 - Knee Displacements at Full Extension, Impact and Maximum Flexion - Oblique View - Subject 1

		Knee Displacement Measure		
		FULL EXT	IMPACT	MAX FLEX
STEP	HOP	(m)	(m)	(m)
		B	B	B
1	1 (0.6sec)	0.088	0.013	0.014
1	2 (1.2sec)	0.032	0.006	0.034
1	3 (1.8sec)	0.026	0.006	0.005
1	4 (2.4sec)	0.107	0.017	0.001
1	5 (3.0sec)	0.035	0.01	0.018
1	6 (3.6sec)	0.011	0.001	0.023
1	7 (4.2sec)	0.015	0.01	0.013
1	8 (4.8sec)	0.081	0.004	0
1	9 (5.4sec)	0.019	0.016	0.048
1	10 (6.0sec)	0.009	0.022	0.036
Mean		0.0421	0.0105	0.0192
Range		0.009-0.107	0.001-0.022	0-0.048
Std. Dev.		0.035582	0.006536	0.016033
6	11 (86.0sec)	0.056	0.002	0.023
6	12 (86.6sec)	0.024	0.006	0.031
6	13 (87.2sec)	0.016	0.013	0.051
6	14 (87.8sec)	0.005	0.016	0.042
6	15 (88.4sec)	0.037	0.014	0.001
6	16 (89.0sec)	0.019	0.001	0.047
6	17 (89.6sec)	0.002	0.014	0.046
6	18 (90.2sec)	0.002	0.029	0.047
6	19 (90.8sec)	0.033	0.007	0.001
6	20 (91.4sec)	0.006	0.019	0.053
Mean		0.02	0.0121	0.0342
Range		0.002-0.068	0.001-0.029	0.001-0.053
Std. Dev.		0.017814	0.008465	0.01973

Table12 - Resultant Displacements for Frontal and Oblique Views - Subject 2

		Knee Displacement Measure		
		Frontal	Oblique	Resultant
STEP	HOP	View (m)	View (m)	(m)
		A	B	C
1	1 (0.6sec)	0.113	0.003	0.133
1	2 (1.2sec)	0.07	0.001	0.071
1	3 (1.8sec)	0.052	0.035	0.08
1	4 (2.4sec)	0.068	0.03	0.092
1	5 (3.0sec)	0.094	0.001	0.095
1	6 (3.6sec)	0.055	0.022	0.072
1	7 (4.2sec)	0.058	0.016	0.07
1	8 (4.8sec)	0.068	0.021	0.084
1	9 (5.4sec)	0.068	0.018	0.082
1	10 (6.0sec)	0.046	0.021	0.063
Mean		0.0692	0.0168	0.0842
Range		0.046-0.113	0.001-0.022	0.07-0.133
Std. Dev.		0.020275	0.01183	0.019876
6	11 (86.0sec)	0.076	0.007	0.081
6	12 (86.6sec)	0.07	0.023	0.088
6	13 (87.2sec)	0.049	0.024	0.068
6	14 (87.8sec)	0.051	0.037	0.081
6	15 (88.4sec)	0.094	0.01	0.101
6	16 (89.0sec)	0.063	0.012	0.072
Mean		0.067	0.0188	0.082
Range		0.049-0.094	0.007-0.037	0.068-0.101
Std. Dev.		0.016822	0.011303	0.011788

Table 13 - Resultant, Force, and Knee Torque Results - Subject 2

		Resultant	Force	Torque
STEP	HOP	(m)	N	Nm
		C		C x Force
1	1 (0.6sec)	0.133	1287.8	171.28
1	2 (1.2sec)	0.071	1287.8	91.43
1	3 (1.8sec)	0.08	1287.8	103.02
1	4 (2.4sec)	0.092	1287.8	118.48
1	5 (3.0sec)	0.095	1287.8	122.34
1	6 (3.6sec)	0.072	1287.8	92.72
1	7 (4.2sec)	0.07	1287.8	90.15
1	8 (4.8sec)	0.084	1287.8	108.18
1	9 (5.4sec)	0.082	1287.8	105.60
1	10 (6.0sec)	0.063	1287.8	81.13
Mean		0.0842	1287.8	108.43
Range		0.07-0.133		81.13-171.28
Std. Dev.		0.019876	0	26.59775
6	11 (86.0sec)	0.081	1218.3	98.68
6	12 (86.6sec)	0.088	1218.3	107.21
6	13 (87.2sec)	0.068	1218.3	82.84
6	14 (87.8sec)	0.081	1218.3	98.68
6	15 (88.4sec)	0.101	1218.3	123.05
6	16 (89.0sec)	0.072	1218.3	87.72
Mean		0.082	1218.3	99.7
Range		0.068-0.101		87.72-123.05
Std. Dev.		0.011788	0	14.36303

