The Biomechanical Effects of Crank Arm Length on Cycling Mechanics

By

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Abstract

The hypothesis of the current investigation was that there existed a relationship between anthropometry (total leg length, thigh length and shank length) and the crank length permitting the lowest heart rate at a given work rate (optimum crank length). In order to understand the mechanisms governing this relationship, segmental energies, average effective forces and average linear velocities of the foot were calculated. Sixteen avid cyclists completed one ride at each of 6 randomly presented crank lengths (120 mm, 140 mm, 160 mm, 180 mm, 200 mm and 220 mm). Subjects rode at a power output that elicited a heart rate response of approximately 155 bpm while riding with 160 mm cranks and were required to maintain a constant cadence of 90 rpm. During each crank length condition, pedal forces and heart rate were measured and videotape was collected. A multiple regression revealed that neither the average effective force, nor the average resultant linear velocity of the foot predicted the heart rates elicited across all crank lengths. A repeated measures ANOVA showed that the lowest segmental energies occurred at the shortest crank length. Optimum crank length was calculated for each subject and a multiple regression revealed that 51% of the variance in optimum crank length could be predicted by the following equation: optimum crank length (mm) = (18.971*shank length) – (7.438*total leg length) + 90.679. However, almost all subjects' optimum crank lengths were in the range of 120 mm to 160 mm; a grouping of cranks that elicited statistically similar physiological responses and that includes crank lengths very close to the industry standard of 170 mm. It was therefore the recommendation of the investigator that crank lengths need not be changed from the industry standard of 170 mm for individuals of various leg lengths as optimum crank lengths predicted from leg

length measures do not differ significantly in terms of physiological responses from crank lengths very close to the current industry standard.

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Chapter I Introduction

Body dimensions play an important role in the design of workspaces, tools, appliances, and athletic equipment used by a wide variety of individuals. Proper ergonomic design is essential to one's comfort, safety, and functional ability. The anthropometry of an individual's segment dimensions provides important information when designing equipment that requires the interaction between a person and an object, or workspace. Dempster (1955) completed an in-depth analysis of the human form and function in order to improve the design of a pilot cockpit. He realized the importance of altering an environment, or piece of equipment, in order to improve the efficiency of a "man-machine system". He stated that "The man, of course, can be trained but he cannot be physically modified. The limitations of his muscles and joints and of his physiology and psychology are built-in and immutable. Only the cockpit and its controls may be changed in the hope that efficiency will be increased." (Dempster, 1955). The principles involved in designing a cockpit are the same as those employed in constructing a bicycle. The bicycle must be designed to fit the human body as incorrectly dimensioned equipment limits comfort and the ability to function at optimal levels, thereby having a detrimental effect on performance (Burke, 1996). There exist many measurable physiological and biomechanical variables that can be optimized when certain geometric parameters, such as crank length (CL), are altered in order to improve bicycle design.

Determining the optimum set-up of a bicycle can be achieved by investigating a number of variables. It has been shown that, in gait, subjects chose a stride length that minimized aerobic demand (Cavanagh, 1982). Many investigators have transferred the concept of minimizing aerobic demand during human gait to the sport of cycling.

Numerous studies (Nordeen-Snyder, 1977; Mandroukas, 1990; Heil, 1995) have used oxygen consumption as a means of determining the optimal set-up of a bicycle by altering such variables as seat height, foot position, and seat-tube angle. In addition, many studies that have optimized seat height, foot position, and seat tube angle through the measurement of both physiological and biomechanical parameters found similar optimization results regardless of the parameters measured (Nordeen-Snyder, 1977; Gonzalez, 1989; Mandroukas, 1990; Heil, 1995). Therefore, by measuring only the physiological demand placed on a cyclist, an individual's optimum CL (OCL) can then be determined. However, there exist many morphological differences among individuals that must also be considered when designing equipment for the broad spectrum of sizes in the population in order to determine the optimal geometric set-up of a bicycle.

It has been documented that the anatomical dimensions of cyclists influence their physiological and biomechanical responses to an alteration in specific geometric variables (Carmichael, 1981; Inbar, 1983; Hull, 1988; Gonzalez, 1989; Burke, 1994). However, the exact nature of the relationship between anthropometry and CL remains unclear. When the current literature was analysed, it was not clear what anatomical measurements best predict optimum CL (the CL that elicits the lowest physiological or biomechanical response) and to what degree OCL may be predicted, if at all. Carmichael (1981) computed a regression equation predicting OCL from thigh length (TL) while Gonzalez and Hull (1989) and Hull and Gonzalez (1988) stated that OCL increases with the size of the rider. In contrast, Morris and Londeree (1997) reported that a cyclist's OCL was not related to any measure of leg length when oxygen consumption was measured while riding at various lengths of crank arms. Therefore, there remains a disparity in the results of studies that have investigated the relationship between OCL and leg length measures and consequently displays the need for further research to ascertain whether there exists a significant relationship between OCL and anthropometry.

A major limitation of the studies that have investigated the relationship between OCL and anthropometry is that a narrow range of sizes of subjects has been employed. For instance, some studies have defined a short rider to be 169.3 cm tall (Carmichael, 1981). However, there exist many competitive and recreational cyclists of shorter statures, for example those riders who are under 160 cm tall. In addition, as Cavanagh and Kram (1989) discuss in their paper investigating the relationship between stride length and velocity, body dimensions and added masses, it is imperative to have a large sample of subjects of many different sizes in order to insure statistical integrity. As an example, if there were two clusters of subjects used (very short and very tall) when attempting to correlate leg length with OCL, the results of the correlation would be confounded by the existence of two sub-populations. The magnitude of the resulting correlation coefficient would then be different than if a single group of subjects of all sizes was used. Therefore, it is important that the sample used to determine the relationship between anthropometry and OCL be large and contain subjects of many different heights.

The industry standard for crank arms found on both competition and recreational-level bicycles remains at 170 mm (Gonzalez, 1989). Using the equation derived by Carmichael (1981), it was calculated that someone 163 cm tall should be riding a bike equipped with 140 mm-long cranks. However, a bicycle with a frame size appropriate for this individual comes supplied with 170 mm-long cranks. Therefore, this cyclist would be riding a bicycle with cranks that are too long and according to Carmichael (1981), would be riding with an increased aerobic demand. Riding with crank arms that are either longer or shorter than that deemed to be optimal increases the physiological demand on the individual (Carmichael, 1981), thereby causing a detriment in performance. Therefore, more information needs to be acquired regarding OCLs for individuals of different sizes in order to supply correctly dimensioned equipment to the cycling community.

No explanation has been given as to why an interrelationship between anthropometry and OCL exists. However, from previous studies it was hypothesized that shorter riders should be using shorter cranks and taller riders should be using longer cranks in order to optimize both the physiology (Carmichael, 1981) and the biomechanics (Hull, 1988; Gonzalez, 1989) of a cyclist. **It was hypothesized by the current study that a convex parabolic relationship between anthropometry and OCL existed due to an interaction between CL and anthropometry and their effects on range of motion (ROM) at the hip, knee, and ankle joints.** The ROM at each of the lower limb joints dictates the motion of the legs and determines what the angular and linear displacements, velocities and accelerations will be. In addition, both the anthropometry and the geometrical set-up of the bicycle; i.e. CL, influence the ROMs of each of the lower limb joints. It was therefore expected that as both anthropometry and CL were altered, the ROMs of the lower limb joints would also change, thereby altering the kinematics of the leg. As the kinematics of the leg play a large role in dictating the total energy of each of the lower limb segments, it was then concluded that by altering anthropometry and/or CL, the total energy of each segment would concurrently be changed. Segmental energies of the lower limb could therefore be calculated from kinematic information and then analysed to determine their role in dictating OCL. As the underlying mechanisms governing the relationship between anthropometry and OCL remain elusive, it was therefore important to investigate the changes taking place in cycling mechanics. It was important to understand the causes of the relationship between anthropometry and OCL in order to optimize the performance of an individual through improving the geometrical set-up of their bicycle.

In addition, there remain many unanswered questions regarding the biomechanical changes in cycling elicited by a change in CL, which result in concurrent changes in the physiological responses of the rider. Very little insight has been given into the changes occurring at the level of the muscles, due to biomechanical changes elicited by a change in CL, that could affect certain physiological parameters such as heart rate (HR). Carmichael (1981) proposed a number of factors, namely the mechanical and metabolic properties of muscle, that allude to the physiologic rationale for an OCL. However, no data were collected to support his conclusions. Therefore, it still remains unclear as to what the biomechanical changes are that are elicited by a change in CL that cause parallel changes in energy expenditure. **It was hypothesized by the current study that the HR response to altering CL was governed by the interacting effects of pedal forces and the linear velocity of the foot.**

The hypothesis of the current investigation was that there existed a relationship between anthropometry (total leg length (TLL), TL, shank length (SL)) and the CL permitting the lowest heart rate at a given work rate (OCL). An understanding of the mechanisms governing the anthropometry – CL relationship as well as the

biomechanical factors influencing the changes in HR elicited when CL was altered were also being searched for.

Chapter II Methods

2.1 Subjects

Sixteen healthy participants, five females and 11 males, aged 24.4 ± 4.5 years (mean ± S.D.) volunteered to take part in this study. Before any testing began, the study protocol was approved by the University Clinical Screening Committee for Experiments with Human Subjects and each subject signed an informed consent. All participants were avid cyclists with eleven currently competing in triathlons, mountain bike races and road races. Subjects were chosen on the basis of their height in order to ensure that a wide range of sizes was employed. Subjects were required to fit within a range of trochanteric heights of 80 cm to 102 cm due to limitations of the cycling equipment.

2.2 Instrumentation and Experimental Set-Up

The experimental protocol included testing the subjects on a bicycle mounted on a Schwinn Velodyne (Schwinn Corporation, Chicago, IL), which is an electronically braked cycle ergometer upon which power output may be modulated according to cadence. There were six criterion rides, each at a different CL. The following CLs were used: 120 mm, 140 mm, 160 mm, 180 mm, 200 mm, 220 mm.

A set of 170 mm alloy cotterless cranks was modified in order to produce two cranks that were adjustable in 20 mm increments from 120 mm to 220 mm. A 5.5 cm piece was cut out of each of the original cranks and each of the four remaining ends was milled so that a tapered lap joint could take place with a tapered aluminum insert. Twelve inserts were machined from a piece of aluminum alloy. The length of the crank was defined as the distance between the centre of the pedal axle and the centre of the bottom bracket axle. Two sets of screws, lock washers and nuts per crank then held the three sections of crank together. Pictures of the adjustable cranks can be found in Appendix E.

The rear tire on the bicycle mounted on the Velodyne was kept at 90 psi. All rides took place at a cadence of 90 rpm and at a power output that elicited a HR response of approximately 155 bpm while riding at a CL of 160 mm. This relative power output was chosen so that it would be submaximal for all riders and yet would be high enough to challenge the rider. Cadence was kept constant with the use of a cycle computer upon which cadence was displayed. The absolute seat height as measured from the top of the pedal platform to the top of the seat was kept constant at 100% trochanteric height (the distance from the greater trochanter to the floor) (Nordeen-Snyder, 1977). Therefore, as CL was altered, e.g. extended by 20 mm, the seat was lowered by 20 mm. The ball of the foot was placed over the pedal spindle and attached via a cleat and pedal strap system and the fore-aft saddle position was set so that the front aspect of the patella was directly over the pedal spindle when the crank was at 90 degrees.

2.3 Procedures

Each subject reported to the lab for one 3-hour testing session. Once the subject had given informed consent and the study protocol had been explained, anthropometric data were collected. In order to minimize variability and to ensure accurate results, the investigator collected all data and each measurement was taken twice and then an average was computed. These measures included standing height, trochanteric height (which, by definition, was the same as TLL), TL and SL. Total leg length was defined as the distance from the greater trochanter to the floor while the subject was standing in bare feet (Nordeen-Snyder, 1977). Thigh length was defined as the distance from the greater trochanter of the femur to the tibiale laterale (lateral potion of the upper border of the tibia) (Ross, 1991). The length of the lower leg from the tibiale mediale (medial potion of the upper border of the tibia) to the sphyrion (distal tip of the medial malleolus) was defined as shank length (Ross, 1991). Mass was also recorded. Reflective markers were placed on the following anatomical landmarks on the left leg of the subject: greater trochanter, lateral aspect of the knee, lateral malleolus, heel and base of the 5^{th} metatarsal. A portable heart rate monitor chest strap was placed around the subject's chest, just below the pectoral muscles. Adjustments were made to seat height, fore-aft saddle position and foot position on the cycle ergometer in order to insure proper positioning for each subject.

After a self-selected warm-up while pedaling with the 160 mm cranks (a mid-length CL close to the industry standard of 170 mm), the subject rode for approximately five minutes in order to determine the power output that elicited a HR response of approximately 155 bpm. This was the power output at which the subject rode. The participants then performed six criterion rides, each one at a different CL and each lasting approximately six minutes. This time was long enough to elicit a steady state response in HR from the cyclists. The order of the CLs was randomized to negate the effect of order and a rest period of at least ten minutes was incorporated between each ride to help minimize fatigue.

During each CL condition, pedal forces and heart rate were measured and videotape was recorded. Forces at the pedal were recorded using two triaxial peizo-electric force transducers mounted in the left pedal. Tangential and normal forces were recorded at 600 Hz for eight seconds after completion of each 6-minute ride via a 12 bit analogue-to-digital converter controlled by a personal computer. A continuous output optical encoder was used to record pedal angle and crank angle at a rate of 600 Hz. These data were recorded through Peak Motus. Kinematic data for the left leg were recorded for the last eight seconds of each criterion ride using videotape. Video data were recorded at 60 Hz. Each eight-second video clip was imported into the Peak Motus motion analysis program for digitization and kinematic variables were then calculated. The resulting data were filtered in Peak Motus using a 2nd order, dual pass Butterworth filter with a cut-off frequency of 5 Hz. Heart rate was collected during the entire 6-minute ride for each of the six CLs using a Sport Tester PE 3000 portable HR monitor (Polar Electro Inc., Finland). The HR data were then downloaded from the portable HR monitor using a Polar interface system. HR, as opposed to oxygen uptake (VO_2), was chosen as the indicator for effort as it was easy to obtain and is a non-invasive measurement. Also, HR is linearly related to VO_2 (Foss, 1998) which is the rate at which oxygen is consumed. VO_2, at a steady state, is a measure of all of the energy required for a particular task (Foss, 1998). Therefore, if VO_2, or in this case HR, changed during a particular ride at a given power output, this indicated a change in the energy requirement and therefore efficiency of a particular CL.

2.4 Data Analysis

This study employed a single group descriptive and correlational research design. Crank arm length was the independent variable and OCL was determined from the heart rate data. The following dependent variables were used: TLL, TL, SL, thigh segmental energy, shank segmental energy, leg segmental energy, average effective force (average Fe), average resultant linear velocity of the crank (average LV), which was used to represent the average LV of the foot, and average HR.

In the determination of the OCL for each subject, an average HR was calculated over minute five for each CL. The data (average HR for each CL) were then differentiated and the CL (to the nearest mm) at which the zero differential occurred was considered to be the OCL as this point represents the CL at which the minimum HR occurred.

