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The effect of measurement technique, and load and fatigue, with changes in crank arm length, on lower limb kinematics in cycle ergometry

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THE EFFECT OF MEASUREMENT TECHNIQUE, AND LOAD AND FATIGUE, WITH CHANGES IN CRANK ARM LENGTH, ON LOWER LIMB KINEMATICS IN CYCLE ERGOMETRY

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ABSTRACT

Lower limb kinematics in a cycling task may be altered by factors which affect the force/torque/power production capabilities of an individual. In a cycling task requiring high power output, high levels of force must be applied to the pedals for a given workload. Pedal forces can be defined by joint moment cost functions which describe the relationship between pedalling rate, crank arm length, and other external mechanical factors at constant power levels. An optimum pedalling rate can be determined for: (1) any given power level and bicycle-rider geometry (defined by external mechanical factors), and (2) with different levels of average constant power yielding different optimization values. Changes in pedalling rate in a task where power output is not constant may result in changes in optimum values contributing to bicycle-rider geometry. With the assumption that no changes occur in the physical dimensions of the cycle ergometer, it may be speculated that joint angle kinematics will change. Changes in joint angle kinematics may be a result of factors which affect pedalling rate and power output (changes in workload and fatigue); and these changes may be further affected by crank arm length. Eight males of recreational cycling experience were tested and measured on a cycle ergometer with a basket, plate-loaded resistance. Four joint angle measurement conditions (static, unloaded, loaded non-fatigued, loaded fatigued) were examined at five different crank arm lengths (10.16, 13.34, 17.15, 22.23, and 26.04 cm) with the minimum

and maximum joint angles of the hip, knee, and ankle determined. DB MANOVA's and post-hoc tests revealed significant differences ($p < 0.05$) between each measurement condition at various crank arm lengths for the minimum and maximum joint angle values of the hip, knee, and ankle. It was concluded that in a cycling task where power output decreases, changes in pedalling rate can result in changes in lower limb joint angle kinematics.

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CHAPTER 1

INTRODUCTION

The role of biomechanics and its application to cycle ergometry has been examined from a variety of areas. These areas have included an examination of the environmental, internal mechanical, and external mechanical factors (Too, 1988, 1990). Environmental factors include gravity, friction, aerodynamic drag, and rolling resistance. Internal mechanical factors are related to force and power generated by the rider and include the force-length relationship and force-velocity relationship of the muscle, the muscle fiber architecture, the lever classification of the skeletal articulations involved in the movement, the force arm length, and the muscle moment arm length. Changes and interactions that occur in the internal mechanical factors are often the result of manipulations of external mechanical factors. External mechanical factors include cycling body position and orientation to the ground, seat to pedal distance, seat height, pedal crank arm length, and lower limb kinematics (in addition to gear ratios, wheel size, wheel mass, wheel diameter, and bicycle mass). As the external factors of cycle ergometry are manipulated, so are the internal mechanical factors.

It is possible to define the external mechanical factors of cycle ergometry as the position of the rider in terms of body position, body orientation, and body configuration.

The term body position refers to the location of the cyclist relative to the pedal axle of the bicycle. It is determined by the angle of the bicycle seat tube and a vertical line (perpendicular to the ground) passing through the pedal axle (Too, 1988, 1990). The term body orientation refers to the posture of the cyclist as defined by the angle of the cyclist's trunk relative to the ground (Too, 1988, 1990). Body configuration refers to the posture of the cyclist as defined by the angles of the different body segments relative to each other (Too, 1988, 1990), and can be affected by changes in seat height, seat to pedal distance, and crank arm length.

In this way, external mechanical factors can be redefined by the terms body position, body orientation, and body configuration; and it is these interactions on bicycle-rider geometry that will affect the internal mechanical factors and, consequently, cycle ergometry performance. Changes in body configuration by a manipulation of seat to pedal distance (either by changing seat height or pedal crank arm length) can result in no changes to body position or body orientation. However, the effect of seat to pedal distance manipulations will result in lower limb changes with regards to: the length of the muscles, muscle moment arm lengths, and force arm length. The effect of these (internal mechanical factor) changes with manipulations in body configuration can affect cycling performance, and has been examined by Too (1988, 1991, 1993) with respect to changes in physiological and biomechanical parameters (such as aerobic capacity, power, EMG data, etc.). However, joint angle measurements (of body configuration) were measured statically (Too, 1991, 1993), and may not reflect the actual joint kinematics of a dynamic task. To determine if this is true, it would be desirable to compare joint kinematics

measured statically with those determined dynamically, and then, if there is a difference, examine factors affecting cycle ergometry and their effect on joint angle kinematics.

In a cycling task, joint kinematics are defined by the constraints of the cycle (the external mechanical factors) on body position, orientation, and configuration. In other words, joint kinematics are constrained (by external mechanical factors) on a cycle ergometer and generally defined throughout a task. However, the effect of the external mechanical factor manipulations (body configuration) on the internal mechanical factors may result in lower limb kinematic measurement differences when determined statically versus those determined dynamically.

The effect of the individual internal mechanical factors and their interactions will change the amount of force/torque/power an individual can produce. In a cycling task, lower limb kinematics may be affected by the force/torque/power production requirements and capabilities of the task and the cyclist, respectively. In a task requiring high (maximal) power output, high levels of force are required to maintain maximal pedalling rate for a given workload. Pedalling effectiveness for a given task has been found to be a complex function of pedal force vector orientation and muscle mechanics (Redfield & Hull, 1986b). Muscle mechanics include: force-length-velocity relationships, muscle fiber architecture, lever classification, and muscle moment arm length; and thus are part of the internal mechanical factors of cycle ergometry. However, pedal forces are a combination of external mechanical factors and pedalling rate.

Pedal forces can be described by joint moment cost functions in which joint moments are minimized for maximum effectiveness. Joint moments are computed by

modeling the lower limb and the parts of the bicycle on which the lower limb act (pedal and seat) as a five-bar linkage system constrained to planar motion. "Joint moments are of interest because they bear some relation to muscular effort and hence rider performance" (Redfield & Hull, 1986a, p. 317). In a cycling task when power output of the subject is constant, the variables which affect joint moments in the lower limbs include: pedalling rate, crank arm length, seat height, seat tube angle, and longitudinal foot position of the pedal (Hull & Gonzalez, 1990). The authors reported that: (1) all the variables interact, (2) the order of the factors (as listed above) is representative of the relative contribution of each factor to joint moments in descending order, and (3) different levels of average constant power yield different optimization values of the variables contributing to joint moment cost. It appears that an optimum pedalling rate can be determined from a mechanical approach for any given power level and bicycle-rider geometry (Redfield & Hull, 1986a).

In a joint moment cost function, the variables of crank arm length, seat height, seat tube angle, and longitudinal foot position of the pedal can be defined by the external mechanical factors of cycle ergometry, and are considered constant. The remaining variables in the joint moment cost function are pedalling rate and power level. Thus, for any given bicycle-rider configuration, there exists an effective (optimum) pedalling rate for a given power level. If a task requires constant, maximal power output, optimal pedalling rate is equivalent to maximal pedalling rate, and continues to be maximal throughout the duration of the task. However, power in a maximal anaerobic power test decreases as time progresses. If the joint moment cost function is to be minimized (to

maximize effectiveness), changes (decreases) in power level will change the optimal relationship between pedalling rate and the external mechanical factors (crank arm length, seat height, seat tube angle, and foot position). Thus, during a task in which power output is not constant, as pedalling rate decreases, body configuration (joint angle kinematics) may change.

With the assumption that no changes occur in the physical dimensions of the cycle ergometer during a task (i.e., seat height, seat tube angle, crank arm length, etc.), it may be speculated that the five-bar linkage system, which represents the lower limb-cycle ergometer interface, undergoes a configurational change as pedalling rate and power output decreases. Any configurational changes in the five-bar linkage system would translate into changes in joint angle of the lower limb, and, consequently, lower limb kinematics. Changes affecting pedalling rate, power output, and body configuration may be the result of factors which affect the subject during performance. This assumption is based on the joint moment cost function which describes the relationship between body configuration, pedalling rate, and power level. For example, if a subject is required to perform a 30-second anaerobic power test, over the duration of the task, power output decreases as pedalling rate decreases. In this task, the kinematics of the subject may change within the test due to factors affecting pedalling rate as power level decreases. The factors that affect pedalling rate are dynamic in nature and include changes in workload and fatigue. For example, a cyclist riding on an open road may have to pedal against increased resistance (workload) due to a headwind or an upgrade, and against fatigue as time progresses. In either case, pedalling rate decreases.

The dynamic nature of cycle ergometry (with regards to the effect of load and fatigue) results in kinematic differences between measurements determined statically versus those determined dynamically (Williams & Too, 1994). Differences in recorded joint angle due to different measurement techniques (as well as conditions of load and fatigue) can be explained by how muscular force is produced, affected, and interacts with cycle ergometry. The effectiveness of muscular force production is dependant upon the interaction of various factors such as: muscle length at a particular joint angle (force-length relationship), the mechanical advantage of the lever arm in the skeletal system (muscle moment arm length), the muscle fiber architecture, and the speed of contraction (the force-velocity relationship). (The factors of muscle force production are part of the internal mechanical factors of cycle ergometry, and the muscle mechanics described by Redfield and Hull (1986b); and, for the purposes of this paper, the terms may be used interchangeably.) The force-length relationship of muscular strength describes the maximum force that can be produced as a function of muscle length, with muscle length affected by the angle of the joint(s) that the muscle crosses. Thus, manipulations of joint angle (body configuration) will change muscle lengths, the amount of force developed by each muscle, and the resultant force output.

Based on the force-length relationship (the force-length curve), a muscle will generate it's largest force at a length which has been described as 100% or slightly greater than its resting length. As the muscle length deviates from this length (from changes in joint angle), force production decreases. Changes in joint angles alter muscle length, muscle moment arm length, and, consequently, force/torque/power generated by the

different muscles and muscle groups. Maximal force output has been defined by a static contraction at a specific joint angle (Kulig, Andrews, & Hay, 1984). With a maximal static contraction, muscle length and muscle moment arm length are constant, and force output is measured as a function of joint angle. A plot of this force output with a change in joint angle is defined as a strength curve.