Table 14 - Knee Displacements at Full Extension, Impact, and Maximum Flexion - Oblique View - Subject 2

		Knee Displacement Measure		
		FULL EXT	IMPACT	MAX FLEX
STEP	HOP	(m)	(m)	(m)
		B	B	B
1	1 (0.6sec)	0.042	0.014	0.003
1	2 (1.2sec)	0.015	0.006	0.001
1	3 (1.8sec)	0.001	0.037	0.035
1	4 (2.4sec)	0.023	0.008	0.03
1	5 (3.0sec)	0.037	0.002	0.001
1	6 (3.6sec)	0.003	0.012	0.022
1	7 (4.2sec)	0.001	0.011	0.016
1	8 (4.8sec)	0.036	0.016	0.021
1	9 (5.4sec)	0	0.009	0.018
1	10 (6.0sec)	0.004	0	0.021
Mean		0.0162	0.0115	0.0168
Range		0-0.042	0-0.037	0.001-0.035
Std. Dev.		0.01695	0.010266	0.01183
6	11 (86.0sec)	0.017	0.004	0.007
6	12 (86.6sec)	0.002	0.005	0.023
6	13 (87.2sec)	0.005	0.005	0.024
6	14 (87.8sec)	0.027	0.019	0.037
6	15 (88.4sec)	0.011	0.009	0.01
6	16 (89.0sec)	0.003	0.008	0.012
Mean		0.011	0.008	0.019
Range		0.002-0.027	0.004-0.019	0.01-0.037
Std. Dev.		0.009725	0.005574	0.011303

Table15 -Resultant Displacements for Frontal and Oblique Views - Subject 3

		Knee Displacement Measure		
		Frontal	Oblique	Resultant
STEP	HOP	View (m)	View (m)	(m)
		A	B	C
1	1 (0.6sec)	0.035	0.044	0.073
1	2 (1.2sec)	0.03	0.033	0.058
1	3 (1.8sec)	0.073	0.003	0.075
1	4 (2.4sec)	0.096	0.004	0.099
1	5 (3.0sec)	0.05	0.038	0.081
1	6 (3.6sec)	0.034	0.035	0.064
1	7 (4.2sec)	0.055	0.034	0.083
1	8 (4.8sec)	0.072	0.018	0.086
1	9 (5.4sec)	0.049	0.053	0.094
1	10 (6.0sec)	0.041	0.035	0.07
Mean		0.0535	0.0297	0.0783
Range		0.03-0.096	0.003-0.053	0.058-0.099
Std. Dev.		0.021067	0.016371	0.012859
6	11 (86.0sec)	0.034	0.017	0.048
6	12 (86.6sec)	0.037	0.054	0.084
6	13 (87.2sec)	0.04	0.037	0.071
6	14 (87.8sec)	0.026	0.045	0.066
6	15 (88.4sec)	0.058	0.005	0.062
6	16 (89.0sec)	0.038	0.047	0.079
6	17 (89.6sec)	0.049	0.029	0.072
6	18 (90.2sec)	0.026	0.032	0.054
6	19 (90.8sec)	0.053	0.011	0.061
6	20 (91.4sec)	0.031	0.055	0.08
Mean		0.0392	0.0332	0.0677
Range		0.026-0.058	0.005-0.054	0.048-0.084
Std. Dev.		0.011003	0.017706	0.011691

Table 16 - Resultant, Force, and Knee Torque Results - Subject 3

		Resultant	Force	Torque
STEP	HOP	(m)	N	Nm
		C		C x Force
1	1 (0.6sec)	0.073	1423.2	103.89
1	2 (1.2sec)	0.058	1423.2	82.55
1	3 (1.8sec)	0.075	1423.2	106.74
1	4 (2.4sec)	0.099	1423.2	140.90
1	5 (3.0sec)	0.081	1423.2	115.28
1	6 (3.6sec)	0.064	1423.2	91.08
1	7 (4.2sec)	0.083	1423.2	118.13
1	8 (4.8sec)	0.086	1423.2	122.40
1	9 (5.4sec)	0.094	1423.2	133.78
1	10 (6.0sec)	0.07	1423.2	99.62
Mean		0.0783	1423.2	111.44
Range		0.058-0.099		82.55-133.78
Std. Dev.		0.012859	0	18.30166
6	11 (86.0sec)	0.048	1448.1	69.51
6	12 (86.6sec)	0.084	1448.1	121.64
6	13 (87.2sec)	0.071	1448.1	102.82
6	14 (87.8sec)	0.066	1448.1	95.57
6	15 (88.4sec)	0.062	1448.1	89.78
6	16 (89.0sec)	0.079	1448.1	114.40
6	17 (89.6sec)	0.072	1448.1	104.26
6	18 (90.2sec)	0.054	1448.1	78.20
6	19 (90.8sec)	0.061	1448.1	88.33
6	20 (91.4sec)	0.08	1448.1	115.85
Mean		0.0677	1448.1	98.04
Range		0.048-0.084		69.51-121.64
Std. Dev.		0.011691	0	16.92973