A Pearson Product Moment Correlation coefficient was calculated for OCL, TL, SL and TLL in order to determine the degree of relationship between OCL and the measured leg lengths. A stepwise multiple regression was then run using OCL as the dependent, or criterion variable, and TLL, TL and SL as the independent, or predictor variables.

Segmental energies were determined by calculating the potential, kinetic and rotational energies were in the horizontal and vertical directions for the thigh, shank and total leg. The thigh and shank segmental energy values were combined to generate the total leg segmental energies. The total segmental energies in the horizontal and vertical directions were then added together to produce an overall segmental energy value for each of the three leg segment definitions. Appendix A illustrates the equation used to calculate the segmental energies.

A single factor repeated measures ANOVA was employed to determine if segmental energies were at a minimum at the OCL. The three dependent measures used were the thigh segmental energy, shank segmental energy and total leg segmental energy. The repeated measures factor was CL with OCL-1 (one CL shorter than optimal), OCL and OCL+1 (one CL longer than optimal) being used in the analysis.

The effects of the average Fe and the average LV of the foot on the HR elicited while cycling with the six different CLs were examined in order to resolve the biomechanical mechanisms governing the effects of altering CL on HR. The average Fe was obtained by calculating the component of the resultant pedal force that was perpendicular to the crank and computing the average of this value for the whole crank cycle. The average LV of the foot was determined by calculating the average of the resultant linear velocity of the end of the crank throughout one entire crank cycle.

A multiple regression was run to determine the degree of relationship between the average Fe and the average LV and the HR elicited at each of the 6 CLs. The independent, or predictor variables were the average Fe and the average LV while the dependent, or criterion variable was the HR elicited at a particular CL. This procedure was completed 6 times, once for each of the 6 CLs tested during this study.

The segmental energy, average Fe and average LV of the foot data were all determined by calculating an average for one crank cycle with the data from 10 crank cycles.

Chapter III Results

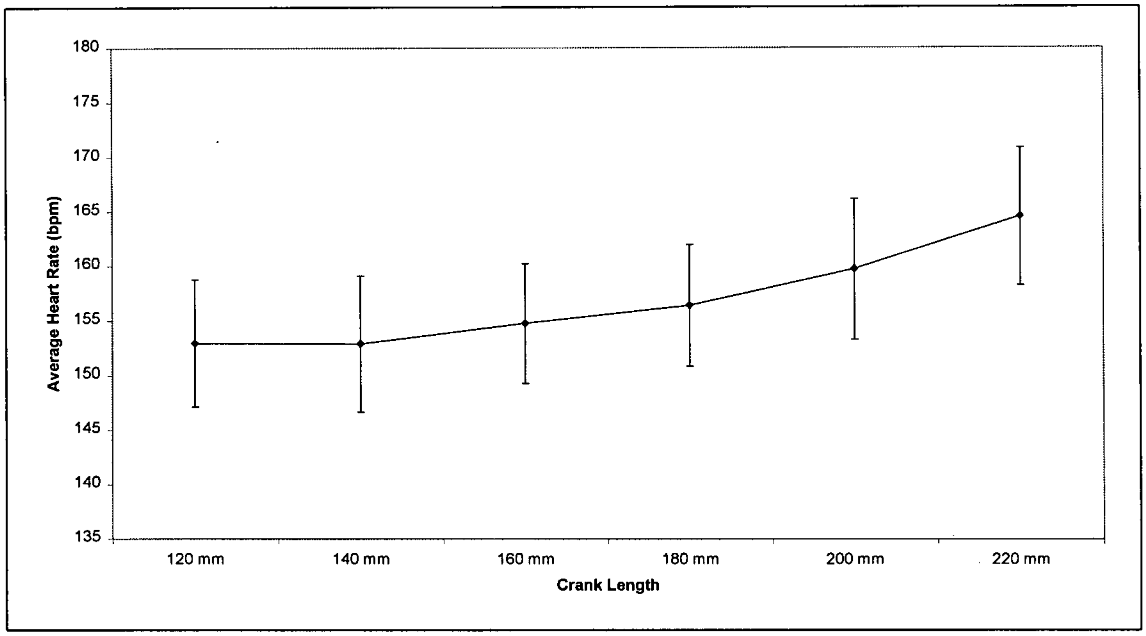
Subject's cycling experience and individual, as well as average characteristics are presented in Table 1. The mean height and mass of the subjects were 174.9 ± 9.6 cm and 68.5 ± 9.2 kg respectively. Mean leg length measures were as follows: total leg length: 89.8 ± 6.0 cm, thigh length: 45.0 ± 2.5 cm, shank length: 37.6 ± 2.9 cm. The mean number of hours of riding per week was 7.8 ± 3.3 hours.

Table 1: Subjects' Cycling Experience and Characteristics. (M=male, F=female)

Subject (Sex)	Age (yrs)	Height (cm)	TLL (cm)	TL (cm)	SL (cm)	Mass (kg)	Weekly Riding (hrs)	Racing Experience (yrs)	OCL (mm)
1 (M)	24	174.4	88.9	42.0	36.3	64.4	1	0	120
2 (M)	23	172.4	89.8	45.7	37.7	64.3	6	0	120
3 (F)	37	161.5	81.8	42.9	34.6	69.8	10	2	142
4 (M)	23	170.0	85.2	42.0	35.5	64.3	10	4	148
5 (M)	20	191.3	98.8	47.9	42.6	89.5	8	2	192
6 (M)	19	174.8	89.0	45.3	37.0	67.2	10	2	147
7 (F)	30	163.2	83.1	41.6	35.5	50.7	5	7	148
8 (M)	24	181.9	94.0	48.0	38.7	77.2	6	2	120
9 (M)	21	189.2	100.8	48.7	43.6	76.4	6	0	172
10 (M)	21	170.9	85.7	42.8	36.0	62.5	8	0	120
11 (F)	29	176.3	92.7	47.8	39.7	75.1	15	2	120
12 (F)	26	158.4	80.6	42.4	33.0	54.7	10	3	120
13 (F)	22	167.1	85.3	44.0	34.6	64.6	5	5	120
14 (M)	24	182.9	94.5	45.5	39.4	73.8	4	0	120
15 (M)	26	180.8	91.7	46.9	37.9	69.5	10	11	120
16 (M)	21	182.9	95.1	46.2	40.0	71.6	10	4	151
Avg.	**24.4**	**174.9**	**89.8**	**45.0**	**37.6**	**68.5**	**7.8**	**2.8**	**136.3**
S.D.	**4.5**	**9.6**	**6.0**	**2.5**	**2.9**	**9.2**	**3.3**	**3.0**	**22.2**

From averaged HR data, OCL was calculated. Individual OCL's are presented in Table 1 and mean HR data plotted against CL are shown in Figure 1. For comparison, mean HR data collected by Carmichael (1981) are presented in Appendix C16.

Figure 1: Mean Heart Rate Plotted With Respect to Crank Length (+1 S.D. error bars).



The correlation between OCL and TL was non-significant ($r=.278$, $p=.149$). Both the correlation between OCL and SL and the correlation between OCL and TLL were significant ($p<.05$, $r=.552$ and $r=.434$ respectively). These results indicated that there was a significant linear relationship between OCL and each of SL and TLL. A multiple regression was run to determine the extent of the relationship between SL, TLL and OCL. SL and TLL were both significant predictors of OCL ($p=.012$ and $p=.036$ respectively) and the model with the highest correlation ($r=.715$) could account for 51.1% of the variance in OCL and could be expressed as follows: OCL (mm) = $(18.971*SL) - (7.438*TLL) + 90.679$.

Through the use of a single factor repeated measures ANOVA, it was determined that there were significant differences ($p<.001$) in the HRs elicited among the different lengths of crank arms ($F_{5,75}=35.16$). A Newman-Keul's post hoc analysis revealed that there were no significant differences between the HRs elicited at the 120 mm, 140 mm and 160 mm cranks and between the 160 mm and 180 mm cranks. However, there were significant differences ($p=.05$) between each of the 180 mm, 200 mm and 220 mm crank lengths.

Segmental energies were calculated for the thigh, shank and the total leg and mean values are presented in Table 2.

Table 2: Mean segmental energies for the thigh, shank and total leg (mean ± S.D.).

	Crank Length					
	120 mm	**140 mm**	**160 mm**	**180 mm**	**200 mm**	**220 mm**
Thigh (J)	66.6±13.2	67.6±13.1	69.3±13.2	69.7±14.0	72.1±13.6	75.2±14.4
Shank (J)	24.4±4.3	27.3±5.0	30.7±5.2	34.0±6.3	37.8±6.5	42.7±7.0
Leg (J)	91.0±17.4	94.9±18.0	100.0±18.4	103.7±20.2	109.9±20.0	118.2±21.5

A single factor repeated measures ANOVA was performed comparing the mean segmental energies for the thigh, shank and total leg elicited at one crank length shorter than optimum (OCL-1), OCL and one crank length longer than optimum (OCL+1) to determine whether segmental energies increased significantly away from the OCL. The analysis was only completed on seven subjects as nine of the 16 subjects had OCLs of 120 mm. Therefore, it was not possible to include these subjects in the repeated measures ANOVA as there was no CL shorter than 120 mm employed during this study and therefore no OCL-1 to use in the analysis. Nonetheless, the results of the ANOVA confirmed that the segmental energies for the thigh ($F_{2,12}$=17.548), shank ($F_{2,12}$=50.376) and total leg ($F_{2,12}$=36.685) differed significantly when CL was altered ($p<.001$). However, the lowest segmental energies were elicited at OCL-1 and not at OCL as hypothesized.

The average Fe and average LV of the foot values are presented in Table 3.

Table 3: Mean Effective Force and Resultant Linear Velocity of the Foot for all Crank Lengths (mean ± S.D.) Averaged Across Subjects.

	Crank Length					
	120 mm	**140 mm**	**160 mm**	**180 mm**	**200 mm**	**220 mm**
Fe (N)	38.8±9.3	31.9±11.7	27.9±10.8	25.9±7.5	21.3±8.3	24.6±9.5
LV (m/s)	1.2±0.03	1.4±0.03	1.6±0.02	1.8±0.03	2.0±0.04	2.2±0.03
HR (bpm)	153.0±5.8	152.9±6.2	154.8±5.5	156.4±5.6	159.8±6.4	164.6±6.3

A multiple regression was used to determine whether average Fe or LV, or a combination thereof, would predict the HR elicited while riding with a particular length of crank arm. The only significant predictor ($p=.008$) of HR was the average Fe, at a crank arm length of 120 mm.

Maximum, minimum and ranges of motion for the hip, knee and ankle angle are displayed in Table 4.

Table 4: Maximum (Max), Minimum (Min) and Range of Motion (ROM) for the Hip, Knee and Ankle Angles for Each of the Six Crank Lengths (mean ± S.D.).

	Crank Length					
	120 mm	**140 mm**	**160 mm**	**180 mm**	**200 mm**	**220 mm**
Hip						
Max (°)	69.6±2.0	69.5±2.5	68.9±2.2	68.1±2.0	68.1±2.1	67.8±2.0
Min (°)	36.1±3.2	32.4±3.4	28.1±3.5	23.7±4.0	20.1±4.0	15.9±4.9
ROM (°)	33.6±2.6	37.1±2.9	40.8±2.8	44.3±3.5	48.0±3.9	52.0±4.5
Knee						
Max (°)	156.3±35	156.0±4.5	155.1±3.7	152.6±3.5	153.4±4.7	152.2±3.7
Min (°)	92.6±3.5	86.3±3.2	79.1±3.7	72.2±3.5	66.9±4.1	60.3±4.9
ROM (°)	63.7±4.9	69.7±5.7	75.9±5.4	80.4±5.1	86.5±5.8	91.9±5.5
Ankle						
Max (°)	98.6±9.5	98.9±10.1	101.2±8.1	101.6±7.9	102.5±7.0	103.9±7.8
Min (°)	74.7±6.2	74.1±5.6	73.8±5.3	72.8±5.3	73.2±5.8	71.8±5.1
ROM (°)	24.0±8.3	24.8±9.0	27.5±7.0	28.8±8.2	29.3±7.7	32.1±8.6

The following significant changes were elicited with an increase in crank arm length ($p<.001$): maximum ($F_{5,75}$=7.69) and minimum ($F_{5,75}$=588.40) hip angles decrease, ROM ($F_{5,75}$=596.88) of the hip increases, maximum ($F_{5,75}$=12.98) and minimum ($F_{5,75}$=1779.19) knee angles decrease, ROM ($F_{5,75}$=725.34) of the knee increases, maximum ($F_{5,75}$=5.39) ankle angle increases, minimum ($F_{5,75}$=4.96) ankle angle decreases and ROM ($F_{5,75}$=11.10) of the ankle increases.

Chapter IV Discussion

4.1 Optimum Crank Length – Leg Length Relationship

The main finding of this study was that OCL can be predicted by both SL and TLL. These data concur with the results of studies completed by Carmichael (1981), Inbar et al. (1983), Hull and Gonzalez (1988), and Gonzalez and Hull (1989) and do not concur with those data reported by Conrad and Thomas (1983) and Morris and Londeree (1997). Carmichael (1981) constructed a regression equation that predicted OCL from TL. There lies a discrepancy between the present study and that completed by Carmichael (1981) as different leg length measures were used to predict OCL. This difference in predictor variables may be attributed to the fact that Carmichael (1981) used different leg length measures. Carmichael (1981) measured leg lengths according to the following definitions: TLL was the distance from the pubic symphysis to the floor with the subject standing with knees extended, TL was the distance from the pubic symphysis to the centre of the medial condyle of the femur and SL was computed SL = TLL – TL. These methods differ greatly from the ones employed in this study. This results in very different leg length proportions between the two studies. In the current investigation, it was computed that TL was 50.1% of TLL on average and SL was 41.9% of TLL on average. Whereas for Carmichael's study (1981), TL and SL were 48.7% and 51.3% of TLL respectively. Therefore, it can be seen that the leg length proportions are different between the two studies due to different measuring techniques and would therefore affect the outcome of a simple multiple regression.

The current study did not replicate the leg length measures used by Carmichael (1981) for a number of reasons. Firstly, the current study employed measurement techniques that are considered anthropometric norms (Ross, 1991) whereas the leg length measures used by Carmichael (1981) are not commonly used in anthropometric practices. It was not outlined in Carmichael's paper (1981) the procedures used to execute the leg length measures made in his study, thereby making it difficult to accurately replicate his measures.

There have been two other studies completed that defined OCL as that CL which elicits the lowest physiological response (as measured by oxygen uptake) and that found no relationship between any measure of leg length and OCL. Morris and Londeree (1997) used a homogeneous group of subjects as their heights ranged from 172.7 cm to 178.5 cm, only a 6 cm range. In addition, the range of crank lengths employed was also small (165 mm to 175 mm). Conrad and Thomas (1983) also used a narrow range of cranks (165 mm to 180 mm) to test the hypothesis that leg length was related to OCL. Therefore, it was not surprising that neither of these studies found a relationship between leg length and OCL, especially as most subjects in the current study had OCL's below those measured by Conrad and Thomas (1983) and Morris and Londeree (1997). In addition, both Carmichael (1981) and the current study found no physiological differences between the shortest CL and the longest CL used in the studies completed by both Conrad and Thomas (1983) and Morris and Londeree (1997).