Strength curves provide information regarding muscular capability (Kulig, et al., 1984). Strength curves generally provide information as to how the configuration of only one joint changes for multi-joint muscles. No study has determined strength curves while controlling for all degrees of freedom for a given movement (Kulig, et al., 1984). The concept of strength curves for movements involving configurations with multiple degrees of freedom (translational and rotational) needs to be carefully examined to determine how it can be formulated in a manner consistent with the strength curve concept for single-degree-of-freedom (rotational) exercises (Kulig et al., 1984). Because cycling is a dynamic activity involving multi-joint muscles, multiple joints, and multiple joint configurational changes; it may not be appropriate or accurate to use static measurements of joint angles (and isometric/static force curves) to describe dynamic tasks, such as cycling. This would suggest that the relationship of force measurements to dynamic or phasic activity needs further exploration (Williams & Stutzman, 1959).

In a dynamic task, the speed of contraction is inversely related to the load that a muscle has to overcome. As described by a force-velocity relationship, with a systematic increase in the velocity of a muscular contraction, the tension that a muscle can produce decreases. This relationship has been supported by experimental procedures using

isokinetic dynamometers, where the angular velocity of a designated articulation was manipulated while muscle torque production was recorded (Huijing, 1992). If a task requires maximum power production throughout it's duration, maximum power will be dependant on pedalling rate (angular velocity) against a given resistance. Decreases in angular joint velocity will result in decreases in pedalling rate and, consequently, decreases in power for a given workload. Thus, manipulations in load and changes in fatigue level may affect power, pedalling rate, angular joint velocities, and joint kinematics.

The effect of load and fatigue in a dynamic task is generally a reduction in pedalling rate with a decrement in power generated by the rider. It may be speculated that kinematic parameters (displacements, velocities, and accelerations) will change as an individual attempts to maintain maximal power output (by maintaining, or attempting to maintain, pedalling rate). Williams and Too (1994) reported that significant differences ($p < 0.05$) do exist between minimum and maximum joint angles of the hip, knee, and ankle with different measurement techniques, and under different conditions of load and fatigue. Using a standard cycle ergometer with a 17.15 cm (6.75 in.) crank arm, the lower limb joint angle measurements were recorded statically with a hand-held goniometer and dynamically with videography (under various conditions of load and with fatigue while cycling). Significant differences ($p < 0.05$) between joint angle measurements were found between conditions of measurement technique, and when load was manipulated and fatigue observed. Therefore, static joint angle measurements used to represent the kinematics in a dynamic task may not accurately describe the actual lower limb

kinematics; and load and fatigue may alter the lower limb joint angles in cycle ergometry.

Statement of the Problem

Do lower limb joint angles in cycle ergometry vary when determined: (1) with different measurement techniques, (2) under conditions of load, (3) with and without fatigue, and (4) with different crank arm lengths? The effect of load and fatigue on joint angle kinematics of the lower limb may interact with changes in the external mechanical factors (which initially define lower limb joint configuration in a cycling task). Joint configurational changes from manipulations of the external mechanical factors may affect the range of motion over which the factors involved in muscular force production interact with the force-length curve. For example, in cycle ergometry, as the hip position changes the hip angle will also change, and the relative contribution to force production by the hip extensors may increase or decrease depending on the length of the hip extensors for that new position. Although there is a similar hip angle range of motion with a systematic change in hip position (i.e., hip angle), Too (1991) noted that there is also a systematic change in the minimum and maximum hip angle values measured. This would suggest that the development of force and power vary at different hip angles with changing hip position during cycle ergometry. The change in joint angle may or may not result in a more mechanically advantageous muscle moment arm length (Titlow, Ishee, & Anders, 1986). Therefore, the joint angle values which define the upper and lower limits of the range of motion about an articulation will also define the range of the force-length curve through which the muscle will perform over one pedal revolution. The range of the force-length curve describing a muscle contraction also describes the maximum force

output attainable at each joint angle within the observed range, and can be used to predict performance. The muscle force developed (and the resulting torque produced) will be based upon the interaction of the position of the muscle in the tension-length curve and its corresponding muscle moment arm length at the new joint angle (Too, 1990).

The range of motion for each of the joints in the lower limb can be defined by the difference between the minimum and maximum lower limb joint angle values (body configuration) over a pedal cycle. It is possible to alter the minimum and maximum joint angle values by manipulating the length of the pedal crank arm, while maintaining body position, body orientation, and seat to pedal distance constant. If the seat to pedal distance is defined as the maximum distance from the seat to the pedal with the lower limb extended, changes in crank arm length would result in a change in the minimum joint angles during a pedal cycle. (Based on external mechanical factors, the maximum joint angles would not be expected to change if seat to pedal distance is held constant.) Manipulations in pedal crank arm length will change: (1) the angles of the hip, knee, ankle relative to each other (joint configuration); (2) the minimum (joint angle) value of the angular range of motion of the hip, knee, and ankle; and, (3) the tension-length relationship area describing lower limb muscle force production. If changes in crank arm length are systematically manipulated with conditions of load and fatigue, lower limb kinematics can also be expected to change.

<u>Purpose of the Study</u>

It may be speculated that joint configuration changes occur when power decreases with a decrement in pedalling rate (in order to provide or maintain maximal force/power

production). It may also be speculated that joint angles recorded during various dynamic test conditions may be different when measured statically under non-test conditions. The effect of change in joint configuration may be further affected by the minimum and maximum joint angle values which define the (initial) range of motion about a joint. Therefore, the purpose of this study is to determine whether lower limb joint kinematics change when determined with different measurement techniques, under various conditions of load with or without fatigue, and with changes in crank arm length.

Need for the Study

Although joint kinematics during test and non-test conditions have been described in various studies (Faria & Cavanagh, 1978; Goodwin & Cornwall, 1989; Nordeen & Cavanagh, 1976; Nordeen-Snyder, 1977; Too, 1988, 1989, 1990, 1991, 1993), it is unknown whether lower limb kinematic patterns change as power and pedalling rate decrease with changes in load and/or fatigue. Cycling is assumed to be a closed-loop system where configurational changes in the joint angles of the lower limb are not expected to occur. However, there is evidence to suggest that: (1) the measurement technique used to determine joint angles in cycling may not always be appropriate (Williams & Too, 1994); and (2) load and/or fatigue may affect lower limb kinematics (Williams & Too, 1994). In addition, lower limb kinematics may be affected by an interaction between load, fatigue, and range of motion (crank arm length).

Hypothesis

Due to the interaction of the factors affecting muscular force production with load and fatigue, it has been reported (Williams & Too, 1994) that joint angles measured

statically may be different when determined under dynamic conditions. It is hypothesized that lower limb joint angles will differ when measured with different measurement techniques (static versus dynamic), and with conditions of load, and fatigue, which would be consistent with what has been reported in the literature (Williams & Too, 1994). By including a systematic manipulation of crank arm length with the preceding conditions, a change in body configuration can be induced while body position, orientation, and seat to pedal distance are maintained. There is evidence to suggest that altering body configuration will have an effect on performance measures such as power, aerobic capacity, and fatigue (Hamley & Thomas, 1967; Nordeen-Snyder, 1977; Shennum & deVries, 1976; Too, 1988) due to the interactions of various factors involved in force production. To maximize power (force) output in an anaerobic power test, it is speculated that changes in body configuration may occur in order to maintain/maximize (optimize) power production with decreasing pedalling rates as a result of load and/or fatigue. Therefore, it is further hypothesized that lower limb kinematics will change under varying conditions of load and fatigue at different crank arm lengths.

Limitations

It is assumed that the lower extremity is represented by a three-bar linkage rigid body with the thigh, shank, and foot as separate segments. It is assumed that: (1) leg motion is confined in the sagittal plane with no relative motion occurring between the pelvis and the bicycle seat, (2) the joint axes of rotation do not shift, and (3) the lengths of the segments remain constant (where changes in one joint angle will affect the other joint angles).

CHAPTER 2

LITERATURE REVIEW

Gregor, Broker, and Ryan (1991) reported that kinematic parameters of the lower extremities (displacements, velocities, and accelerations) during cycle ergometry are principally affected by bicycle geometry (seat height and crank arm length), pedalling rate, body position, and hip and ankle motion (body configuration). Only one study was found which directly addressed the accuracy of joint angle measurement in a cycling task (Williams & Too, 1994). However, to understand how force is produced in cycle ergometry, several studies were found in which the authors have chosen to systematically vary lower limb kinematics by changing either bicycle-rider geometry, pedalling cadence, or both (Nordeen & Cavanagh, 1976; Nordeen-Snyder, 1977; Hull & Gonzalez, 1988, 1990).

Bicycle Geometry: Seat Height

One of the factors affecting bicycle-rider geometry is seat height (with constant crank arm length). Alteration of the seat height would alter joint angles, muscle lengths, and muscle moment arm lengths, thereby changing the kinematics of cycling. This, in turn, affects the force output of a muscle and has been demonstrated by using simulation output with varying seat heights (Nordeen & Cavanagh, 1976). Whether the resulting

force will be greater or lower will be dependant upon the muscle length and location in the tension-length curve. Changes in seat height have been reported to result in changes in the range of motion in hip, knee, and ankle joints (Houtz & Fischer, 1959; Nordeen & Cavanagh, 1976; Nordeen-Snyder, 1977).

The optimal seat height in the standard upright seating position was studied by Hamley and Thomas (1967) and reported to be 109% of the symphysis pubis-to-ground leg length. This position was found to be the most efficient for anaerobic work of high intensity and short duration. Shennum and deVries (1976) reported the most efficient seat to pedal distance for aerobic work to be 105% to 108% of the symphysis pubis-to-ground leg length, but suggested a saddle height of 108% to 109% for overall efficiency when incorporating data from Hamley and Thomas (1967). This is supported by Nordeen-Snyder (1977) who found the most efficient seat to pedal distance for aerobic work to be 107.1% of the symphysis pubis-to-ground leg length (100% of greater trochanter-to-ground leg length).