Table17 - Knee Displacements at Full Extension, Impact and Maximum Flexion - Oblique View - Subject 3

		Knee Displacement Measure		
		FULL EXT	IMPACT	MAX FLEX
STEP	HOP	(m)	(m)	(m)
		B	B	B
1	1 (0.6sec)	0.001	0.028	0.044
1	2 (1.2sec)	0.002	0.017	0.033
1	3 (1.8sec)	0.015	0.007	0.003
1	4 (2.4sec)	0.03	0.01	0.004
1	5 (3.0sec)	0	0.012	0.038
1	6 (3.6sec)	0	0.017	0.035
1	7 (4.2sec)	0.003	0.024	0.034
1	8 (4.8sec)	0.006	0.016	0.018
1	9 (5.4sec)	0.009	0.025	0.053
1	10 (6.0sec)	0.003	0.023	0.035
Mean		0.0069	0.0179	0.0297
Range		0-0.015	0.007-0.028	0.003-0.053
Std. Dev.		0.009362	0.006967	0.016371
6	11 (86.0sec)	0.002	0.004	0.017
6	12 (86.6sec)	0.001	0.022	0.054
6	13 (87.2sec)	0.005	0.019	0.037
6	14 (87.8sec)	0.006	0.022	0.045
6	15 (88.4sec)	0.002	0.002	0.005
6	16 (89.0sec)	0.013	0.009	0.047
6	17 (89.6sec)	0.016	0.005	0.029
6	18 (90.2sec)	0.002	0.017	0.032
6	19 (90.8sec)	0.006	0.008	0.011
6	20 (91.4sec)	0.007	0.018	0.055
Mean		0.006	0.0126	0.0332
Range		0.001-0.016	0.002-0.022	0.005-0.054
Std. Dev.		0.004989	0.007777	0.017706

Table 18 - Resultant Displacements for Frontal and Oblique Views - Subject 4

		Knee Displacement Measure		
		Frontal	Oblique	Resultant
STEP	HOP	View (m)	View (m)	(m)
		A	B	C
1	1 (0.6sec)	0.111	0.015	0.122
1	2 (1.2sec)	0.044	0.027	0.066
1	3 (1.8sec)	0.021	0.023	0.041
1	4 (2.4sec)	0.067	0.016	0.079
1	5 (3.0sec)	0.109	0.025	0.128
1	6 (3.6sec)	0.031	0.03	0.056
1	7 (4.2sec)	0.034	0.035	0.064
1	8 (4.8sec)	0.05	0.014	0.061
1	9 (5.4sec)	0.09	0.009	0.097
1	10 (6.0sec)	0.038	0.058	0.089
Mean		0.0595	0.0252	0.0803
Range		0.021-0.111	0.009-0.058	0.041-0.128
Std. Dev.		0.033043	0.014062	0.028574
6	11 (86.0sec)	0.078	0.009	0.085
6	12 (86.6sec)	0.021	0.056	0.072
6	13 (87.2sec)	0.008	0.045	0.051
6	14 (87.8sec)	0.03	0.044	0.069
6	15 (88.4sec)	0.043	0.034	0.071
6	16 (89.0sec)	0.026	0.068	0.088
6	17 (89.6sec)	0.004	0.064	0.067
6	18 (90.2sec)	0.063	0.033	0.089
6	19 (90.8sec)	0.018	0.054	0.068
6	20 (91.4sec)	0.027	0.038	0.06
Mean		0.0318	0.0445	0.072
Range		0.008-0.078	0.009-0.064	0.051-0.089
Std. Dev.		0.023427	0.017322	0.012247