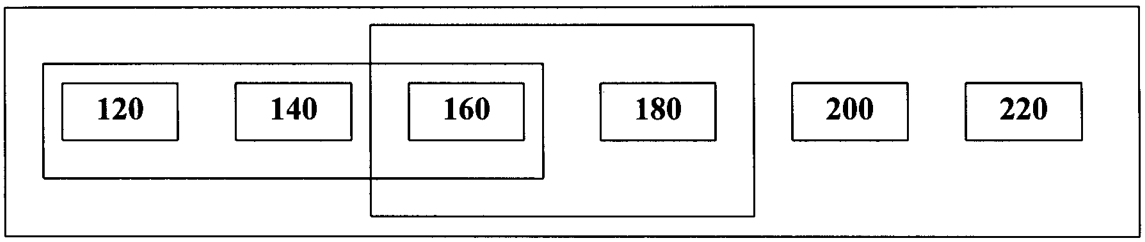
Three other studies have attempted to relate OCL to a measure of leg length but have used parameters other than physiological measures in defining a particular CL as optimal. Hull and Gonzalez (1988) and Gonzalez and Hull (1989) both defined OCL as that CL which elicited the smallest moment-based cost function. Inbar et al. (1983) characterized the OCL as being that CL which optimized power output. Hull and Gonzalez (1988) and Gonzalez and Hull (1989) stated that taller riders should use longer cranks. Inbar et al. (1983) defined ratios of leg length over crank length that optimized mean and peak power. In conclusion, regardless of the optimizing method used, the results of all three of these studies concur with the present one in that OCL was related in some manner to leg length.

Finally, it does appear from the results of the above-mentioned studies that OCL was indeed related to some measure of leg length, independent of the parameters used to define OCL. However, the question remained as to whether crank lengths outside of those determined to be "optimal" for an individual were physiologically inferior to other lengths of crank arms, including the industry standard of 170 mm, i.e. do different CLs elicit significantly different physiological responses. This would lead to the conclusion that in reality, the relationship between OCL and leg length is irrelevant in optimizing performance as the CLs commonly used in industry are not physiologically significantly different from those CLs deemed to be "optimal" for an individual through regression equations.

4.2 Physiological Changes Elicited with Changes in Crank Length

The results of the current study demonstrated that HR increased in a parabolic manner when CL was increased from 120 mm to 220 mm. It was found that the HR elicited while riding with cranks of lengths 120 mm, 140 mm and 160 mm were not significantly different from one another. In addition, the 160 mm and 180 mm cranks elicited statistically similar HRs but there were differences found in the HR between the longer cranks employed in the current study. Figure 2 displays the CLs that elicited statistically similar HR responses.

Figure 2: Boxed CLs Elicited Statistically Similar HR Responses.



These data concur with those published by Goto et al. (1976), Carmichael (1981), Conrad and Thomas (1983), and Morris and Londeree (1997) and disagree with Astrand (1953). Carmichael (1981) found that there were no significant differences in the HRs elicited by the 150 mm, 160 mm, 170 mm and 180 mm cranks but that the longer cranks did produce significantly higher HRs. In the study completed by Goto et al. (1976), it was determined that cranks of lengths 80 mm, 160 mm and 240 mm all elicited statistically different physiological responses. Morris and Londeree (1997) stated that there were significant differences in the oxygen consumption (VO_2) responses elicited with CLs of 165 mm, 170 mm, and 175 mm. However, they placed VO_2 values into three efficiency categories and determined that there were differences between these efficiency categories and not between the three CL categories. However, when VO_2 data were separated into 165 mm, 170 mm and 175 mm crank length groups and re-analysed by the investigator of the present study, there were no significant differences (p=.635) found between the three CL groups ($F_{2,10}$=.48) when a repeated measures ANOVA was used. Conrad and Thomas (1983) also found no significant differences in VO_2 responses when CL was altered from 165 mm to 180 mm. The only study that disputes all of the above-results was completed by Astrand (1953). Using cranks of lengths 160 mm, 180 mm and 200m, Astrand found that there were no significant differences in VO_2 responses between the three CLs. However, only one subject was used in the study and therefore it was difficult to make conclusions about the population when the data for only one subject were analysed.

By examining the above-mentioned studies, it becomes clear that shorter cranks of approximately 120 mm to 160 mm elicited statistically similar physiological responses. Additionally, there was a second group of cranks, from approximately 160 mm to 180 mm, that also produce HRs and VO_2s that were not significantly different from one another. However, 180 mm, 200 mm and 220 mm cranks all elicited statistically different HRs ((Carmichael, 1981) and the current study). It was then interesting to note that 100% of the subjects in Carmichael's study (1981) had OCLs that were within the 150 mm to 180 mm range where they showed no significant differences in HR to exist between CLs. As well, 87.5% of the subjects in the current study had OCLs in the range of 120 mm to 160 mm where no differences in HR occurred between CLs. This led to the conclusion that, despite the fact that there existed a relationship between OCL and some measure of leg length, almost all subjects' OCLs fell within a range of cranks that elicited HRs that were not statistically different from one another and that were very close to the industry standard of 170 mm. In addition, the investigator of this study does not feel that the CLs in this range elicited physiologically significantly different HRs. The range of HRs was less than 2 bpm for cranks of 120 mm to 160 mm for the current study and for cranks of 150 mm to 180 mm for the study completed by Carmichael (1981).

4.3 Segmental Energy Theory

No attempts have been made to explain why a relationship between OCL and anthropometry exists. One of the purposes of the current study was to attempt to explain why a relationship between OCL and leg length exists through a model employing segmental energies of the thigh, shank and leg.

During cycling, the legs are required to move back and forth and up and down in a cyclical manner. These movements require constant direction reversals of the motions of all three of the lower limb segments: the foot, shank and thigh. The direction reversal movements are produced through muscular contractions, which act to cause, and change, angular accelerations. As the lower limb accelerates through the movements required when cycling, there are constant changes taking place in the energy states of each of the segments. These changes in kinematics, and therefore energy states, are elicited by alterations made in the ROM of each of the lower limb joints. As both anthropometry and CL affect the ROM of the lower limb, it was concluded that each anthropometry-CL combination would have associated with it, individual and unique segmental energies.

The total energy expenditure of the body during cycling is influenced by the energy levels of each of its parts, including the segments of the lower limb. HR is a measure of the amount of energy being expended during riding. Also, recall that the OCL was defined as the crank arm length that elicited the lowest HR response while riding. Therefore, as both anthropometry and CL influence the energy levels of the segments, the hypothesis that the OCL reflected the situation where the energy levels of the segments are at a minimum and the cyclist's movements are most effective, becomes clear.

After careful analysis of the kinematic data, it was determined that there was a flaw with the above-explained theory. Part of this theory relies on the fact that the ROM's at the joints, and therefore segmental energies of the lower limb, are dictated by both the anthropometry of the individual and CL. However, it appears that CL has a much larger magnitude of effect on the ROM at the various joints of the lower limb and that TLL, SL and TL may only play a small part in dictating ROM. After a one-way ANOVA was completed, it was revealed that only the hip ROM was affected by anthropometry. In contrast, the ROMs at the hip, knee and ankle all changed significantly with concurrent changes in CL. It can therefore be concluded that the ROMs of the lower limb were being governed much more heavily by CL than by the anthropometry of the individual. This provides part of the explanation as to why the combined segmental energies in the horizontal and vertical directions for the thigh, shank and leg simply increased as CL was increased.

Additional exploration into the changes taking place in the kinematics of the lower limb when CL was altered help to further explain why the segmental energies of the lower limb simply increase when CL was increased. When the segmental energies were broken down into horizontal and vertical components, it was found that almost all of the increase in energy was due to the vertical component of the shank and the thigh. The segmental energies partly rely on the displacement of the segment centre of mass (COM) from the origin of the pedal axle at bottom dead centre (BDC). As CL increased, the displacement of the COM from the origin also increased as both the thigh and the shank are raised further at top dead centre (TDC) at the longer crank arm length, thereby increasing the potential energy of the segments thereby resulting in higher segmental energies.

It now becomes clear that the segmental energies of the thigh, shank and leg do not explain the relationship between OCL and anthropometry but may lead to a clearer understanding as to why there was an increase in HR at the longer crank arm lengths. The total energy expenditure of the body, as measured by HR, is influenced by the energy expenditure of each of its parts, including the lower limb. Therefore, the segmental energies of the thigh, shank and leg must have at least partially contributed to the changes taking place in HR, which occurred when CL was altered.

4.4 Heart Rate Mechanisms

As has already been expressed, HR did not differ significantly between CLs at the shorter crank arm lengths but did increase significantly at the longer CLs. Therefore, there were some physiological changes occurring in the body at the longer CLs that resulted in a significant increase in HR between CLs. Recall that energy is defined as the ability to do work (Foss, 1998) and work is the application of a force through a distance. As HR is a non-invasive method of measuring the work completed it now becomes clear from the discussion of segmental energies why energy, and therefore HR, increased when CL was altered. The total work completed in one revolution remained constant across all CLs (see Appendix C15). In contrast, the work done in the vertical direction from BDC to TDC increased at the longer CLs as the body had to lift the weight of the leg (i.e. the *force*) a greater *distance* (i.e. the length of the crank from the bottom bracket to TDC) every crank cycle. In order to accomplish this greater amount of work at the longer CLs, the muscles of the lower limb needed to generate more force. This was accomplished through either an increase in the firing rate of the motor units, and therefore the contraction rate of the muscle fibres, and/or by increasing the number of motor units, and therefore the number of muscle fibres being used. Regardless of the mechanisms involved, either of these changes at the level of the skeletal muscles would have resulted in an increased demand of oxygen and energy, which could be met through an increase in blood flow to the lower limb area. This would be accomplished through an increase in the action of the heart as measured by HR. However, it cannot be accurately concluded whether more motor units were being recruited as muscle electromyography was not recorded. As well, no muscle blood flow measurements were taken therefore the mechanisms taking place at the level of the muscle resulting in an increase in HR may only be hypothesized. As all subjects were reasonably well trained and with the highest average HR elicited during the study being 176 bpm, it can be reasonably assumed that the participants of the current study were working below their anaerobic threshold. This would indicate that the additional energy being supplied for the cycling movements was being satisfied by oxidative mechanisms and was therefore quantifiable by HR.

In addition to understanding the physiological mechanisms involved in the increase in HR, an underlying question still remains as to what the fundamental biomechanical factors are that affect the energy cost of riding with different crank arm lengths. As both pedal forces and the resultant linear velocity of the foot are known to change when CL is altered, when both cadence and power output remain constant, it was theorized that the HR elicited during this study would be a function of both of these parameters.

The average, resultant linear velocity of the foot (LV) changes in a predictable manner when CL is altered. From the following relationship, it can be seen that as CL (or radius) is increased while angular velocity (cadence) is maintained, the LV of the foot must also increase:

1. Linear velocity = radius * angular velocity

Where: linear velocity = the LV of the foot
angular velocity = angular velocity of the crank
radius = CL

Therefore, as the CL increases, the LV of the foot must also increase for a given cadence. This was indeed found during the current study.

Concurrent to the changes in LV, were the changes taking place in the effective force (Fe) applied at the pedal. (Effective force was defined as the component of force applied at the pedal that is perpendicular to the crank.) The dependence of Fe on both power output, angular velocity and CL is due to the following two relationships:

2. Power = τ * ω

Where: power = power output
τ = torque about the bottom bracket
ω = angular velocity of the crank

3. Torque = Fe * CL

The above relationships can then be combined and simplified as follows:

4. Fe = power / CL * ω

Thus, it can be seen that as angular velocity (i.e. cadence) and power output are kept constant, and as CL is altered, there must be a concurrent change in the average Fe applied at the pedal. It was hypothesized that Fe would decrease as CL was increased, resulting in a concurrent decrease in HR. From the results of this study, it was found that Fe decreased as CL increased as predicted.

From the above-three relationships, it was then hypothesized that one biomechanical parameter (LV of the foot) would cause an increase in HR while the other biomechanical parameter (Fe) would cause a decrease in HR, combining to result in unique HRs at each CL. It was therefore hypothesized that the HR elicited at each CL would be a function of both LV and Fe. This was not found to be the case. After careful analysis, it was determined that neither LV nor Fe were significantly correlated to HR across all CLs. It was concluded that the HR elicited at a particular CL was not due to changes in LV or Fe even though both LV and Fe changed in the manners predicted. Upon reflection, it was believed that there were other undetermined mechanisms that were governing the changes seen in HR. One such mechanism may have been the segmental energies of one of the leg segments however no further insight into this hypothesis has been acquired at this time.

4.5 Kinematics

Joint angles of the hip, knee and ankle were found to change when CL was altered. Both the maximum hip angle and the maximum knee angle decreased slightly meaning that both joints became slightly more flexed at approximately BDC as CL increased. These data do not concur with those recorded by Too and Landwer (Too, 2000). It was hypothesized that changes in joint angle would not occur as the extension in both of these joints was governed by the distance from the top of the saddle to the top of the pedal at BDC, which was kept constant across all CLs. However, the changes in joint angle elicited by CL were very small and were not considered to be biomechanically significant. Maximum hip angle changed by less than two degrees from the shortest CL to the longest CL and maximum knee angle only changed by approximately four degrees.

The minimum hip and knee angles both decreased (i.e. became more flexed) as CL was increased. These data concur with those recorded by Too and Landwer (2000). The minimum hip angle occurred just after TDC whereas the minimum knee angle occurred just before TDC. CL at TDC dictates the height of the pedal, and therefore the distance the foot must rise. It then becomes apparent that as CL is increased, the foot must rise farther above the bottom bracket, leading to increased flexion in both the knee and the hip at or around TDC. Due almost entirely to the decrease in the minimum joint angles, the ROM at both the hip and the knee also increased significantly when CL was lengthened. These data concur with those reported by Too and Landwer (2000).

Too and Landwer (2000) reported that no trends were seen in ankle angle however the results of this study suggested that there was a small increase in maximum ankle angle and a slight decrease in minimum ankle angle with increasing CL which resulted in a small increase in ankle ROM. However, the changes in the maximum and minimum ankle angles were only approximately five and three degrees respectively. It was therefore felt that these changes did not reflect biomechanically significant changes in ankle motion.

4.6 Conclusions

From the results of the current study and from those reported in recent literature, it can be concluded that there was a weak correlation between OCL and a measure of leg length, provided that the ranges of CLs and leg lengths used are appropriately large. Therefore, there was an ability of a certain measure of leg length to predict a portion of the variance in OCL. In the current study, it was found that both SL and TLL could predict 51% of the variance in OCL.

In addition, it can be concluded that there were no significant differences in the physiological responses to riding at CLs of approximately 120 mm to 160 mm. On the contrary, when CL was lengthened to 180 mm and beyond, significantly different physiological responses were elicited when cycling at each different CL. In conjunction, almost all of the OCL's of the individuals in the current study fell within the range of cranks that do not elicit significantly different physiological responses from one another, which are very close to the industry standard CL of 170 mm. It was therefore the recommendation of the investigator of the current study that CLs need not be changed from the industry standard for individuals of various leg lengths. This was due to the fact that those CLs predicted from the leg length – OCL relationship did not differ significantly in terms of physiological responses from CLs close to, and perhaps including, the current industry standard. In addition, other parameters such as power output (Inbar, 1983; Too, 2000) and joint moment cost functions (Gonzalez and Hull, 1989) are being optimized at or around the industry standard of 170 mm.

