UNIVERSITY OF ALBERTA

A kinematic analysis of an ultra-marathon run.

By

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ABSTRACT

Few studies have investigated the effects of fatigue and described biomechanical changes during the course of a 100 km ultra-marathon. The purpose of this study was to investigate kinematic changes in elite ultra-marathon runners during a 100 km ultra-marathon. Thirteen well-trained males, between the ages of 20-39 years, served as subjects. Each runner was a member of their respective ultra-marathon national team and had run the chosen racecourse at least once previously. As well, each subject had a previous best time of 6:45:00 (hrs:min:sec) or faster. Data was collected on the course, 15 meters from the finish line. A length of 2.4 meters served as the area of capture, and each subject was analyzed, in the sagittal plane, at distances of 10 km, 50 km, 70 km, 90 km, and 100 km. The variables quantified were shank angles, knee angles, thigh angles, forward trunk lean and vertical oscillations. The results showed consistent characteristics of gait during the entire race. No statistically significant changes were seen in any variable during the course of the race, though some interesting, nonsignificant changes were seen in maximum hip extension. Though no marked changes in running kinematics were seen, individual changes were at times rather noticeable and of interest.

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CHAPTER 1

Introduction

1.1 Purpose

The purpose of this study was to determine the extent to which gait kinematics change during the course of a 100 km ultra-marathon . Specifically leg kinematics were analyzed and quantified at the distances of 10 km, 50 km, 70 km, 90 km, and 100 km. It was hypothesized that the gait kinematics of ultra-marathon runners would deteriorate during the course of the 100 km run. Thirteen male ultra-marathon runners, between the ages of 20 and 39 years, served as subjects. A distance of 2.40 meters was filmed at each of the specified distances, quantifying the angle of the thigh with horizontal, angle of the shank with vertical, and hip and knee joint flexion and extension angles. As well the degree of forward lean with respect to the vertical and the vertical oscillations of the body, taken from the hip, were measured.

1.2 Significance

Few studies have investigated the gait kinematics of runners at distances any longer than the standard marathon. This study is one of the first contributions in the area of biomechanics concerning extreme distance running. The possible applications of this study may include modifications of equipment design and race strategy. The results could lead to more efficient racers and faster completion times, and may be teamed with physiological studies in the future, resulting in a new field of extreme distance research.

1.3 Limitations

Limitations of the study included the fact that the subjects were racing at an extreme distance and not all racers completed the 100 km distance. As well each individual displayed a unique running style and strategy for completing the ultra-marathon. The terrain for the race was variable as well. This 100 km race was run on a combination of pavement and cobblestone roads. This combination of terrain may have been a factor in the race, though subjects had competed on this course at least once in their racing history. As well each subject was filmed at the same location on the course, which was flat pavement. Ideally, the entire course of a subject's ultra-marathon run would have been recorded, though the number of available cameras and investigators limited this study. The result of such a limitation was that only 2.40 meters, 15 meters short of the start/finish line, could be recorded and analyzed. At times the subjects in the study were obscured from view by other runners, which limited the choice of laps that could be digitized. Weather conditions were variable and changes in the weather could have caused subjects to alter their race strategy and therefore affect the timing and/or magnitude of kinematic changes. Fitting subjects with markers over points of interest was not possible; therefore data collection was limited to manual digitizing. Manual digitization introduced random error although the digitizing precision was evaluated and smoothing was applied to the data.

1.4 Delimitations

The subjects in this study were all male runners between the ages of 20 and 39 years. They were all considered trained runners, as they were members of their respective ultra-marathon national teams. The kinematic variables were investigated by filming runners in the sagittal plane. The only independent variable was the time or distance at which the data collection was taken. The distances considered independent variables were 10 km, 50 km, 70 km, 90 km, and 100 km. Kinematic variables measured at set intervals throughout the race were the dependent variables. During analysis the thigh and shank angle with the horizontal, hip and knee extension and flexion angles were determined. Also quantified were the linear velocity of the knee, the flexion and extension velocities of the trunk, thigh, and knee. Stride cadence and the vertical displacement of the body, measured from the greater trochanter, was also collected and analyzed. The same individual analyzed each measure for all subjects, thus limiting measurement error that could have possibly occurred as a result.

1.5 Definition of Terms

Gait: manner of walking or running.

Hip flexion/extension: the joint angle between the thigh segment and trunk segment, throughout the running movement.

Kinematics: describes motion but without reference to forces involved.

Knee flexion/extension: angle of flexion/extension at the knee defined by an included angle between the thigh and shank segments. In this study, flexion was recorded during midswing and midstance phases, and extension was during toe-off and contact phases.

Marker: an object fixed to a point on skin or clothing that is visible to an optical measurement system.

Reference system: a right-handed orthogonal triad, XYZ, fixed in the ground. The axes for a person standing in an anatomically defined neutral position was defined as:

X pointing forward (anteriorly)

Y pointing upward (superiorly)

Z pointing rightward.

Relative angle: the angle between the distal segment and the extension of the proximal segment.

Sagittal axis: the plane dividing the body into left and right parts going longitudinally.

Stride: basic unit of locomotion and has been described in the literature as a cycle that is measured from the initial point of touchdown of one foot to the next point of contact with that same foot (Vaughan, 1983).

Stance: part of the gait cycle when the leg is in contact with the ground, which includes:

1) after contact
2) midstance
3) before toe-off.

Step: considered half of the stride, assuming the stride is symmetrical. A step is made up of two consecutive points of touchdown (Vaughan, 1983).

Swing: part of the gait cycle when the leg is not in contact with the ground which includes (Ounpuu, 1994):

1) after toe-off
2) midswing
3) before contact.

Thigh segment angle: angle of the thigh defined by the absolute angle of the horizontal axis and thigh segment. Minimum thigh angle in this study was found during the swing phase and maximum thigh angle during the toe-off phase.

Trained subject: someone who had been training with their respective national ultra-marathon team for at least one year, and had run at least one 100km in a time of 6:45:00 (hrs:min:sec) or less.

Trunk angle: angle of forward flexion defined by an angle of the trunk segment with respect to vertical.

Ultra-marathon: any distance longer than the standard marathon distance of 42.2 kilometers, the 100 kilometer race of this study, is a common race distance.

Vertical oscillations: the displacement of a subject's center of gravity. In this study it was measured as the vertical displacement of the hip, more specifically the point of the greater trochanter.

CHAPTER 2

Literature Review

2.1 Gait

From a general viewpoint, running and walking seem to be extremely similar forms of locomotion. They are both skills that seem to require no conscious input or thought. Each gait consists of alternating coordinated movements, influenced by the bones, joints and muscles, of the legs and trunk (Nutt, Marsden, & Thompson, 1993). Both forms of locomotion require individuals to possess equilibrium, so that one may keep balance and upright posture, as well as the ability of generating locomotion. This skill allows us to maintain rhythmic stepping patterns, be they a walk or a run (Nutt et al., 1993).

The stride in gait is the basic unit of locomotion, measured from initial ground contact of one foot to the next touchdown of the same foot (Vaughan, 1983). One of the most distinct differences between the running and walking patterns of locomotion is the double support phase in walking, where both feet are in contact with the ground, and the airborne phase in running, where an individual has no contact with the ground (Vaughan, 1983). Important to note, though rare, the double support phase has been observed in running at very low velocities (Thorstensson & Robertson, 1987). The amount of support time relative to total stride time has been shown to decrease as both walking and running speed increases (Vaughan, 1983; Hreljac, 1995). Hreljac (1995) collected kinematic data for four walking speeds and one running speed for treadmill inclinations of 0, 10 and 15% grade. He then measured the percentage of support time relative to total stride time as ranging between 57.8 ± 1.3% to 61.5 ± 1.3% for walking and 55.7 ± 1.5% to 55.9 ± 2.1% for running.

In both the walking and running gait, the muscles involved in landing, or touchdown, help decrease the forward momentum of the body segments by being forcibly lengthened, imparting a large negative force on the body (Dillingham, Lehmann, & Price, 1992; Bobbert, Yeadon, & Nigg, 1992). At the instant of contact, the foot velocity is quickly reduced to zero, though the horizontal velocity of the head, arms and trunk segment remains almost constant (Bobbert et al., 1992). Bobbert, Yeadon, and Nigg (1992) showed that initial contact with the rearfoot results in an impact force peak cycle during the first 50 ms of ground contact. This impact force peak is a high frequency peak in the vertical component of ground reaction force, which seems to increase to a maximum within 25 ms of contact, decrease to a local minimum 15 ms later and then increase once again. Nyland, Shapiro, Stine, Horn, and Ireland (1994) suggested that this impact force peak might be a major cause of running injuries, which could be reduced with greater knee flexion at the point of touchdown. During this phase of contact, the knee joint goes through a negative or flexion phase, which exhibits an almost constant maximum angular velocity regardless of speed (Vaughan, 1983). In the middle portion of the stance phase, the knee extensor muscles are dominant, as it becomes necessary to stop the downward motion of the body (Vaughan, 1983). Those muscles then work to produce positive horizontal and vertical velocity of the knee prior to toe-off (Vaughan, 1983). Vaughan (1983) also noted that at the instant of contact the hip is close to full extension and works with the knee joint to absorb some of the force initiated with ground impact. During the contact phase, after initial touch, the hip no longer flexes and does positive work. The relationship between the hip angle at touchdown and toe-off works as such: a more extended hip near toe-off is related to a more extended knee position at toe-off and a less flexed hip position near footstrike (Vaughan, 1983). Research conducted by Vaughan (1983) has shown that a positive linear relationship between the positive phases of the ankle, knee and hip angular velocity, and hip extension is considered key in increasing running speed and contributing to the forward component of force application. In walking and running, toe-off occurs with predictable changes in ankle, knee and hip angles, similar to those seen during the late stance phase (Elble, Moody, Leffler, & Sinha, 1994). Between 0-20ms after the initiation of these joint angle changes of the stance leg, the limb begins propulsion or push-off (Elble et al., 1994). The forward impulse provided by the muscle forces generates the joint angle changes (Dillingham et al., 1992). Anderson (1996) has explained the alternating pattern of stance and swing, seen at this point. There are forces applied to the pelvis by the leg during both support and propulsion. Remarkably these forces are applied "off-center" which, when combined with the resulting forces from the upward forward acceleration of the recovery leg, produces torques. These torques are affected by the rotation of the trunk, caused by the forward and backward swing of the arms. This upper body torque is opposed, yet eclipsed, by the lower body torque and the resultant generates the alternating pattern of stance and swing.

2.2 Distance running mechanics

The goal of competitive ultra-marathon running is to run a given, extreme, distance in the least amount of time. This requires the important balance between fatigue and power production (Anderson, 1996). It has been noted that success in endurance events of any distance is highly related to the energy cost of the run and is independent of the actual work done (Anderson, 1996). Knowing this, it was logical that Kaneko (1990) concluded that trained distance runners were more efficient at relatively lower speeds, (<7m/s), than untrained distance runners. For elite distance runners, economy is therefore essential. Morgan, Martin, Krahenbuhl, and Baldini (1991) found that a small, 2% improvement in economy could improve elite marathon racing performance by only two and a half minutes. It may be hypothesized that, for elite marathoners, fatigue is, in essence, a controllable factor, but for ultra distance runners fatigue is unavoidable. Fatigue can force changes in the running gait that can negatively affect performance.

Nyland et al. (1994) noted that, mechanically, lower extremity fatigue is thought to cause changes in ankle and knee deceleration strategies. The ankle angle is increased at the point of the peak passive vertical ground reaction force, intensifying the effect of this reaction force (Nyland et al., 1994). During contact in a fatigued run, the mean height of the center of gravity seems to decrease (Candau et al., 1998). This effect suggests a shortened stride length (Anderson, 1996), though various studies have reported fatigued stride length to both increase and decrease (Candau et al., 1998). Stride lengths that are too long require more propulsive power than usual, therefore resulting in the excessive vertical oscillation of a runner's center of mass (Anderson, 1996). It is common to observe changes in muscle stiffness during prolonged, fatigued runs (Anderson, 1996; Candau et al. 1998). When compared with non-fatigued runs, Candau et al. (1998) noted that the inability to control increased muscle stiffness has been postulated to reduce the amount of mechanical energy that is stored. This hypothesis is supported by the drastic reduction in force noted after initial peak force of impact, along with a lengthened stride and higher support time to flight time ratio (Candau et al., 1998). This study found that individuals in a fatigued state have been noted to run in an almost seated position, compensating for the lower body stiffness by stretching their leg extensors. Also affected by fatigue are the mechanical and energy costs of running. A consistent increase in the mechanical cost of running has been quantified; from a mean of 2.36 J/kgm to 2.74 J/kgm in a non fatigued and fatigued state, respectively. Interestingly the mechanical cost of running had a more substantial increase with fatigue than the metabolic cost. A congruous relationship between the increased energy cost of running and step variability was observed. This inability to control step frequency has been associated with a reduced ability to store and use mechanical energy, less energy recoil and increased energy expenditure. Curiously a relationship between the mechanical cost and energetic cost of running has not been shown in a fatigued state; indicating running economy could be a combination of physiological and mechanical factors not solely dependent on increased external work done per unit of distance (Candau et al., 1998).

In terms of elite athletes and recreational runners, elite marathoners displayed slightly smaller vertical amplitude of the center of gravity, as well as a smaller maximum extension angle of the thigh and a reduced knee angle during take-off (Anderson, 1996). Each of these mechanical variables seemed to be related to better economy of running (Anderson, 1996). Anthropometrically, elite runners tended to be shorter and have shorter leg lengths than recreational runners (Martin & Morgan, 1992). The distinction between the two groups is that the elite marathoners are able to minimize the negative affects of mechanical or physical responses through functional adaptation to leg length discrepancies (Williams, Cavanagh, & Ziff, 1987). Enomoto and Fujii (2001) observed distance runners with fatigue to display reduced running velocities, shortened step lengths, and lowered step frequencies between the initial and final stages of a fatiguing run. Also observed in this study were changes in the joint torques of the lower limb; specifically a marked increase in the hip joint torque along with a decrease in the peak of the knee joint torque. The changes in these values were thought not to be a result of the change of magnitude of the impact ground reaction force, but rather direction. In the final stages of this fatiguing run, the ground reaction force vector passed further from the hip joint than it did initially. The investigators indicated that this hip joint torque result played more of a role to compensate the decrease in the knee joint torque with fatigue for sustaining the moment to support the body immediately after foot strike.

Martin and Morgan (1992) concluded that biomechanical factors contributed markedly to determining the economy of a motion. In conclusion to their study, it was suggested that these biomechanical factors are most notable prior to contact, where the need for cushioning during early stance may have important effects on the demands placed on the muscles and joints. The most striking observation is that a runner's freely chosen stride length is their most economical, evoking the greatest mechanical efficiency (Anderson, 1996). Anderson (1996) compared elite with "good" runners and found that the elite runners have a shorter relative and absolute stride length. Anderson also noted that relative stride length was measured as 2.048 x stature or 4.037 x leg length. It has been suggested that a nearly erect trunk seems to favor the mobility of the lumbar spine-pelvic unit, needing less effort to maintain postural equilibrium; the opposite which occurs in runners displaying excessive forward lean (Anderson, 1996). Williams and Cavanagh (1987) found, when comparing distance runners grouped by running economy, that less efficient distance runners displayed a slightly greater lean of 5.9 degrees relative to vertical, compared to more efficient runners at 2.4 degrees.

In terms of joint flexion and economy, Martin and Morgan (1992) stated that there are two main, yet contradicting, theories. The first theory suggests that elastic energy contributions may be enhanced, along with less of a need for neutralization of active musculature of unproductive energy draining movements as less flexion is seen with a subject. This would consequently lower the metabolic cost of producing any running related movements. The second theory hypothesizes that less flexion of a body's joints would result in a modified gait pattern that would be less economical. There would need to be an increased muscular effort generated to produce a non fatigued gait pattern due to the higher resistance to motion that occurs at the extremes of joint ranges of motion. Williams, Cavanaugh, and Ziff (1987) and Anderson (1996) related a greater maximum hip extension angle to more economical gait patterns. The same studies both found a smaller knee angle at toe-off also correlated with increased economy. In terms of knee angles, this finding was of some debate, as other studies found that experimentally increased knee flexion during a run resulted in a 50% increase of oxygen cost (Anderson, 1996). As well, Anderson found that within elite marathoners, elite females displayed more acute knee angles during the swing phase of a run; displaying slower velocity thigh extension and knee flexion during this same phase. In this same study, "good" distance runners showed 10 degrees more plantarflexion of the ankle at toe-off. With all of these variations and differences between economy and running ability the only kinematic variable that was found linked to increased economy was the lower minimum resultant linear velocity of a point of the knee during foot contact (Anderson, 1996).

2.3 Proximal-Distal Sequence

Locomotion is a distinct pattern of segment motions. Putnam (1991) described the interaction between these segments as the function of the linear acceleration of the proximal end of a linked system and the angular velocity and acceleration of each segment in that system. In running and walking, Putnam noted the sequence of motion to begin with the swing phase. Gravity dependent and motion dependent interactions of segments mainly determine the natural pattern of thigh and leg motion (Putnam, 1991). This natural pattern includes the reduction in angular velocity of the proximal segment that occurs along with a simultaneous increase to a maximum angular velocity of the distal segment and is important for proximal to distal sequencing of segments. The increase in the proximal segment angular velocity usually precedes an increase in distal segment angular velocity, which allows greater angular velocity of the distal segment. This is made possible by the muscles acting directly on the distal segment. These advantages also occur regardless of speed.

In a run, Putnam (1991) noted that toe-off to maximum angular velocity of the leg results from the forward rotation of the thigh while the leg rotates backward then forward. The angular velocity of the leg reached the same magnitude of the thigh just as, or shortly after, the thigh reached peak angular velocity. Leg angular velocity continuously increased to a maximum value while the thigh angular velocity consistently decreased to a small magnitude (Putnam, 1991). The peak values of ankle angular velocity and acceleration occurred soon after the moment of toe-off (Hreljac, 1995). The initiation of toe-off in a walking gait is the same as in a run, until the thigh reaches the peak angular velocity (Hreljac, 1995). Hreljac (1995) observed that immediately after toe-off the thigh angular velocity decreased while leg angular velocity increased to a maximum. In addition, during a run, after peak angular velocity was reached, the leg negatively accelerated for foot strike. Meanwhile the thigh initially accelerates in the negative direction then in the positive direction. The difference between thigh motion pattern at the end of the swing phase in a walk and run is that the thigh was rotating in the positive direction in a run and a negative direction in a walk (Hreljac, 1995). There is a motion dependent interaction between segments, which has a major influence on the thigh and the leg in the swing phases of both a walk and run (Hreljac, 1995; Putnam, 1991). The final phase of the proximal to distal sequence is noted by a decrease in the angular velocity of the thigh (Hreljac, 1995; Putnam, 1991). As well there is a simultaneous acceleration of the leg to a maximum angular velocity. It seems the influence of the angular motion of the leg causes the drop in the angular velocity of the thigh (Hreljac, 1995).