Table 19 - Resultant, Force, and Knee Torque Results - Subject 4

		Resultant	Force	Torque
STEP	HOP	(m)	N	Nm
		C		C x Force
1	1 (0.6sec)	0.122	1216.9	148.46
1	2 (1.2sec)	0.066	1216.9	80.32
1	3 (1.8sec)	0.041	1216.9	49.89
1	4 (2.4sec)	0.079	1216.9	96.14
1	5 (3.0sec)	0.128	1216.9	155.76
1	6 (3.6sec)	0.056	1216.9	68.15
1	7 (4.2sec)	0.064	1216.9	77.88
1	8 (4.8sec)	0.061	1216.9	74.23
1	9 (5.4sec)	0.097	1216.9	118.04
1	10 (6.0sec)	0.089	1216.9	108.30
Mean		0.0803	1216.9	97.72
Range		0.041-0.128		80.32-155.76
Std. Dev.		0.028574	0	34.77033
6	11 (86.0sec)	0.085	1311	111.44
6	12 (86.6sec)	0.072	1311	94.39
6	13 (87.2sec)	0.051	1311	66.86
6	14 (87.8sec)	0.069	1311	90.46
6	15 (88.4sec)	0.071	1311	93.08
6	16 (89.0sec)	0.088	1311	115.37
6	17 (89.6sec)	0.067	1311	87.84
6	18 (90.2sec)	0.089	1311	116.68
6	19 (90.8sec)	0.068	1311	89.15
6	20 (91.4sec)	0.06	1311	78.66
Mean		0.072	1311	94.4
Range		0.051-0.089		78.66-116.68
Std. Dev.		0.012247	0	16.0574

Table 20 - Knee Displacements at Full Extension, Impact, and Maximum Flexion - Oblique View - Subject 4

		Knee Displacement Measure		
		FULL EXT	IMPACT	MAX FLEX
STEP	HOP	(m)	(m)	(m)
		B	B	B
1	1 (0.6sec)	0.062	0.032	0.015
1	2 (1.2sec)	0.008	0.012	0.027
1	3 (1.8sec)	0.013	0.014	0.023
1	4 (2.4sec)	0.002	0	0.016
1	5 (3.0sec)	0.026	0.013	0.025
1	6 (3.6sec)	0.001	0.019	0.03
1	7 (4.2sec)	0.005	0.013	0.035
1	8 (4.8sec)	0.001	0.015	0.014
1	9 (5.4sec)	0.043	0.018	0.009
1	10 (6.0sec)	0.02	0.035	0.058
Mean		0.0181	0.0171	0.0252
Range		0.001-0.062	0-0.035	0.009-0.058
Std. Dev.		0.020431	0.010071	0.014062
6	11 (86.0sec)	0.007	0.006	0.009
6	12 (86.6sec)	0.008	0.022	0.056
6	13 (87.2sec)	0.005	0.027	0.045
6	14 (87.8sec)	0.004	0.037	0.044
6	15 (88.4sec)	0.018	0.018	0.034
6	16 (89.0sec)	0.008	0.034	0.068
6	17 (89.6sec)	0.013	0.029	0.064
6	18 (90.2sec)	0.011	0.016	0.033
6	19 (90.8sec)	0	0.022	0.054
6	20 (91.4sec)	0.029	0.005	0.038
Mean		0.0103	0.0216	0.0445
Range		0-0.029	0.005-0.037	0.009-0.064
Std. Dev.		0.008247	0.010741	0.017322

Table 21 - Resultant Displacements for Frontal and Oblique Views - Subject 5

		Knee Displacement Measure		
		Frontal	Oblique	Resultant
STEP	HOP	View (m)	View (m)	(m)
		A	B	C
1	1 (0.6sec)	0.096	0.024	0.114
1	2 (1.2sec)	0.04	0.064	0.097
1	3 (1.8sec)	0.054	0.05	0.096
1	4 (2.4sec)	0.096	0.029	0.118
1	5 (3.0sec)	0.055	0.054	0.1
1	6 (3.6sec)	0.049	0.036	0.079
1	7 (4.2sec)	0.033	0.06	0.087
1	8 (4.8sec)	0.052	0.016	0.064
1	9 (5.4sec)	0.031	0.065	0.086
1	10 (6.0sec)	0.044	0.016	0.056
Mean		0.055	0.0414	0.0897
Range		0.031-0.096	0.016-0.065	0.056-0.114
Std. Dev.		0.023128	0.0195	0.019782
6	11 (86.0sec)	0.025	0.049	0.069
6	12 (86.6sec)	0.012	0.085	0.101
6	13 (87.2sec)	0.003	0.083	0.085
6	14 (87.8sec)	0.014	0.078	0.085
6	15 (88.4sec)	0.053	0.045	0.091
6	16 (89.0sec)	0.004	0.08	0.083
6	17 (89.6sec)	0.008	0.057	0.06
6	18 (90.2sec)	0.032	0.053	0.079
6	19 (90.8sec)	0.09	0.032	0.115
6	20 (91.4sec)	0	0.026	0.026
Mean		0.0241	0.0588	0.0794
Range		0-0.053	0.026-0.085	0.026-0.115
Std. Dev.		0.028243	0.021622	0.024222