Bicycle Geometry: Crank Arm Length

Changing crank arm length instead of the seat height will also alter the seat to pedal distance; although, there are differences between the two manipulations. First, altering crank arm length can result in greater torques being produced (with longer cranks), whereas raising the seat to obtain a greater seat to pedal distance will not. Second, to produce a given torque with a given workload, decreasing muscle tension with increasing crank arm length can affect the amount of muscular fatigue experienced over time. Finally, with increasing crank lengths, muscular force patterns can change and

deviate from the optimal pattern (Inbar, Dotan, Trousil, & Dvir, 1983). Goodwin and Cornwall (1989) determined that a shortened pedal shaft significantly reduces ($p < 0.05$) the amount of knee flexion required for cycling without altering the muscle contraction patterns of the muscles studied. This would imply that any changes in force output while pedalling with a shortened pedal crank arm would result from changes in the tension-length relationship of the muscles studied. From the available literature, the crank lengths which have been investigated ranged from 3.1 inches (7.9 cm.) to 9.45 inches (24 cm.) (Goto, Toyoshima, & Hoshikawa, 1976). To maintain a constant seat to pedal distance with different crank arm lengths, saddle height is raised or lowered correspondingly.

Pedalling Rate and Load

Information needed to understand the pedalling process includes identifying the leg muscles involved, the pedal loads, and the kinematics of the leg segments (Jorge and Hull, 1984). Although many of these areas have been examined, information on pedal loading data and the affect on kinematics of the leg are still needed (Jorge and Hull, 1984).

In a study by Redfield and Hull (1986a), the relationship between joint moments and pedalling rate was investigated. Using pedal force data, pedal position data, and kinematic position information derived from vector addition techniques, an optimum pedalling rate can be determined from a mechanical perspective for any power output level and bicycle-rider geometry. It was reported that a crank arm length of 170 mm (7.72 in.) and a pedalling rate of 100 rpm result in the joint moment cost function

minimum, but the cost function minimum changed as the pedalling rate changed (Hull & Gonzalez, 1988). At increased power, the cost function minimum is more strongly related to the pedalling rate, with higher pedalling rates corresponding to the minimum cost. This would imply that at higher power output, higher pedalling rates result in lower joint moments.

Optimization analysis for a cycling task, as proposed by Redfield and Hull (1986b) has the capability of handling multiple variables. In an earlier study, Hull and Gonzalez (1988) completed a two-variable optimization of pedalling rate and crank arm length using the joint moment based cost function. However, the number of variables which affect intersegmental loads in the leg when the power output is constant also include: seat height, seat tube angle, and longitudinal foot position of the pedal (Hull & Gonzalez, 1990). In analytical optimization analysis, performance measures take the form of objective (cost) functions which then is either minimized or maximized. In a later study, Hull and Gonzalez (1990) used optimization analysis with all five variables. The results indicated: (1) the hierarchy of affect on joint moment for a specific rider anthropometry is pedalling rate, crank arm length, seat tube angle, seat height, and foot position on the pedal, (2) all variables interact in descending order of relative contribution, and (3) when anthropometric parameters varied, the optimum values of all five variables change significantly at the overall cost function minimum. The results emphasize the importance of tailoring bicycle equipment to the individual in order to optimize performance and lower limb kinematics. Manipulations of bicycle-rider geometry prior to the task may result in lower limb kinematic changes which, in turn, may

affect performance. Therefore, if kinematics significantly change during the course of a task, the benefits of any such tailored bicycle equipment may be lost.

Bicycle-rider Geometry: Body Position, Orientation, and Configuration

A study conducted by Faria and Cavanagh (1978) compared an upright body orientation (a top bar cycling position) with a prone orientation (a drop bar cycling position). A top bar position is described as sitting semi-upright on the saddle with the hands resting on the uppermost portion of the handlebars; while a drop bar position is described as sitting in the saddle while leaning forward, with the hands resting on the drop portion of the turned-down handlebars, and the torso placed in a prone or semi-prone orientation. The drop bar position was reported to result in significantly greater oxygen uptake when measured in both L/min ($p < 0.05$) and ml/kg/min ($p < 0.01$), and in maximal work output ($p < 0.05$). In addition, the authors indicated that the two different riding orientations were not significantly different when the oxygen uptake was calculated relative to maximum oxygen uptake (ml/kg/min). However, the absolute values of the drop bar position were significantly greater ($p < 0.01$). This study would suggest that different body orientations will result in different maximal work outputs and possibly different energy expenditures. It is unknown whether the greater lean in the drop bar position altered the hip angle and placed the working muscles and muscle moment arm lengths in a more mechanically advantageous position to produce force when compared to the top bar position. The hip, knee, and ankle angles were not reported and do not appear to have been controlled for.

Several studies were found which suggested different body positions and bicycle-

rider geometry for optimization, maximization, and prediction of performance, without reporting the lower limb kinematics of the task (Diaz, Hagen, Wright, & Horvath, 1978; Hugh-Jones, 1947; Metz, Moeinzadeh, White, & Groppel, 1986; Metz, Moeinzadeh, & White, 1990). One study comparing cycling in an upright position to other positions reported significantly greater ($p < 0.05$) maximal oxygen consumption in an upright position (Diaz et al., 1978). It was believed that greater maximal work output was achieved in an upright position because of a direct relationship between maximal oxygen consumption and maximal work output. However, for submaximal workloads, the relative oxygen consumption (when expressed as a percentage of maximal oxygen consumption) was found to be greater for a low sitting position (a cycling position where the torso is upright and the legs extend horizontally). It is unknown to what these differences were attributed, since physiological baselines, seat to pedal distance, or lower limb kinematics for the different seating positions were not reported. Similarly, Hugh-Jones (1947) published results on the efficiency of pedalling in different seating positions. Again, actual efficiency calculations were not made, comparisons of energy expenditure and seat to pedal distances were not reported, and there was no description regarding lower limb kinematics.

In a comparison between an upright racing position and a semi-recumbent position, Metz et al. (1986, 1990) reported cycling performance to be superior in the upright position. Although the semi-recumbent position configured the cyclists' legs differently with respect to the line of gravity, no significant differences were found in joint forces or moments. Instrumented pedals were not used, and physiological data were

not collected. Therefore, it is unknown whether differences in cycling performance were attributed to varying leg weight contribution, efficiency, oxygen consumption, energy expenditure, or some other factor. Based upon visual observations of the reported cycling positions, it is speculated that differences in performance may be attributed to differences in muscle length and muscle moment arm length interactions of the two different body configurations.

Studies by Too (1988, 1989, 1990, 1991, 1993) have examined the effect of systematic manipulations of body position, configuration, and orientation on cycling performance. It was concluded that an optimum cycling body position/configuration exists that maximizes aerobic work and anaerobic power and capacity. Total work output and maximal energy expenditure determined aerobically, and power determined anaerobically were significantly greater ($p < 0.01$) in the 75° seat tube angle (76.8° mean hip angle) when compared to other body positions. It was reported that a systematic decrease in hip angle occurred when the angle formed by the bicycle seat tube and a vertical line passing through the pedal axis was systematically manipulated (increased) while the backrest was kept perpendicular to the ground. (It should be noted that joint angle measurements were obtained statically with a hand-held goniometer.) With a change in hip angle, the hip angle range of motion did not change (although there were differences in minimum and maximum hip angle values). This would suggest that the development of force and the production of power varied at different hip angles with changes in hip position.

Measurement Technique

Williams and Too (1994) reported that static measurements of joint angle may not be reflective of the actual joint angle kinematics during a dynamic task (such as cycle ergometry). Using a standard Monarch 814E cycle ergometer with a crank arm length of 17.15 cm, they compared joint angle measurements across conditions of measurement technique, load, and fatigue. Joint angles in the static measurement condition were determined with a hand-held goniometer, while joint angles in the dynamic measurement conditions (joint angle displacement data) were determined from an Ariel Performance Analysis System. Conditions of load included: minimal load (0.5 kg as the subject pedalled at a self-selected cadence), load with no fatigue, and load with fatigue. Each subject performed a 30-second Wingate Anaerobic Power test with a fixed resistance (85 gm/kg of body mass), and was asked to maintain maximal power output for the duration of the task. For each condition, minimum and maximum lower limb joint angle measurements were recorded. It was reported that significant differences exist ($p < 0.05$) in: (1) the maximum angle of the hip across unloaded, loaded non-fatigued, and loaded fatigued conditions; (2) the maximum angle of the knee across unloaded and loaded fatigued conditions; (3) the maximum angle of the ankle across goniometer, loaded non-fatigued, and loaded fatigued conditions; and (4) the minimum angle of the ankle across the goniometer and loaded-fatigued conditions. It would appear that different measurement techniques, load, and fatigue can result in different lower limb joint angle measurements. Thus, it may not be appropriate to describe lower limb kinematics using static measurements of joint angles during non-test conditions (Williams & Too, 1994).

CHAPTER 3

METHODS

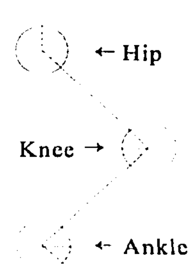
Eight male volunteers with recreational cycling experience participated in this study. Their average age, height, and weight were 25.7 years (SD = 3.41), 178.7 cm (SD = 8.07), and 76.2 kg (SD = 5.66), respectively. All subjects completed six test sessions. The first session was used to obtain informed consent and anthropometric measurements, and to familiarize each subject with the apparatus and test protocol. A Monarch 814E cycle ergometer with a plate-loaded resistance mechanism was used in conjunction with two Rangemaker™ adjustable crank arm shafts. To manipulate the kinematics of the lower limb with changes in crank arm length, seat-to-pedal distance was maintained at 109% of the subject's symphysis pubis-to-ground leg length (±1 cm) (Hamley & Thomas, 1967). The crank arm lengths selected were: 10.16, 13.34, 17.15, 22.23, and 26.04 cm (4.00, 5.25, 6.75, 8.75, and 10.25 in.). The preceding crank arm lengths were labeled crank arm lengths 1, 2, 3, 4, and 5, and represented the five selected lengths in ascending order. Pedal toeclips were used, and each subject's upper body was kept perpendicular to the ground for all trials. The test sequence for each subject was randomized, and a minimum of 24 hours rest was required between test sessions.