Putnam (1991) suggested that one possible explanation for the proximal to distal sequential segment pattern seen in both the running and walking gait is the summation of speed principle. This states that in order to maximize the speed at the distal end of a linked system, the movement should begin with the more proximal segments and progress distally. This works in a manner such that each segment begins motion at the point of greatest velocity of the preceding segment, attaining a maximum speed greater than that of the more proximal segment.

2.4 Surfaces

Past research concerning any type of gait analysis has generally taken place in a lab setting, on a treadmill (Creagh, Reilly, & Lees, 1998; Nigg, De Boer, & Fisher, 1995). This research displayed no consideration of terrain effects, assuming treadmill and overground locomotion are similar. Nigg, De Boer, and Fisher (1995) noted that individuals could display substantial and unpredictable adaptations to the treadmill and the belt speed. When comparing treadmill and overground running, this research has found that treadmills tend to significantly over and under predict subject foot and ankle joint inversion and eversion, respectively. Biomechanically, no difference has appeared between treadmill and overground running for speeds up to 5.37 m/s, though with faster speeds greater stride rate and shorter stride length are commonly observed (Creagh et al., 1998). Another significant factor is that treadmill velocity artificially increases during the flight phase of a run, as compared too overground locomotion (Candau et al., 1998). Therefore the mean velocity of an entire step during contact, when compared to overground running was overpredicted.

Nigg et al. (1995) found treadmill running shows longer support time, smaller vertical velocity of the center of mass and fewer variations in both vertical and horizontal velocity of the center of mass. This same research reported that specific speeds resulted in variations of kinematic data. Middle distance race speed mechanics were similar to those seen with overground running (Nigg et al., 1995). As well, slow jogging on a treadmill consistently displayed shorter stride lengths, quicker stride rates and shorter non-support phases. Greater hip and knee extension at toe-off and an increase in ankle range of motion was also noted. As to why such differences exist between treadmill and overground running kinematics has resulted in conflicting hypotheses and results. One study done by Nigg et al. (1995) hypothesized that a runner gets energy from the treadmill belt at contact and imports that energy to the treadmill at toe-off, though their review of literature reported that other studies found no such notable energy difference.

Most studies are completed in a lab setting in order to avoid any terrain effects. For the studies that are done in the field, there are terrain effects that should first be considered. There have been significant terrain effects displayed for most gait variables, excluding any temporal variables (Creagh et al., 1998). These include a decrease in step length, increase in vertical displacement of the hip, greater knee lift and a larger upper body peak angle; all noted with increasingly difficult and uneven terrain. The increased vertical oscillation seen with off-road running is thought to be an important adaptation, providing additional time to adapt to the terrain. Step frequency did not change despite varying terrain, though step length did, which resulted in a simultaneous alteration of CM vertical oscillation. The relationship was such that both or either a slower velocity or more uneven terrain resulted in a greater amount of vertical oscillation (Creagh et al., 1998). These changes in the normal running stride have been hypothesized by Creagh, Reilly, and Lees (1998) to be due to the higher energy demand elicited from running off-road. This research investigating varying off-road terrain has concluded that individuals tend to alter stride, displacement and velocity patterns significantly in response to different running surfaces. In kinematic terms, though step frequency remains constant, a shorter stride length and slower run velocity was commonly observed off-road (Creagh et al., 1998).

2.5 Quantifying Smoothness

Elite runners are often observed to have “smoother” running styles than their recreational counterparts. Hreljac and Martin (1993; 1994) assessed this measure by the endpoint jerk-cost criterion; defined as the integral of the mean squared jerk function, being the third derivative of position. Initially, the jerk-cost was used as measure of smoothness of hand movements (Schneider & Zernicke, 1989). Hreljac and Martin (1994) were the first investigators to quantify the smoothness of the human running gait, studying runners at a regulated running velocity and for a limited running time. This study would have been the first to look at jerk-cost over a prolonged period of time and with fatigue presumably being a factor.

Both Nelson (1993) and Stein et al. (1986) hypothesized that there was a relationship between minimizing energy and maximizing smoothness as complementary performance criteria during skilled movement. This hypothesis was further reinforced by Hreljac and Martin (1994) as they suggested that runners were “inherently smoother” than non-runners, and that jerk-cost decreases as a task is practiced (Hreljac, 1993; Schneider & Zernicke, 1989).

It is essential to note that the kinematics of ultra-distances has yet to be investigated. As noted earlier, past research on gait has usually taken place in a lab setting and on a treadmill. Lab settings negate any terrain effects as well as natural adjustments in running speed and mechanical technique that may occur during a prolonged run or that may be a result of fatigue. A field test of any distance longer than a marathon is unprecedented. Though the idea of ultra-distance running has an obvious link with physiological studies, it is important that the initial gait kinematics be measured and analyzed before delving in to physiological analyses.

CHAPTER 3

Methods and Procedures

3.1 Subjects

Subjects were chosen, based on personal best 100 km finishing times. The subjects were all members of their respective national ultra marathon teams, and had a personal best time of 6:45:00 (hrs:min:sec) or less. As well, each subject was competing in the M20 category, indicating they were between the ages of 20 and 39 years. The top ten finishers were grouped together as the top group. Three subjects that met all necessary subject criteria, but finished as the final three elite males, were grouped as the bottom runners. The bottom runners were the final three national ultra-running team members to complete the race. Subjects were identified by their race numbers and filmed between seven to ten times as they completed the 10 km loop, en route to finishing the 100km race.

3.2 Equipment

Kinematics of the lower extremities were obtained using a JVC Cybercam 9800 digital video camera, filming at 60 Hz with a shutter speed of 1/250. The strides in an area of 2.4 meters in length were analyzed using the Ariel Performance Analysis System (APAS) 2000, version 1.4. Besser, Anton, Denny and Quaile (1996) and Klein and DeHaven (1995) found that the Ariel computer system reduced instrument bias and was considered reliable with excellent reproducibility.

3.3 Error Assessment and Data Smoothing

To measure digitizing precision, one subject was randomly selected to be re-digitized. The hip and knee joint angle results of the original digitization were then compared with the results of the re-digitization to obtain a correlation between the two data sets. Appendix A contains sets of both original digitized data and the re-digitized data with the correlation between the two. For the subject chosen, the correlation between the original and re-digitized measure of the hip joint and the knee joint was 0.994 and 0.998, respectively. This measure of precision suggests that random errors associated with digitization were small. To provide an estimate of measurement accuracy the measurements of a known distance, the distance between bars on the railing that secured the running corridor, were compared with that same measurement found via digitization of random trials. The average error between these known distances was 6.0 mm (± 1.0 mm), thereby allowing the data collection procedure to be considered accurate.

Data was smoothed using a fourth order, zero lag Butterworth low pass filter, with a cutoff frequency generally between 6-8 Hz, with a few exceptions of 5 Hz and 9 Hz. The cutoff frequency was determined by the use of a harmonic analysis. Winter et al. (1974) determined that the majority of human movement occurs at frequencies below 10 Hz and that the optimal cutoff frequency for filtering human movement is 6 Hz. The chosen cutoff frequencies were confirmed using residual analysis, a method adopted in a majority of biomechanical research. The smoothed data was used to derive the desired angle measurements, joint velocities and vertical displacements. Re-smoothing selected points of a randomly selected subject, followed by the use of residual analysis, confirmed the choices of cutoff frequencies selected. An example of the smoothing process, including the residual analysis can be found in Appendix A.

3.4 Experimental Setup

The camera was positioned approximately 15.0 meters from the finish line of the 10km race loop. The placement of the camera was restricted by race organizers, and allowed for a 2.4 meters length of capture, in the sagittal plane (Figure 3.1). All subjects passed through the area of capture in each lap, which allowed for gait analysis at their preferred speed and with their preferred running style. Data collected at the distances of 10 km, 50 km, 70 km, 90 km and 100 km were analyzed. Though the runners completed ten 10 km laps, these distances were the only ones where the thirteen subjects were unobstructed from view of the camera. These distances, also known as the time in the race, served as the independent variables. The kinematic variables were the dependent variables.

3.5 Data Collection

The approximate positions of the greater tubercle of the humerus (estimated joint center of the shoulder), the greater trochanter of the femur (estimated joint center of the hip), the lateral epicondyle of the femur (estimated joint center of the knee), lateral malleolus, heel of the shoe, and fifth metatarsal head were determined and the kinematic variables then analyzed (Figure 3.2). The segment angles measured were those of the trunk and shank with respect to the vertical, the thigh with respect to the horizontal, along with the joint angles of the hip and knee. (Figure 3.3). As well the vertical displacements of the hip were measured. The variables used in analysis were the vertical oscillations, trunk lean, hip flexion and extension, knee flexion and extension, shank angles, and joint ranges of motion.

3.6 Statistical Analysis

A one-way repeated measures ANOVA was used to test the differences between more than two means, for each distance. This test offered more design options than the t-test, as the differences between a number of means could be tested at the same time. Conversely, multiple t-tests increased the probability of type-I errors. As well, the pooled within group variance could serve as an error variance estimate. Where appropriate, Tukey post-hoc tests were carried out on the variables to identify the sources of significant differences. Statistical significance was determined using a value of $p < 0.05$ for all measures.

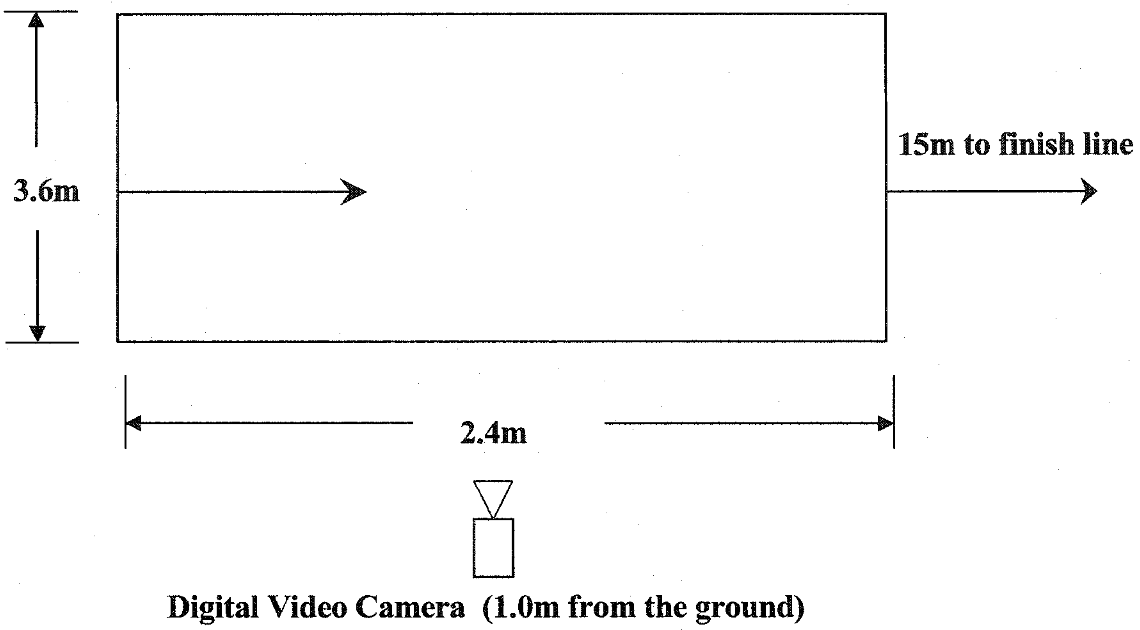

Figure 3.1. Data collection camera set-up and measurements.

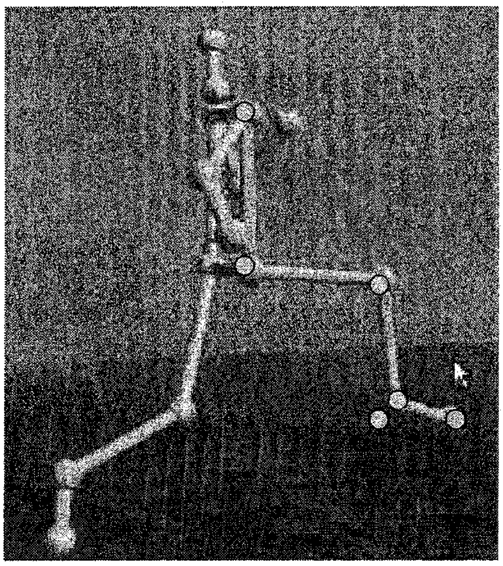

Figure 3.2. Estimated joint center of the shoulder, hip, knee, ankle, heel and head of the fifth metatarsal.

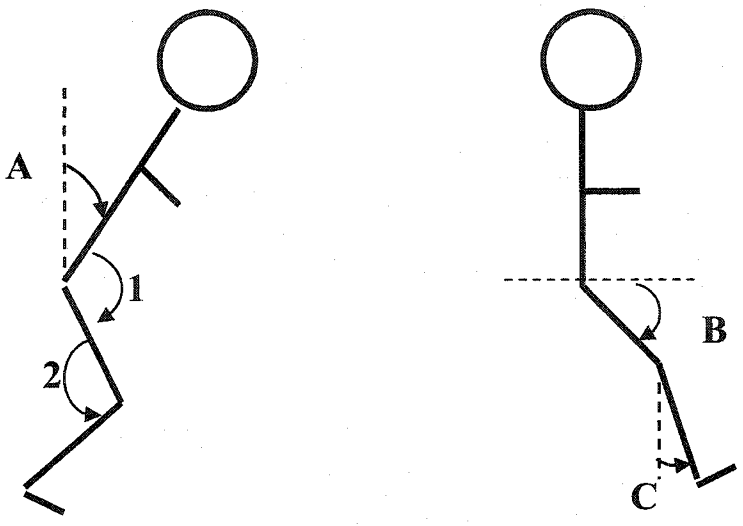

Figure 3.3. Angle definitions on right side of body, A=trunk angle to the vertical, B=thigh segment angle to the horizontal, C=shank angle to the vertical, 1=hip joint angle, 2=knee joint angle.

CHAPTER 4

Results and Discussion

The purpose of the study was to determine the extent to which gait kinematics change during a 100 km ultra-marathon run. The hypothesis was that gait kinematics would deteriorate during the 100 km race. With all the variables measured: trunk and shank angles with respect to vertical; thigh angle with respect to horizontal; hip and knee joint angles; hip and knee joint flexion and extension range of motion; and the vertical displacement of the hip, there were no statistically significant changes observed; therefore no significant deterioration of the running gait. Results are presented in graphical and table format throughout the chapter. Smoothed kinematic data for one single subject is contained in Appendix B. Variability in one stride for the marked distances was investigated using angle-angle diagrams of the thigh and knee. Angle-angle diagrams of the thigh and knee, for each subject are found in Appendix C and for one single subject in Figure 4.8. The variables are presented as follows:
1) Vertical oscillations, 2) Trunk lean, 3) Hip flexion and extension, 4) Knee flexion and extension, 5) Shank angles, 6) Joint ranges of motion, followed by a discussion of various factors affecting the running kinematics.

It should be of no doubt that biomechanical variables contribute significantly to the economy of motion (Martin & Morgan, 1992). Williams and Cavanagh (1987) identified numerous biomechanical factors that played a significant role in relation to running economy, supporting the hypothesis that running mechanics affect metabolic energy demand. (Martin & Morgan, 1992)

It is evident that mechanical factors aide the explanation of economy differences, though it is not completely understood as to what extent biomechanical factors can consistently explain these differences, as well as whether these differences can be attributed to specific biomechanical factors. Research undertaken since 1950 seems to support the idea of a linear relationship between running speed and aerobic demand; though the slope of the relationship varied depending on the range of speeds chosen for analysis (Daniels, 1985). Most of the research to date has concentrated on the effects of stride length and rate changes rather than establishing the mechanisms behind the economy response and whether these mechanisms are rate-based or length-based.

4.1 Vertical Oscillations

The current study showed no significant difference among the top 10 finishers of the 100 km race. The mean vertical amplitude of the top ten runners in the current study was 10.62 cm. Although greater than that found by Williams and Cavanagh (1987), the present study found that the top ten runners, assumed to have better efficiency in oxygen consumption, did not exhibit any statistically significant differences in the vertical displacement of the hip, taken as center of mass, with an F-value of 0.14 (p=0.996).

This result may reflect the unavoidable errors associated with manual digitization even though standard collection and smoothing protocols were followed. Between the top 10 finishers and the bottom three finishers there was a noticeable, though not significant (F-value of 0.23, p=0.919), difference as seen in Figure 4.1. The F-values and corresponding *p*-values, as well as the full ANOVA tables and coefficients of variation, for all variables measured can be found in Appendix D. The mean vertical amplitude for the bottom three runners was 9.6 cm. This finding is in agreement with that by Williams and Cavanagh in which the most efficient runners displayed 0.5 cm more vertical amplitude of their center of gravity than less efficient runners.

Cavanagh, Pollock, and Landa (1977) found that, though nonsignificant, elite distance runners had slightly smaller vertical amplitudes of their center of mass than good runners. In contrast, though not significant the lower VO_2 max group in the Williams and Cavanagh (1987) study had a mean amplitude of 9.1 cm, compared to 9.3 cm and 9.6 cm of the middle and high VO_2 max groups. The greater range of results, observed in the current study between individual subjects can be attributed to the fact that this run was 100 km in length versus the much shorter run analyzed in the Williams and Cavanagh study at a pace of 3.57 m/s. Tabakin, Burgess, Izzett, Lambert, and Vaughan (2001) examined the kinematics of runners after a 90 km run, looking at whether altered biomechanics could explain increased efficiency in oxygen consumption at a fixed submaximal rate. The conclusions stated that no differences in the vertical component of center of mass; stride length or stride cadence had any significant effect on increased efficiency. Unfortunately, stride lengths could not be measured due to limitations of the experimental setup. There is a basic assumption in running economy research that states that strides, which are too long, require a considerable amount of power during the propulsion phase of a stride, and would therefore result in a disproportionate amount of vertical oscillation of the center of mass (Anderson, 1996). This would in turn create a footstrike position that would generate large braking forces, thereby requiring joint ranges of motion that would invoke greater internal friction and stiffness (Anderson, 1996).