4.7 Future Recommendations

Optimum crank length has been shown to change when power output and/or cadence are manipulated (Hull, 1988; Gonzalez, 1989). It is therefore suggested that the current study be replicated using a number of different cadences and power outputs while riding with different lengths of crank arms. It would be interesting to note whether the trends in HR could still be observed between the different CLs and whether subjects maintained similar OCLs as power output and cadence were altered.

In addition, it would also be of interest to see if there continues to exist a relationship between OCL and a measure of leg length if cyclists pedaled at a preferred cadence for each of the six different CLs as it has been shown through biomechanical modeling that there lies an interaction between CL and cadence (Gonzalez, 1989). It is hypothesized by the investigator of the current study that the preferred cadence would change across crank lengths and would therefore potentially alter the HR response to changing CL, leading to an alteration in the OCL-leg length relationship.

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Appendix A: Segmental Energy Calculations

The following equation was used to determine the total segmental energies (S.E.) in both the horizontal and vertical planes for the thigh and shank:

$$\mathbf{S.E.} = \mathbf{mgh}\ \text{(potential)} + \mathbf{1/2mv^2}\ \text{(kinetic)} + \mathbf{1/2I\omega^2}\ \text{(rotational)}$$

Where:

m = mass of the segment
g = acceleration due to gravity
h = vertical displacement
v = linear velocity of the segment centre of mass
I = inertia of the segment centre of mass
ω = angular velocity of the segment centre of mass

Appendix B: Literature Review

An important area in the study of cycling involves the interface between the rider and the bicycle and how physiological and biomechanical responses of the body occur due to altered body position. This change in body position may be produced by a change in a number of geometric variables of a bicycle: seat height (SH), foot position on the pedal (FP), seat tube angle (STA) and CL. There have been two methods thus far that have been used to investigate the changes that occur within the body when certain geometric variables are altered. The first method involved empirically measuring the physiological responses elicited when certain geometric variables were altered. The second method studied the body's biomechanical responses to altered positioning by employing various mathematical modeling techniques as well as empirical measurements.

Along with understanding the effects of altering body position by changing geometric variables, many researchers have attempted to define the optimal set-up of a bicycle in relation to the anthropometry of the rider. This literature review will encompass the results obtained from both the empirical and modeling techniques of investigating the responses of the body elicited by altering geometric variables of the bicycle. The relationship between anthropometry and optimal set-up of a bicycle will also be explored.

2.1 Empirical Physiological Measurements

The first method of investigating the effects of altering body position through a change in geometric variables involved the measurement of certain physiological parameters. Criteria, such as VO_2, were used to determine the physiological changes evoked by a change in body position through alteration of a geometric variable. This allowed investigators to optimize bicycle set-up by determining the body position which elicited the most metabolically efficient (lowest VO_2) response for a fixed workload.

2.1.1 Seat Height

There have been many studies that have measured discrete physiological parameters, such as VO_2, in order to determine the SH which optimized the physiological responses of the rider. SH was defined as the distance from the pedal spindle to the top of the seat as measured by a straight line formed by the crank, seat tube and seat post (Too, 1990). Please refer to Figure 3. Table 5 summarizes the results of various investigations on optimal SHs.

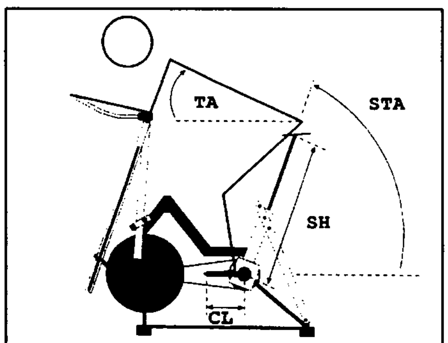


Fig. 1 Geometry variables on a cycle ergometer that dictate the overall positioning of a cyclist. (*TA* Trunk angle, *STA* seat-tube angle, *SH* seat height, *CL* crank length)

Figure 3: Definition of various geometric variables (Heil, 1997).

Table 5: Summary of Studies Investigating Optimal Seat Height During Cycling.

Author	*Optimal SH*
Hamley and Thomas (1967)	109% of the medial aspect of the inside leg from the floor to the symphysis pubis
Shennum and deVries (1976)	105-108% of the inside leg from the floor to the symphysis pubis
Nordeen-Snyder (1977)	100% trochanteric leg length
Gregor et al. (1981)	106% symphysis pubis height

The results indicating the most efficient SH in terms of eliciting the lowest VO_2 response agree fairly well with one another. There are two definitions of leg length that have been used in order to predict optimal SH. Symphysis pubis height was defined as the distance of the medial aspect of the inside leg from the floor to the symphysis pubis (Hamley, 1967; Gregor, 1981). It was determined that 109% of symphysis pubis height was the most efficient SH for anaerobic work (Hamley, 1967) and that anything outside of this value was less efficient and metabolically more costly. Shennum and deVries (1976) found the SH that elicited the lowest VO_2 response was between 105-108%, based on the leg length definition set out by Hamley and Thomas (1967). They determined that their measurement of leg length (ischium to floor) was in general 5% lower than that determined by Hamley and Thomas (1967). Therefore, in order to compare the two sets of data, 5% of the leg length measure was added onto that determined by Shennum and deVries (1976). Shennum and deVries (1976) then suggested a SH of 108-109% based on their data which corresponded to the SH recommended by Hamley and Thomas (1967).

The second definition of leg length used to predict optimal SH was that of trochanteric height. This was defined as the length of the leg from the floor (while standing in bare feet) to the greater trochanter of the femur (Nordeen-Snyder, 1977). Nordeen-Snyder (1977) determined that a SH equal to 100% trochanteric height elicited the lowest VO_2 response. When values were converted to a leg length based on symphysis pubis height, her values (107.1% symphysis pubis height) corresponded well with those determined by Hamley and Thomas (1967). There was a difference of 1.9 % between the two sets of values however Nordeen-Snyder felt that this disparity between values was not significant enough to contradict those results found by Hamley and Thomas (1967).

The results from the studies discussed until now do agree with one another. There is, however, one study that differs in the prediction of most efficient SH. Using symphysis pubis height as a measure of leg length, it was found that 106% was the average saddle height of 10 elite male cyclists (Gregor, 1981). This study, however, did not include any measure of efficiency and therefore it cannot be assumed that these results conflict with those stated in the previously mentioned studies.

2.1.2 Foot Position

Foot position is another geometric variable of a bicycle that may be modified, thereby affecting the physiological responses of the rider. Table 6 summarizes the study that investigated the effects of altering FP on heart rate (HR) during submaximal cycling.

Table 6: The Effects of Foot Position on Heart Rate During Cycling.

Study	*Results*
Mandroukas (1990)	anterior aspect of the foot elicited a lower HR response

The effect of altering FP has been looked at in only one study (Mandroukas, 1990). In this study, the investigators recorded HR, blood pressure and RPE (Ratings of Perceived Exertion) while cycling in three different positions. The three cycling postures included riding with the anterior aspect of the foot, the posterior part of the foot and at a saddle height that resulted in a knee angle of 120° to 125° at both a maximal and submaximal workload. It was then concluded that cycling with the anterior part of the foot elicited a lower HR response at most workloads than does cycling with the posterior portion. When cycling with the posterior aspect of the foot, no plantar flexion took place (Mandroukas, 1990). Therefore, the amount of work done by the gastrocnemius muscle decreased when compared to normal riding. This increased the work that was completed by the thigh muscles which consequently decreased the actual muscle mass involved in pedaling (Mandroukas, 1990). Bergh et al. (1976) has stated that when a smaller muscle mass is involved in a movement, a higher HR response is elicited. In summary, it has been seen that changing foot placement on the pedals also has an effect on the physiological responses of the cyclist.

2.1.3 Seat-tube Angle

Seat-tube angle is another geometric variable that may affect VO_2 when altered. STA was defined as the position of the seat relative to the crank axis (Heil, 1995). Please refer to Figure 3. Table 7 summarizes the results of the effects of altering STA on VO_2.

Table 7: Effects of Altering Seat-Tube Angle on Oxygen Consumption During Cycling.

Study	***Results***
Too (1990)	VO_2 changed with a change in STA
Heil et al. (1995)	VO_2 changed with a change in STA
Heil and Whittlesey (1997)	VO_2 did not change with a change in STA

As can be seen from the above table, both Too (1990) and Heil et al. (1995) did find a change in VO_2 when STA was altered. However, the results of the study conducted by Heil and Whittlesey (1997) contradict with those published by Too (1990) and Heil (1995). Heil and Whittlesey (1997) found that VO_2 did not change with a concurrent change in STA. In this study, VO_2 was measured by altering STA as well as trunk position. Therefore, body position was manipulated by altering two variables: STA and trunk angle. As has been discussed previously, the manipulation of one geometric variable, such as SH or FP, results in a change in the physiological responses of the rider. If the effects of two variables are then measured concurrently, the resultant effects of one variable may be confounded in the analysis. If the physiological responses to the two variables are opposite in nature, the physiological effects of one variable may cancel out the effects of the other variable thereby resulting in no net change in VO_2. Therefore, it can still be concluded that manipulation of STA does have an effect on VO_2.

2.1.4 Crank Length

Crank arm length is yet another geometric variable, that when altered, causes a simultaneous change in the physiological responses of the rider. Table 8 summarizes the results of the physiological responses incurred when CL is altered.

Table 8: Physiological Responses to Altering Crank Length.

Author	***Results of Study***	***Length of crank arm used***
Astrand (1953)	No change in VO_2	160 mm, 180 mm and 200 mm
Goto et al. (1976)	VO_2 response changes as CL changes at a preferred cadence	80 mm, 160 mm, 240 mm
Carmichael (1981)	One CL elicits the lowest VO_2 response	150 mm – 200 mm
Conrad and Thomas (1983)	No change in VO_2	165 mm – 180 mm
Morris and Londeree (1997)	One CL elicits the lowest VO_2 response	165 mm – 175 mm

When the above results are examined, it is clear that there lies a discrepancy in the outcome of the studies. Three investigations proved that VO_2 was altered when CL was adjusted (Goto, 1976; Carmichael, 1981; Morris, 1997). However, it has been shown by two studies (Astrand, 1953; Conrad, 1983) that there was no change in VO_2 when CL was altered. Possible explanations for the disparity in these results include the cadence at which the subjects rode and the range of CLs employed during testing.

One possible explanation as to the current disparity in VO_2 results involves the cadence that the various studies used. Hull and Gonzalez (1988) showed that the OCL does change when cadence is altered. Hagberg et al. (1981) showed that the most efficient cadence for cyclists ranged between 72 and 102 rpm. This may be due to the fact that optimal cadence is governed by muscle fibre composition (Suzuki, 1979). As each rider has a different muscle fibre composition, each rider may therefore display a different optimal cadence. Therefore, an OCL, as dictated by minimizing VO_2, may not be apparent if subjects are not riding at their most efficient cadence. The effect of CL on VO_2 may therefore be confounded in the effects of cadence on VO_2 during submaximal cycling.

In addition, the range of CLs used may also explain the incongruity in the results recorded by various investigators while researching the effects of altering CL on physiological responses. Carmichael (1981) found that there were no significant differences in the physiological responses elicited by the 150 mm, 160 mm, 170 mm and 180 mm cranks but that longer cranks of lengths 190 mm and 200 mm, did produce significantly higher responses. In the study completed by Goto et al. (1976), it was determined that cranks of lengths 80 mm, 160 mm and 240 mm all elicited statistically different physiological responses. Morris and Londeree (1997) stated that there were significant differences in the VO_2 responses elicited with CLs of 165 mm, 170 mm, and 175 mm. However, they placed the VO_2 values into three efficiency categories and determined that there were differences between these efficiency categories and not between the three CL categories. However, when VO_2 data were separated into 165 mm, 170 mm and 175 mm groups and re-analysed by the investigator of the present study, there were no significant differences found between the three CL groups. Conrad and Thomas (1983) also found no significant differences in VO_2 responses when CL was altered from 165 mm to 180 mm, in 2.5 mm increments. Therefore, through careful interpretation of the results of studies investigating the effects of altering CL on the physiology of a cyclist, it becomes apparent that shorter cranks of approximately 150 mm to 180 mm elicit statistically similar physiological responses. However, longer cranks start to evoke statistically different physiological responses. When the results of the above-mentioned studies are grouped into under 150 mm, 150 mm – 180 mm and above 180 mm crank length categories, all but one study produce concurring results. Using cranks of lengths 160 mm, 180 mm and 200m, Astrand (1953) found that there were no significant differences in VO_2 responses between the three CLs. However, only one subject was used in the study and therefore it is difficult to make conclusions about the population when the data for only one subject were analysed.

To summarize, when the physiological responses to altering CL are divided into groups of different CLs, the data recorded by Goto et al. (1976), Carmichael (1981), Conrad and Thomas (1983), and Morris and Londeree (1997) are all in agreement with Astrand (1953) being the only study that produced conflicting results. With the knowledge that Astrand only used one subject in his study, it can therefore be concluded that physiological responses do not change significantly between certain groupings of CLs.

2.2 Biomechanics and Mathematical Optimization

Another method that has been used to investigate the effects of altering geometric variables on the functioning of the human body involved a theoretical optimization procedure. This method employed mathematical modeling to determine how certain geometric variables influenced the biomechanics of cycling. In this method, performance measures that dictated optimum set-up of a bicycle were defined as objective, or cost, functions and took on numeric values. During the optimization procedure, these cost functions were then either minimized or maximized through the use of a mathematical modeling equation in order to define an optimal situation. This equation required two types of inputs. The first type of inputs included experimentally determined anthropometric measures along with both bicycle (crank and pedal) as well as subject kinematic inputs (angular and linear displacement, velocity and acceleration). The second set of inputs was then composed of the geometric aspects of the bicycle that the investigator wished to optimize. These included such parameters as SH, CL and STA and were systematically changed during the optimization procedure in order to observe the contribution of these changes to the cost function. In order to derive the mathematical model (which included the above-mentioned inputs and which was used to compute the cost function), a biomechanical model of the lower limb and Newton's Laws of Motion were employed.

The results of these optimization procedures were then the computed cost functions. A cost function is a mathematical term that represents the biomechanics of the human body. When the desired geometric variable was altered mathematically, the result could be seen in the change of the numeric value of the computed cost function. The new calculated value reflected the changes incurred in the biomechanics of an individual due to an alteration of a particular geometric variable. This procedure allowed biomechanists to determine the combination of geometric variables that elicited the most favourable biomechanical responses of the lower limb during cycling.

Biomechanists have also used empirical measurements in order to define the optimal set-up of a bicycle. This method is very similar to that used by physiologists to determine the physiological changes evoked by a change in body position through the alteration of geometric variables. In contrast, biomechanists observed and recorded changes in biomechanical variables, such as power, in order to determine the effects of altering geometrical variables on the cyclist.

2.2.1 Seat Height

Seat height is the most easily adjusted geometric variable found on a bicycle. If not set up correctly, it can also elicit less than optimal responses in the rider. Table 9 displays a summary of the studies that have determined optimal SH through mathematical modeling techniques.