Table 22 - Resultant, Force, and Knee Torque Results - Subject 5

		Resultant	Force	Torque
STEP	HOP	(m)	N	Nm
		C		C x Force
1	1 (0.6sec)	0.114	1524.8	173.83
1	2 (1.2sec)	0.097	1524.8	147.91
1	3 (1.8sec)	0.096	1524.8	146.38
1	4 (2.4sec)	0.118	1524.8	179.93
1	5 (3.0sec)	0.1	1524.8	152.48
1	6 (3.6sec)	0.079	1524.8	120.46
1	7 (4.2sec)	0.087	1524.8	132.66
1	8 (4.8sec)	0.064	1524.8	97.59
1	9 (5.4sec)	0.086	1524.8	131.13
1	10 (6.0sec)	0.056	1524.8	85.39
Mean		0.0897	1524.8	136.78
Range		0.056-0.114		85.39-173.83
Std. Dev.		0.019782	0	30.16469
6	11 (86.0sec)	0.069	1607	110.88
6	12 (86.6sec)	0.101	1607	162.31
6	13 (87.2sec)	0.085	1607	136.60
6	14 (87.8sec)	0.085	1607	136.60
6	15 (88.4sec)	0.091	1607	146.24
6	16 (89.0sec)	0.083	1607	133.38
6	17 (89.6sec)	0.06	1607	96.42
6	18 (90.2sec)	0.079	1607	126.95
6	19 (90.8sec)	0.115	1607	184.81
6	20 (91.4sec)	0.026	1607	41.78
Mean		0.0794	1607	127.60
Range		0.026-0.115		41.78-162.31
Std. Dev.		0.024222	0	38.9271

Table 23 - Knee Displacements at Full Extension, Impact, and Maximum Flexion - Oblique View - Subject 5

		Knee Displacement Measure		
		FULL EXT	IMPACT	MAX FLEX
STEP	HOP	(m)	(m)	(m)
		B	B	B
1	1 (0.6sec)	0.053	0.028	0.024
1	2 (1.2sec)	0.001	0.017	0.064
1	3 (1.8sec)	0.012	0.03	0.05
1	4 (2.4sec)	0.023	0.014	0.029
1	5 ([illegible].0sec)	0.003	0.038	0.054
1	6 ([illegible].6sec)	0.011	0.032	0.036
1	7 (4.2sec)	0.026	0.046	0.06
1	8 (4.8sec)	0.012	0.015	0.016
1	9 (5.4sec)	0.014	0.037	0.065
1	10 (6.0sec)	0.005	0.02	0.016
Mean		**0.016**	**0.0277**	**0.0414**
Range		0.001-0.053	0.014-0.046	0.016-0.065
Std. Dev.		**0.015253**	**0.010924**	**0.0195**
6	11 (86.0sec)	0.021	0.048	0.049
6	12 (86.6sec)	0.046	0.074	0.085
6	13 (87.2sec)	0.035	0.051	0.083
6	14 (87.8sec)	0.06	0.075	0.078
6	15 (88.4sec)	0.04	0.047	0.045
6	16 (89.0sec)	0.044	0.051	0.08
6	17 (89.6sec)	0.049	0.048	0.057
6	18 (90.2sec)	0.006	0.031	0.053
6	19 (90.8sec)	0.013	0.026	0.032
6	20 (91.4sec)	0.024	0.056	0.026
Mean		**0.0338**	**0.0507**	**0.0588**
Range		0.013-0.049	0.026-0.075	0.026-0.085
Std. Dev.		**0.017242**	**0.015592**	**0.021622**