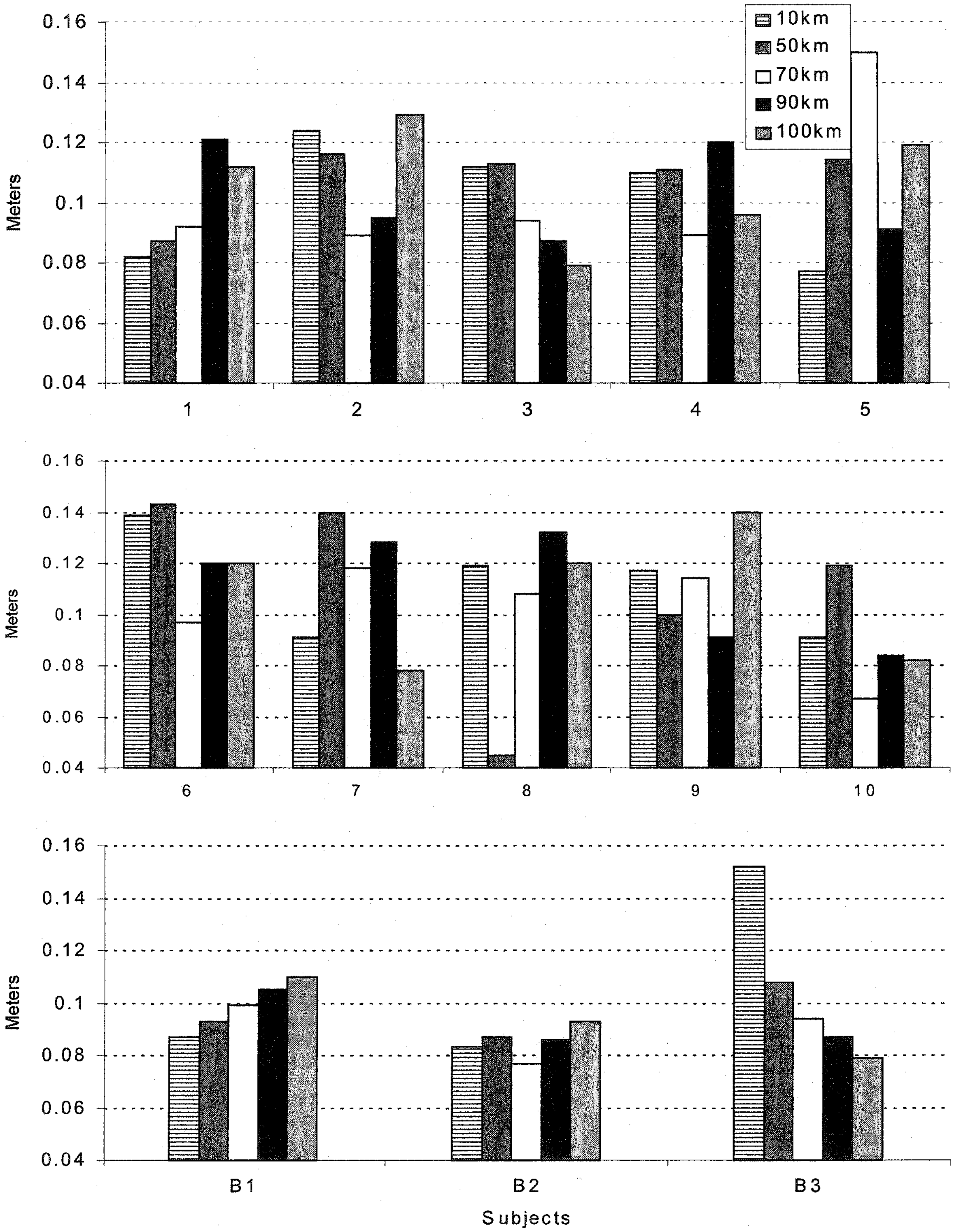

Figure 4.1. Mean vertical oscillations of all subjects for each distance throughout the race.

Strides that are too short would require increased frequency of steps and therefore increase the amount of internal work (Anderson, 1996). The most common finding in the literature is that elite distance runners choose a stride length that is the most economical and mechanically efficient (Anderson, 1996).

Morgan et al. (1996) observed short-term changes in gait mechanics while running at a 10 km race pace, following a bout of high intensity distance running. The investigation shows no significant changes in any of the biomechanical variables investigated, including the maximum vertical excursion of the center of mass. The lack of significant changes was postulated to be due to the imposed workload that, while being demanding, was not of sufficient duration or intensity to invoke any biomechanical change. A more theoretical perspective is that gait mechanics are not easily perturbed in highly efficient and trained runners, such as those used for the current study.

4.2 Trunk Lean

In the present study there was no significant increase in forward lean over time (F-value of 0.21 p= 0.931); suggesting that the trunk lean stayed consistent and was not used to brake any lateral movement. Figure 4.2 displays the mean trunk angles for all subjects at each of the analyzed distances throughout the race. Interestingly the tenth finisher displayed a mean trunk angle noticeably smaller than any other runner. This subject's tenth place finish could simply be an indication of a breakdown of some other kinematic variable, as opposed to a lack in this subject's ability to maintain an almost erect trunk while running. Also of note is the larger mean trunk angle of 6.8 degrees from vertical, for Subject B2 along with the small standard deviation of 0.35. Though this runner seemed to have a larger forward lean, it was very consistent throughout the entire race.

Anderson (1996) described that a nearly erect trunk tends to facilitate the mobility of the lumbar spine and pelvic unit. This trunk position requires less effort in maintaining postural equilibrium than excessive forward lean; a position, which necessitates greater muscular effort to sustain postural equilibrium. Williams and Cavanagh (1987) noted that high economy runners displayed greater forward lean than lower economy runners. The most efficient runners in their study exhibited a forward lean of 2.4 degrees relative to the vertical, compared with 5.9 degrees for the least efficient group. Thorstenssen, Carlson, Zomlefer, and Nilsson (1982) looked at EMG activity of the erector spinea and found it to be more symmetrical in running which correlated with a forward inclination of the trunk. The function of this muscle is to brake forward motion while running and lateral motion while walking.

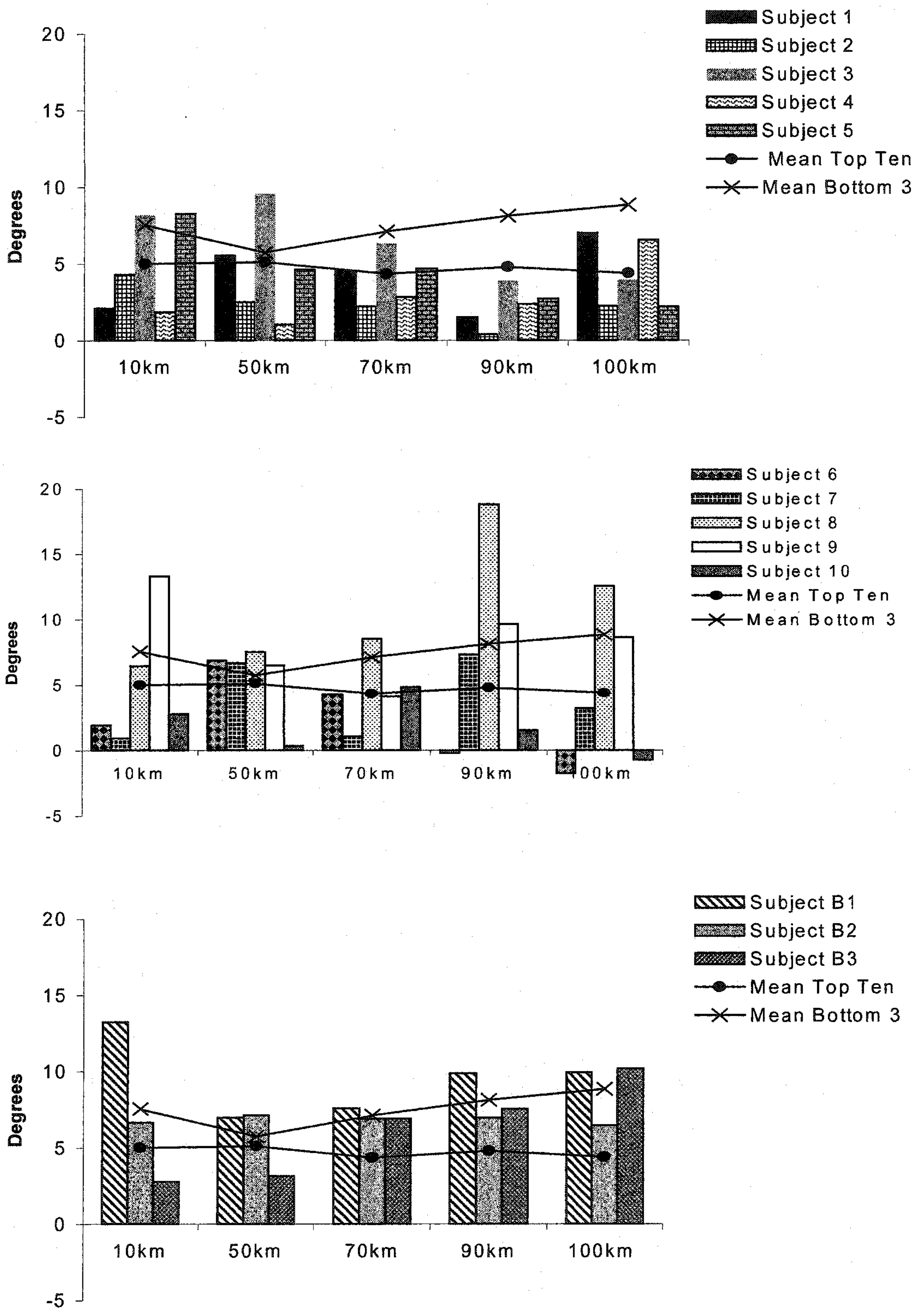

Figure 4.2. Mean trunk angles for all subjects during the 100 km run, with means for the top ten and bottom three finishers displayed.

4.3 Thigh Segment Flexion and Extension

In the current study the mean maximum thigh angle for the top ten runners was 114.6 degrees and 114.3 degrees for the bottom three runners. All but one runner displayed a decrease in thigh angle from early in the race to late in the race (Table 4.1). Though not statistically significant (F-value of 0.32, p= 0.866), the mean at 10 km was 119.0 degrees and 119.2 degrees, for the top ten and bottom three finishers respectively. At the 100 km mark the thigh angle was consistently smaller, showing 112.9 and 113.0 degrees for the top ten and bottom three finishers, respectively; implying that fatigue was influencing gait mechanics. As well, there were no significant differences in leg extension among the top ten runners as the race progressed (F-value of 0.28, p= 0.890). The maximum thigh angles for each subject at each marked distance of the race along with overall variability are listed in Table 4.1. The coefficients of variance, which measured the precision of a subject's thigh extension measure for each of the 10 km laps analyzed, were between 0.01 and 0.04, indicating that each subjects was able to maintain very consistent form throughout the 100 km run.

The lack of statistically significant findings does not imply that the bottom three runners were not elite; as all runners in the current study are considered elite, as per the criteria for subjects to be included in the investigation. Williams et al. (1987) found that females with better economy displayed less extension of the leg whereas elite male runners, like those that this study examined, showed just the opposite. In the Williams et al. (1987) study the elite women displayed more hip flexion, greater angular velocities in hip flexion and extension, and longer strides relative to leg length than their male counterparts running at the same velocity. Williams and Cavanagh (1987) found that elite male distance runners with better economy were associated with a greater maximum angle of the thigh during extension and a smaller knee angle at toe-off.

Table 4.1.

Maximum thigh angle (degrees) at toe-off for all Subjects with Std Deviations (Std Dev) and Coefficients of Variation (CV)

Subject	*10km*	*50km*	*70km*	*90km*	*100km*	*Std Dev*	*C V*
1	116.98	113.03	112.49	111.02	112.76	2.22	0.02
2	120.93	119.67	117.88	113.88	116.74	2.73	0.02
3	117.17	117.53	117.90	110.3	110.34	3.95	0.03
4	122.15	121.34	120.04	120.68	124.16	1.59	0.01
5	120.80	118.32	118.88	116.82	115.82	1.92	0.02
6	112.71	110.53	114.37	113.66	108.53	2.40	0.02
7	119.97	117.45	121.25	116.20	114.75	2.67	0.02
8	112.29	112.74	110.82	111.37	106.77	2.38	0.02
9	115.38	111.64	113.36	114.65	114.38	1.45	0.01
10	112.82	110.62	108.79	103.55	103.46	4.22	0.04
B1	124.56	120.01	122.16	121.30	121.67	1.67	0.01
B2	113.93	110.65	110.38	112.13	112.32	1.43	0.01
B3	113.77	115.66	110.38	105.76	104.96	4.74	0.04

The current study does show some interesting trends concerning extension of the thigh segment. Twelve of the thirteen subjects showed a progressive decrease of the maximum thigh angle to some degree, as the distance increased and the runners fatigued. This can be noted, as illustrated graphically, in Figure 4.3. This could be a kinematic indication of fatigue; as various muscles fatigue the leg is no longer able to extend maximally. The results of this may be seen by a slower stride, less powerful toe-off, shorter stride, and smaller hip flexion velocity.

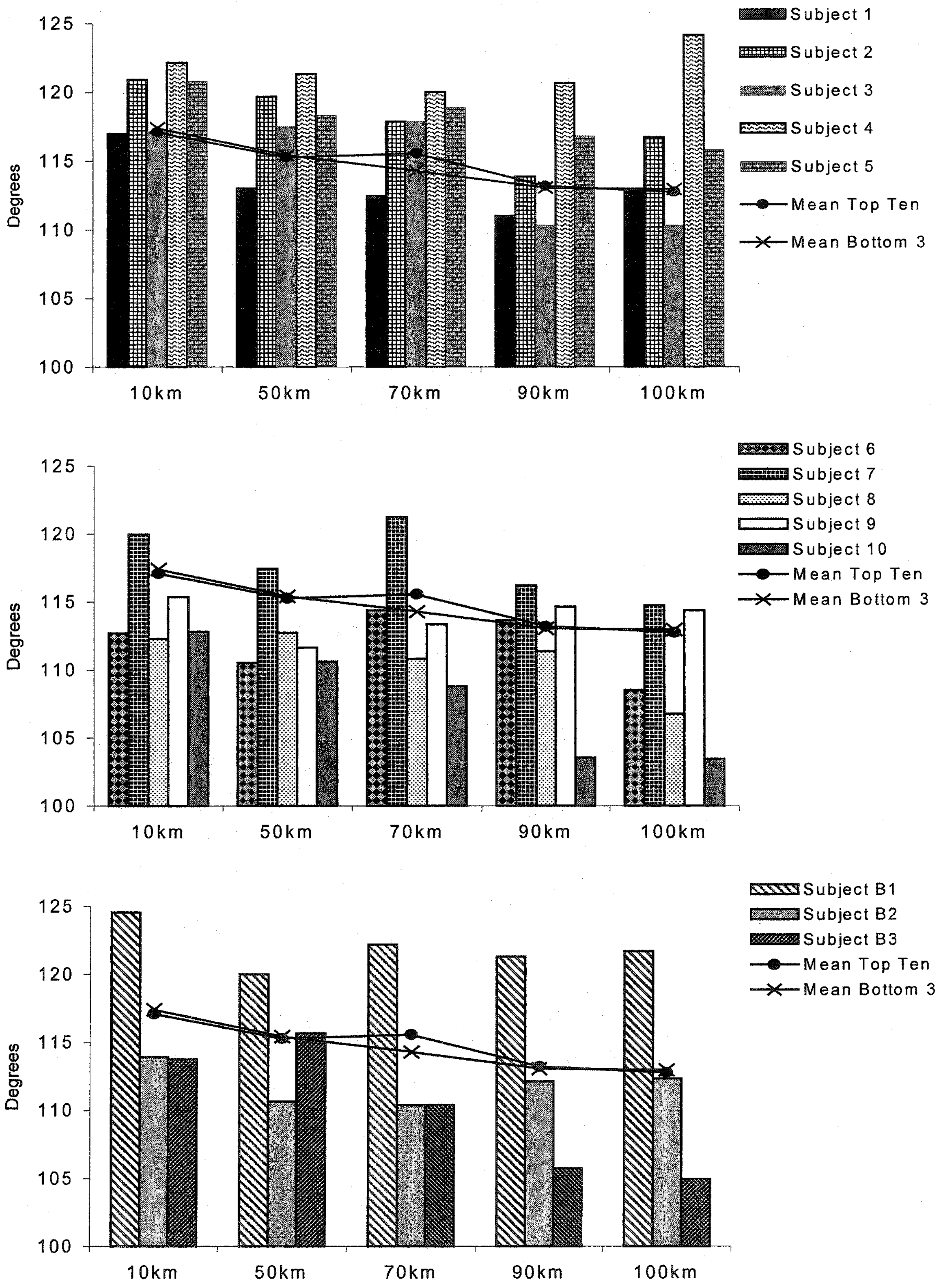

Figure 4.3. Thigh segment extension angles for all subjects throughout the 100km run, with means for the top ten and bottom three finishers

4.4 Knee Flexion and Extension

4.4.1. Knee Joint in Support

Knee angles during midsupport are displayed in Figure 4.4. The top ten runners had a mean knee angle during midsupport of 138.3 (±4.7) degrees compared to that of 137.2 (±5.0) degrees for the bottom three elite runners. Though this is not statistically significant (F-value of 0.43, p= 0.786), it is in agreement with the results of Williams and Cavanagh (1987) and Bailey and Pate (1991) who found that runners in the lower VO_2 submax group displayed greater knee flexion during midsupport than less efficient runners. Interestingly, the mean angle for the top ten runners at the 10 km mark was 139.6 degrees and 136.6 degrees at the 100 km mark, whereas the bottom three finishers showed more consistency throughout the run with a mean angle of 136.1 the 10 km distance and 136.2 at the 100 km mark. Though this displays consistency between the start of the run and the finish, throughout the run it appears that different strategies were employed. At the 70 km mark the bottom three runners had a mean knee joint angle of 140.1 degrees compared to 137.3 degrees for the top ten finishers. For the top ten finishers this may indicate a pattern of a slow, but steady decrease in knee joint angle; whereas the bottom three runners suddenly displayed a more extended knee joint at the 70 km distance, before regaining a knee joint angle similar to those observed at previous distances. This could be a strategic effort to speed up during this time or an alternate response to fatigue.

Based on the Williams and Cavanagh finding, this would suggest that the runners in the current study became more inefficient, though slightly, as the race progressed. As muscles fatigue, the runners may be forced to absorb more of the impact through knee flexion, from which a less powerful toe-off could result. This could not be more evident as with Subject B3, where knee flexion at 100 km is 127.2 degrees compared to 139.7 degrees at 70 km, a range of 12.5 degrees (Figure 4.4).

McKeown, Brown, Chu, and Hamill (2001) observed different changes in the knee flexion/ankle eversion coupling with fatigue. Interestingly, half the subjects accommodated for fatigue with an increase in the magnitude of knee flexion and ankle eversion, while the other half displayed a decreased magnitude. Though ankle eversion was not measured this could suggest that the subjects running the 100 km race accommodated fatigue with strategies other than the ankle eversion/knee flexion coupling. One possible strategy may be during swing, with an increase in the knee flexion angle thereby decreasing the moment of inertia about the hip.