The effect of four measurement conditions were examined for the joint angles of

the hip, knee, and ankle (Figure 1). In the first condition, the minimum and maximum joint angles were determined statically with a hand-held goniometer. In the remaining three test conditions, joint angles were determined with an Ariel Performance Analysis System (APAS). A video camera positioned perpendicular to the median plane of the subject pedalling on the cycle ergometer was used to record minimum and maximum joint angles in an unloaded, loaded non-fatigued, and loaded fatigued condition. Digitizing points were attached to the right side of the subjects at the following anatomical sites: the 5th metatarsal; the lateral malleolus; the axis of rotation of the knee; the greater trochanter of the femur; and a point attached to a plumb line positioned to intersect the marking on the greater trochanter, and located on the deltoid as viewed through the camera.

During the unloaded condition the subject pedalled at a self-selected cadence and one pedal revolution was selected for digitizing. The Wingate Anaerobic Cycling Test (Lamb, 1984) was used in the loaded non-fatigued and loaded fatigued conditions. These conditions were defined by the maximum and minimum power outputs, respectively. Power output was determined by the Sports Medicine Industries, Inc. Power Program (version 1.02a, ©1992). Subjects were instructed to warm-up and encouraged to cycle on the ergometer with maximal, intermittent bursts, 2-4 seconds in duration. To initiate the test, the subject was instructed to pedal as fast as possible with no load; during which, 85 gm/kg of the subject's body mass

Figure 1: Joint Angle Definitions



(5.0 joules /pedal revolution/kg of body mass) was instantaneously applied. The subject was verbally motivated to continue to pedal as fast as possible for the duration of the 30-second test. After completion of the test, the subject was encouraged to pedal with reduced resistance to facilitate recovery. Loaded-non fatigued and loaded-fatigued joint angles were determined by a synchronization of the video data with the recorded power output. The pedal revolution occurring at the third second of the maximum and minimum 5-second power intervals, as recorded by the SMI Power Program, was used for digitizing purposes. The four conditions were labeled goniometer (gon), unloaded (unl), loaded non-fatigued (lnf), and loaded fatigued (lf).

The data was analyzed using doubly multivariate repeated measures analysis of variance (DB MANOVA) on the hip, knee, and ankle to determine whether there were significant differences in lower limb joint kinematics between conditions (gon, unl, lnf, lf), across all joint angles (minimum and maximum), and across all crank arm lengths (1-5). Multivariate repeated measures analysis of variance (MANOVA) were used to determine if significant differences exist between conditions, at the minimum and at the maximum joint angle values (separately) for the hip, knee, and ankle, across all crank arm lengths. Repeated measures analysis of variance (ANOVA) were used to determine if significant differences exist between the conditions for: (1) the minimum joint angle values for each joint (hip, knee, and ankle), at each crank arm length (1-5); and (2) the maximum joint angle values for each joint, at each crank arm length. For each ANOVA with significant differences, multiple comparisons with Scheffe's test were used to determine the conditions where significant differences occurred. This would provide

information regarding joint angle measurements under various conditions of measurement technique, and conditions of load and fatigue, with changes in crank arm length.

CHAPTER 4

RESULTS

To examine the effect of measurement technique, and load and fatigue, with changes in crank arm length on lower limb joint angle kinematics in cycle ergometry, four conditions (goniometer, unloaded, loaded non-fatigued, and loaded fatigued) were examined at each of five crank arm lengths. The recorded joint angles are summarized in Tables 1, 2, and 3 for the hip, knee, and ankle, respectively.

Table 1: Descriptive Statistics on Joint Angle Measurements of the Hip

Joint Angle of the Hip										
	Crank Arm Length 1		Crank Arm Length 2		Crank Arm Length 3		Crank Arm Length 4		Crank Arm Length 5	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Gon										
M	126.75	157.13	118.88	155.38	111.13	155.00	102.25	157.13	91.50	156.13
SD	4.23	4.05	4.09	5.24	4.82	4.72	7.23	4.12	6.50	6.49
Unl										
M	125.01	150.81	121.59	151.63	112.64	150.95	100.54	153.91	91.71	153.56
SD	4.42	3.22	4.86	4.86	5.61	7.61	6.04	3.98	7.67	7.18
LNF										
M	126.98	161.50	123.66	161.26	113.05	158.50	107.05	161.35	93.80	159.29
SD	5.41	6.69	4.81	4.22	5.28	7.94	8.64	6.65	4.80	5.97
LF										
M	129.38	163.71	122.18	163.78	115.49	158.80	103.98	161.14	91.53	153.59
SD	4.38	6.69	4.61	6.93	4.36	7.94	5.13	7.00	5.84	6.04

Table 2: Descriptive Statistics on Joint Angle Measurements of the Knee

Joint Angle of the Knee										
	Crank Arm Length 1		Crank Arm Length 2		Crank Arm Length 3		Crank Arm Length 4		Crank Arm Length 5	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Gon										
M	97.12	148.00	85.00	149.13	72.87	148.25	60.00	153.88	50.50	154.63
SD	4.49	7.21	5.01	6.58	5.91	6.43	6.50	6.10	6.74	8.50
Unl										
M	94.52	145.05	84.27	143.81	71.27	141.76	58.00	149.88	45.92	147.19
SD	2.74	5.82	5.95	6.09	4.37	10.25	4.37	5.38	6.65	7.04
LNF										
M	94.62	151.84	83.42	149.90	72.14	146.26	60.17	155.60	49.96	153.99
SD	4.40	8.58	4.14	7.02	4.30	8.97	5.15	7.06	5.58	8.74
LF										
M	96.34	159.73	88.02	155.84	75.67	148.36	60.24	156.13	49.42	149.90
SD	3.02	9.31	5.19	9.99	5.05	10.29	5.05	7.55	5.55	7.46

Table 3: Descriptive Statistics on Joint Angle Measurements of the Ankle

Joint Angle of the Ankle										
	Crank Arm Length 1		Crank Arm Length 2		Crank Arm Length 3		Crank Arm Length 4		Crank Arm Length 5	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Gon										
M	102.88	123.63	96.00	121.13	97.37	120.88	93.62	121.75	94.12	126.88
SD	9.72	7.56	10.53	8.47	10.94	9.26	8.75	3.99	9.69	9.63
Unl										
M	104.70	124.78	96.85	123.94	98.26	124.13	93.30	126.79	89.80	123.59
SD	8.74	8.43	9.74	7.20	9.88	8.64	8.71	13.32	8.61	6.56
LNF										
M	105.83	127.88	100.90	126.26	102.73	125.79	93.64	128.66	88.49	128.06
SD	9.14	5.80	7.34	4.61	9.52	6.86	10.98	13.41	10.31	7.53
LF										
M	90.60	134.15	89.50	130.11	91.04	132.55	94.94	130.33	85.34	134.38
SD	6.65	6.58	4.92	3.92	3.78	9.22	6.37	10.36	8.51	13.79

Doubly multivariate repeated measures analysis of variance (DB MANOVA's) were used to compare joint angles of the hip, knee, and ankle between conditions (gon, unl, lnf, lf) across all crank arm lengths (1-5). This global view of the data described significant differences between conditions for the hip joint angle with F (30, 35.9) = 4.704, $p = 0.000$ (Wilks' Lamda); for the knee joint angle with F (30, 35.9) = 5.227, $p = 0.000$ (Wilks' Lamda); and for the ankle joint angle with F (30, 35.9) = 2.222, $p = 0.012$ (Wilks' Lamda). Repeated measures MANOVA's were used to compare the minimum joint angle measurements of the hip, knee, and ankle, and maximum joint angle measurements of the hip, knee, and ankle, between all conditions across all crank arm lengths. Significant differences were found between conditions for the following joint angle measurements: (1) minimum angle of the hip with F (15, 47.3) = 3.318, $p = 0.001$ (Wilks' Lamda); (2) minimum angle of the knee with F (15, 47.3) = 3.223, $p = 0.001$ (Wilks' Lamda); (3) the minimum angle of the ankle with F (15, 47.3) = 2.85, $p = 0.003$ (Wilks' Lamda); (4) the maximum angle of the hip with F (15, 47.3) = 6.588, $p = 0.000$ (Wilks' Lamda); (5) the maximum angle of the knee with F (15, 47.3) = 6.622, $p = 0.000$ (Wilks' Lamda); and (6) the maximum angle of the ankle with F (15, 47.3) = 2.101, $p = 0.027$ (Wilks' Lamda).

Post-hoc tests using: (1) repeated measures ANOVA's found significant differences between conditions of goniometer, unloaded, loaded non-fatigued, loaded fatigued for each crank arm length ($p < 0.05$), and (2) Scheffe's test was used to determine where significant differences ($p < 0.05$) occurred between conditions of goniometer, unloaded, loaded non-fatigued, loaded fatigued at each crank arm length. The results are

summarized in Tables 4, 5, and 6 for the hip, knee, and ankle, respectively. In addition, the results are depicted graphically for further reference in Figures 2, 3, 4, 5, 6 and 7.