Table 9: Optimization of Seat Height.

Authors	***Optimal Set-up***
Gonzalez and Hull (1989)	SH + CL = 97% trochanteric height

It was determined through mathematical modeling that the SH corresponding to the lowest cost function, and therefore the most favourable biomechanical position, was equal to 97% trochanteric height (Gonzalez, 1989). These results closely match those determined through a physiological analysis which indicated that 100% trochanteric height was the most efficient SH (Nordeen-Snyder, 1977).

2.2.2 Foot Position

Foot position is another variable that is easily adjusted when a bicycle is being set-up for a new rider. There have been a limited number of studies investigating the effects of altering longitudinal FP on the pedals, in both the physiological as well as the biomechanical domains. FP on the pedal was defined as the longitudinal distance from the ball of the foot to the ankle axis (Gonzalez, 1989). Table 10 displays the current results of optimal foot positioning to be used while cycling.

Table 10: Optimization of Foot Position.

Authors	*Optimal Set-up*
Gonzalez and Hull (1989)	54% of foot length

It has been determined that, for optimal positioning favouring the biomechanics of the lower limb, the distance from the ankle axis to the portion of the foot resting on the pedal should be equal to 54% of the length of the foot (Gonzalez, 1989). The results from this study are in agreement with, and are in fact more precise than, the conclusions drawn by Mandroukas (1990) who stated that placing the anterior aspect of the foot on the pedal elicited a minimum HR response.

2.2.3 Seat-Tube Angle

Seat-tube angle is a very difficult geometric variable to alter, as it requires frame builders to alter the geometry of the bicycle before it is manufactured. This makes it very difficult to adjust STA for the individual riding the bicycle. Table 11 displays the biomechanical optimization results for STA for an average rider of 1.78 m.

Table 11: Optimization of Seat-Tube Angle.

Authors	*Optimal Set-up*
Gonzalez and Hull (1989)	76°

The results show that a STA of 76° has been determined to be related to the most effective biomechanics of the lower limb (Gonzalez, 1989). It is difficult to compare the results determined through biomechanical optimization techniques and those determined via physiological testing. Through optimization methods, a discrete value of 76°, in combination with other geometric variables, was found to be optimal whereas through the measurement of physiological variables, VO_2 was elevated for a STA of 60° and was minimized over a range of STAs from 76° to 90° (Heil, 1995). Nonetheless, the optimization results using both empirical physiological measurements and biomechanical modeling techniques do concur fairly well. However, any slight discrepancies that exist in the results may be due to the fact that studies employing biomechanical optimization methods altered STA in combination with other factors such as SH and CL in contrast to the studies employing physiological parameters where STA was investigated on its own. Therefore it is very difficult to compare optimization of many variables with those physiological investigations that only looked at one particular parameter. Nonetheless, the results obtained through both methods do agree well with one another in that 76° represented both a biomechanically optimal situation as well as a STA that elicited a low physiological response.

2.2.4 Crank Length

Crank arm length is another geometric variable that is easily manipulated, simply by purchasing and installing crank arms of different lengths. Biomechanical analyses using optimization methods have been used a number of times in order to determine the CL that elicits the lowest cost function. Table 12 describes the various results of biomechanical optimization of CL.

Table 12: Optimization of Crank Length.

Authors	*Cost Function*	*Optimal Set-up*
Hull and Gonzalez (1988)	Minimized joint moments	145 mm, 140 mm (depending on power output)
Gonzalez and Hull (1989)	Minimized joint moments	140 mm
Yoshihuku and Herzog (1990)	Maximized power output	170 mm (reclined)
Yoshihuku and Herzog (1996)	Maximized power output	145 mm, 170 mm (depending on the definition of the force-length relation)

The typical CL used on bicycles is 170 mm (Gonzalez, 1989) and is at present the industry standard. However, when looking at the results of the optimization procedures, it appears as though the OCL is quite a bit shorter. The OCLs determined through biomechanical analyses varied in length from 140mm (Gonzalez, 1989) to 145 mm (Hull, 1988; Yoshihuku, 1996) to the industry standard of 170mm (Yoshihuku, 1990; Yoshihuku, 1996). Most of the results were quite similar in that the OCL was approximately 140 mm – 145 mm. The difference of 5mm found in the study by Hull and Gonzalez (1988) was due to the effect of altering power output.

There is however a larger incongruity between the results obtained by Yoshihuku and Herzog (1990; 1996) and the rest of the studies. One explanation for the apparent disparity in OCL results lies in the body position defined in the optimization procedures. In the study by Yoshihuku and Herzog (1990), the OCL was dependent on the body being in a reclined position. Thus, a change in trunk angle took place as well as changes in CL during the modeling processes. As has already been mentioned above, it has been determined that there is an interrelationship between a number of geometric variables and therefore body positions and biomechanical efficiency (Hull, 1988; Gonzalez, 1989). Consequently, it is very difficult to tease out the effects of altering CL with the effects of altering trunk angle in the study completed by Yoshihuku and Herzog (1990).

In addition, there is a large disparity in the results obtained within the study completed by Yoshihuku and Herzog in 1996 (OCLs of 145 mm vs. 170 mm). This was due to the definition of the force-length relation and the length of various muscles that served as inputs into the various optimization equations. These two parameters were altered according to different theories of the force-length relation and different interpretations of muscle length. As these two inputs have a direct effect on the biomechanics of the lower limb, a change in their definitions will lead to a concurrent change in the optimization results.

Another method used in the evaluation of OCLs was the measurement of maximum leg power produced while riding with various CLs. A Wingate Anearobic Test was used to determine the CLs at which the maximum mean power and peak power occurred. Table 13 displays the results of the two studies that employed this biomechanical method of determining OCL.

Table 13: Optimization of Crank Length by Measuring Peak and Mean Power.

Authors	*OCL for peak power*	*OCL for mean power*
Inbar et al. (1983)	166 mm	164 mm
Too and Landwer (2000)	180 mm	180 mm

The OCLs proposed by Too and Landwer (2000) and by Inbar et al. (1983) are different between the two studies. A possible explanation for this inconsistency involves the trunk angle employed in the two studies. Too and Landwer (2000) had their subjects perform the Wingate Anaerobic Test with the upper body kept perpendicular to the ground. This is contrary to the body position used in most studies where subjects typically ride with their hands on the handlebars, resulting in increased trunk flexion. As has been mentioned previously, it is then very difficult to resolve the contribution of only one geometric variable when more than one is being altered. However, it is impossible to conclude whether this change in trunk angle is indeed the cause of the incongruity in results between these two studies as Inbar et al. (1983) do not state what trunk angle was employed in their study.

In summary, most of the optimization literature points to an OCL of 140 mm to 145 mm which is dependent upon power output (Hull, 1988) and various definitions of the function and length of the muscles (Yoshihuku, 1996) used in the optimization procedure. This value for OCL does differ slightly from the recommended CL of 164 to

180 mm when leg power is being maximized (Inbar, 1983; Too, 2000). It is apparent that there remains a disparity in the results from studies employing mathematical modeling and those that determined OCL through empirical measurements. One explanation for the apparent inconsistency in results lies in the cadence employed in the two methods. As has been found by Gonzalez and Hull (1989), when cadence is manipulated, the OCL determined through mathematical modeling is concurrently altered. However, when a cadence matching that which is naturally selected by cyclists, the optimization results dictated an OCL very close to the industry standard of 170 mm. This OCL then falls within the CL range of 164 mm – 180 mm which was deemed optimal through empirical measurements of leg power.

To conclude, the results of studies utilizing mathematical modeling techniques and empirical biomechanical and physiological measurements agree well with one another. When the cadence that is typically used by cyclists was employed, a CL close to the industry standard of 170 mm was found to be optimal using mathematical optimization (Gonzalez, 1989). The range of cranks deemed to be optimal via empirical leg power measurements was 164 mm – 180 mm (Inbar, 1983; Too, 2000), which includes the industry standard. Finally, CLs of approximately 150 mm – 180 mm all elicited statistically similar physiological responses, which were lower than crank arms of longer lengths (Goto, 1976; Carmichael, 1981; Conrad, 1983; Morris, 1997). To conclude, a CL close to the industry standard of 170 mm would be deemed optimal through investigations using both optimizing techniques and empirical measurements.

2.3 Anthropometry

Optimum crank arm length has been found to be reliant upon certain anthropometric variables. This has lead to the conclusion that each individual has an OCL that is dependent on some measure of their leg length. Table 14 summarizes the effects of various anthropometric variables on OCL.

Table 14: The Effects of Anthropometry on Optimal Crank Lengths.

Authors	*Results*	*Size of Subject and Length of Cranks Used*
Carmichael (1981)	OCL (mm) = 0.233 * (TL (mm)) + 55.8	Height: 169.3 cm – 195.5 cm
Inbar et al. (1983)	Vary CL 1 cm for every 6.3 cm difference in leg length	Leg Length: 92.0 cm – 107.2 cm
Hull and Gonzalez (1988)	↑ CL with ↑ size of rider	162.6 cm tall TL = 39.9 cm
Gonzalez and Hull (1989)	↑ CL with ↑ size of rider	162.6 cm tall TL = 39.9cm
Burke (1994)	CL should be matched to leg length	Height: <5'5" to >6'4" CL: 165 mm – 185 mm
Morris and Londeree (1997)	No correlation with CL	Height: 176.5 cm – 178.5 cm CL: 165 mm – 175 mm

A number of studies have shown that OCL is related to the size of the individual riding the bike (Carmichael, 1981; Inbar, 1983; Hull, 1988; Gonzalez, 1989; Burke, 1994). Two studies simply stated that the OCL should increase with the size of the rider (Hull, 1988; Gonzalez, 1989). However, Carmichael (1981) took this relationship one step further and determined that OCL (in mm) can be predicted by a cyclist's TL (in mm).

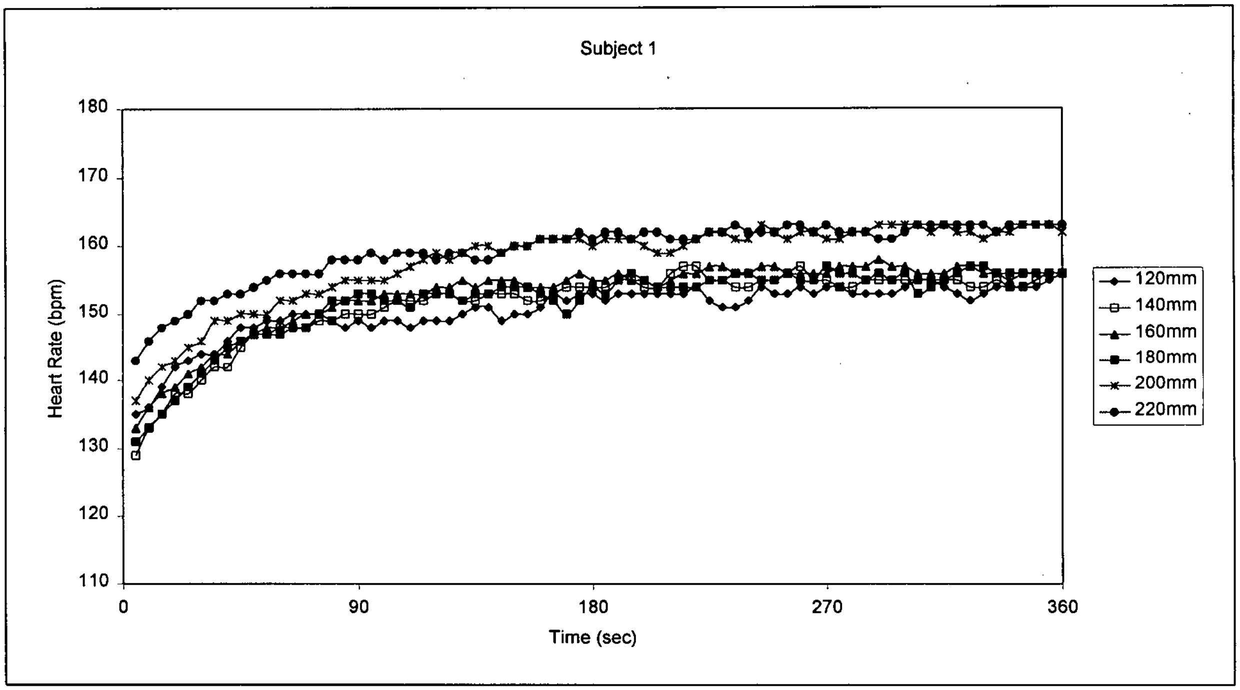
There is one study whose results dispute the conclusions reached by most studies indicating that OCL is related to the anthropometry of a rider. Morris and Londeree (1997) concluded that each individual has an OCL but that this OCL was not related to any anthropometric variables. However, this study employed a very narrow range of CL's: from 165 mm to 175 mm. Also, the subjects ranged in height from 176.5 cm to 178.5 cm, a range of only 2 cm. Both of these ranges are very small and therefore it may be hard to derive a relationship between such a limited range for each of the variables.

2.4 Conclusion

As both the biomechanical optimization method and the method involving the investigation of the affects of altering geometric variables on physiological parameters have shown, it is clear that improper bicycle fit does have an effect on the human body. CL is one such geometric variable that can be optimized in order to improve the interaction between bicycle and rider. As has been discussed above, a significant relationship between body dimensions, such as TL, and OCL may also exist.