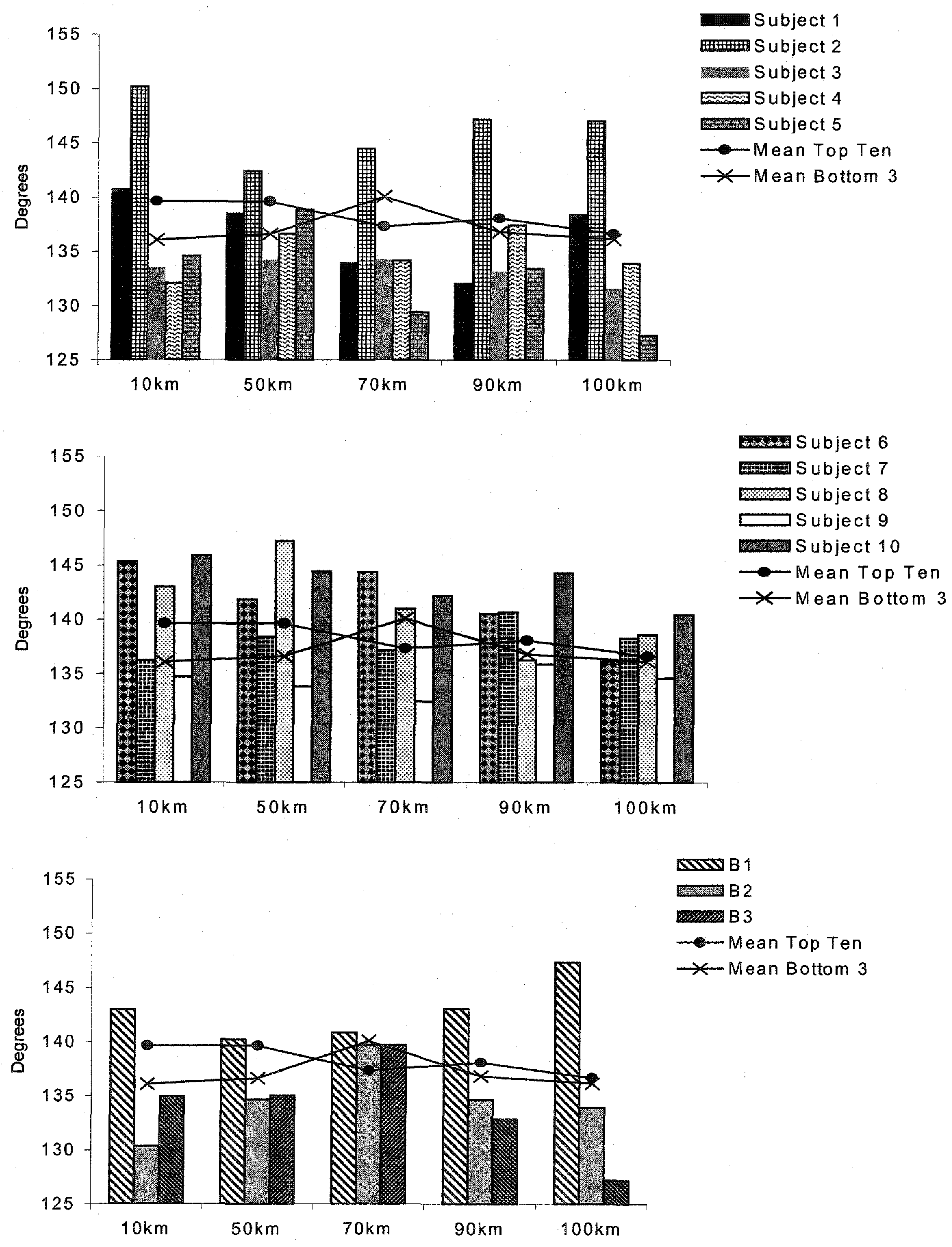

Figure 4.4. Subject knee angle in support with group means displayed.

4.4.2. Knee joint at Toe-Off

The present study found that the runners had knee joint angles varying from 139.3 degrees to 166.2 degrees at the moment of toe-off (Figure 4.5). This does not indicate that the runners in the present study were not elite, but that the runners were running a 100 km distance at a mean velocity ranging from 2.42m/s to 4.18m/s, as compared to Williams et al. (1987) where the results were collected while running at 5.36m/s. The mean angle of the knee joint at toe-off, for all thirteen subjects in the present study, ranged a mere 26.9 degrees throughout the 100 km distance. This indicates that, as a group, the knee angle at toe-off remained extremely consistent throughout the 100 km run. Although more variability or potential fatigue effects were observed during midstance, the knee angle at toe-off remained consistent throughout the duration of the run, indicated with an F-value of 0.09, $p= 0.99$. Therefore it would appear that fatigue did not influence knee extension during the toe-off phase.

Anderson (1996) and Williams et al. (1987) found that better economy in elite male runners was associated with a smaller relative knee angle, at toe-off. In the Anderson (1996) study elite male runners displayed a mean knee joint angle of 166.8 degrees at toe-off.

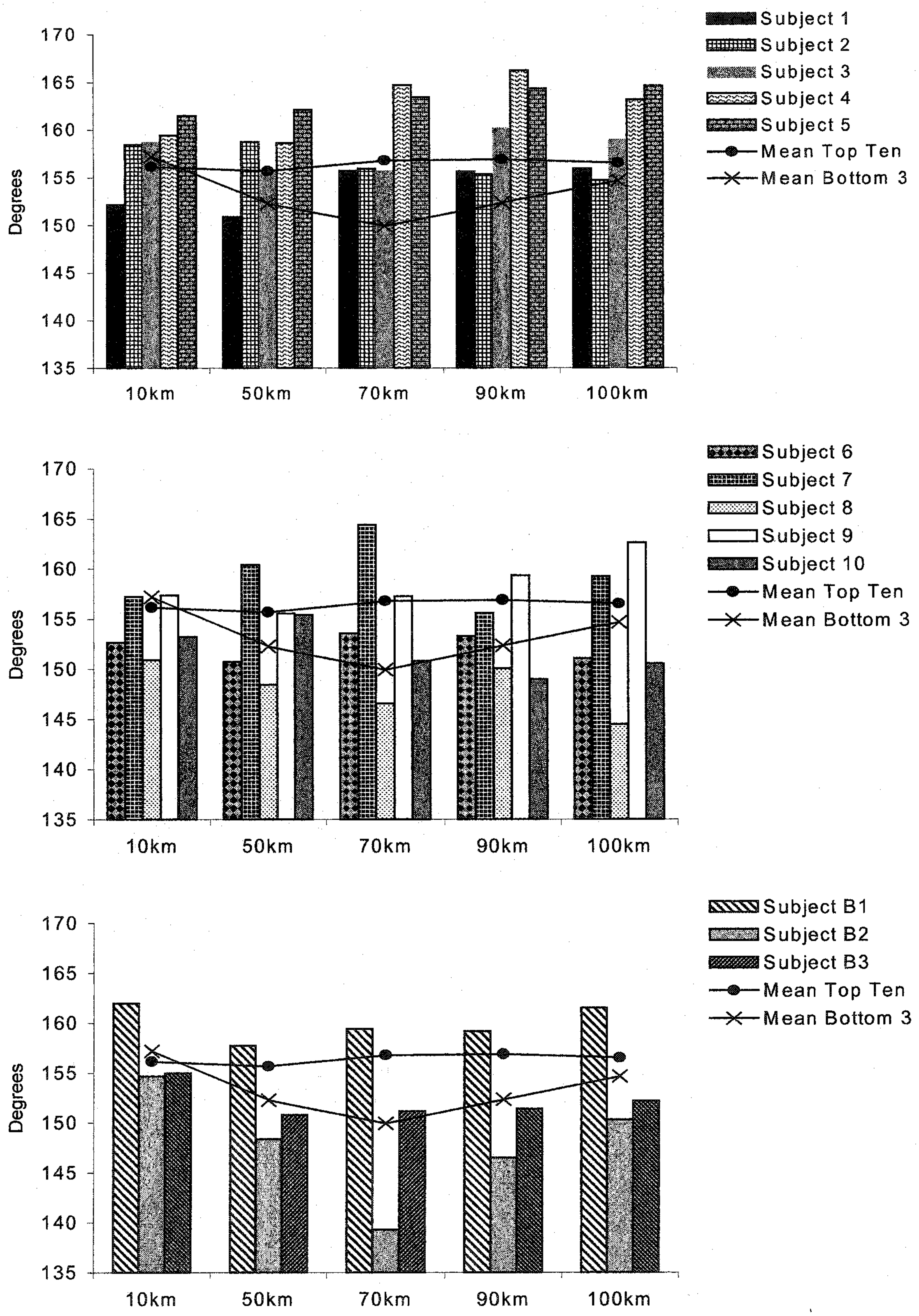

Figure 4.5. Knee angle for all subjects at toe-off, with groups means displayed.

4.4.3. Knee Joint in Swing

The present study did not show any significant changes in the maximum knee flexion during swing though there were marked individual differences, as the race progressed (Figure 4.6). It was assumed that as runners fatigued there would be a decrease in maximum knee flexion. Though not significant, there was an obvious difference between the top ten finishers and the bottom three finishers (F-value of 0.49, $p = 0.746$). The bottom three finishers displayed less flexion at the knee during swing throughout the entirety of the race, with a drop of 4.8 degrees of the means from the 10 km mark to the 100 km mark. The top ten finishers showed a drop of only 3.4 degrees of maximal knee flexion (F-value of 0.69, $p = 0.605$),during swing from the start to the finish of the race, with a noted increase at the 50 km, 70 km, and 90 km points (Figure 4.6).

This suggests that the top ten finishers attempted to combat fatigue with a strategy that, as noted earlier, included reducing the moment of inertia about the hip joint, requiring less hip flexor torques to bring the leg through in swing. Cavanagh et al. (1977) showed that more acute knee angles during swing were seen in elite distance runners over "good" runners. Williams, Snow, and Agruss (1991) reported an increase in step length, knee flexion angle during swing, and thigh angle during hip flexion as competitive runners became fatigued. In contrast Elliot and Ackland (1981) reported a decrease in stride length and an inconsistent leg position at footstrike with fatigue. It may be puzzling to think that with fatigue the knee flexion during swing would increase, but this reduces the moment of inertia of the leg about the hip joint. Williams et al. (1991)

postulated that exerting a bit more energy flexing the knee is beneficial, as it reduces the magnitude of the hip flexor torques needed to bring the leg through the swing.

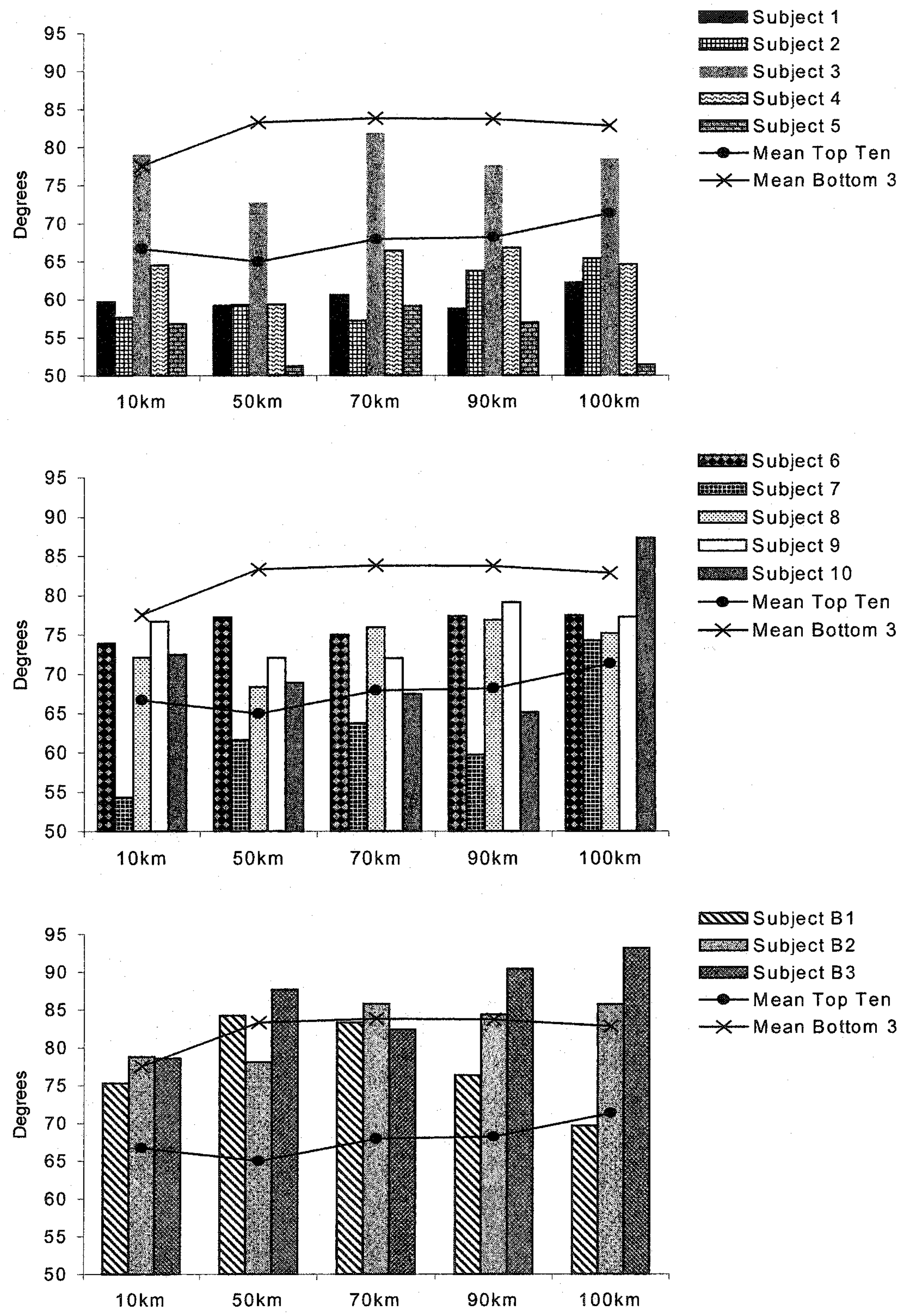

Figure 4.6. Maximum knee joint angle in swing for all runners with group means displayed.

4.5 Shank Angles

The current study observed subject mean shank angles ranging from 4.9 to 5.5 degrees, from vertical, for the top ten runners. Though this was statistically nonsignificant (F-value of 0.06, p= 0.994), it may indicate that the differences seen in this investigation and that of Williams and Cavanagh (1987) could be due to the prolonged run of the 100 km race versus the shorter run to volitional exhaustion. Interestingly, the bottom three runners had mean shank angles ranging from 7.0 to 7.8 degrees, suggesting they made contact with their foot more forward than those of the top ten finishers who appeared to land with the shank in a more vertical position (Table 4.2). Making contact with the shank more extended, as the bottom three runners displayed, would increase the breaking forces upon contact. Interestingly the bottom runner consistently landed with the shank extended, indicating greater braking forces were applied upon contact. This is compared to the top finisher who landed with a smaller mean shank angle, indicating less breaking force was applied upon contact. Subject B3 had a mean shank angle of 8.7 degrees, compared to 3.3 degrees for Subject 1. In terms of consistency Subject B1 was most consistent with a coefficient of variation of 0.08, while subject 3 was the most inconsistent with a coefficient of variation of 0.76. Though some subjects were not very consistent, the mean shank angles that they landed with varied a mere 5.5 degrees. Williams and Cavanagh (1987) found that lower economy running was associated with shank angles of greater deviation from vertical upon footstrike, with the highVO_2 max runners displaying a shank angle of 5.5 degrees from vertical and 8.3 degrees and 8.2 degrees for the lowest and middle VO_2 max groups, respectively.

Table 4.2.

Shank angle with respect to vertical at contact (degrees) with Std Deviations (Std Dev) and Coefficients of Variation (CV).

Subject	*10km*	*50km*	*70km*	*90km*	*100km*	*Stv Dev*	*C V*
1	3.24	3.84	5.00	1.86	2.75	1.18	0.35
2	9.72	6.65	2.93	5.23	8.15	2.62	0.40
3	8.51	5.35	0.92	1.31	2.41	2.28	0.72
4	7.61	4.65	0.93	1.74	2.66	2.67	0.76
5	7.85	6.63	10.33	9.67	3.68	2.65	0.35
6	3.54	5.07	5.30	4.45	1.82	1.41	0.35
7	3.91	3.47	11.60	5.65	9.44	3.56	0..52
8	0.35	6.12	2.49	5.47	6.92	2.76	0.65
9	4.33	5.82	4.36	10.30	6.88	2.46	0.39
10	3.35	6.92	5.12	6.75	5.56	1.44	0.26
B1	9.62	7.75	8.86	8.18	8.39	0.71	0.08
B2	4.83	5.92	3.75	6.25	3.24	1.31	0.27
B3	7.61	8.39	8.39	8.86	10.31	1.00	0.11

4.6 Joint Range of Motion

Vaughan (1993) noted that when going from jogging (3.8 m/s) to racing pace (5.6 m/s) there was a significant increase in the range of motion of both the hip and knee joints during the swing phase of the stride. As fatigue developed in the 100 km ultra-marathon runners it was hypothesized that their horizontal velocity would decrease, and could be reflected in a decrease in the range of motion of the hip and knee joints during swing. This current study saw no statistically significant changes, suggesting the runners were able to maintain their hip or knee ranges of motion and hence, did not slow their pace significantly. This is also seen through the consistency of the 10 km lap times, presented in Tables 4.3 and 4.4, and the running velocities throughout the race presented in Table 4.5.

Table 4.3.

10 km Lap Times for All Subjects (min:sec)

Subject	*10km*	*20km*	*30km*	*40km*	*50km*	*60km*	*70km*	*80km*	*90km*	*100km*
1	38:14	38:42	39:53	38:50	39:29	39:38	40:20	39:36	40:30	43:04
2	38:13	38:42	39:52	39:34	39:36	40:16	39:42	40:38	41:49	41:17
3	38:22	38:31	39:56	39:31	38:53	40:22	41:03	42:18	43:44	41:16
4	39:56	39:50	38:52	39:07	38:21	38:27	39:09	42:07	47:44	46:02
5	38:16	38:31	39:01	39:39	40:34	41:03	42:31	42:04	43:01	44:13
6	41:17	41:07	41:12	41:39	41:01	41:03	41:01	42:18	42:41	43:25
7	38:12	39:28	37:55	39:06	39:22	42:05	47:20	46:18	45:14	43:09
8	38:14	38:40	39:54	39:32	40:05	45:17	44:15	45:18	44:50	43:34
9	40:54	42:09	40:31	41:29	41:35	41:11	42:36	43:20	44:29	44:00
10	38:15	39:30	40:01	41:25	44:12	46:13	44:51	42:47	43:39	40:30
B1	46:49	48:33	50:13	54:44	58:48	60:30	65:04	64:03	66:05	62:03
B2	49:31	51:11	55:35	54:13	61:20	59:04	64:22	68:51	57:27	57:34
B3	52:59	51:36	51:19	54:04	58:18	60:31	60:59	61:13	66:24	64:09

Table 4.4.