Table 4: Multiple Comparisons Between Conditions at the Hip Joint

Joint Angle @ Crank Arm Length (CAL)	RM ANOVA F	p	Multiple Comparisons with Significance t-tests with Scheffe ($p < 0.05$)
Hip Minimum @ CAL 1	3.43	0.0358	Loaded Fatigued vs. Unloaded
Hip Minimum @ CAL 2	5.85	0.0046	Loaded Non-fatigued vs. Goniometer
Hip Minimum @ CAL 3	2.71	0.0713	none
Hip Minimum @ CAL 4	6.69	0.0024	Loaded Non-fatigued vs. Goniometer Loaded Non-fatigued vs. Unloaded
Hip Minimum @ CAL 5	1.50	0.2442	none
Hip Maximum @ CAL 1	12.87	0.0001	Loaded Fatigued vs. Unloaded Loaded Non-fatigued vs. Unloaded
Hip Maximum @ CAL 2	20.70	0.0001	Loaded Fatigued vs. Goniometer Loaded Fatigued vs. Unloaded Loaded Non-fatigued vs. Goniometer Loaded Non-fatigued vs Unloaded
Hip Maximum @ CAL 3	11.43	0.0001	Loaded Fatigued vs. Unloaded Loaded Non-fatigued vs. Unloaded
Hip Maximum @ CAL 4	12.68	0.0001	Loaded Non-fatigued vs. Unloaded Loaded Fatigued vs. Unloaded
Hip Maximum @ CAL 5	4.98	0.0091	Loaded Non-fatigued vs. Unloaded Loaded Fatigued vs. Unloaded

Table 5: Multiple Comparisons Between Conditions at the Knee Joint

Joint Angle @ Crank Arm Length (CAL)	RM ANOVA F	p	Multiple Comparisons with Significance t-tests with Scheffe ($p < 0.05$)
Knee Minimum @ CAL 1	1.13	0.36	none
Knee Minimum @ CAL 2	5.45	0.0063	Loaded Fatigued vs. Unloaded Loaded Fatigued vs. Loaded Non-fatigued
Knee Minimum @ CAL 3	3.51	0.033	Loaded Fatigued vs. Unloaded
Knee Minimum @ CAL 4	1.13	0.359	none
Knee Minimum @ CAL 5	9.90	0.0003	Goniometer vs. Unloaded Loaded Non-fatigued vs. Unloaded Loaded Fatigued vs. Unloaded

Table 5 (continued)

Knee Maximum @ CAL 1	6.71	0.0024	Loaded Fatigued vs. Goniometer Loaded Fatigued vs. Unloaded
Knee Maximum @ CAL 2	12.61	0.0001	Loaded Fatigued vs. Goniometer Loaded Fatigued vs. Unloaded Loaded Non-fatigued vs. Unloaded
Knee Maximum @ CAL 3	3.20	.0444	none
Knee Maximum @ CAL 4	18.29	0.0001	Loaded Non-fatigued vs. Unloaded Loaded Fatigued vs. Unloaded Goniometer vs. Unloaded
Knee Maximum @ CAL 5	10.63	0.0002	Goniometer vs. Loaded Fatigued Goniometer vs. Unloaded Loaded Non-fatigued vs. Unloaded

Table 6: Multiple Comparisons Between Conditions at the Ankle Joint

Joint Angle @ Crank Arm Length (CAL)	RM ANOVA F	 p	Multiple Comparisons with Significance t-tests with Scheffe ($p < 0.05$)
Ankle Minimum @ CAL 1	10.35	0.0002	Goniometer vs. Loaded Fatigued Loaded Non-fatigued vs. Loaded Fatigued Unloaded vs. Fatigued
Ankle Minimum @ CAL 2	7.47	0.0014	Loaded Non-fatigued vs. Loaded Fatigued
Ankle Minimum @ CAL 3	4.95	0.0094	Loaded Non-fatigued vs. Loaded Fatigued
Ankle Minimum @ CAL 4	0.10	0.957	none
Ankle Minimum @ CAL 5	2.67	0.0741	none
Ankle Maximum @ CAL 1	5.15	0.0079	Loaded Fatigued vs. Unloaded Loaded Fatigued vs. Goniometer Loaded Non-fatigued vs. Goniometer
Ankle Maximum @ CAL 2	9.25	0.0004	Loaded Fatigued vs. Unloaded Loaded Fatigued vs. Goniometer Loaded Non-fatigued vs. Goniometer
Ankle Maximum @ CAL 3	7.14	0.0017	Loaded Fatigued vs. Unloaded Loaded Fatigued vs. Goniometer Loaded Non-fatigued vs. Goniometer
Ankle Maximum @ CAL 4	2.06	0.13	none
Ankle Maximum @ CAL 5	1.93	0.15	none