Table 24 - Resultant Displacements for Frontal and Oblique Views - Subject 6

		Knee Displacement Measure		
		Frontal	Oblique	Resultant
STEP	HOP	View (m)	View (m)	(m)
		A	B	C
1	1 (0.6sec)	0.054	0.005	0.057
1	2 (1.2sec)	0.001	0.062	0.063
1	3 (1.8sec)	0.026	0.027	0.049
1	4 (2.4sec)	0.011	0.049	0.057
1	5 (3.0sec)	0.015	0.02	0.032
1	6 (3.6sec)	0.056	0.055	0.103
1	7 (4.2sec)	0.019	0.051	0.066
1	8 (4.8sec)	0.018	0.087	0.1
1	9 (5.4sec)	0.014	0.054	0.065
1	10 (6.0sec)	0.013	0.029	0.039
Mean		0.0227	0.0439	0.0631
Range		0.001-0.056	0.005-0.087	0.032-0.103
Std. Dev.		0.018172	0.023755	0.023062
6	11 (86.0sec)	0.016	0.081	0.093
6	12 (86.6sec)	0.03	0.11	0.133
6	13 (87.2sec)	0.023	0.068	0.086
6	14 (87.8sec)	0.015	0.099	0.11
6	15 (88.4sec)	0.002	0.086	0.087
6	16 (89.0sec)	0.012	0.072	0.081
6	17 (89.6sec)	0.018	0.08	0.093
6	18 (90.2sec)	0.038	0.049	0.08
6	19 (90.8sec)	0.026	0.016	0.039
6	20 (91.4sec)	0.003	0.036	0.038
Mean		0.0183	0.0697	0.084
Range		0.003-0.038	0.016-0.11	0.038-0.133
Std. Dev.		0.011363	0.028748	0.028709

Table 25 - Resultant, Force, and Knee Torque Results - Subject 6

		Resultant	Force	Torque
STEP	HOP	(m)	N	Nm
		C		C x Force
1	1 (0.6sec)	0.057	1419.2	80.89
1	2 (1.2sec)	0.063	1419.2	89.41
1	3 (1.8sec)	0.049	1419.2	69.54
1	4 (2.4sec)	0.057	1419.2	80.89
1	5 (3.0sec)	0.032	1419.2	45.41
1	6 (3.6sec)	0.103	1419.2	146.18
1	7 (4.2sec)	0.066	1419.2	93.67
1	8 (4.8sec)	0.1	1419.2	141.92
1	9 (5.4sec)	0.065	1419.2	92.25
1	10 (6.0sec)	0.039	1419.2	55.35
Mean		0.0631	1419.2	89.55
Range		0.032-0.103		45.41-146.18
Std. Dev.		0.023062	0	32.73162
6	11 (86.0sec)	0.093	1130	105.09
6	12 (86.6sec)	0.133	1130	150.29
6	13 (87.2sec)	0.086	1130	97.18
6	14 (87.8sec)	0.11	1130	124.30
6	15 (88.4sec)	0.087	1130	98.31
6	16 (89.0sec)	0.081	1130	91.53
6	17 (89.6sec)	0.093	1130	105.09
6	18 (90.2sec)	0.08	1130	90.40
6	19 (90.8sec)	0.039	1130	44.07
6	20 (91.4sec)	0.038	1130	42.94
Mean		0.084	1130	94.92
Range		0.038-0.133		42.94-150.29
Std. Dev.		0.028709	0	32.44148

Table 26 - Knee Displacements at Full Extension, Impact, and Maximum Flexion - Oblique View - Subject 6

		Knee Displacement Measure		
		FULL EXT	IMPACT	MAX FLEX
STEP	HOP	(m)	(m)	(m)
		B	B	B
1	1 (0.6sec)	0.044	0.001	0.005
1	2 (1.2sec)	0.021	0.026	0.062
1	3 (1.8sec)	0.012	0.004	0.027
1	4 (2.4sec)	0.012	0.027	0.049
1	5 (3.0sec)	0.041	0.001	0.02
1	6 (3.6sec)	0.001	0.028	0.055
1	7 (4.2sec)	0.007	0.011	0.051
1	8 (4.8sec)	0.018	0.053	0.087
1	9 (5.4sec)	0.008	0.038	0.054
1	10 (6.0sec)	0.003	0.008	0.029
Mean		0.0165	0.0197	0.0439
Range		0.001-0.044	0.001-0.038	0.005-0.087
Std. Dev.		0.014916	0.017525	0.023755
6	11 (86.0sec)	0.004	0.019	0.081
6	12 (86.6sec)	0.022	0.057	0.11
6	13 (87.2sec)	0.021	0.023	0.068
6	14 (87.8sec)	0.012	0.051	0.099
6	15 (88.4sec)	0.002	0.037	0.086
6	16 (89.0sec)	0.002	0.05	0.072
6	17 (89.6sec)	0.007	0.029	0.08
6	18 (90.2sec)	0.01	0.027	0.049
6	19 (90.8sec)	0.054	0.021	0.016
6	20 (91.4sec)	0.089	0.003	0.036
Mean		0.0223	0.0317	0.0697
Range		0.002-0.089	0.003-0.057	0.016-0.11
Std. Dev.		0.028099	0.016932	0.028748