Running Times for All Subjects (hr:min:sec)

Subject	*10 km*	*20 km*	*30 km*	*40 km*	*50 km*	*60 km*	*70 km*	*80 km*	*90 km*	*100 km*
1	0:38:14	1:16:56	1:56:09	2:34:59	3:13:48	3:52:46	4:32:26	5:11:22	5:51:52	6:34:16
2	0:38:13	1:16:55	1:56:07	2:35:01	3:14:37	3:54:13	4:33:55	5:13:53	5:55:02	6:36:19
3	0:38:22	1:16:53	1:56:09	2:35:00	3:13:53	3:53:35	4:34:38	5:16:56	6:00:00	6:41:16
4	0:39:56	1:19:06	1:57:58	2:36:25	3:14:46	3:52:33	4:31:02	5:13:09	6:00:53	6:46:15
5	0:38:16	1:17:07	1:56:08	2:35:07	3:15:01	3:56:04	4:38:35	5:20:39	6:03:40	6:47:53
6	0:41:17	1:22:24	2:03:36	2:44:35	3:25:36	4:06:39	4:47:40	5:29:18	6:11:59	6:54:44
7	0:38:12	1:17:00	1:54:55	2:33:21	3:12:43	3:54:48	4:41:28	5:27:46	6:12:20	6:55:29
8	0:38:14	1:16:54	1:56:08	2:35:00	3:15:05	4:00:22	4:44:37	5:29:55	6:14:05	6:57:39
9	0:40:54	1:22:23	2:02:54	2:43:43	3:24:38	4:05:49	4:47:45	5:30:25	6:14:14	6:58:14
10	0:38:15	1:17:05	1:57:06	2:38:31	3:22:43	4:08:56	4:53:07	5:35:54	6:18:53	6:58:43
B1	0:46:49	1:34:42	2:24:15	3:18:59	4:17:07	5:17:37	6:23:01	7:27:04	8:33:09	9:35:12
B2	0:49:31	1:40:42	2:35:37	3:29:50	4:30:30	5:29:34	6:33:56	7:42:07	8:39:34	9:36:28
B3	0:52:59	1:43:55	2:34:34	3:28:38	4:26:56	5:26:47	6:27:06	7:28:19	8:34:03	9:38:12

Table 4.5

10 km Lap Velocities for All Subjects (m/s)

Subject	*10km*	*20km*	*30km*	*40km*	*50km*	*60km*	*70km*	*80km*	*90km*	*100km*
1	4.36	4.31	4.18	4.29	4.22	4.21	4.13	4.21	4.12	3.87
2	4.36	4.31	4.18	4.21	4.21	4.14	4.20	4.10	3.99	4.04
3	4.34	4.33	4.17	4.22	4.29	4.13	4.06	3.94	3.81	4.04
4	4.18	4.23	4.13	4.26	4.35	4.33	4.26	3.96	3.49	3.62
5	4.36	4.22	4.11	4.20	4.11	4.06	3.96	3.96	3.87	3.77
6	4.04	4.05	4.05	4.00	4.06	4.06	4.06	3.94	3.90	3.84
7	4.36	4.22	4.40	4.26	4.23	3.96	3.52	3.60	3.68	3.86
8	4.36	4.31	4.18	4.22	4.16	3.68	3.77	3.68	3.72	3.83
9	4.07	3.95	4.35	4.02	4.01	4.05	3.91	3.85	3.75	3.79
10	4.36	4.22	4.16	4.02	3.77	3.61	3.72	3.90	3.82	4.12
B1	3.56	3.43	3.32	3.05	2.83	2.75	2.56	2.60	2.52	2.69
B2	3.31	3.26	3.00	3.07	2.77	2.82	2.59	2.42	2.90	2.90
B3	3.15	3.23	3.25	3.08	2.86	2.75	2.73	2.72	2.51	2.60

Angular kinematic data is often presented through angle-angle diagrams. Miller (1978) presented an angle-angle diagram showing the effects of increasing running speed on the range of motion of the knee joint segment angle, and the thigh relative to horizontal. Noted through the diagram was this increase in the range of motion for both the knee joint and thigh segment angles as running speed increased. An angle-angle diagram for one subject in the present study is displayed in Figure 4.7, Appendix C contains the angle-angle diagrams for all subjects. Vaughan (1983) investigated running biomechanics at speeds of 3.8 m/s, 5.6 m/s, and 7.5 m/s, providing knee /thigh angle angle diagrams which display the effect of increasing distance on the knee and hip joint ranges of motion. Through this study it was found that stride to stride variation was less at the faster running speeds. The gait deterioration that was hypothesized to occur would first be seen through a decrease in running speed, accompanied by greater stride to stride variations as the race progressed and the running velocity decreased. Looking at Figure 4.7 it is apparent that a substantial increase in stride to stride variability did not occur. The runners in the present study were running at a mean velocity ranging from 2.42 m/s to 4.18 m/s, within the range that Vaughan (1983) noted the most stride to stride variability.

Vaughan (1983) also noted that when going from a jogging pace of 5.9 m/s to a racing pace of 7.5 m/s there was an increase in the range of motion of both joints during swing. The angle-angle diagrams in Figure 4.7 and Appendix C, indicate that the hip angles at the point of contact remain very consistent and the knee joint angle, not being statistically significant, is slightly more extended as the distance increased. With the knee being slightly more extended at contact, the runner would not be in a position where the knee is able to help attenuate the landing forces as well as if it were a bit more flexed. At toe-off, these same angles show a trend which, though not statistically significant, indicate a faint pattern of decreased hip extension as the distance increases. This effect of fatigue would lessen the propulsive forces that the runner is able to generate, causing the runner's velocity to slow. Fittingly the last 10 km lap for Subject 1 was the slowest by 0:02:30 (hrs:min:sec).

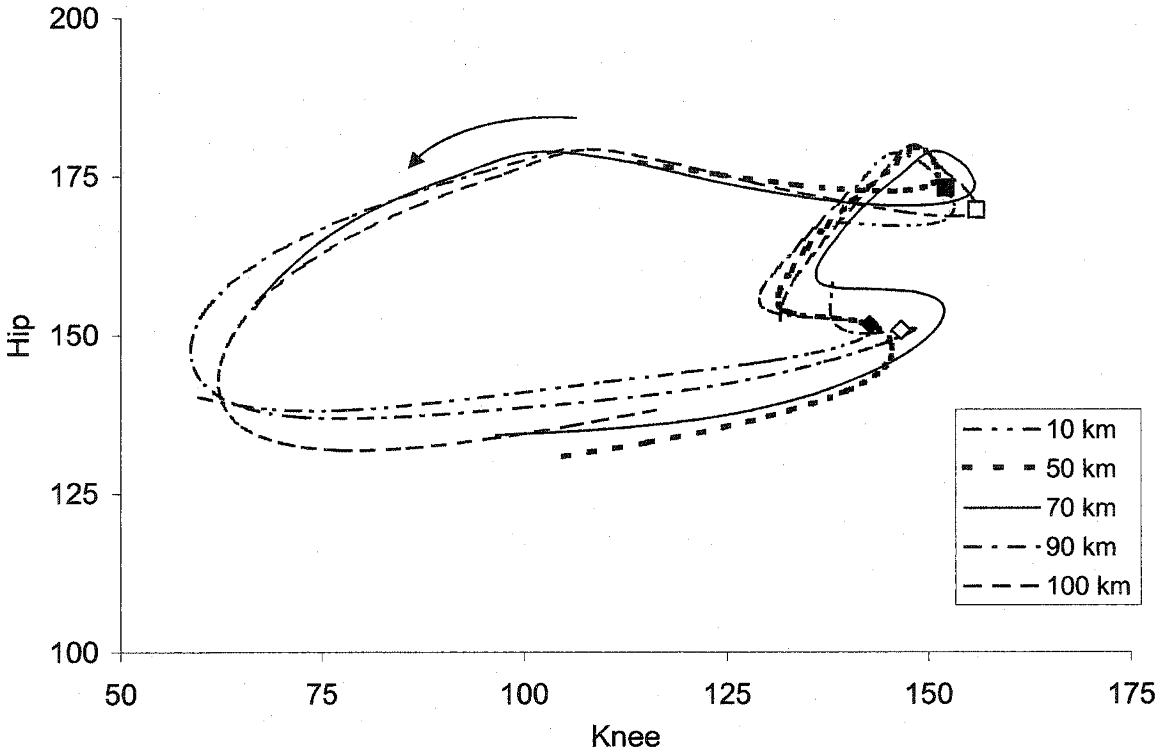

Figure 4.7. Subject 1 knee/hip angle diagram. ♦ Indicates heel contact at 10 km; ◇ represents heel contact at 100 km. ■ Indicates toe-off at 10 km and □ indicates toe-off at 100 km.

With increased fatigue expected over the course of 100 km, it was hypothesized that the runner's gait would deteriorated. Therefore, one would expect to see a decrease in the range of motion instead of an increase. Figure 4.8 displays the knee joint angle range of motions for each subject throughout the run. Interestingly Subject 1 displayed consistency unparalleled to any other subject. This may indicate that consistency in joint range of motion is a main biomechanical factor when maintaining form while fatigued. Of note, the bottom three subjects are also able to maintain more consistent knee joint ranges of motion throughout the run, than the majority of the top ten finishers, with coefficients of variation ranging from 0.03 to 0.06 for the bottom three finishers and 0.02 to 0.19 for the top ten finishers. This might indicate that a mechanical breakdown due to fatigue, if any, occurred at other segments or joints while knee joint range of motion was maintained. Figure 4.9 displays the hip joint range of motions for each subject throughout the run. Interestingly these joint ranges of motion are much more varied than the knee joint ranges. This could indicate that a mechanical breakdown, due to fatigue, may have affected the hip joint ranges throughout the run. Differences between and among these ranges were not of statistically significant value, though should be taken as a note of interest.

It has been postulated that limitations to the range of motion of joints could be involved in decreasing segmental energy levels (Williams, 1985). Though most movements occur at an intermediate range of motion, there are instances where limits to joint motion are reached. Williams (1985) gave the example of running at a moderate distance running speed. At these moderate speeds maximal hip hyperextension usually averages 26 degrees, approximately the same as typical maximal voluntary hyperextension. When compared to data collected in the present study the mean thigh segment hyperextension angle for all thirteen subjects, being that angle beyond 90 degrees vertical, was 29.1 degrees at the 10 km distance and 23.0 degrees at the 100 km distance. This indicates that as a group all runners tended to hyperextend the thigh segment to a point near the capable maximal voluntary hyperextension, though this hyperextension lessened as the duration of the run progressed and fatigue become more of an influential factor. Knowing this, the range of motion could be more of a factor in running than compared to walking, except at high walking speeds.

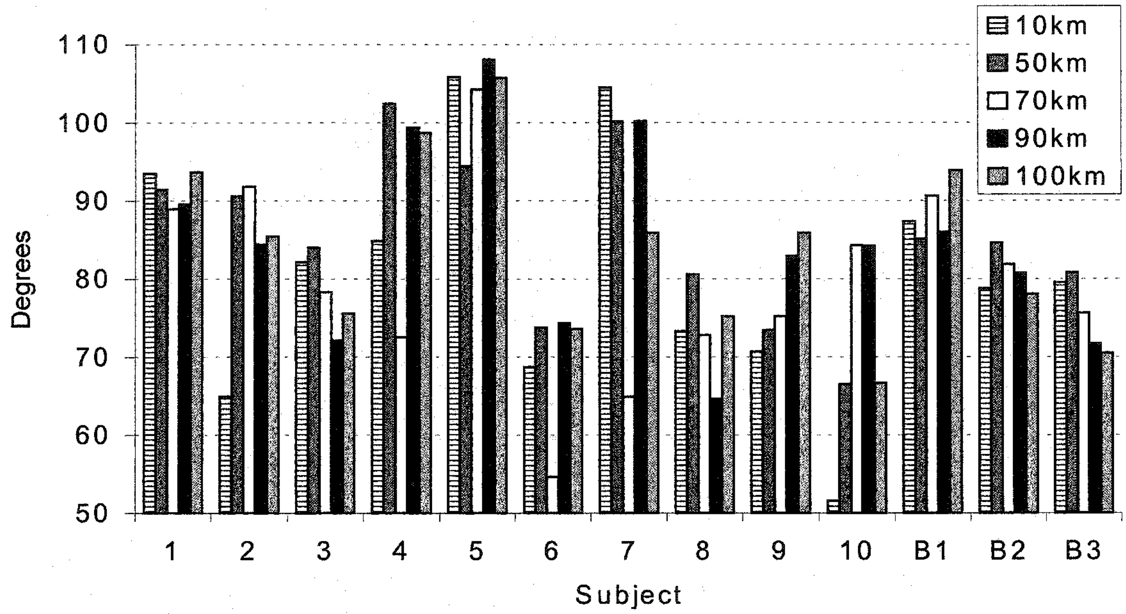

Figure 4.8. Knee joint angle range of motion for all subjects throughout the 100 km run.

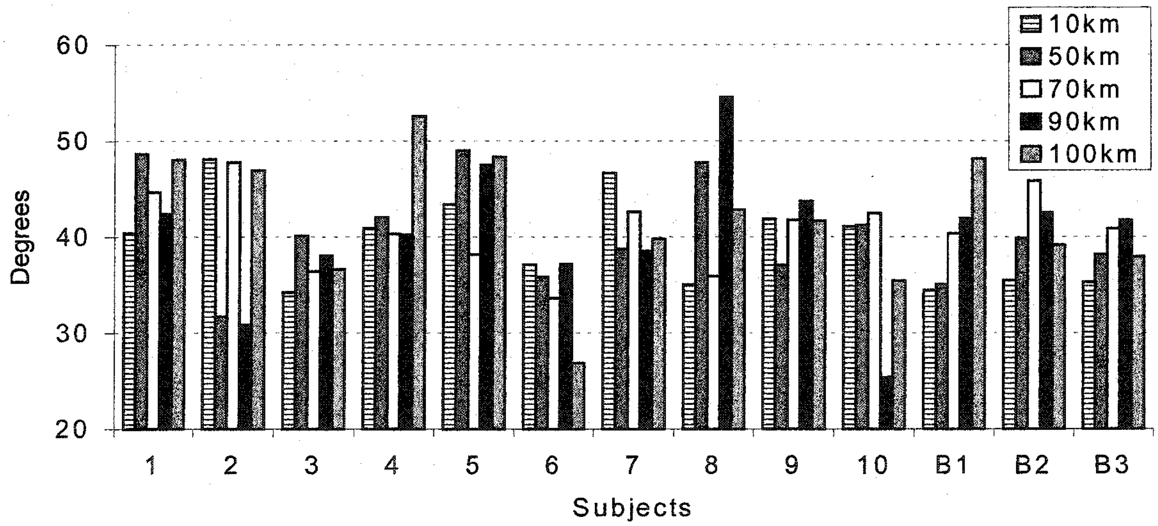

Figure 4.9. Hip joint angle range of motion for all subjects throughout the 100 km run.

4.7 Intersegmental Interactions

Martin and Cavanagh (1990) noted that most of the energy changes within the lower extremity could be attributed to intersegmental energy transfers, distally during early swing and proximally later in the swing. These energy transfers are associated with the joint reaction forces that seem to redistribute the mechanical energy that's generated from other sources. Their findings are in agreement with previous literature noting that segment motion of the swing leg are controlled as well as generated proximally. The majority of this control is initiated from the musculature of the hip and the interactions of the thigh with the trunk. (Martin & Cavanagh, 1990)

The current study showed no significant changes with increased distance, or significant differences between groups, in any of the forward trunk lean, thigh extension angle at toe-off, or thigh flexion angles. These angles are all related to the control and power generation of the musculature about the trunk and hip. During swing, the musculature about the knee of the swing leg mainly dissipates mechanical energy and the ankle musculature makes little contribution. Whereas, during the toe-off phase, Winter (1983) has shown that in heel strikers the ankle functions as a principle energy generator while the knee functions as an absorber. His study showed that the ankle does three times the work of the knee in generating energy, and the knee absorbs 3.5 times the energy of the ankle.

4.8 Stride-to-Stride Consistency

An explanation for the lack of stride to stride variation in each 100 km racer could be taken from the results of Miller (1978) where it was noted that stride to stride variation of joint angles were less at faster running speeds of between 5.6 m/s and 7.5 m/s. The runner's in this study were running at speeds between, 2.9 m/s and 4.2 m/s, over 100 km. Morgan et al. (1991) noted that the stride-to-stride variation in the running pattern was minimal. They concluded that biomechanical data obtained from two or more strides would yield little advantage over a single stride analysis. Due to restrictions imposed by the IAAF, the present study was restricted to a single stride analysis of the runners. Though, the stride to stride consistency can be noted in the hip/knee angle-angle diagrams, such as Figure 4.7. Knee/hip angle-angle diagrams for all subjects can be seen in Appendix C. These diagrams show the consistency of the knee joint angle and the hip joint angle for one stride, at each of the 5 marked distances throughout the race. This consistency is not unexpected given the close finishing times of the 100 km run previously noted in Table 4.5.

4.9 Impact Loading while Running

Hreljac, Marshall, and Hume (2000) found that a group of injured runners displayed a significantly greater rate and magnitude of impact loading than injury free runners. These results agree with previous findings that suggest repeated excessive loading cause functional adaptations, leading to further overload and eventually causing tissue injury.

Willson and Kernozek (1999) investigated plantar loading and cadence alterations with fatigue. It has been suggested that the ability of the body to absorb the impact of the ground reaction forces while running, which can be up to four times those of walking, may change as a runner becomes fatigued. Nyland et al. (1994) concluded that running while fatigued would result in a diminished stabilizing capacity of the runner's muscles.

Internal tissues such as ligaments, cartilage, and bones would absorb the loads delivered to the feet. If these loads were perceived to become too harmful, Nigg, Bahlsen, Luethi, and Stokes (1987) stated that these runners have the ability to alter their technique in response. Other authors have suggested that changes associated with fatiguing exercise were made to increase running efficiency rather than to prevent injury. As there were no significant technique alterations or adaptations to fatigue with the runners in the present study, the smaller, individual changes could very well have been those associated with increasing running efficiency. Noting Tables 4.3 and 4.4, of 10 km lap times and 100 km running times, respectively, the consistency of subjects is apparent, alone an indication of their efficiency. While running, subjects of the Williams et al. (1991) investigation showed a markedly faster cadence and tended to increase loading under the first metatarsal with increases in fatigue. As well loading characteristics of the heel regions were also significantly reduced during this condition.

4.10 Fatigued Running

Morgan et al. (1996) observed short-term changes in 10 km race pace gait mechanics following a bout of high intensity distance running. Their investigation showed no significant changes of biomechanical variables, including shank angle at heel strike, mean trunk angle throughout the stride cycle, maximum knee flexion angle during stance and the maximum vertical excursion of the center of mass. The reasoning for the lack of significant changes was that the imposed workload, while being demanding, was not of sufficient duration or intensity to alter basic motor unit recruitment patterns; in which a high intensity run would feature the recruitment of type II fibers, and may result in type II motor units providing a greater contribution to output force generation. Though

Morgan et al. (1996) didn't test this hypothesis the lack of intensity and workload seemed to be a plausible suggestion. The 100 km distance of this study was thought to be sufficiently demanding to be able to alter basic motor unit recruitment patterns. The results of this study would support the theoretical perspective from Morgan et al. (1996) that gait mechanics are not easily perturbed in highly efficient and trained runners.