Appendix C: Subject Data

Appendix C1: Individual Heart Rate versus Time Plots



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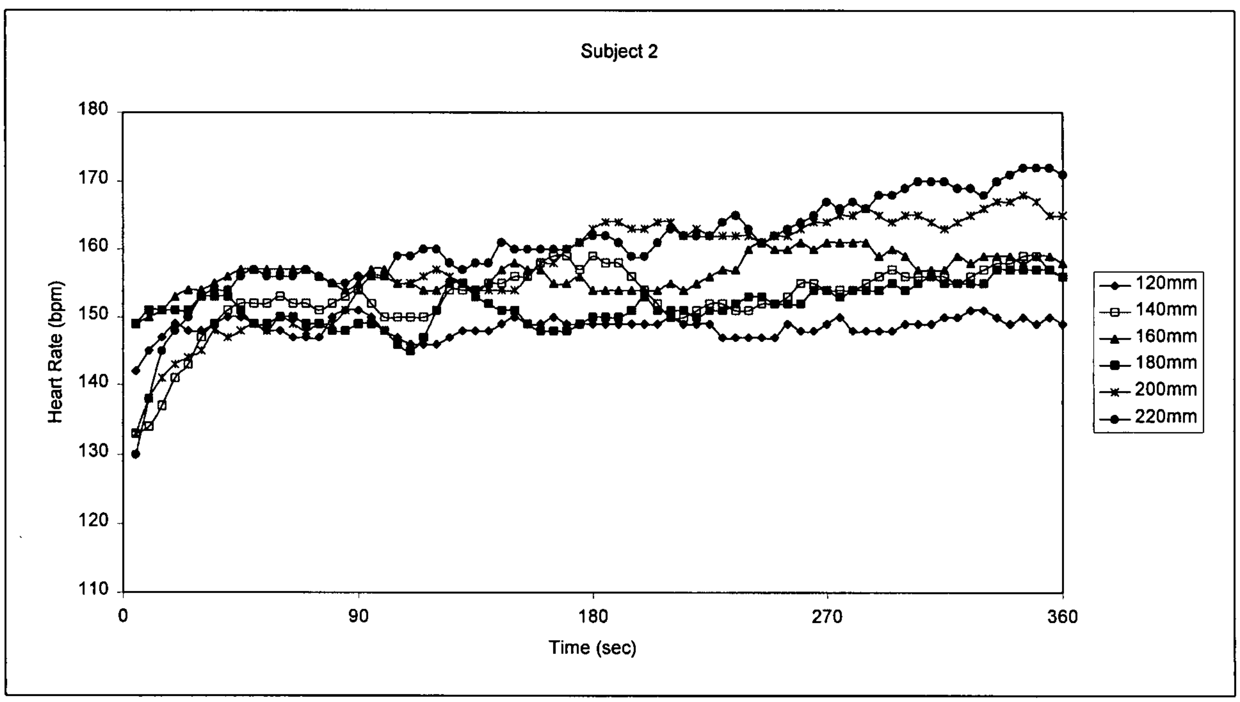
160mm
180mm
200mm
220mm



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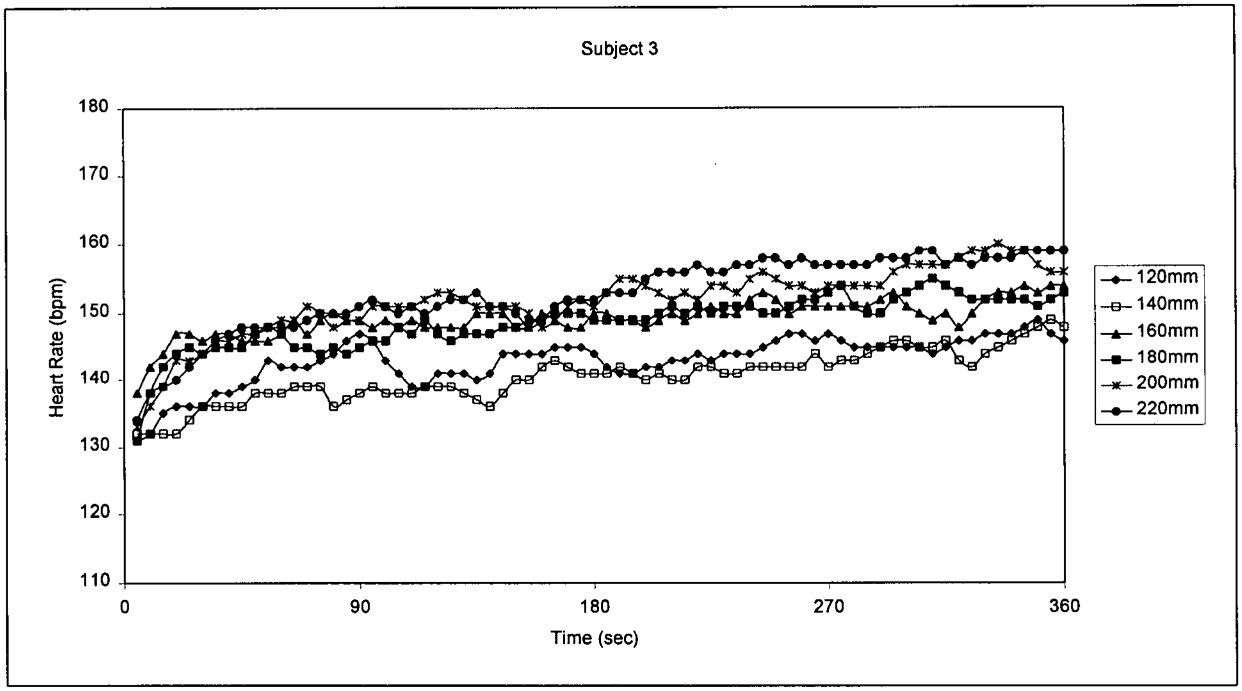
160mm
180mm
200mm
220mm



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Time (sec)
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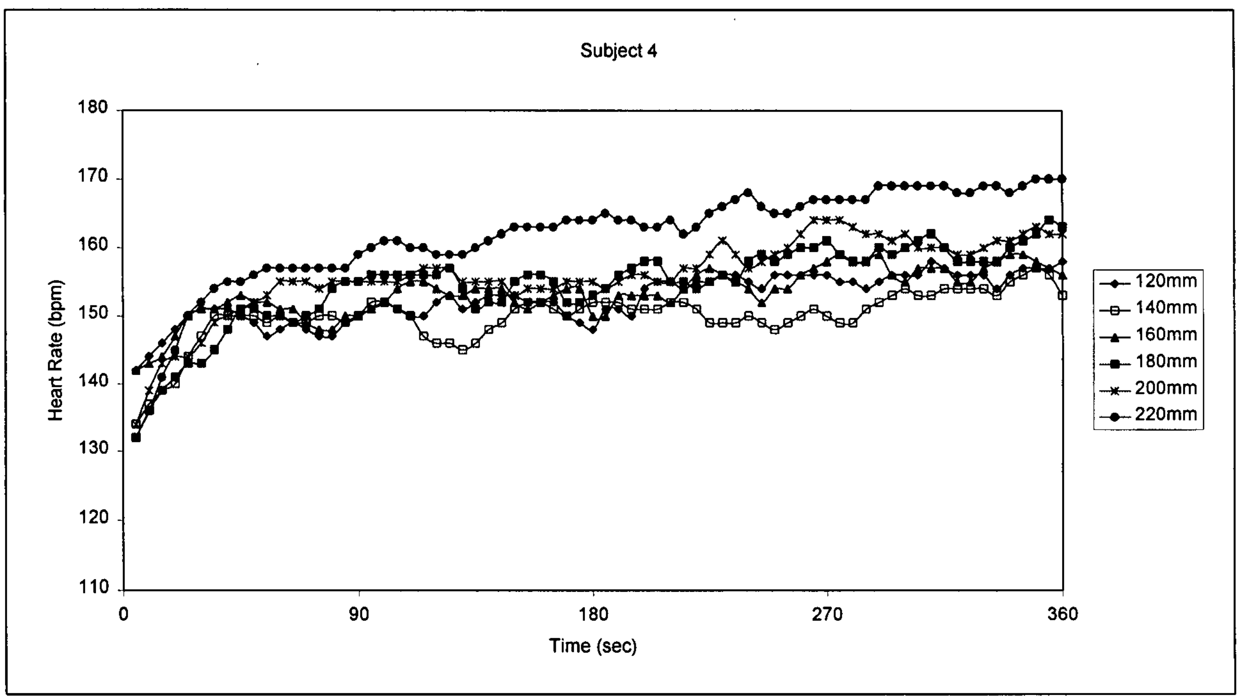
180mm
200mm
220mm