Table 27 - Resultant Displacements for Frontal and Oblique Views - Subject 7

		Knee Displacement Measure		
		Frontal	Oblique	Resultant
STEP	HOP	View (m)	View (m)	(m)
		A	B	C
1	1 (0.6sec)	0.091	0.014	0.101
1	2 (1.2sec)	0.037	0.026	0.058
1	3 (1.8sec)	0.022	0.007	0.027
1	4 (2.4sec)	0.037	0.01	0.045
1	5 (3.0sec)	0.064	0.006	0.068
1	6 (3.6sec)	0.031	0.033	0.06
1	7 (4.2sec)	0.044	0.044	0.081
1	8 (4.8sec)	0.063	0.032	0.089
1	9 (5.4sec)	0.081	0.017	0.094
1	10 (6.0sec)	0.045	0.018	0.059
Mean		0.0515	0.0207	0.0682
Range		0.022-0.091	0.006-0.044	0.027-0.101
Std. Dev.		0.022431	0.012623	0.023165
6	11 (86.0sec)	0.059	0.042	0.094
6	12 (86.6sec)	0.005	0.082	0.086
6	13 (87.2sec)	0.049	0.012	0.058
6	14 (87.8sec)	0.002	0.093	0.094
6	15 (88.4sec)	0.021	0.047	0.063
6	16 (89.0sec)	0.009	0.082	0.089
6	17 (89.6sec)	0.025	0.047	0.067
6	18 (90.2sec)	0.033	0.014	0.044
6	19 (90.8sec)	0.029	0.013	0.039
6	20 (91.4sec)	0.032	0.011	0.041
Mean		0.0264	0.0443	0.0675
Range		0.002-0.059	0.011-0.093	0.039-0.094
Std. Dev.		0.018386	0.032118	0.022077

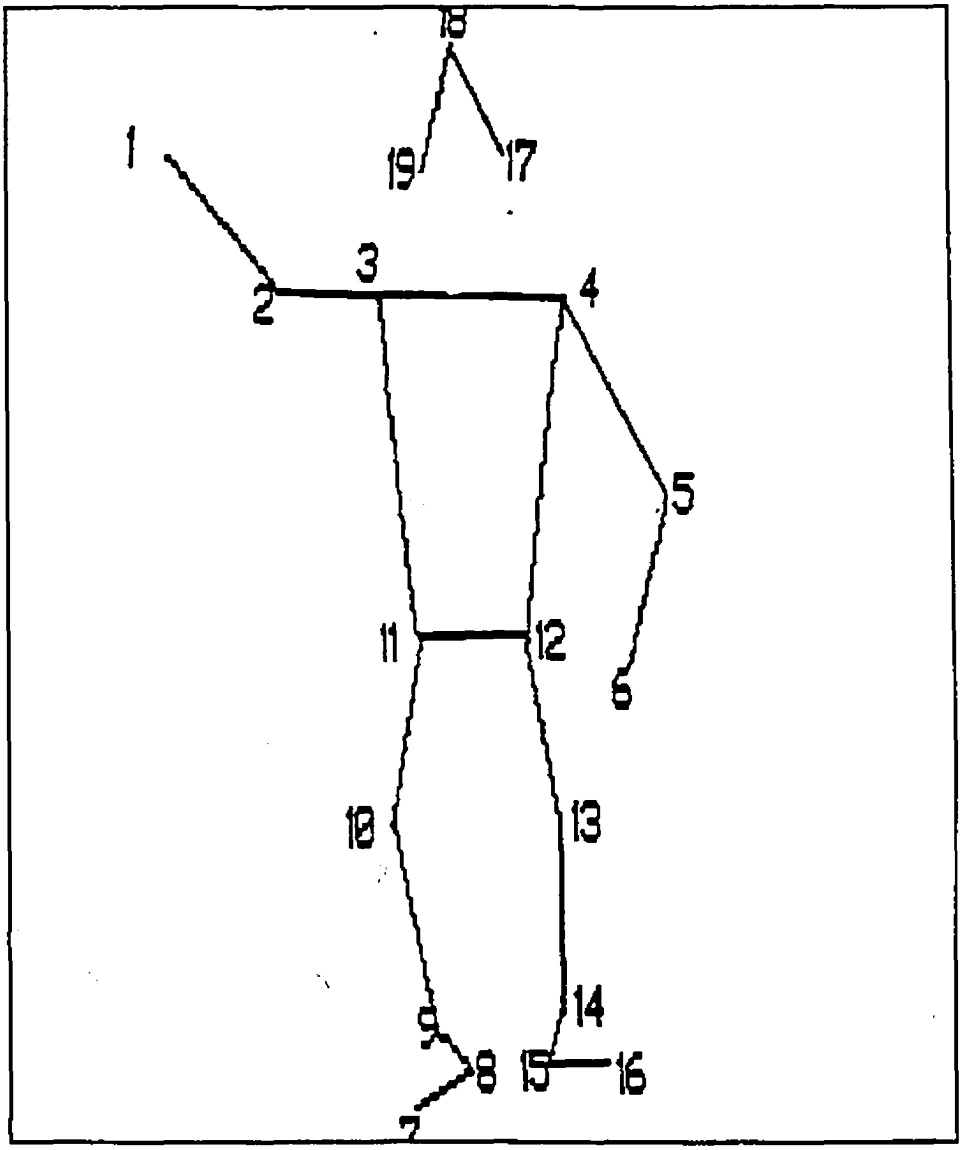
Table28 - Resultant, Force, and Knee Torque Results - Subject 7