Figure 2: Minimum Hip Angle Means

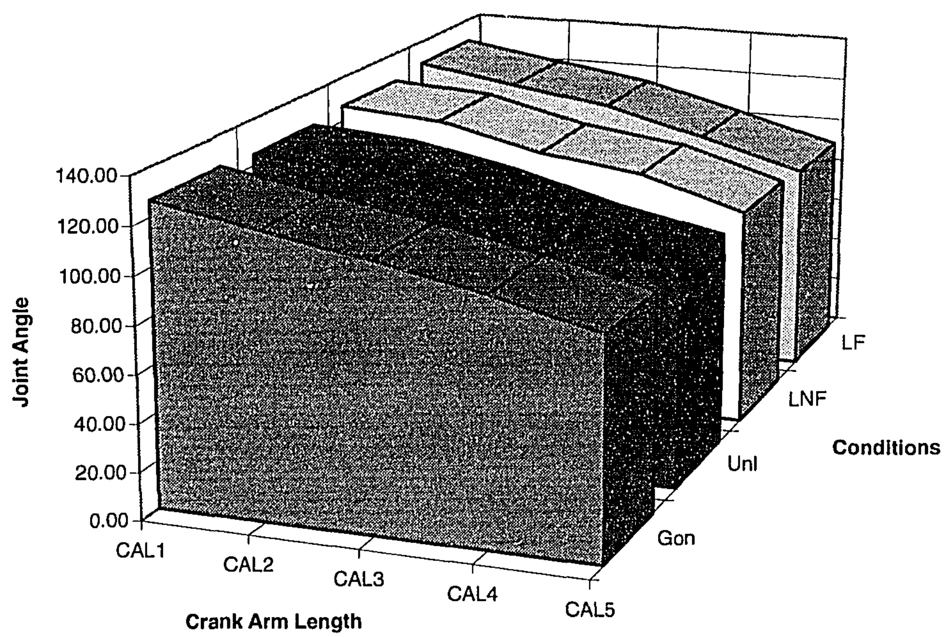


Figure 3: Maximum Hip Angle Means

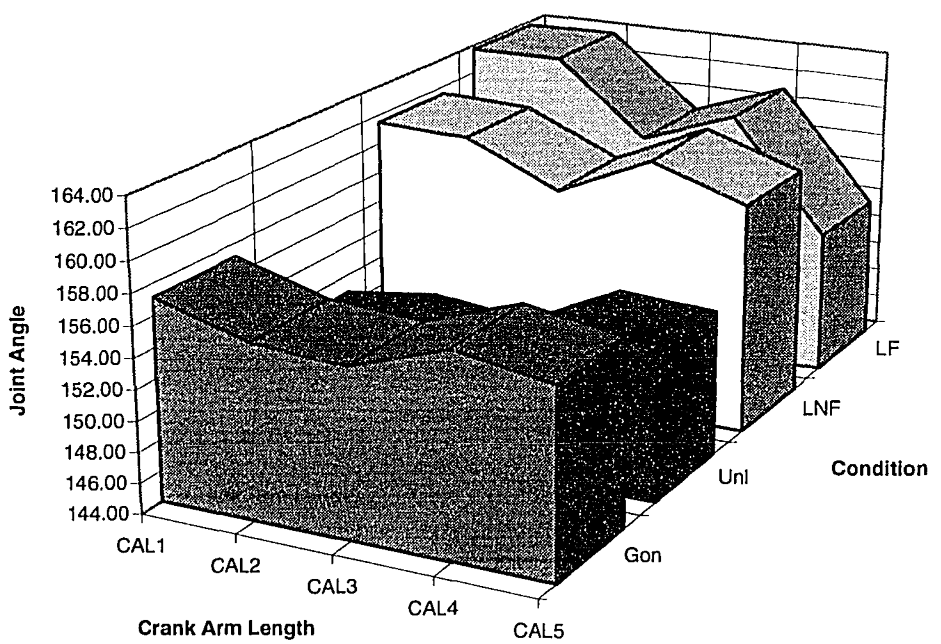


Figure 4: Minimum Knee Angle Means

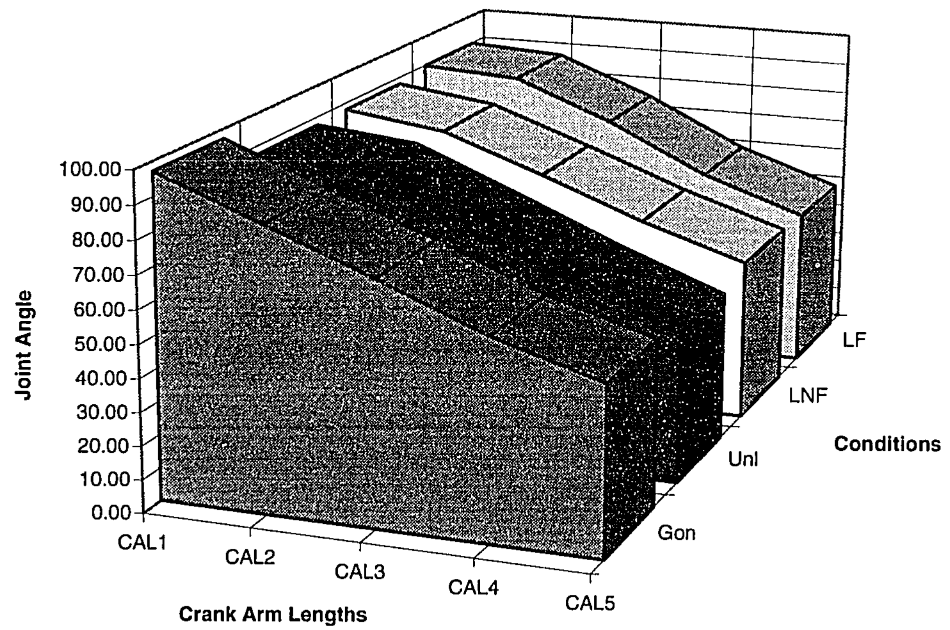


Figure 5: Maximum Knee Angle Means

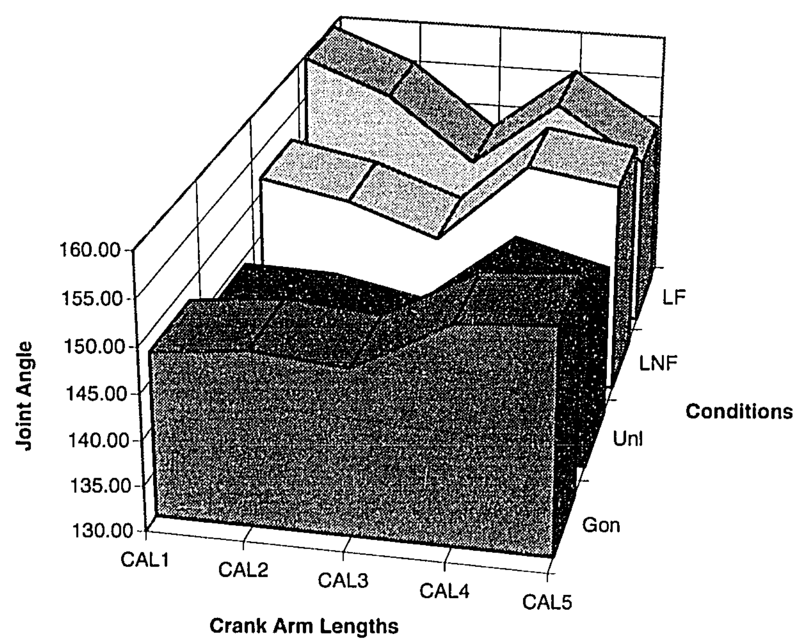


Figure 6: Minimum Ankle Angle Means

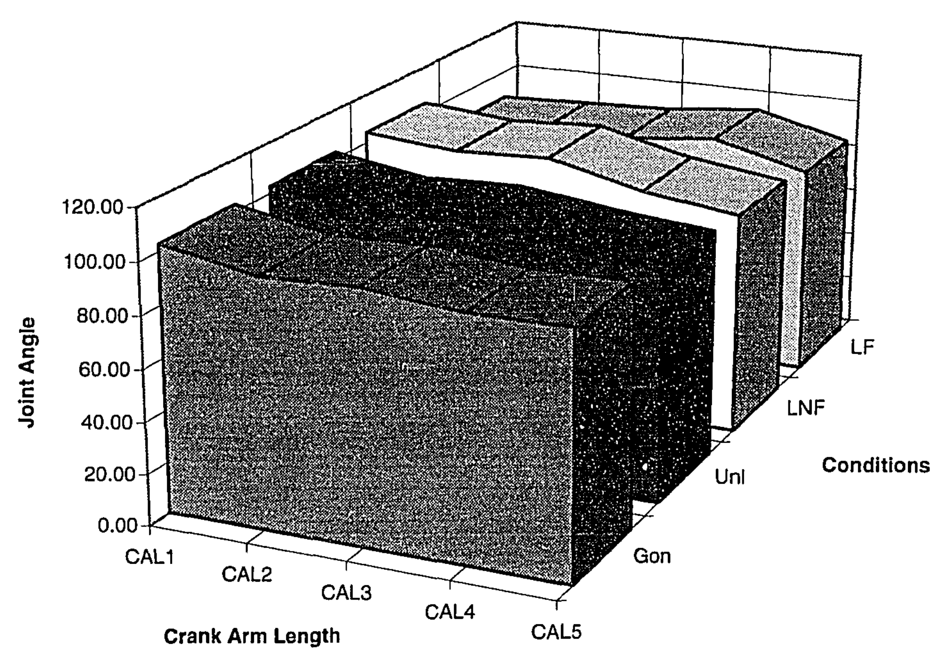
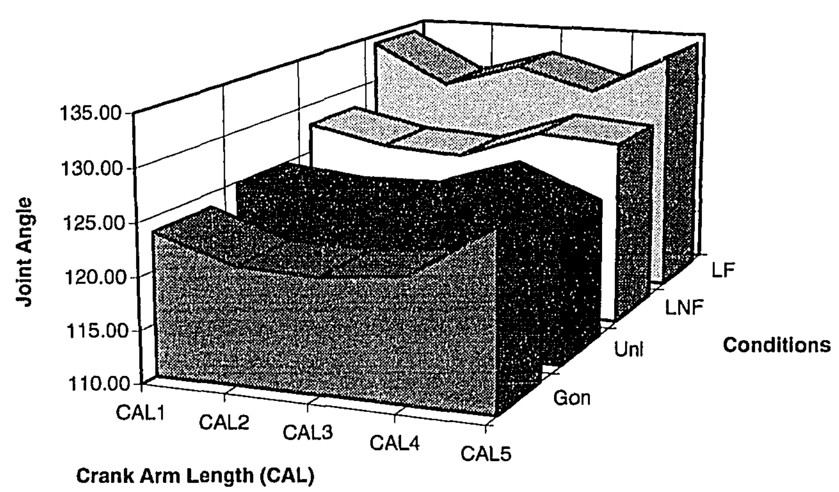


Figure 7: Maximum Ankle Angle Means



CHAPTER 5

DISCUSSION

The purpose of this study was to determine whether lower limb joint kinematics change when determined with different measurement techniques, under various conditions of load with or without fatigue, and with changes in crank arm length. The results indicate that differences may exist between joint angle measurements when recorded under the following conditions: (1) goniometer, (2) unloaded, (3) loaded non-fatigued, and (4) loaded fatigued. Therefore, joint angle kinematics may change when determined with different measurement techniques, under conditions of load and fatigue, at different crank arm lengths.

Significant differences ($p < 0.05$) were found between conditions of measurement technique at the minimum and maximum joint angles of the hip, knee, and ankle. Significant differences were found between the goniometer (static) condition and one or more of the other (dynamic) conditions in: (1) the minimum angle of the hip at crank arm lengths 2 and 4; (2) the maximum angle of the hip at crank arm length 2; (3) the minimum angle of the knee at crank arm length 5; (4) the maximum angle of the knee at crank arm lengths 1, 2, 4, and 5; (5) the minimum angle of the ankle at crank arm length 1; and (6) the maximum angle of the ankle at crank arm lengths 1, 2, and 3. During static

conditions, the segmental positions defining the joints were maintained by the subject and measured with a hand-held goniometer. Significant differences between the static and dynamic conditions may be attributed to: (1) measurement error and variability of the tester and the subject when using the goniometer during static measurement, and/or (2) kinematic changes that may have occurred during the task to maintain maximal power production with decreasing pedalling rate. Therefore, under dynamic conditions, changes in joint angle kinematics may not be accurately represented by static joint angle measurements.

Significant differences ($p < 0.05$) were found between the unloaded condition and one or more of the other conditions in: (1) the minimum angle of the hip at crank arm lengths 1 and 4; (2) the maximum angle of the hip at all crank arm lengths; (3) the minimum angle of the knee at crank arm lengths 2, 3, and 5; (4) the maximum angle of the knee at crank arm lengths 1, 2, 4, and 5; (5) the minimum angle of the ankle at crank arm length 1; and (6) the maximum angle of the ankle at crank arm lengths 1, 2, and 3. These differences may be attributed to strategies utilized by subjects to maximize power output. These strategies may include the use of body weight to assist in the movement, involving: (1) a lateral shift of body position from side-to-side to distribute more weight over the active leg, and (2) changes in the range of motion of the knee (Nordeen-Snyder, 1977). As a load is applied, to more effectively apply the body's weight to force/power production, the hip and knee may be extended to a greater degree. This appears to be supported by significant differences ($p < 0.05$) found between the unloaded condition and conditions with load (loaded non-fatigued and/or loaded fatigued) at: (1) the maximum

angle of the hip, and (2) the minimum and maximum angle of the knee. At both joints, the mean joint angle value of the unloaded condition was significantly less ($p < 0.05$) than the mean joint angle value of the conditions with load. This would suggest that the presence of load (with or without fatigue) may be attributed to increases in hip and knee joint angle. Reported increases in maximum joint angle measurements at the hip and knee would reflect greater extension of the lower limb, and would appear to support results reported by Nordeen-Snyder (1977).

Significant differences ($p < 0.05$) between the loaded non-fatigued condition and one or more of the other conditions were found in: (1) the minimum angle of the hip at crank arm lengths 2 and 4; (2) the maximum angle of the hip at all crank arm lengths; (3) the minimum angle of the knee at crank arm lengths 2 and 5; (4) the maximum angle of the knee at crank arm lengths 2, 4, and 5; (5) the minimum angle of the ankle at crank arm length 1, 2, and 3; and (6) the maximum angle of the ankle at crank arm lengths 1, 2, and 3. The differences found in the loaded non-fatigued condition support speculations made when similar differences were found in the unloaded condition. Recorded joint angle was significantly greater ($p < 0.05$) in the loaded non-fatigued condition than in the unloaded condition for each comparison that was found to be significantly different (with the minimum angle of the knee at crank arm length 2 as the only exception). The effect of greater values at each joint appears to support the conclusions that the subject may be extending the hip and knee to a greater extent in order to more effectively apply the body's weight to force/power production against a given load (Nordeen-Snyder, 1977).

Significant differences ($p < 0.05$) between the loaded fatigued condition and one

or more of the other conditions were found in: (1) the minimum angle of the hip at crank arm length 1; (2) the maximum angle of the hip at all crank arm lengths; (3) the minimum angle of the knee at crank arm lengths 2, 3, and 5; (4) the maximum angle of the knee at crank arm lengths 1, 2, 4, and 5; (5) the minimum angle of the ankle at crank arm lengths 1, 2, and 3; and (6) the maximum angle of the ankle at crank arm lengths 1, 2, and 3. These differences in the loaded fatigued condition may also be attributed to a lateral shift of body position as previously reported by Nordeen-Snyder (1977). A lateral shift in body position may be reflected in the significantly higher values of the maximum angle of the hip and the knee at all crank arm lengths. However, based on the three-bar linkage rigid mass body (where the length of the segments do not change), these differences may also be attributed to an increased range of motion at the ankle.

Significant differences ($p < 0.05$) between conditions for the minimum and maximum joint angle of the ankle were found only across the shorter crank arm lengths (1, 2, and 3). It was found that for the minimum joint angle of the ankle, measurements taken in the loaded fatigued condition yielded the lowest mean value. For the maximum joint angle of the ankle, measurements taken in the loaded fatigued condition yielded the highest mean value. This indicates an increase in the range of motion at the ankle when crank arm length (force arm length) is small. Increased dorsiflexion and plantar flexion may be indicative of changes in ankling patterns (Nordeen-Snyder 1977; Too 1991), and would seem to be affected by fatigue. It is speculated that with fatigue, joint angle changes at the ankle result in muscle length changes of the lower leg, and may involve a different segment (range) of the tension-length curve to maintain maximal power

production. Changes in ankling patterns may be used to increase the relative power contribution of the lower leg muscles to compensate for the power decrement due to fatigue in the upper leg muscles. Differences reported (in the shorter crank arm lengths) for the ankle would seem to support this speculation. Based on visual observations, it would appear that the amount of fatigue during the Wingate anaerobic power test increases as crank arm length decreases. When using shorter crank arm lengths, the force arm length of the lever (represented by the crank arm) decreases, resulting in a mechanical disadvantage for force production by the lower limb(s). Thus, as fatigue results in decreasing pedalling rate, the lower limbs are at a mechanical disadvantage in maximizing or maintaining power production. With the shortest crank arm length, the level of fatigue at the end of a Wingate anaerobic power test is greatest. Greater levels of fatigue may be reflected between conditions at the ankle, and by reported differences in the minimum and maximum hip angles, and the minimum knee angle at crank arm length 2. At the hip and knee, the mean joint angle value in the loaded fatigued condition was greater than the mean joint angle value in the loaded non-fatigued condition at shorter crank arm lengths.