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Time (sec)
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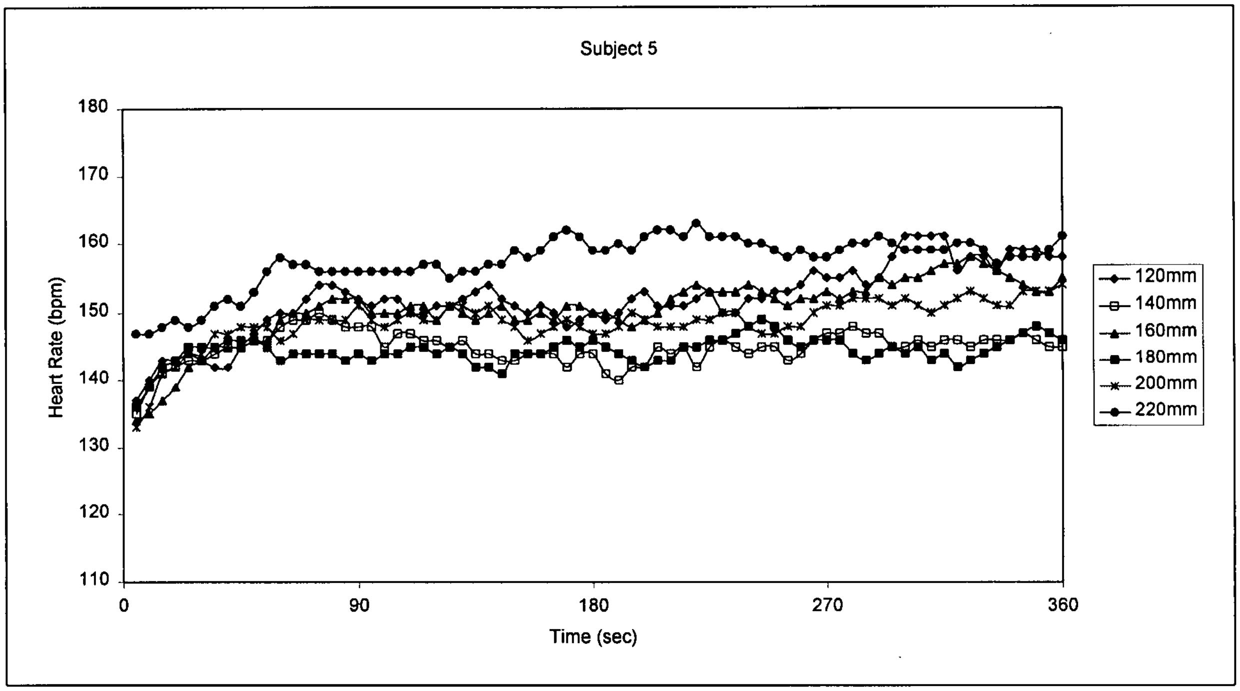
180mm
200mm
220mm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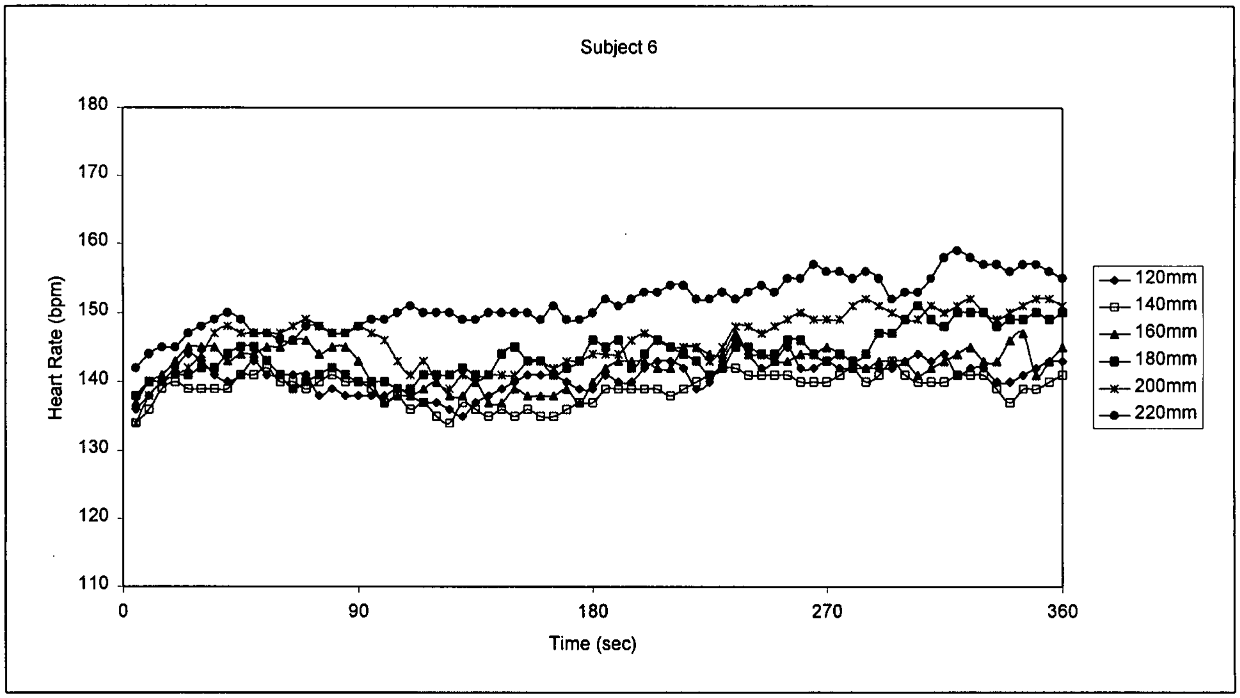
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180mm
200mm
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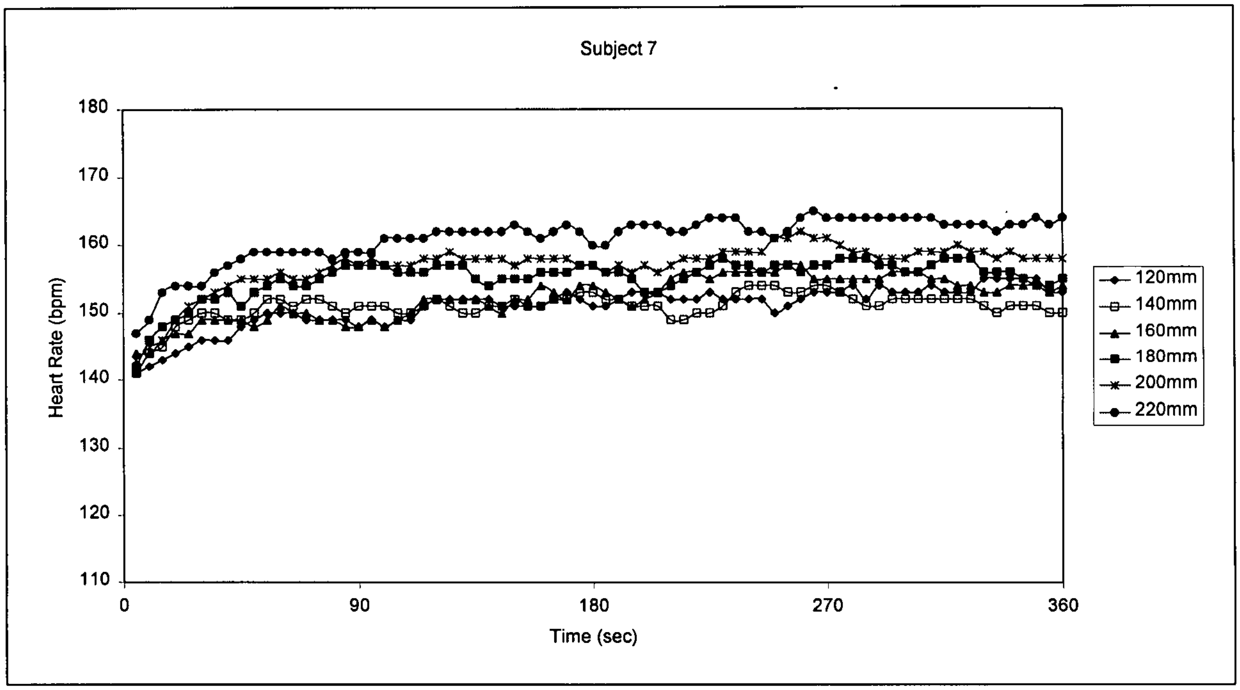
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200mm
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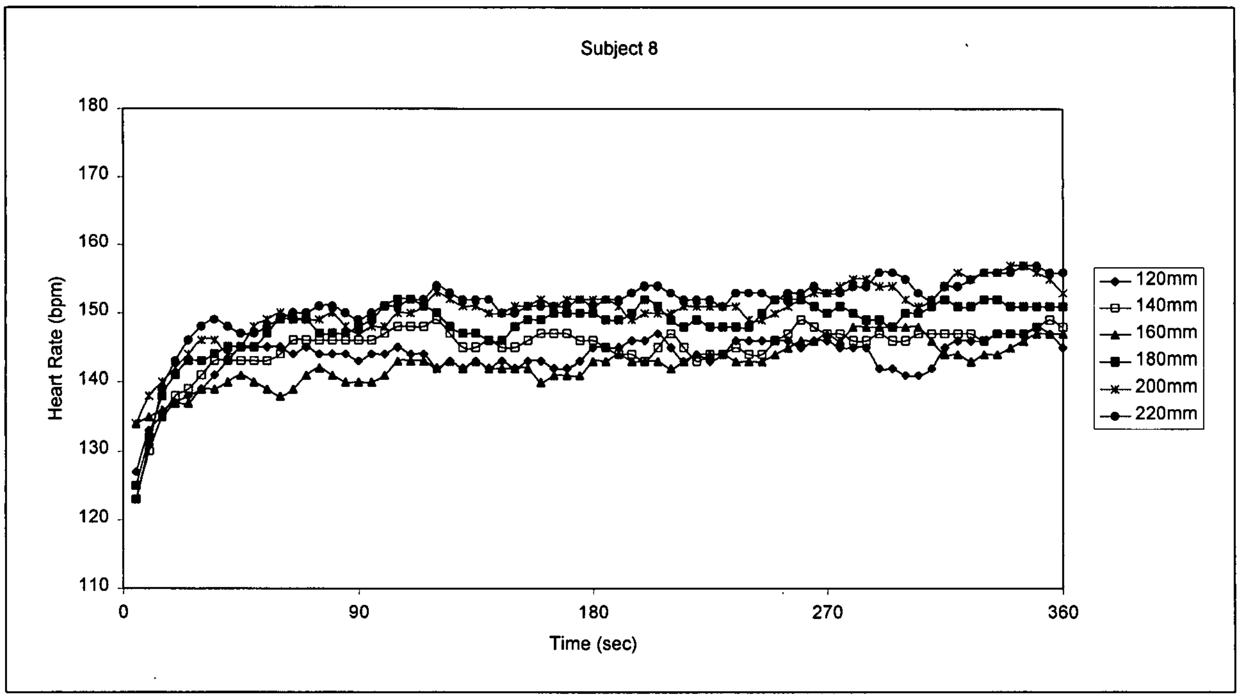
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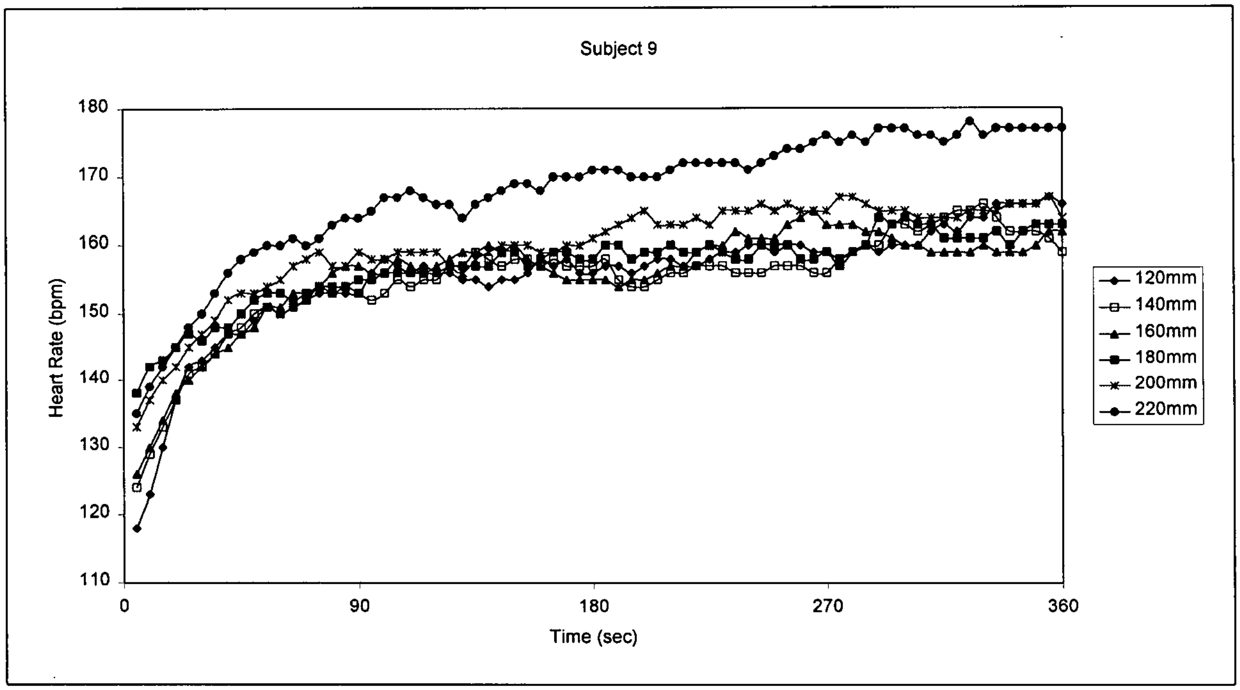
200mm
220mm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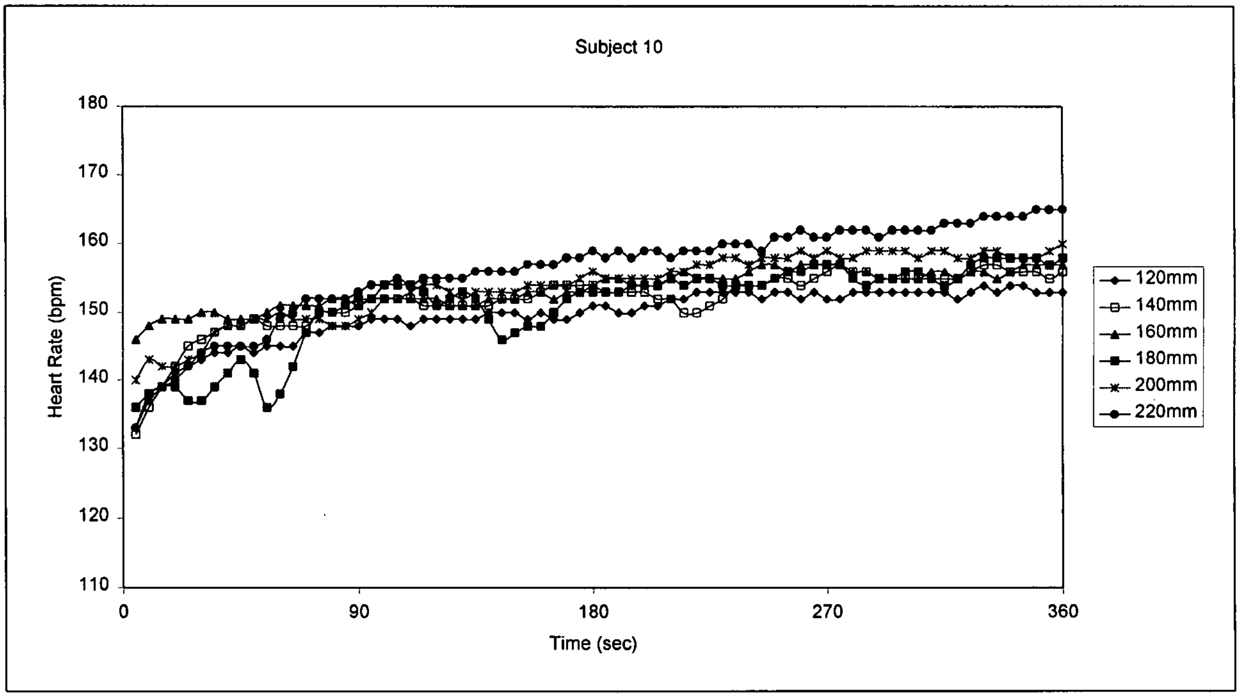