		Resultant	Force	Torque
STEP	HOP	(m)	N	Nm
		C		C x Force
1	1 (0.6sec)	0.101	1759.1	177.67
1	2 (1.2sec)	0.058	1759.1	102.03
1	3 (1.8sec)	0.027	1759.1	47.50
1	4 (2.4sec)	0.045	1759.1	79.16
1	5 (3.0sec)	0.068	1759.1	119.62
1	6 (3.6sec)	0.06	1759.1	105.55
1	7 (4.2sec)	0.081	1759.1	142.49
1	8 (4.8sec)	0.089	1759.1	156.56
1	9 (5.4sec)	0.094	1759.1	165.36
1	10 (6.0sec)	0.059	1759.1	103.79
Mean		0.0682	1759.1	119.73
Range		0.027-0.101		47.5-177.67
Std. Dev.		0.023165	0	40.74933
6	11 (86.0sec)	0.094	1672.6	157.22
6	12 (86.6sec)	0.086	1672.6	143.84
6	13 (87.2sec)	0.058	1672.6	97.01
6	14 (87.8sec)	0.094	1672.6	157.22
6	15 (88.4sec)	0.063	1672.6	105.37
6	16 (89.0sec)	0.089	1672.6	148.86
6	17 (89.6sec)	0.067	1672.6	112.06
6	18 (90.2sec)	0.044	1672.6	73.59
6	19 (90.8sec)	0.039	1672.6	65.23
6	20 (91.4sec)	0.041	1672.6	68.58
Mean		0.0675	1672.6	112.90
Range		0.039-0.094		65.23-157.22
Std. Dev.		0.022077	0	36.92454

Table 29 - Knee Displacements at Full Extension, Impact, and Maximum Flexion - Oblique View - Subject 7

		Knee Displacement Measure		
		FULL EXT	IMPACT	MAX FLEX
STEP	HOP	(m)	(m)	(m)
		B	B	B
1	1 (0.6sec)	0.037	0.004	0.014
1	2 (1.2sec)	0.012	0.011	0.026
1	3 (1.8sec)	0.029	0.006	0.007
1	4 (2.4sec)	0.011	0.021	0.01
1	5 (3.0sec)	0.068	0.022	0.006
1	6 (3.6sec)	0.004	0.01	0.033
1	7 (4.2sec)	0.004	0.012	0.044
1	8 (4.8sec)	0.015	0.013	0.032
1	9 (5.4sec)	0.022	0.001	0.017
1	10 (6.0sec)	0.014	0	0.018
Mean		0.0216	0.01	0.0207
Range		0.011-0.068	0-0.022	0.006-0.044
Std. Dev.		0.019352	0.007542	0.012623
6	11 (86.0sec)	0.034	0.01	0.042
6	12 (86.6sec)	0.001	0.03	0.082
6	13 (87.2sec)	0.013	0.03	0.012
6	14 (87.8sec)	0.011	0.035	0.093
6	15 (88.4sec)	0.003	0.008	0.047
6	16 (89.0sec)	0.002	0.001	0.082
6	17 (89.6sec)	0.027	0.009	0.047
6	18 (90.2sec)	0.006	0.006	0.014
6	19 (90.8sec)	0.074	0.022	0.013
6	20 (91.4sec)	0.046	0.015	0.011
Mean		0.0217	0.0166	0.0443
Range		0.001-0.074	0.001-0.035	0.011-0.093
Std. Dev.		0.023824	0.011834	0.032118

APPENDIX C



Spatial Reference Model