The effect of changes in ankling pattern and/or lower limb extension (accompanying a lateral shift of body position) can affect lower limb kinematics. It is unknown whether an interaction exists between the relative contributions of ankling patterns and lower limb extension to lower limb kinematics in cycle ergometry, and how such an interaction would affect lower limb kinematics. It is also unknown as to the exact mechanism(s) which may cause lower limb kinematic variations in cycle ergometry.

However, it is reported that lower limb kinematics can significantly change ($p < 0.05$) with various conditions of measurement technique, and load and fatigue, with changes in crank arm length.

Future Directions

It would be desirable to determine if an interaction exists between contributions of ankling patterns and lower limb extension (accompanying a lateral shift of body position). Based on the results of this study, ankling patterns are speculated to be affected by the presence of fatigue, and a lateral shift of body position is speculated to be affected by the presence of load. It may be possible to manipulate conditions of load and/or fatigue imposed on the subject during a cycling task to determine the relative effect(s) of different levels of each condition and/or the effect of interaction between both conditions on lower limb kinematics. If a manipulation of the crank arm is included as an additional independent variable for either condition separately or combined (affecting the length of the force arm and resulting in a mechanical disadvantage for force production as crank arm length decreases), it may be possible to determine trends for joint angle changes that occur at each condition. The results of potential studies such as these may be used to develop a mathematical model incorporating the variables of (but not limited to): (1) load, (2) fatigue, (3) pedalling rate, and/or (4) power output. A mathematical model may be used to predict patterns, trends, or change in: (1) the amount of dorsiflexion and plantar flexion of the ankle, and/or (2) the amount of lateral shift by the body, for any given workload and/or level of fatigue (if any such patterns, trends, or changes exist).

A mathematical model already exists (the joint moment cost function) which

compares the effect of pedalling rate, power output, and lower limb kinematics (as defined by external mechanical factors) (Hull & Gonzalez, 1990). It may be possible to predict and calculate joint angle values based on the configurational variables (crank arm length, seat height, seat tube angle, and longitudinal foot position of the pedal) for a given rider anthropometry. If joint angles values can be predicted over the duration of a cycling task, it may be possible to compare these values to those obtained experimentally. Empirical data of joint angle values could be obtained with cinematographic techniques over the duration of a cycling task, and a comparison could be made with values determined from the joint moment cost function.

Further research such as this is required if the relationship between the presence of load and fatigue in a cycling task is to be further understood. It has been suggested that tailoring bicycling equipment to the individual in order to optimize performance with the lower limb kinematics is important (Hull & Gonzalez, 1990). If optimal performance is a desired end result, any changes in lower limb kinematics during the task can have potentially negative effects on performance. It has been determined that lower limb kinematics may change during a cycling task in which the presence of load and/or fatigue reduces pedalling rate and power output (Williams & Too, 1994). Therefore, in order to optimize performance, it is recommended that factors affecting performance be researched further.

CHAPTER 6

CONCLUSIONS

DB MANOVA's and post-hoc tests revealed significant differences ($p < 0.05$) between conditions of measurement technique, and load and fatigue, in the: (1) minimum angle of the hip at crank arm length 1, 2, and 4; (2) maximum angle of the hip at all crank arm lengths; (3) the minimum angle of the knee at crank arm lengths 2, 3, and 5; (4) the maximum angle of the knee at all crank arm lengths; (5) the minimum angle of the ankle at crank arm lengths 1, 2, and 3; and (6) the maximum angle of the ankle at crank arm lengths 1, 2, and 3. It is concluded that in a cycling task in which power output changes, changes in pedalling rate can result in changes in lower limb joint angle kinematics. In cycle ergometry, measurements of lower limb joint angles can vary when determined with different measurement techniques, under various conditions of load and fatigue, and with different crank arm lengths. It may then be important to obtain joint angle measurements during the actual task. But whether joint angles should be measured during an actual test condition would be dependent on the nature of the question and the degree of measurement accuracy required. However, it is recommended that joint angle measurements be determined during the actual test performance.

APPENDIX A

INFORMED CONSENT FORM

CONSENT FOR RESEARCH PARTICIPATION
UNIVERSITY OF NEVADA, LAS VEGAS

TITLE OF STUDIES
The Effect of Pedal Crank Arm Length on Upright and Recumbent Cycling Performance.
The Effect of Measurement Technique, and Load and Fatigue, with Changes in Crank Arm Length, on Lower Limb Kinematics in Cycle Ergometry.

PURPOSE
You are being asked to participate in a research study. We hope to learn how changes in pedal crank arm length will affect (1) aerobic and anaerobic cycling performance in a traditional upright position and in a recumbent position, and (2) lower limb kinematics. In addition, we hope to learn how conditions affecting the cyclist during performance will affect lower limb kinematics.

SUBJECTS
Male volunteer recreational cyclists who:
1. are interested in determining how their cycling performance may change with changes in pedal crank arm lengths, and
2. have not had any knee injuries or history of lower limb injuries.

PROCEDURES
If you decide to volunteer, the following will apply:
1. Six laboratory visits will be required.
2. Age, height, weight, total leg length, and upper and lower leg length measurements will be taken.
3. You will be assigned to one of four test conditions:
    a. upright cycling position and tested aerobically
    b. upright cycling position and tested anaerobically
    c. recumbent cycling position and tested aerobically
    d. recumbent cycling position and tested anaerobically
4. For the test condition assigned, you will be tested 6 times (with a different crank arm length each time), and with at least a one-day rest between test sessions. Each test session will be scheduled according to a mutually convenient time and your availability.
5. Still photographs and video may be taken of you in the assigned test condition for research purposes. If you are selected (because of your assigned test condition), photographs will be taken ONLY IF you agree to allow the photographs to be used in research presentations and publications, with the knowledge that you may be identified.

ANAEROBIC TEST
If you are assigned to an anaerobic test condition, each test session will be approximately 15-20 minutes in duration (depending on how much time you need to warm up and cool down). The test is called a Wingate Anaerobic Power Test, and consist of 30 seconds of "all out" pedalling. You are trying to complete as many pedal revolutions as possible in 30 seconds. You will start to pedal with no resistance, and the resistance will be instantaneously applied. The resistance used will be based on a percentage of your body weight. After 30 seconds, the resistance will be removed, and you will be asked to continue to pedal for several minutes to facilitate recovery from the test.
Risks
1. Localized muscle fatigue and discomfort towards the end of the test.
2. Possible "light-headedness" and, in some very remote and extreme cases, fainting (this is usually attributed to subjects not pedalling for a sufficient period of time during the recovery, after the test is completed).

AEROBIC TEST

If you are assigned to an aerobic test condition, each test session will be approximately 30-60 minutes in duration. You will be pedalling in synchronization to a metronome. Every 3 minutes the cycling resistance will be increased (or the metronome rate will be increased) and continually increased until you can no longer keep pace with the metronome. At this point, the resistance will be removed , and you will be asked to continue to pedal for several more minutes until you feel sufficiently recovered.

BENEFITS

1. The repeated test sessions will provide some training effect and will result in some improvement in your aerobic or anaerobic performance (depending on which test condition you are assigned) on a bicycle ergometer.
2. Information will be provided to you regarding you power production capabilities in the anaerobic tests, or estimated oxygen consumption values in the aerobic tests.
3. Participation as a subject will provide an educational experience and exposure to the types of research that is continually ongoing in the Biomechanics Research Laboratory, and the types of measurements involved.

CONFIDENTIALITY

Your participation and results from this investigation will remain confidential. No outside parties, or individual(s) will have access to your file. If this data is presented at scientific conferences or reported in a research journal, you will only be indentified by your subject identification number. HOWEVER, WITH YOUR CONSENT, if still photographs of you are taken during the test sessions and used in research presentations and/or publications, you may be indentified.

RIGHT TO REFUSE OR WITHDRAW

You may refuse to participate in any part of this study, and you may change your mind about being in the study and withdraw at any time after the study has started. However, extreme difficulties in scheduling or failing to appear at a scheduled test session without notifying the tester may result in your termination from this study.

QUESTIONS

If you have any questions, please ask. The testers can be contacted at the following numbers:

Danny Too	895-4875
Chris Williams	895-4494 or 895-4102

You will be given a signed and dated copy of this form to keep.

****

MY SIGNATURE BELOW INDICATES THAT I HAVE DECIDED TO VOLUNTEER AS A RESEARCH SUBJECT AND THAT I HAVE READ THE INFORMATION PROVIDED ABOVE.