Candau et al. (1998) investigated energy cost and running mechanics during a treadmill run to voluntary exhaustion and noted that no relationship between the mechanical cost of running and the energy cost of running has been observed in a fatigued state. Candau et al. (1998) summarized that the increase in energy cost with fatigue could be due to a combination of physiological and mechanical parameters. Dickinson, Cook, and Leinhardt (1985) measured the shock waves on the body during both a fatigued and unfatigued run. Cavanagh and Lafortune (1980) concluded that the initial peak correlates with the vertical impact force of heel landing, and the maximum vertical peak correlated with forefoot loading. The forces of impact loading are mainly absorbed by the system with muscle, bone, cartilage and joint movements. Along with this notion is the finding by both Paul et al. (1978) and Dickinson et al. (1985) that the timing of the maximum heel strike spike is related to the vibrational frequency of the axial skeleton. In the study by Dickinson et al. (1985) there was no noticeable change in the vibrational frequency before or after fatigue. Though no change in the vibrational frequency was seen, the magnitude of the heel strike increased with fatigue, from 186% of bodyweight to 203% of bodyweight when measures at 15 min, 30 min, and 45 min into the fatiguing treadmill run were taken. It was postulated that the change in heel strike magnitude with fatigue could be due to many factors including altered gait due to fatigue, decreased capacity to attenuate fatigued muscle, or even altered proprioception and pain sensation resulting form the release of the body's own endorphins. Though the magnitude of forces was not measured in the present study, it could be of interest in future research to investigate these forces and whether there was a change in the magnitude of the heel strike over time. One would expect to see an increase in the magnitude of heel strike over time, as the runners fatigued, assuming the bottom three runners fatigued more rapidly.

Ito, Komi, Sjordin, Bosco, and Karlsson (1983) investigated mechanical efficiency of positive work in running at different speeds and concluded that the mechanical efficiency during positive work of the running stride cycle stayed approximately the same at all measured running speeds, ranging from 7 km/hr to 22 km/hr.

Cavanagh et al. (1977) studied a number of biomechanical measures on a group of elite and a group of good distance runners and concluded that only minor, nonsignificant differences existed between the two groups. Primarily the good distance runners took longer strides; with the angular kinematics of the lower extremity, vertical oscillations, and muscle torques during swing being very similar for the two groups. Looking at Figures 4.1 – 4.9 it appeared that, in this study, any possible significant differences in VO_2 max of the subjects participating in this study, could not be directly linked to differences in the biomechanical parameters measured.

4.11 Jerk Cost

Jerk cost was not taken into consideration for a number of reasons. The endpoint jerk-cost criterion is the integral of the mean squared jerk function, being the third derivative of position (as the third derivative of position, though smoothed to an acceptable level, resulted in magnifying the amplitude of any random errors to an unacceptable level making the jerk-cost unreliable as a measure of movement consistency). For this reason the end point jerk-cost was not a variable that was investigated further.

CHAPTER 5

Summary and Conclusions

5.1 Summary

This study was undertaken in an attempt to gain an understanding of running mechanics and any kinematic deterioration that may occur with ultra-marathon running in particular. The purpose of this study was to determine the extent to which gait kinematics change during the course of a 100 km ultra-marathon. Thirteen subjects were filmed while running ten laps of a 10 km looped course. One camera was used during filming, capturing one stride of each subject at each 10 km interval. This data was then transformed into specific lower body kinematic parameters with the use of the Ariel APAS motion analysis system.

Based on the results of this study, it is possible to conclude that no variables attained statistically significant change for the 100 km distances. There were no statistically significant findings between the top ten elite finishers and the bottom three elite finishers. However, there were noticeable, nonsignificant, differences between individual runners. The kinematic variables of the top ten elite finishers appeared to become more similar as the 100 km run progressed. Vertical oscillations, forward trunk lean with respect to vertical, thigh angle with respect to the horizontal, hip and knee joint angle, and shank angle with respect to vertical showed individual changes, which although not significantly different, these small changes usually highlighted the consistency between subjects and distances.

5.2 Recommendations for future research

This was one of the few field studies focused on the biomechanics of the running gait during a race longer than a standard marathon, and the first study of a distance of 100 km. Therefore, the opportunities for future research are numerable. A prime recommendation for further investigation is continued field and laboratory study with the combination of physiological data collection, including blood lactate and VO_2 max, as well as biomechanical data collection. A laboratory setting would allow for a controlled environment where the collection of many strides could occur at any predetermined intervals. Though this study was able to investigate kinematic variables of the lower limb segments in the sagittal plane it would be of great importance to look at both the upper body segments and lower body segments through other planes. With respect to the actual data collection, future recommendations include increasing the volume of the area of capture in addition to the horizontal length of the area. This would allow for more measures to be taken when athletes are running side by side or on the far or near side of the running lane. As well, it is recommended that a longer area, along the sagittal plane, be captured. Although this study was restricted by race organizers as to where the camera setup could occur, it would be ideal that at least two full stride cycles at each predetermined distance would be analyzed.

An increased sample size will improve generalizability of the findings within the study. In order to separate this study from others that focus on a two-dimensional view it could be of interest to research a three dimensional view of the running gait over such a long distance. A further step in the realm of ultra-distance gait research would be to focus on the kinetics of the movement. This could be accomplished through the use of force plates and such equipment as in-shoe pressure sensors. The jerk cost could easily and reliably be studied through the use of an accelerometer placed on the particular segment or segments of interest. This measure would allow “smoothness” to be quantified for each runner at different levels of fatigue and over time.

The conclusions of this study could be provided to the athletes themselves with some training recommendations and points of interest. The top six finishers displayed very consistent times for each 10 km lap that the other runners were unable to follow. It seems that runners with a strategy of quicker and slower 10 km laps were not as effective as those runners who chose to maintain a fairly even pace throughout the race, even though at times throughout the race, they were trailing the others.

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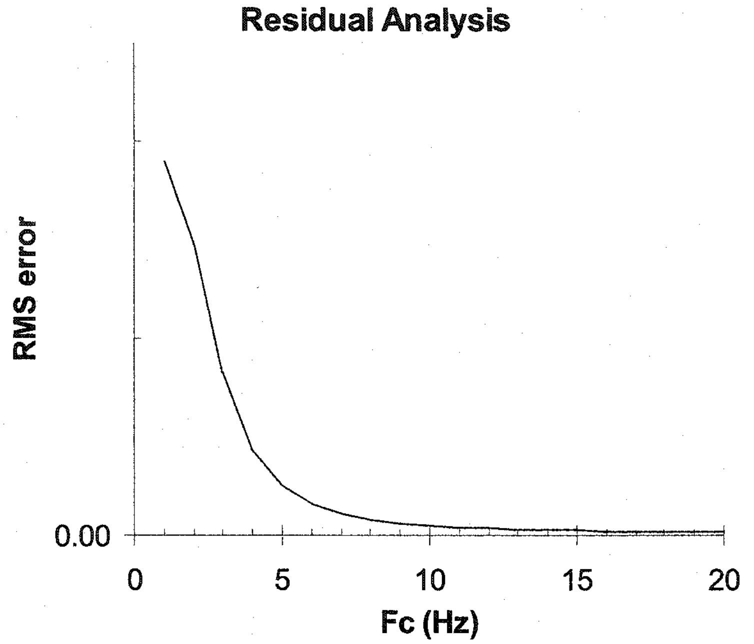
APPENDICES

- Appendix A – Data Smoothing and Error Assessment
- Appendix B – Smoothed Kinematic Data for One Subject
- Appendix C – Thigh/Knee Angle-Angle Diagrams for All Subjects
- Appendix D – Statistical Measures

Appendix A-

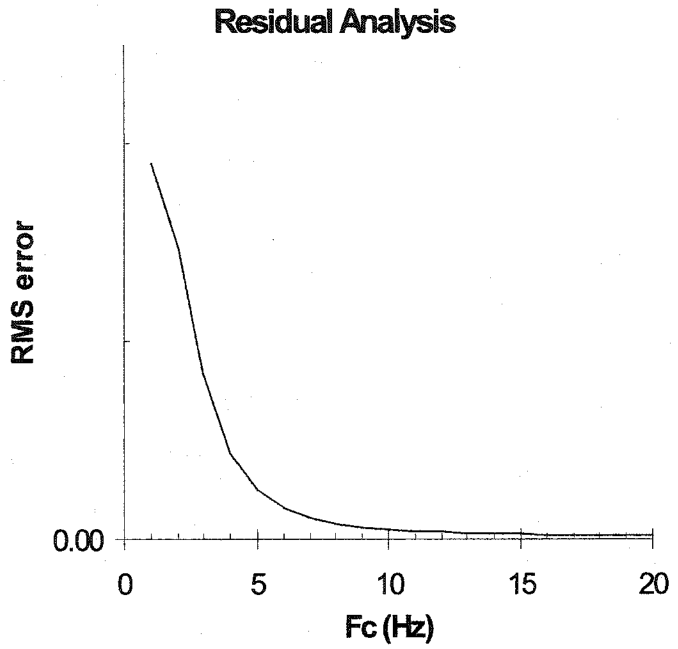
Data Smoothing and Error Assessment

Hip X	
Table of "fc" values and associated RMSerror	
fc	**RMS**
1.0	0.0706
2.0	0.0154
3.0	0.0088
4.0	0.0060
5.0	0.0044
6.0	0.0035
7.0	0.0028
8.0	0.0024
9.0	0.0020
10.0	0.0018
11.0	0.0016
12.0	0.0014
13.0	0.0013
14.0	0.0012
15.0	0.0011
16.0	0.0010
17.0	0.0010
18.0	0.0009
19.0	0.0008
20.0	0.0008



Residual Analysis = 6 Hz
Smoothed at 5 Hz

Hip Y	
Table of "fc" values and associated RMSerror	
fc	**RMS**
1.0	0.0190
2.0	0.0148
3.0	0.0083
4.0	0.0044
5.0	0.0025
6.0	0.0016
7.0	0.0011
8.0	0.0008
9.0	0.0006
10.0	0.0005
11.0	0.0004
12.0	0.0004
13.0	0.0003
14.0	0.0003
15.0	0.0003
16.0	0.0002
17.0	0.0002
18.0	0.0002
19.0	0.0002
20.0	0.0002



Residual Analysis = 6 Hz
Smoothed at 6 Hz

Measuring precision

Correlations

Subject B1

1st	2nd	1st	2nd
Hip Joint	Hip Joint-2	Knee Joint	Knee Joint-2
145.246	141.020	159.073	153.682
146.168	142.650	153.881	149.098
146.812	143.810	148.099	143.708
147.137	144.381	141.834	137.684
147.430	144.777	135.716	132.019
148.134	145.691	130.721	127.954
149.618	147.668	127.709	126.131
152.093	150.858	127.055	126.357
155.656	155.120	128.659	128.154
160.366	160.298	132.235	131.398
166.223	166.335	137.501	136.356
173.030	173.095	144.087	143.077
179.715	179.868	151.259	150.782
172.963	173.495	157.751	157.800
167.504	168.557	161.986	162.173
163.971	165.591	162.668	162.527
162.499	164.588	159.411	158.644
162.760	165.108	152.885	151.425
164.062	166.502	144.288	142.264
165.643	168.193	134.640	132.282
167.080	169.897	124.463	122.024
168.546	171.659	113.981	111.715
170.643	173.707	103.526	101.652
173.994	176.273	93.556	92.238
178.842	179.477	84.237	83.610
175.196	176.725	75.282	75.342
Correlation		Correlation	
0.99388957		**0.997812**	

Appendix B-

Smoothed Kinematic Data for One Subject

10km

ChanDesc	hip RY	ankle RX	ankle RY	trunk DZ	trunk VZ	thigh DZ
X-Axis	Time	Time	Time	Time	Time	Time
X-Units	Sec	Sec	Sec	Sec	Sec	Sec
Y-Units	M	M	M	Deg	Deg/s	Deg
1st Sample	1.000	1.000	1.000	1.000	1.000	1.000
X1st	2.117	2.117	2.117	2.117	2.117	2.117
Xinc	0.017	0.017	0.017	0.017	0.017	0.017
#Saved	30.000	30.000	30.000	30.000	30.000	30.000
	0.570	0.052	0.158	90.661	111.307	130.400
	0.577	0.147	0.131	92.515	111.107	133.571
	0.593	0.289	0.104	94.355	109.082	136.236
	0.609	0.428	0.065	96.114	100.373	137.924
	0.643	0.570	0.034	97.643	81.052	138.440
	0.633	0.692	-0.005	98.766	52.708	137.933
	0.615	0.830	-0.057	99.386	21.912	136.786
	0.648	0.963	-0.084	99.519	-4.960	135.333
	0.652	1.072	-0.106	99.255	-25.601	133.640
	0.633	1.166	-0.136	98.693	-41.187	131.571
	0.616	1.252	-0.141	97.899	-53.740	129.091
	0.611	1.299	-0.158	96.910	-64.790	126.459
	0.618	1.342	-0.179	95.739	-75.857	124.046
	0.600	1.361	-0.180	94.369	-89.041	121.984
	0.591	1.381	-0.180	92.748	-106.089	119.981
	0.586	1.381	-0.171	90.814	-126.191	117.465
	0.598	1.389	-0.180	88.550	-144.683	113.911
	0.580	1.381	-0.184	86.037	-154.952	109.192
	0.570	1.392	-0.167	83.456	-152.465	103.648
	0.570	1.400	-0.167	81.027	-136.806	97.827
	0.590	1.412	-0.147	78.952	-110.602	92.151
	0.585	1.416	-0.142	77.373	-78.237	86.830
	0.618	1.447	-0.113	76.345	-45.673	81.901
	0.634	1.470	-0.105	75.816	-19.497	77.278
	0.637	1.520	-0.085	75.636	-3.961	72.858
	0.636	1.548	-0.068	75.628	1.682	68.751
	0.635	1.594	-0.035	75.665	2.372	65.426
	0.635	1.641	-0.006	75.710	3.443	63.455
	0.634	1.695	0.032	75.794	7.106	63.017
	0.628	1.754	0.069	75.952	11.707	63.752

30.000	30.000	30.000	30.000	30.000	30.000	30.000
193.577	10.116	493.311	140.261	-82.270	59.716	299.733
180.708	18.343	497.609	138.943	-69.601	64.771	316.900
134.075	26.899	534.836	138.119	-24.993	70.663	400.761
66.301	36.296	592.165	138.191	34.071	78.373	525.864
-2.711	46.522	627.454	139.203	83.763	88.082	630.165
-53.680	56.940	614.320	140.833	106.388	99.006	668.000
-80.155	66.758	557.852	142.600	102.068	109.972	638.007
-93.620	75.368	470.503	144.185	88.661	120.035	564.124
-111.465	82.306	357.603	145.615	85.864	128.666	469.069
-137.539	87.167	222.131	147.122	96.352	135.596	359.670
-157.060	89.618	69.959	148.808	103.320	140.527	227.019
-154.367	89.469	-87.467	150.451	89.577	143.010	66.900
-133.445	86.761	-233.884	151.692	57.588	142.715	-100.439
-117.151	81.852	-347.198	152.385	28.110	139.868	-230.047
-129.423	75.531	-398.374	152.767	23.334	135.550	-268.951
-178.373	68.982	-376.367	153.350	52.183	131.518	-197.993
-249.381	63.208	-313.935	154.639	104.698	129.297	-64.554
-312.905	58.485	-256.150	156.846	157.953	129.294	56.755
-346.092	54.548	-219.648	159.807	193.627	130.899	126.445
-347.951	51.097	-195.109	163.200	211.146	133.270	152.843
-331.032	48.057	-168.481	166.801	220.431	135.905	162.551
-307.167	45.535	-132.026	170.544	228.930	138.705	175.141
-285.240	43.706	-86.348	174.444	239.567	141.804	198.892
-270.795	42.621	-46.888	178.512	248.958	145.343	223.907
-258.559	41.947	-42.555	177.222	-254.598	149.089	216.004
-228.947	40.907	-91.491	173.123	-230.629	152.155	137.455
-163.434	38.663	-182.698	169.761	-165.806	153.237	-19.264
-71.075	34.732	-288.950	167.745	-74.519	151.277	-217.875
14.217	29.077	-386.162	167.223	7.111	146.060	-400.379
67.745	22.008	-455.581	167.800	56.038	138.256	-523.326

50km

ChanDesc	hip DY	ankle DX	ankle DY	trunk DZ	trunk VZ	thigh DZ
X-Axis	Time	Time	Time	Time	Time	Time
X-Units	Sec	Sec	Sec	Sec	Sec	Sec
Y-Units	M	M	M	Deg	Deg/s	Deg
1st Sample	1.000	1.000	1.000	1.000	1.000	1.000
X1st	0.033	0.033	0.033	0.033	0.033	0.033
Xinc	0.017	0.017	0.017	0.017	0.017	0.017
#Saved	27.000	27.000	27.000	27.000	27.000	27.000
	0.589	0.178	-0.144	91.528	83.294	140.692
	0.589	0.322	-0.194	92.855	72.736	139.826
	0.588	0.457	-0.237	93.881	49.213	138.460
	0.587	0.578	-0.271	94.495	25.544	136.437
	0.585	0.681	-0.294	94.780	10.319	133.964
	0.581	0.763	-0.311	94.878	2.059	131.303
	0.574	0.825	-0.323	94.839	-7.928	128.534
	0.565	0.870	-0.334	94.563	-27.070	125.670
	0.554	0.902	-0.343	93.886	-55.283	122.885
	0.542	0.927	-0.350	92.706	-85.967	120.425
	0.531	0.945	-0.354	91.047	-111.728	118.224
	0.522	0.959	-0.356	89.028	-129.006	115.714
	0.517	0.968	-0.356	86.790	-138.362	112.202
	0.517	0.970	-0.354	84.450	-141.361	107.452
	0.521	0.971	-0.350	82.114	-137.711	101.901
	0.529	0.973	-0.344	79.906	-125.545	96.237
	0.539	0.981	-0.334	77.979	-104.289	90.790
	0.550	0.999	-0.321	76.462	-77.087	85.471
	0.561	1.026	-0.307	75.407	-50.188	80.202
	0.570	1.061	-0.291	74.755	-29.373	75.255
	0.576	1.102	-0.270	74.385	-16.204	71.154
	0.581	1.150	-0.242	74.192	-7.281	68.334
	0.583	1.206	-0.204	74.149	2.823	66.969
	0.582	1.274	-0.160	74.311	17.505	67.026
	0.578	1.356	-0.112	74.755	36.156	68.381
	0.572	1.455	-0.065	75.519	55.176	70.820
	0.563	1.568	-0.021	76.572	70.193	73.997

thigh VZ	shank DZ	shank VZ	trunk-thigh D3D	trunk-thigh V3D	thigh-shank D3D	thigh-shank V3D
Time	Time	Time	Time	Time	Time	Time
Sec	Sec	Sec	Sec	Sec	Sec	Sec
Deg/s	Deg	Deg/s	Deg	Deg/s	Deg	Deg/s
1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.033	0.033	0.033	0.033	0.033	0.033	0.033
0.017	0.017	0.017	0.017	0.017	0.017	0.017
27.000	27.000	27.000	27.000	27.000	27.000	27.000
-46.358	65.582	592.056	130.836	129.652	104.890	638.414
-63.318	74.989	528.879	133.029	136.054	115.163	592.198
-102.134	83.032	431.590	135.422	151.347	124.572	533.724
-137.770	89.240	308.319	138.058	163.314	132.802	446.089
-155.882	93.196	163.663	140.816	166.201	139.232	319.545
-162.921	94.681	16.402	143.575	164.980	143.378	179.323
-169.651	93.841	-112.562	146.305	161.723	145.307	57.089
-172.012	91.070	-215.664	148.893	144.942	145.400	-43.652
-158.861	86.773	-296.724	151.001	103.578	143.888	-137.863
-136.505	81.312	-353.528	152.280	50.538	140.887	-217.023
-134.056	75.198	-372.365	152.823	22.328	136.975	-238.309
-175.129	69.135	-348.555	153.314	46.124	133.421	-173.425
-248.984	63.704	-301.855	154.588	110.622	131.502	-52.872
-315.691	59.041	-260.406	156.999	174.330	131.590	55.284
-342.207	54.940	-233.723	160.213	204.496	133.039	108.483
-334.007	51.253	-206.518	163.670	208.463	135.016	127.489
-321.240	48.158	-160.761	167.188	216.951	137.368	160.479
-318.352	45.967	-101.567	170.991	241.265	140.496	216.785
-310.836	44.677	-59.438	175.205	260.648	144.475	251.398
-276.647	43.710	-66.803	179.475	245.795	148.455	209.845
-210.706	42.146	-128.917	176.769	-194.503	150.991	81.789
-126.081	39.248	-220.933	174.143	-118.800	150.913	-94.852
-38.374	34.784	-312.303	172.820	-41.197	147.815	-273.929
44.002	28.938	-384.837	172.715	26.497	141.912	-428.839
116.542	22.087	-433.010	173.627	80.385	133.705	-549.552
172.529	14.627	-458.541	175.301	117.353	123.807	-631.070
204.078	6.907	-464.472	177.425	133.886	112.910	-668.550

70km

ChanDesc	hip DY	ankle DX	ankle DY	trunk DZ	trunk VZ	thigh DZ
X-Axis	Time	Time	Time	Time	Time	Time
X-Units	Sec	Sec	Sec	Sec	Sec	Sec
Y-Units	M	M	M	Deg	Deg/s	Deg
1st Sample	1.000	1.000	1.000	1.000	1.000	1.000
X1st	0.500	0.500	0.500	0.500	0.500	0.500
Xinc	0.017	0.017	0.017	0.017	0.017	0.017
#Saved	34.000	34.000	34.000	34.000	34.000	34.000
	0.594	0.060	-0.045	97.513	-30.859	143.271
	0.598	0.190	-0.077	97.008	-29.249	142.003
	0.601	0.313	-0.107	96.547	-25.978	140.300
	0.602	0.423	-0.135	96.145	-22.274	137.971
	0.602	0.518	-0.160	95.809	-17.742	135.009
	0.600	0.597	-0.182	95.563	-11.421	131.480
	0.596	0.658	-0.204	95.428	-5.214	127.535
	0.591	0.704	-0.225	95.353	-5.469	123.594
	0.585	0.734	-0.241	95.171	-19.111	120.289
	0.576	0.753	-0.250	94.639	-46.637	117.989
	0.567	0.766	-0.251	93.586	-79.477	116.383
	0.558	0.775	-0.246	92.024	-106.022	114.644
	0.550	0.783	-0.240	90.118	-120.673	111.992
	0.545	0.789	-0.236	88.050	-126.386	108.139
	0.543	0.792	-0.233	85.922	-128.770	103.330
	0.547	0.796	-0.227	83.770	-128.878	98.089
	0.554	0.804	-0.217	81.663	-122.290	92.886
	0.564	0.818	-0.204	79.755	-104.600	87.906
	0.575	0.840	-0.189	78.233	-76.556	83.054
	0.586	0.868	-0.174	77.226	-44.186	78.285
	0.596	0.901	-0.159	76.739	-15.487	73.941
	0.603	0.940	-0.140	76.655	3.253	70.582
	0.609	0.983	-0.112	76.783	10.212	68.481
	0.611	1.032	-0.077	76.949	8.852	67.509
	0.610	1.087	-0.035	77.068	5.804	67.588
	0.607	1.153	0.008	77.165	6.801	68.922
	0.599	1.230	0.048	77.328	13.648	71.583
	0.590	1.320	0.084	77.641	24.378	75.203
	0.579	1.423	0.114	78.142	35.440	79.304
	0.567	1.538	0.136	78.806	43.479	83.698
	0.556	1.664	0.151	79.561	45.999	88.400
	0.546	1.795	0.156	80.304	42.042	93.484
	0.538	1.926	0.156	80.937	33.375	99.265
	0.531	2.050	0.152	81.416	24.653	106.192

thigh VZ	shank DZ	shank VZ	trunk-thigh D3D	trunk-thigh V3D	thigh-shank D3D	thigh-shank V3D
Time	Time	Time	Time	Time	Time	Time
Sec	Sec	Sec	Sec	Sec	Sec	Sec
Deg/s	Deg	Deg/s	Deg	Deg/s	Deg	Deg/s
1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.500	0.500	0.500	0.500	0.500	0.500	0.500
0.017	0.017	0.017	0.017	0.017	0.017	0.017
34.000	34.000	34.000	34.000	34.000	34.000	34.000
-70.248	59.881	628.141	134.241	39.389	96.610	698.389
-86.046	70.170	590.205	135.005	56.797	108.167	676.251
-120.105	79.168	482.113	136.247	94.127	118.867	602.218
-159.179	86.151	356.118	138.174	136.905	128.180	515.297
-195.564	91.108	241.562	140.799	177.821	136.099	437.126
-226.818	94.263	137.670	144.083	215.397	142.784	364.488
-242.206	95.652	25.759	147.893	236.991	148.117	267.964
-223.262	95.000	-107.951	151.759	217.793	151.406	115.311
-168.717	92.005	-250.217	154.882	149.606	151.716	-81.500
-110.721	86.838	-359.568	156.650	64.084	148.850	-248.847
-91.324	80.425	-395.130	157.203	11.846	144.042	-303.806
-125.902	74.070	-357.967	157.380	19.880	139.426	-232.065
-195.091	68.646	-292.957	158.125	74.418	136.654	-97.866
-264.272	64.219	-243.084	159.912	137.886	136.080	21.188
-307.017	60.407	-217.536	162.592	178.246	137.077	89.481
-316.766	56.917	-200.798	165.682	187.887	138.829	115.967
-305.503	53.767	-173.997	168.777	183.212	140.882	131.505
-293.478	51.229	-127.033	171.849	188.878	143.323	166.445
-289.808	49.588	-70.241	175.179	213.252	146.534	219.567
-278.557	48.747	-38.513	178.920	232.694	150.462	240.044
-235.896	47.982	-64.531	177.201	-220.409	154.041	171.365
-164.120	46.298	-144.323	173.927	-167.373	155.716	19.797
-90.377	43.048	-246.625	171.698	-100.589	154.567	-156.249
-27.632	38.070	-349.647	170.560	-36.483	150.561	-322.015
40.168	31.434	-443.770	170.520	34.364	143.845	-483.938
121.335	23.457	-504.610	171.757	114.534	134.535	-625.944
193.463	14.968	-502.356	174.255	179.815	123.386	-695.819
235.209	7.032	-442.548	177.549	208.459	111.829	-677.757
255.253	0.373	-353.337	178.838	-219.813	101.069	-608.590
272.418	-4.677	-250.744	175.109	-228.939	91.625	-523.162
291.851	-7.948	-140.887	171.161	-245.852	83.652	-432.738
321.198	-9.360	-28.752	166.820	-279.156	77.156	-349.950
378.528	-8.946	75.273	161.671	-345.153	71.789	-303.255
451.223	-7.045	144.364	155.224	-426.570	66.763	-306.859

90km

ChanDesc	hip DY	ankle DX	ankle DY	trunk DZ	trunk VZ	thigh DZ
X-Axis	Time	Time	Time	Time	Time	Time
X-Units	Sec	Sec	Sec	Sec	Sec	Sec
Y-Units	M	M	M	Deg	Deg/s	Deg
1st Sample	1.000	1.000	1.000	1.000	1.000	1.000
X1st	1.667	1.667	1.667	1.667	1.667	1.667
Xinc	0.017	0.017	0.017	0.017	0.017	0.017
#Saved	27.000	27.000	27.000	27.000	27.000	27.000
	0.612	0.002	0.128	80.960	-20.936	81.661
	0.592	0.114	0.152	80.646	-14.669	84.626
	0.573	0.227	0.172	80.534	2.874	88.015
	0.554	0.344	0.186	80.785	28.098	92.190
	0.538	0.465	0.194	81.486	56.065	97.337
	0.525	0.589	0.194	82.641	81.694	103.409
	0.517	0.712	0.186	84.176	101.388	110.109
	0.514	0.829	0.172	85.980	113.819	116.951
	0.515	0.941	0.152	87.931	118.958	123.402
	0.522	1.051	0.127	89.905	116.572	128.991
	0.534	1.165	0.097	91.771	105.882	133.357
	0.548	1.286	0.065	93.387	86.559	136.277
	0.565	1.414	0.031	94.618	60.132	137.736
	0.579	1.546	-0.004	95.375	30.672	137.946
	0.590	1.679	-0.038	95.655	3.881	137.243
	0.596	1.807	-0.072	95.546	-15.389	135.888
	0.597	1.927	-0.103	95.190	-25.926	133.959
	0.592	2.034	-0.132	94.710	-31.297	131.424
	0.585	2.126	-0.159	94.138	-38.299	128.348
	0.577	2.201	-0.182	93.389	-53.334	125.052
	0.567	2.259	-0.201	92.305	-78.128	122.042
	0.556	2.303	-0.215	90.763	-106.593	119.700
	0.544	2.333	-0.225	88.803	-125.729	117.998
	0.532	2.353	-0.230	86.694	-122.830	116.432
	0.520	2.364	-0.231	84.845	-95.267	114.168
	0.509	2.370	-0.229	83.594	-54.035	110.409
	0.501	2.373	-0.225	83.015	-17.936	104.905

thigh VZ	shank DZ	shank VZ	trunk-thigh D3D	trunk-thigh V3D	thigh-shank D3D	thigh-shank V3D
Time	Time	Time	Time	Time	Time	Time
Sec	Sec	Sec	Sec	Sec	Sec	Sec
Deg/s	Deg	Deg/s	Deg	Deg/s	Deg	Deg/s
1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.667	1.667	1.667	1.667	1.667	1.667	1.667
0.017	0.017	0.017	0.017	0.017	0.017	0.017
27.000	27.000	27.000	27.000	27.000	27.000	27.000
173.843	6.474	-359.219	179.299	-194.779	104.813	-533.062
186.414	0.412	-359.804	176.020	-201.083	95.786	-546.218
224.032	-5.223	-307.272	172.518	-221.158	86.761	-531.304
278.815	-9.565	-206.784	168.594	-250.717	78.245	-485.598
338.242	-11.935	-73.234	164.149	-282.177	70.728	-411.475
387.125	-11.899	79.673	159.231	-305.430	64.692	-307.452
411.479	-9.267	234.285	154.068	-310.091	60.624	-177.194
403.875	-4.225	364.310	149.029	-290.056	58.824	-39.565
365.321	2.635	451.181	144.528	-246.362	59.232	85.860
301.586	10.605	500.110	140.913	-185.014	61.613	198.523
219.879	19.198	528.618	138.415	-113.996	65.841	308.740
130.326	28.182	548.013	137.110	-43.767	71.905	417.687
47.021	37.435	560.907	136.882	13.112	79.700	513.887
-18.050	46.841	566.008	137.429	48.722	88.895	584.059
-63.452	56.232	557.698	138.411	67.333	98.988	621.151
-98.458	65.298	525.048	139.658	83.069	109.410	623.506
-133.667	73.553	459.663	141.231	107.741	119.594	593.330
-170.129	80.457	364.391	143.286	138.831	129.032	534.520
-195.662	85.591	249.093	145.790	157.363	137.244	444.754
-194.148	88.690	120.761	148.337	140.814	143.637	314.909
-162.620	89.567	-16.578	150.263	84.492	147.524	146.042
-118.569	88.143	-152.415	151.064	11.976	148.444	-33.847
-90.922	84.618	-264.168	150.805	-34.807	146.620	-173.246
-105.969	79.601	-328.433	150.263	-16.861	143.170	-222.465
-174.472	73.951	-342.068	150.678	79.205	139.783	-167.596
-279.476	68.358	-326.386	153.185	225.441	137.949	-46.910
-374.218	63.076	-308.956	158.110	356.282	138.171	65.261

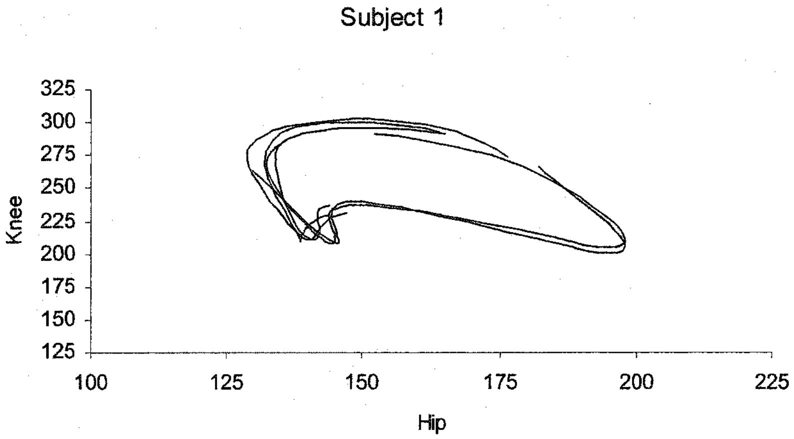
100km

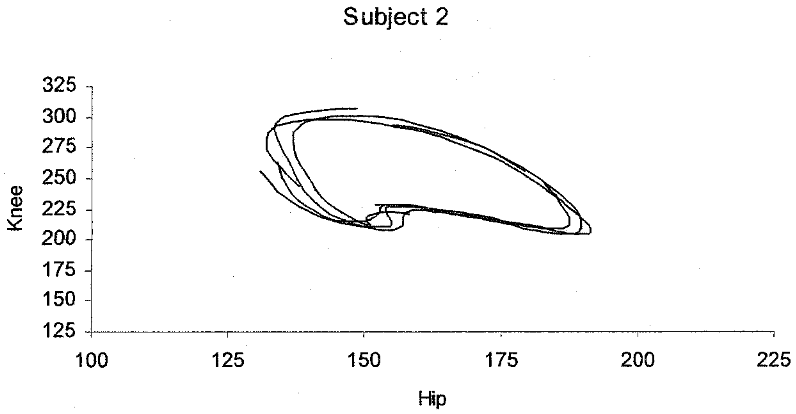
ChanDesc	hip RY	ankle RX	ankle RY	trunk DZ	trunk VZ	thigh DZ
X-Axis	Time	Time	Time	Time	Time	Time
X-Units	Sec	Sec	Sec	Sec	Sec	Sec
Y-Units	M	M	M	Deg	Deg/s	Deg
1st Sample	1.000	1.000	1.000	1.000	1.000	1.000
X1st	1.867	1.867	1.867	1.867	1.867	1.867
Xinc	0.017	0.017	0.017	0.017	0.017	0.017
#Saved	31.000	31.000	31.000	31.000	31.000	31.000
	0.548	0.022	-0.183	86.694	-65.573	114.410
	0.504	0.038	-0.170	85.644	-60.543	110.786
	0.516	0.045	-0.158	84.669	-56.589	105.947
	0.486	0.049	-0.141	83.755	-53.130	99.821
	0.545	0.061	-0.137	82.899	-49.482	93.201
	0.544	0.064	-0.116	82.106	-45.753	86.970
	0.544	0.076	-0.107	81.369	-42.858	81.429
	0.543	0.096	-0.112	80.667	-41.670	76.490
	0.564	0.119	-0.095	79.971	-42.046	72.208
	0.588	0.158	-0.066	79.265	-42.515	68.979
	0.592	0.197	-0.037	78.566	-40.830	67.273
	0.565	0.236	-0.011	77.926	-35.038	67.238
	0.565	0.286	0.030	77.424	-24.479	68.624
	0.564	0.353	0.055	77.131	-10.182	71.056
	0.563	0.415	0.089	77.093	5.655	74.271
	0.537	0.509	0.122	77.316	20.840	78.137
	0.510	0.591	0.142	77.778	34.235	82.572
	0.501	0.709	0.158	78.448	45.910	87.532
	0.500	0.819	0.165	79.301	56.263	93.047
	0.483	0.952	0.172	80.315	64.915	99.154
	0.528	1.074	0.175	81.450	70.675	105.768
	0.515	1.195	0.157	82.652	73.128	112.627
	0.497	1.312	0.152	83.880	74.192	119.359
	0.480	1.418	0.126	85.136	77.150	125.576
	0.500	1.539	0.095	86.471	83.474	130.893
	0.546	1.648	0.073	87.922	90.246	134.957
	0.541	1.768	0.051	89.443	90.387	137.552
	0.557	1.897	-0.009	90.858	76.508	138.664
	0.565	2.017	-0.014	91.906	46.984	138.390
	0.572	2.137	-0.061	92.380	9.673	136.822
	0.588	2.256	-0.104	92.266	-21.043	134.139

thigh VZ Time Sec Deg/s	shank DZ Time Sec Deg	shank VZ Time Sec Deg/s	trunk-thigh D3D Time Sec Deg	trunk-thigh V3D Time Sec Deg/s	thigh-shank D3D Time Sec Deg	thigh-shank V3D Time Sec Deg/s
1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.867	1.867	1.867	1.867	1.867	1.867	1.867
0.017	0.017	0.017	0.017	0.017	0.017	0.017
31.000	31.000	31.000	31.000	31.000	31.000	31.000
-195.481	66.021	-198.520	152.284	129.908	131.611	-3.039
-248.411	62.683	-199.694	154.858	187.867	131.897	48.717
-333.162	59.411	-192.091	158.722	276.573	133.464	141.071
-392.537	56.303	-179.962	163.934	339.407	136.482	212.575
-391.776	53.475	-156.457	169.698	342.294	140.274	235.318
-353.201	51.183	-115.941	175.136	307.448	144.213	237.259
-313.336	49.620	-73.632	179.930	269.909	148.191	239.704
-278.871	48.563	-60.771	175.823	-237.201	152.073	218.101
-230.391	47.302	-100.508	172.237	-188.345	155.093	129.884
-151.630	44.926	-191.941	169.714	-109.115	155.947	-40.311
-51.463	40.759	-309.024	168.708	-10.633	153.485	-257.562
44.176	34.707	-410.554	169.311	79.213	147.469	-454.730
117.896	27.347	-462.538	171.200	142.375	138.723	-580.434
171.171	19.584	-461.344	173.925	181.353	128.529	-632.515
213.372	12.148	-427.484	177.173	206.434	117.877	-640.855
249.745	5.426	-376.601	179.179	-228.905	107.288	-626.345
281.923	-0.308	-307.527	175.206	-247.688	97.120	-589.450
313.632	-4.695	-214.452	170.916	-267.722	87.772	-528.083
348.530	-7.342	-100.457	166.255	-292.267	79.611	-448.986
383.281	-7.996	22.016	161.161	-318.366	72.850	-361.266
407.485	-6.631	140.082	155.681	-336.810	67.601	-267.403
411.554	-3.380	248.203	150.025	-338.426	63.993	-163.351
392.274	1.592	347.088	144.521	-318.082	62.233	-45.186
349.729	8.134	436.038	139.560	-272.578	62.558	86.309
284.352	16.043	509.598	135.578	-200.878	65.150	225.246
200.875	25.001	560.569	132.965	-110.630	70.045	359.694
110.610	34.574	582.388	131.891	-20.222	77.022	471.778
24.172	44.241	572.094	132.194	52.337	85.577	547.922
-56.289	53.515	538.062	133.516	103.273	95.125	594.350
-130.567	62.164	501.068	135.559	140.240	105.342	631.635
-186.513	70.306	478.970	138.127	165.470	116.167	665.483