Date	Name of Participant (print)	Signature of Participant
Date	Name of Witness (print)	Signature of Witness

APPENDIX B

SAMPLE DATA FORM

Name ______________________ Subject # _____ File ID ______________

Birthdate (month/day/year) __________ Age ________________________

Weight (kg) ______________________ Standing height (cm) ____________

Total leg length (cm) _______________ Upper leg length (cm) ____________

Lower leg length (cm) ______________ Test leg length used _____________

Crank length # 1 (long/short Hole # _________) Seat tube # _________

Crank length # 2 (long/short Hole # _________) Seat tube # _________

Crank length # 3 (long/short Hole # _________) Seat tube # _________

Crank length # 4 (long/short Hole # _________) Seat tube # _________

Crank length # 5 (long/short Hole # _________) Seat tube # _________

Ergometer resistance (85 gm/kg BM) ______________________ kp

Test sequence ______________________________________

	Hip Angles				Knee Angles				Ankle Angles			
	Min	Max	Mean	Range	Min	Max	Mean	Range	Min	Max	Mean	Range
1												
2												
3												
4												
5												

Cranklength	Max (watts)	(watts/kg)	Mean (watts)	(watts/kg)	FI%
1					
2					
3					
4					
5					

NAME ____________________ SUBJECT # _________ FILE ID _________

SESSION # 1 Date ______________ Day _________ Time _________

Crank length # _____ (long/short Hole # _________) Seat tube # _____

SESSION # 2 Date ______________ Day _________ Time _________

Crank length # _____ (long/short Hole # _________) Seat tube # _____

SESSION # 3 Date ______________ Day _________ Time _________

Crank length # _____ (long/short Hole # _________) Seat tube # _____

SESSION # 4 Date ______________ Day _________ Time _________

Crank length # _____ (long/short Hole # _________) Seat tube # _____

SESSION # 5 Date ______________ Day _________ Time _________

Crank length # _____ (long/short Hole # _________) Seat tube # _____

APPENDIX C

SUBJECT DATA SETS

Crank Arm Length 1 (shortest)

Minimum Joint Angles

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	130	92	84	132.4	96.7	92.7	131.8	102.5	90.4	133.6	102.6	90.8
2	129	98	102	126.8	96.3	113.8	134.6	94.3	113.8	136.4	98.3	88.2
3	125	104	106	118.7	34.9	85.0	117.8	39.7	87.7	122.4	42.2	80.6
4	129	101	102	123.8	95.9	100.1	124.7	95.7	98.5	127.0	96.7	89.9
5	133	100	99	125.5	95.7	102.4	126.1	88.6	108.5	131.7	95.1	78.4
6	125	96	107	128.2	95.4	100.8	130.0	94.6	117.3	129.0	96.0	91.0
7	123	95	119	124.9	95.5	120.0	128.5	97.9	113.1	127.2	95.3	99.3
8	120	91	104	119.8	88.8	107.8	122.3	89.7	105.3	127.7	93.5	88.1

Maximum Joint Angles

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	162	144	121	153.1	147.0	131.9	166.3	164.3	131.3	166.0	169.3	131.7
2	161	146	121	151.3	139.8	130.5	169.0	162.7	133.7	168.3	166.6	135.9
3	159	161	138	146.0	138.6	109.3	151.5	141.5	121.2	143.5	139.8	129.8
4	159	152	115	152.2	150.3	116.7	161.5	152.5	119.9	163.0	154.1	126.2
5	156	151	124	152.7	150.3	132.4	165.2	149.6	134.4	168.1	163.6	146.5
6	157	150	127	155.4	149.9	131.1	168.0	155.2	126.3	171.0	164.6	136.0
7	153	143	128	147.4	137.6	124.9	154.9	146.6	132.4	165.8	159.8	138.8
8	150	137	115	148.4	138.9	121.4	155.6	142.3	123.8	164.0	160.0	128.3

Crank Arm Length 2

Minimum Joint Angles

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	125	79	82	126.8	82.1	84.7	127.6	82.7	87.9	130.9	87.3	81.8
2	123	89	91	125.1	86.7	94.9	130.1	87.2	96.5	126.9	93.4	84.2
3	117	92	92	127.9	91.6	86.2	128.5	90.1	95.7	123.5	94.7	93.1
4	120	89	94	122.6	88.1	95.3	122.9	86.4	101.1	118.9	93.2	91.7
5	121	86	98	116.8	81.8	100.5	119.9	78.7	104.4	120.6	83.1	92.2
6	117	85	97	118.3	80.8	97.8	121.1	81.4	110.6	119.9	86.8	95.1
7	115	82	119	120.7	89.8	116.3	123.3	82.4	108.1	118.9	84.9	92.5
8	113	78	95	114.5	73.3	99.1	115.9	78.5	102.9	117.8	80.8	85.4

Maximum Joint Angles

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	163	141	119	158.1	142.1	121.6	163.7	150.0	123.6	166.5	149.2	125.0
2	159	150	121	150.3	150.1	123.6	160.1	157.8	128.7	163.4	163.4	131.8
3	155	160	132	154.6	152.3	131.8	168.2	162.9	133.2	173.8	174.6	128.6
4	161	153	106	158.0	144.5	110.9	164.2	145.1	119.9	165.1	157.3	126.7
5	151	149	127	146.8	147.3	126.2	155.2	147.5	127.8	158.5	150.6	129.9
6	155	153	123	151.7	141.6	131.0	161.3	144.2	129.0	163.2	151.0	133.9
7	150	147	128	145.9	139.0	129.1	161.0	149.0	127.6	169.0	158.4	136.9
8	149	140	113	147.6	133.6	117.3	156.4	142.7	120.3	150.7	142.2	128.1

Crank Arm Length 3

Minimum Joint Angle

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	116	66	89	116.5	71.4	96.6	118.1	75.2	90.4	118.7	76.0	88.9
2	112	78	99	114.3	76.1	99.2	117.2	77.6	117.9	113.5	82.0	93.6
3	113	79	81	123.6	76.4	84.8	121.4	77.7	91.1	125.0	78.7	92.9
4	109	80	109	112.3	73.6	106.3	109.9	71.1	110.2	113.1	82.7	92.7
5	119	71	108	106.7	66.8	100.6	109.3	71.4	107.6	115.0	69.7	89.1
6	109	73	102	112.0	72.9	90.0	112.8	69.5	100.7	112.4	72.7	89.5
7	106	72	106	108.4	68.8	116.3	109.3	68.7	106.0	113.9	70.2	97.0
8	105	64	85	107.3	64.2	92.3	106.4	65.9	97.9	112.3	73.4	84.6

Maximum Joint Angle

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	157	140	114	150.2	142.2	118.6	158.5	151.3	119.5	160.0	153.8	117.9
2	161	149	116	151.7	148.4	131.2	158.9	150.3	137.6	163.5	158.6	148.1
3	156	160	133	157.0	150.8	134.4	166.1	160.4	133.4	169.1	157.2	138.2
4	161	153	106	158.0	144.5	110.9	164.2	145.1	119.9	165.1	157.3	126.7
5	153	148	130	149.8	141.5	127.3	161.4	142.6	121.6	157.4	140.6	137.1
6	154	150	125	159.5	151.1	131.0	163.2	150.8	129.7	158.8	150.2	131.9
7	150	142	127	144.8	135.7	125.6	149.9	138.2	122.7	153.1	136.4	134.8
8	148	144	116	136.6	119.9	114.0	145.8	131.4	121.9	143.4	132.8	125.7

Crank Arm Length 4

Minimum Joint Angles

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	107	55	81	106.8	58.4	82.3	110.1	58.9	81.8	102.6	55.7	100.8
2	105	62	91	107.2	62.9	93.7	114.6	66.9	101.2	109.9	67.4	98.6
3	115	68	86	106.6	65.4	86.7	122.4	69.1	77.6	110.6	68.7	84.2
4	103	69	92	98.9	57.9	98.2	104.8	56.7	93.2	102.7	58.7	93.5
5	102	57	93	94.4	55.3	96.3	99.2	58.2	94.1	101.7	57.6	87.7
6	98	62	109	98.3	56.0	86.4	105.2	58.3	91.2	104.5	56.9	100.0
7	97	57	102	101.0	56.5	110.2	105.2	59.4	112.9	105.5	60.5	101.2
8	91	50	95	91.1	51.6	92.6	94.9	53.9	97.1	94.3	56.4	93.5

Maximum Joint Angles

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	160	150	126	156.6	146.9	100.8	164.2	152.2	100.1	161.1	149.2	108.6
2	161	158	121	158.3	154.2	138.2	163.3	157.1	138.9	164.1	158.9	139.1
3	159	162	119	155.5	154.1	134.8	168.1	164.4	136.8	168.4	165.9	136.3
4	162	159	117	155.9	154.1	134.8	168.1	164.4	136.8	168.4	165.9	136.3
5	157	157	127	153.2	152.8	126.9	158.1	156.8	128.7	161.0	158.3	130.5
6	155	153	126	156.0	152.8	136.0	165.3	157.1	139.2	160.2	155.4	138.2
7	152	145	118	148.5	142.0	130.5	151.9	144.5	129.8	159.8	146.1	131.5
8	151	147	120	147.3	142.1	112.3	151.8	148.3	119.0	146.1	149.3	122.1

Crank Arm Length 5 (longest)

Minimum Joint Angles

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	93	47	106	94.9	42.4	84.4	93.6	50.4	78.7	90.9	49.2	77.5
2	99	60	85	103.6	53.1	82.2	102.2	57.2	78.7	98.3	58.1	76.2
3	98	56	87	101.2	50.8	82.6	99.6	55.5	80.0	97.1	54.1	78.5
4	93	55	97	87.9	53.0	91.5	92.7	53.6	106.0	87.2	53.4	92.2
5	95	49	89	90.1	45.2	96.8	92.0	48.4	91.0	92.7	47.4	85.5
6	85	51	107	86.0	41.6	88.9	90.1	48.1	86.7	88.9	44.0	85.8
7	89	48	100	88.9	47.6	107.2	92.5	46.8	101.0	96.2	48.1	101.7
8	80	38	82	81.1	33.7	84.8	87.7	39.7	85.8	80.9	41.2	85.3

Maximum Joint Angles

	Goniometer			Unloaded			Loaded Non Fatigued			Loaded Fatigued		
SUBJ.	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle
1	165	154	126	152.0	142.7	125.3	161.6	159.3	119.6	152.5	152.6	124.0
2	165	168	136	165.8	159.2	126.5	166.9	166.7	129.8	159.5	158.1	164.2
3	158	156	130	156.9	149.3	120.0	160.3	151.8	127.1	152.2	155.5	129.8
4	158	162	114	158.5	153.6	127.5	161.8	160.9	145.1	162.6	158.9	144.4
5	154	157	129	154.8	149.1	129.4	164.2	157.7	124.9	152.9	146.3	131.9
6	150	152	142	151.7	144.6	126.3	158.5	150.6	123.7	154.3	147.0	122.4
7	149	140	123	144.2	141.6	124.9	150.5	143.3	126.5	152.7	141.0	127.0
8	150	148	115	144.6	137.4	108.8	150.5	141.6	127.8	142.0	139.8	131.3

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