Appendix C-

Thigh/Knee Angle-Angle Diagrams for All Subjects


Subject 1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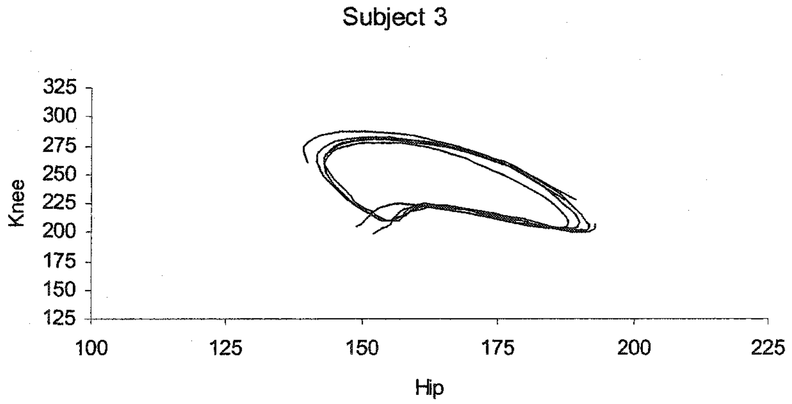
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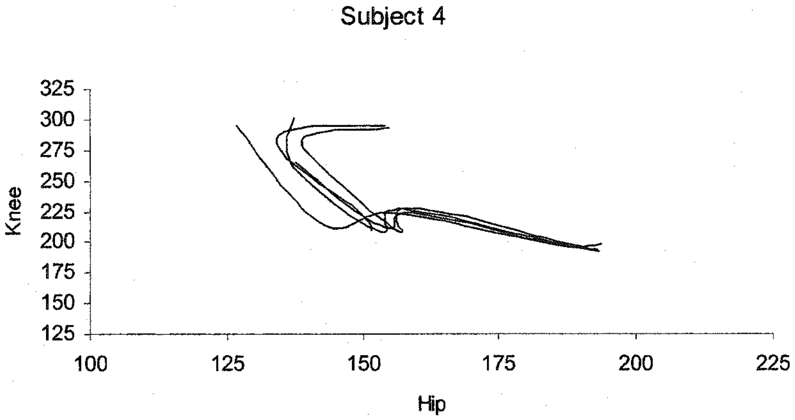
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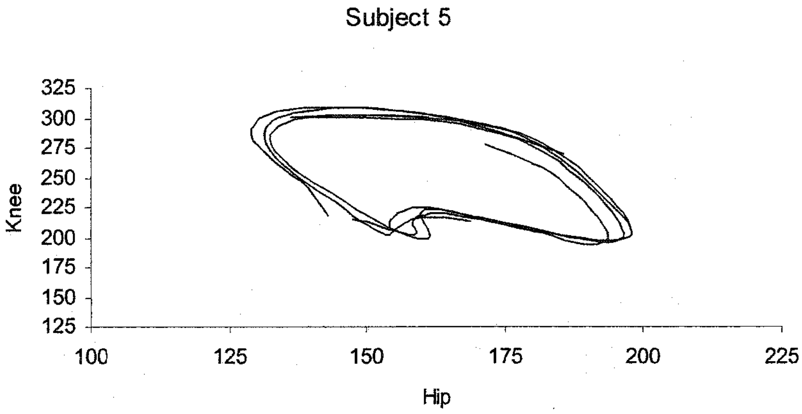
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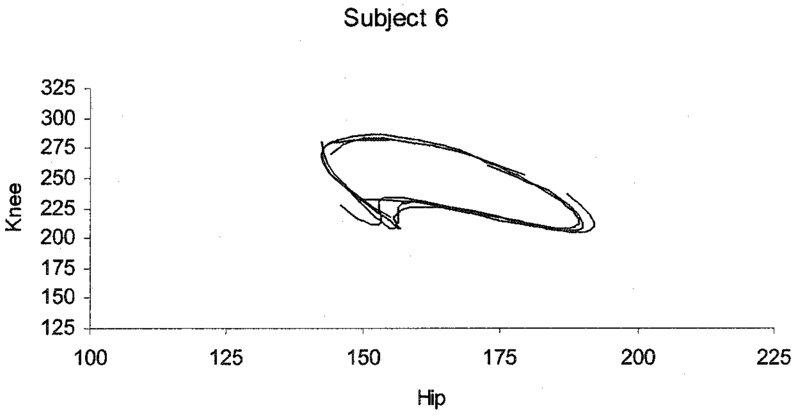
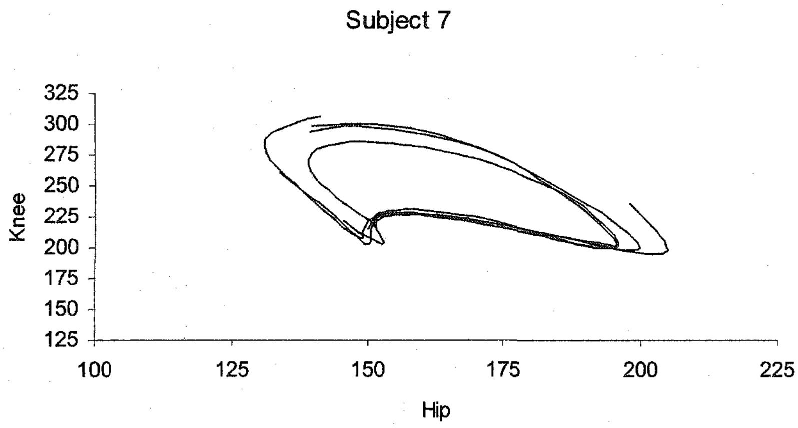
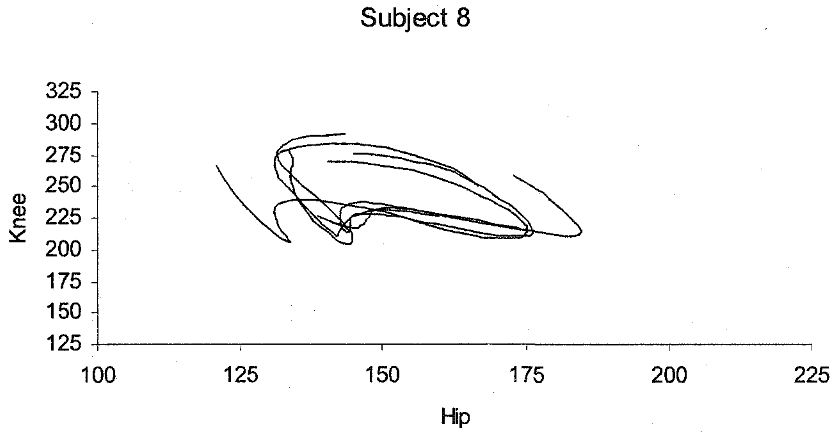
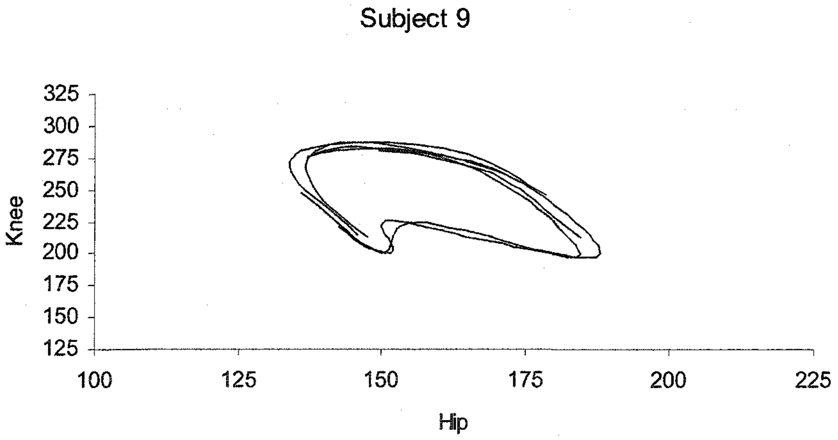
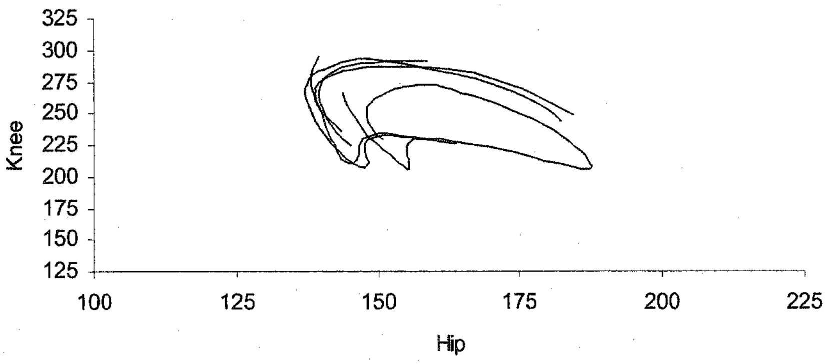

Subject 6


Subject 7
325
300
275
250
225
200
175
150
125
Knee
100
125
150
175
200
225
Hip

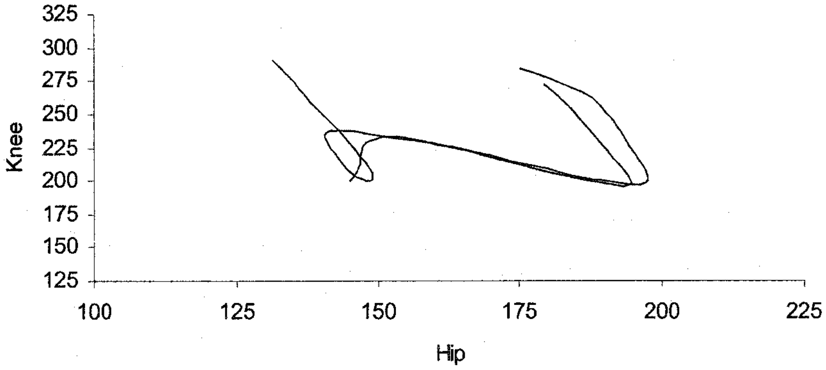

Subject 8
325
300
275
250
225
200
175
150
125
Knee
100
125
150
175
200
225
Hip


Subject 9
325
300
275
250
225
200
175
150
125
Knee
100
125
150
175
200
225
Hip

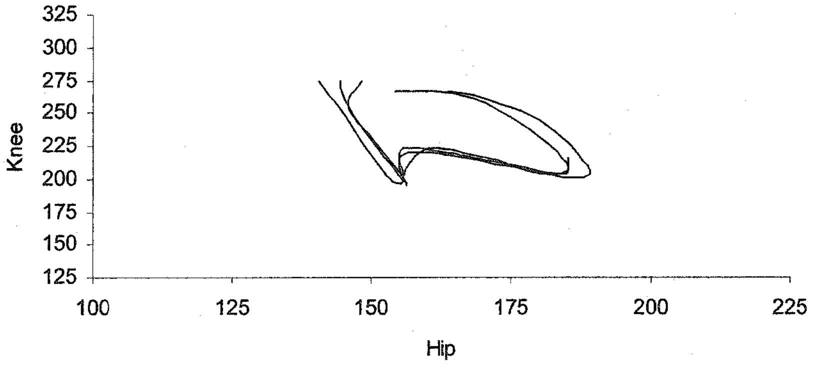
Subject 10

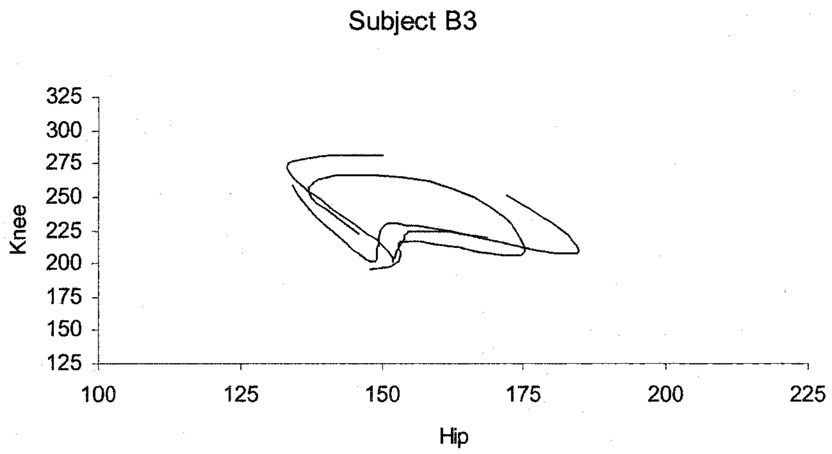


Subject B1



Subject B2




Subject B3
Knee
325
300
275
250
225
200
175
150
125
100
125
150
175
200
225
Hip

Appendix D-
Statistical Measures

Vertical Oscillations

top 10

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.000283	4	7.07E-05	0.140101	0.966427	2.578737
Within Groups	0.022718	45	0.000505			
Total	0.023001	49				

all subjects

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.000441	4	0.000110	0.231951	0.919355	2.525212
Within Groups	0.028520	60	0.000475			
Total	0.028961	64				

Trunk Angle

top 10

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	33.97167	4	8.492917	0.450838	0.771221	2.578737
Within Groups	847.7133	45	18.83807			
Total	881.6849	49				

all subjects

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	30.9395	4	7.734875	0.21065	0.931545	2.525212
Within Groups	2203.148	60	36.71913			
Total	2234.088	64				

Thigh Extension

top 10

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	207.3888	4	51.8472	0.279001	0.890034	2.578737
Within Groups	8362.425	45	185.8317			
Total	8569.813	49				

all subjects
ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	189.8481	4	47.46203	0.316687	0.86573	2.525212
Within Groups	8992.238	60	149.8706			
Total	9182.086	64				

Knee Jt in Support

top 10
ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	72.53447	4	18.13362	0.651533	0.628794	2.578737
Within Groups	1252.45	45	27.83221			
Total	1324.984	49				

all subjects
ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	48.69335	4	12.17334	0.431014	0.785665	2.525212
Within Groups	1694.608	60	28.24347			
Total	1743.301	64				

Knee Jt at Toe-Off

top 10
ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10.06276	4	2.51569	0.088616	0.985556	2.578737
Within Groups	1277.488	45	28.38861			
Total	1287.55	49				

all subjects
ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	20.23271	4	5.058179	0.158956	0.958176	2.525212
Within Groups	1909.269	60	31.82115			
Total	1929.502	64				

Knee Jt in Swing

top 10

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	218.398	4	54.59949	0.686912	0.604785	2.578737
Within Groups	3576.846	45	79.48547			
Total	3795.244	49				

all subjects

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	210.7227	4	52.68068	0.485337	0.746408	2.525212
Within Groups	6512.674	60	108.5446			
Total	6723.396	64				

Shank Angle at Contact

top 10

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.823931	4	0.455983	0.056548	0.993843	2.578737
Within Groups	362.8641	45	8.063647			
Total	364.6881	49				

all subjects

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.210391	4	0.552598	0.069121	0.991044	2.525212
Within Groups	479.6766	60	7.994609			
Total	481.887	64				

Knee Jt ROM

top 10

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	458.9665	4	114.7416	0.578728	0.679541	2.578737
Within Groups	8921.93	45	198.2651			
Total	9380.896	49				

all subjects

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	323.8374	4	80.95935	0.50248	0.733997	2.525212
Within Groups	9667.182	60	161.1197			
Total	9991.019	64				

Coefficients of Variation

Subject	***Vert Osc***	***Trunk Lean***	***Thigh Ext***	***Knee Supp***	***Knee Swing***
1	0.1704797	0.55877596	0.019627	0.0262395	0.022542477
2	0.1602939	0.590258923	0.023187	0.0201359	0.060781603
3	0.1558373	0.395041223	0.034463	0.0081153	0.042417767
4	0.118612	0.728287306	0.013099	0.0160761	0.04646742
5	0.2545206	0.528033862	0.016294	0.0341578	0.064965017
6	0.148218	1.55705946	0.021454	0.0253336	0.021310906
7	0.2326698	0.787993902	0.022647	0.0121334	0.116934943
8	0.3291224	0.46884247	0.021447	0.029722	0.046892345
9	0.1662773	0.408192255	0.012698	0.0094312	0.04288726
10	0.2157203	1.24047291	0.039084	0.0148873	0.122086564
B1	0.0928751	0.259174097	0.01367	0.0194892	0.077959244
B2	0.0686394	0.03902797	0.012813	0.0248586	0.046155687
B3	0.2776	0.511937981	0.043022	0.0338194	0.068595453

Subject	***Knee TO***	***Shank Ang***	***KneeROM***	***Hip Jt ROM***
1	0.0153486	0.353395844	0.023833	0.4302008
2	0.0117522	0.40103473	0.129647	0.5187525
3	0.0127635	0.864773508	0.061455	0.3697622
4	0.02028	0.759784955	0.137612	0.4276721
5	0.0083655	0.347244107	0.051424	0.4181981
6	0.0084666	0.350558649	0.120727	0.4178579
7	0.021026	0.523152748	0.178421	0.4204445
8	0.0176684	0.646580849	0.07833	0.4204381
9	0.0170268	0.388128986	0.083654	0.3713241
10	0.0166402	0.260582126	0.195859	0.4159989
B1	0.0110216	0.083686749	0.040946	0.4086946
B2	0.0381688	0.273190225	0.032475	0.3739086
B3	0.0111198	0.114761988	0.060379	0.3986565