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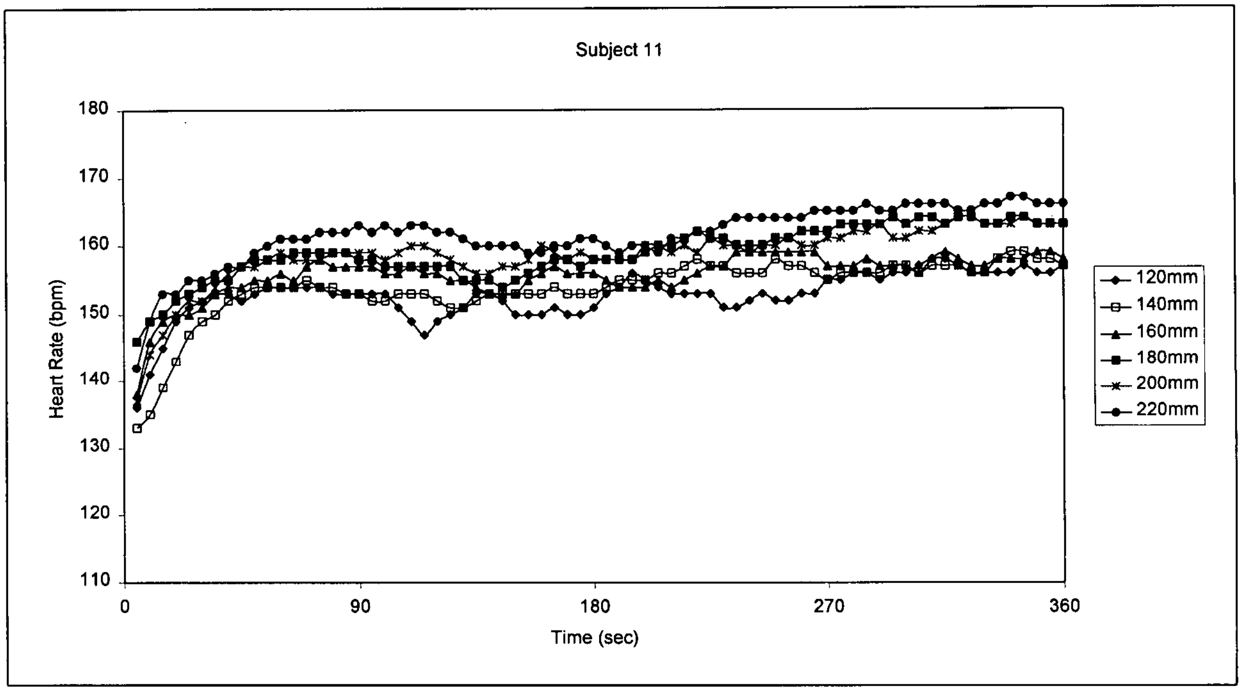
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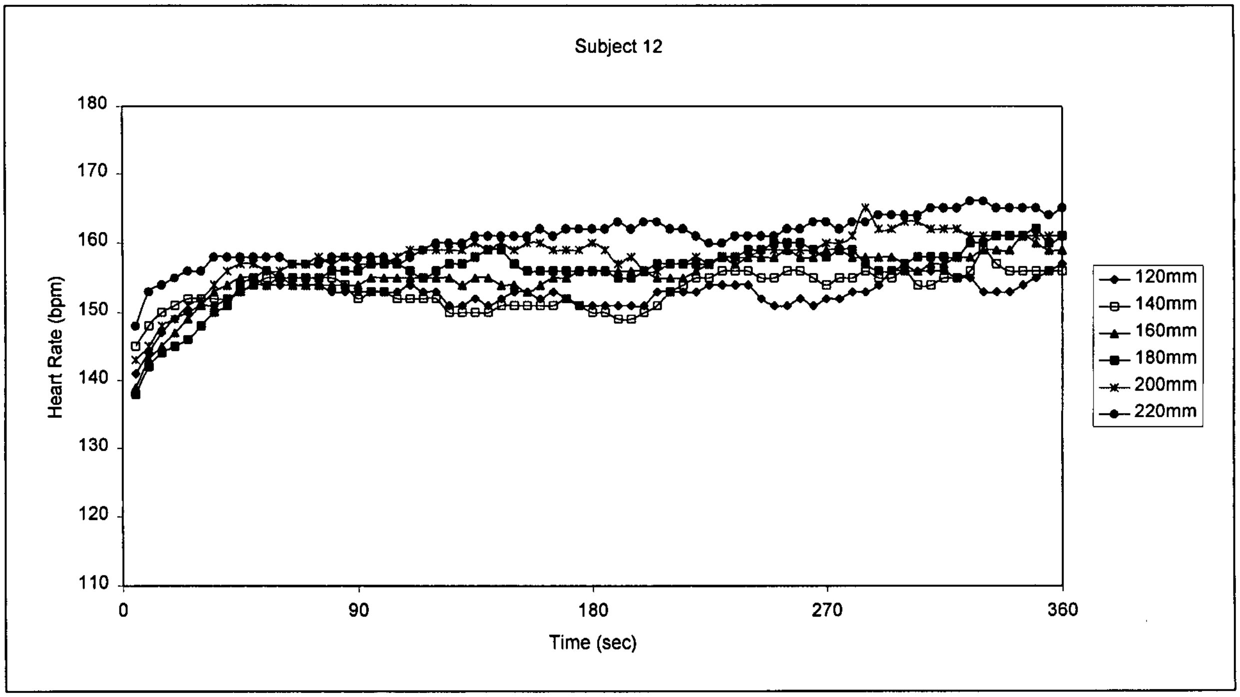
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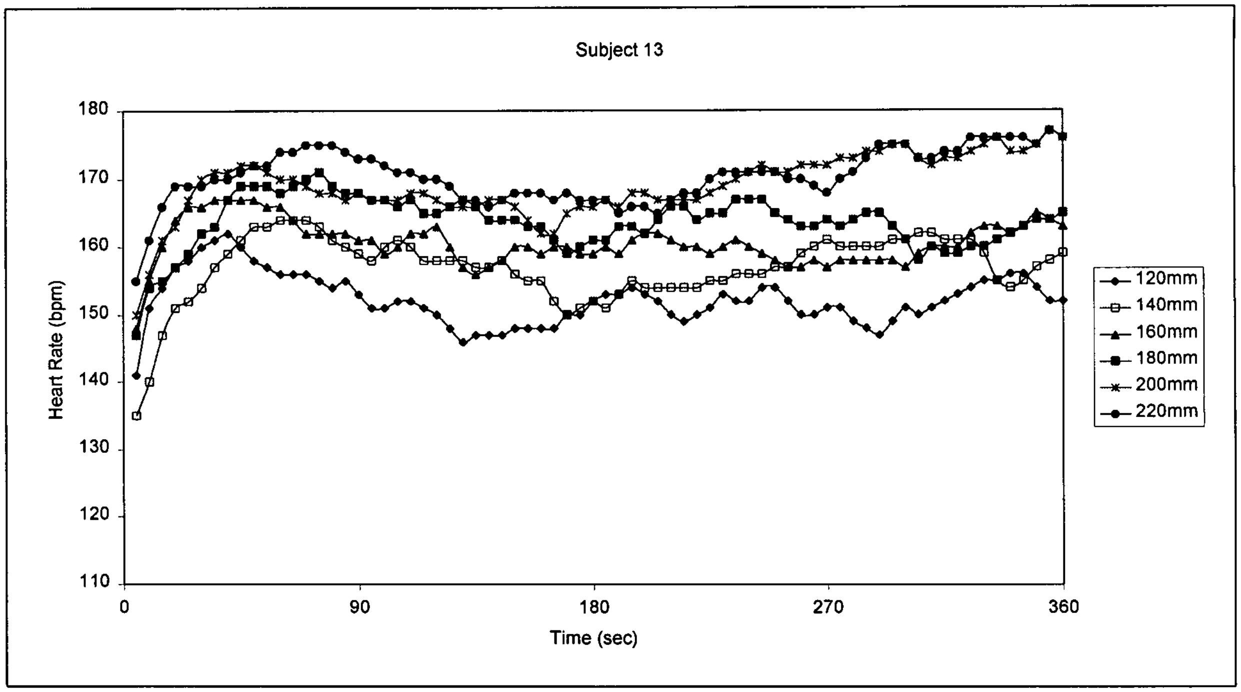
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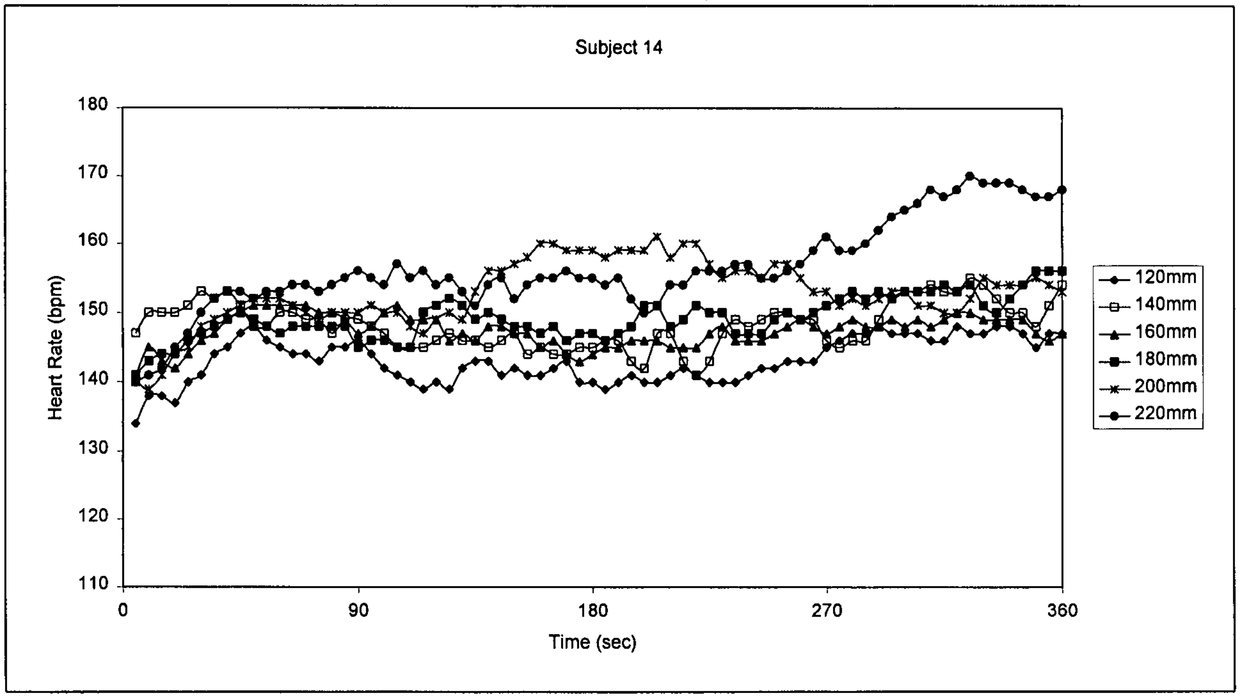
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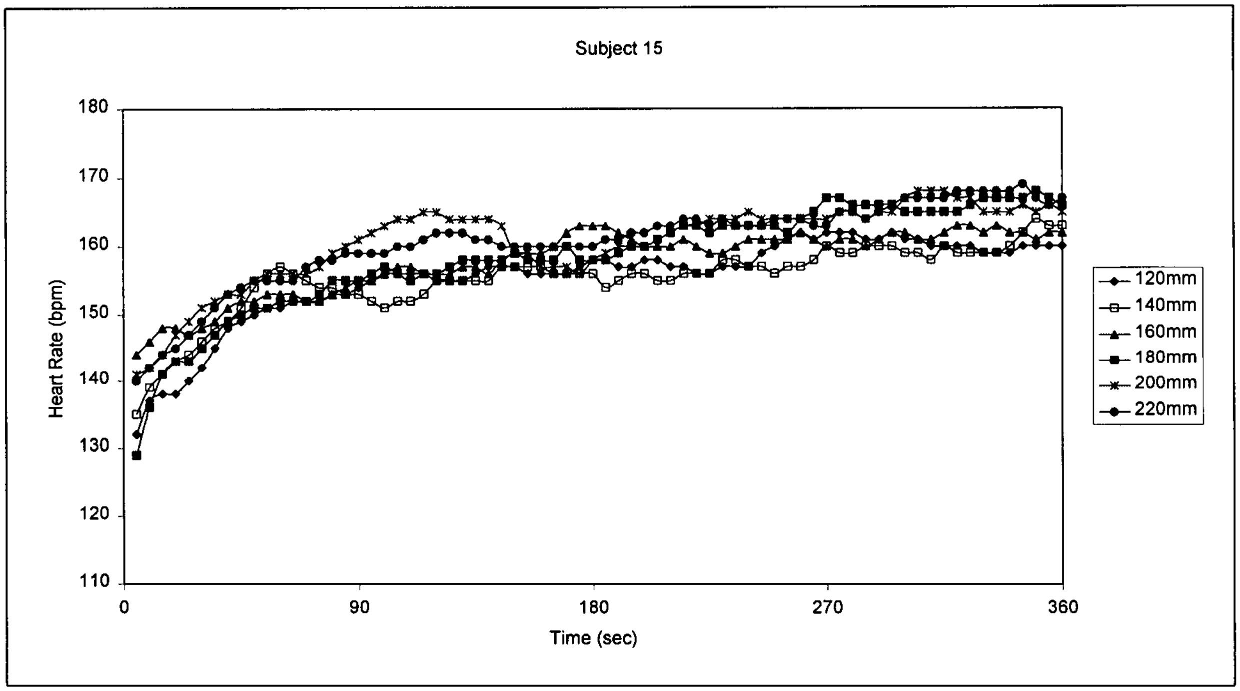
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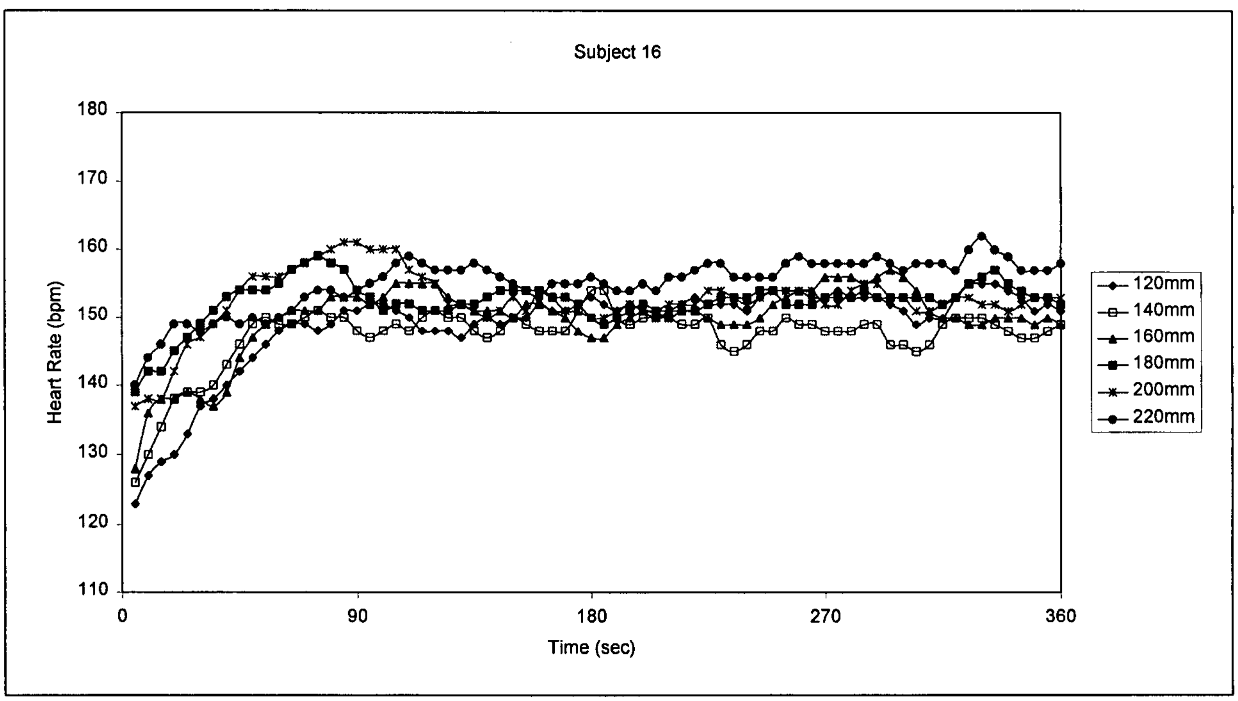
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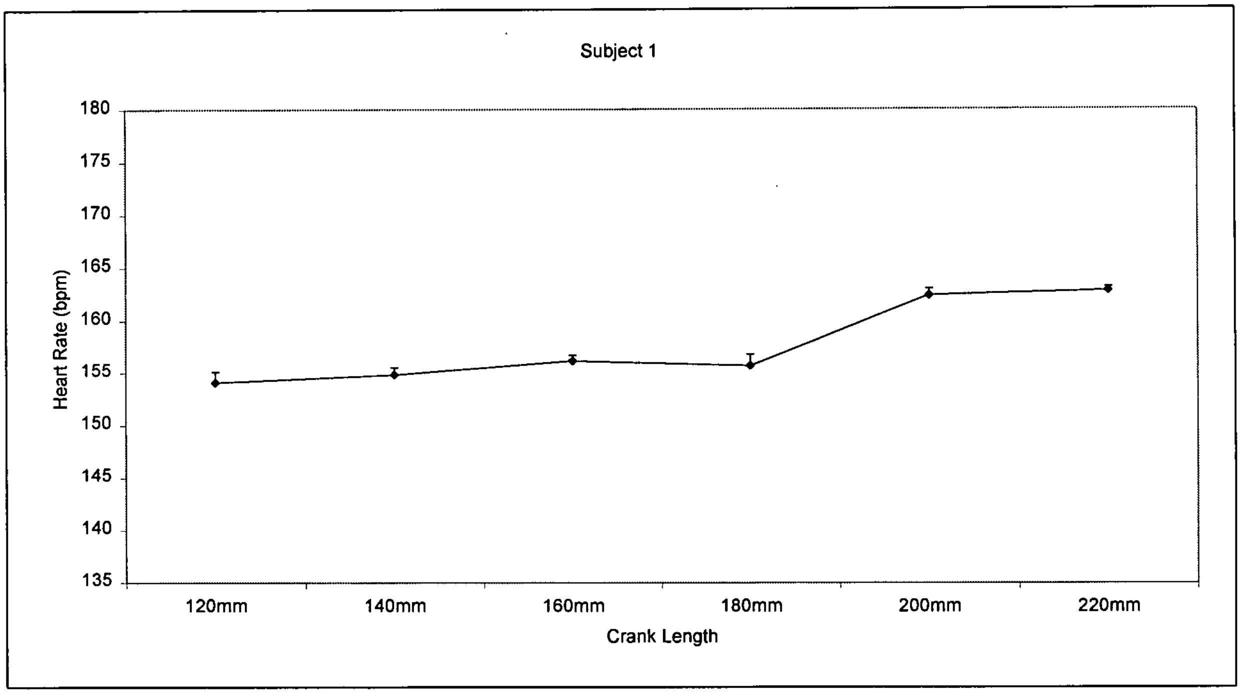
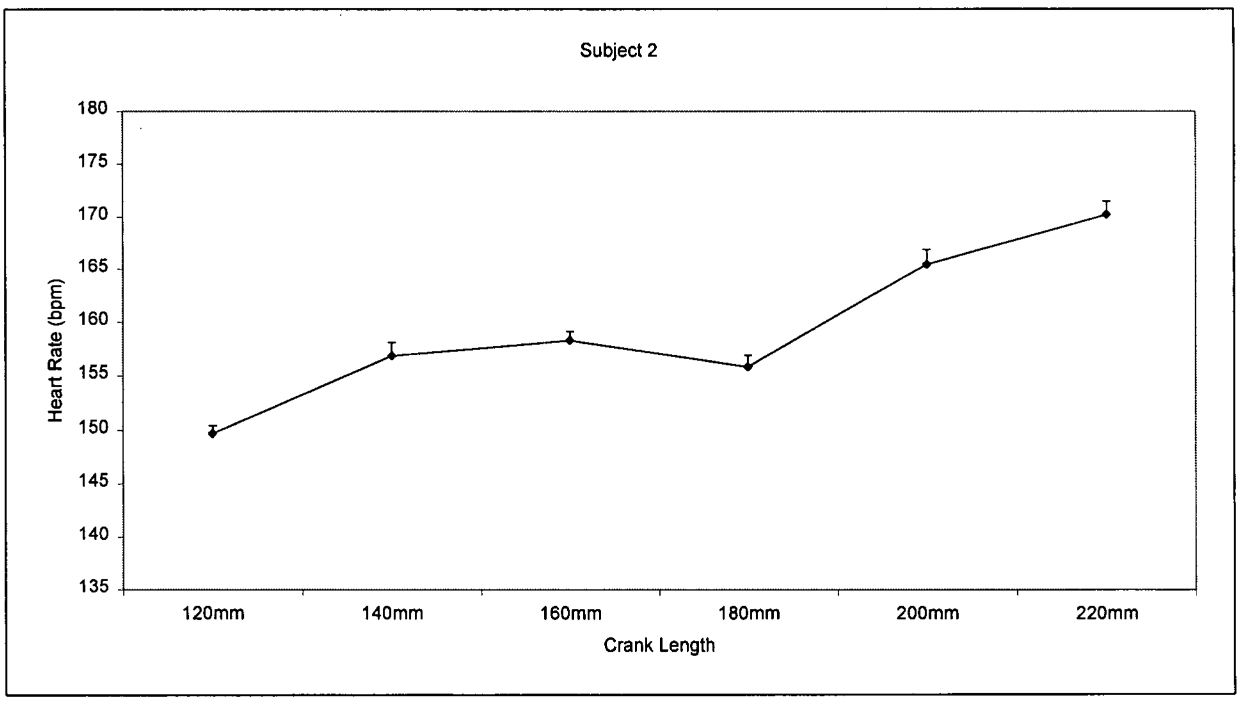
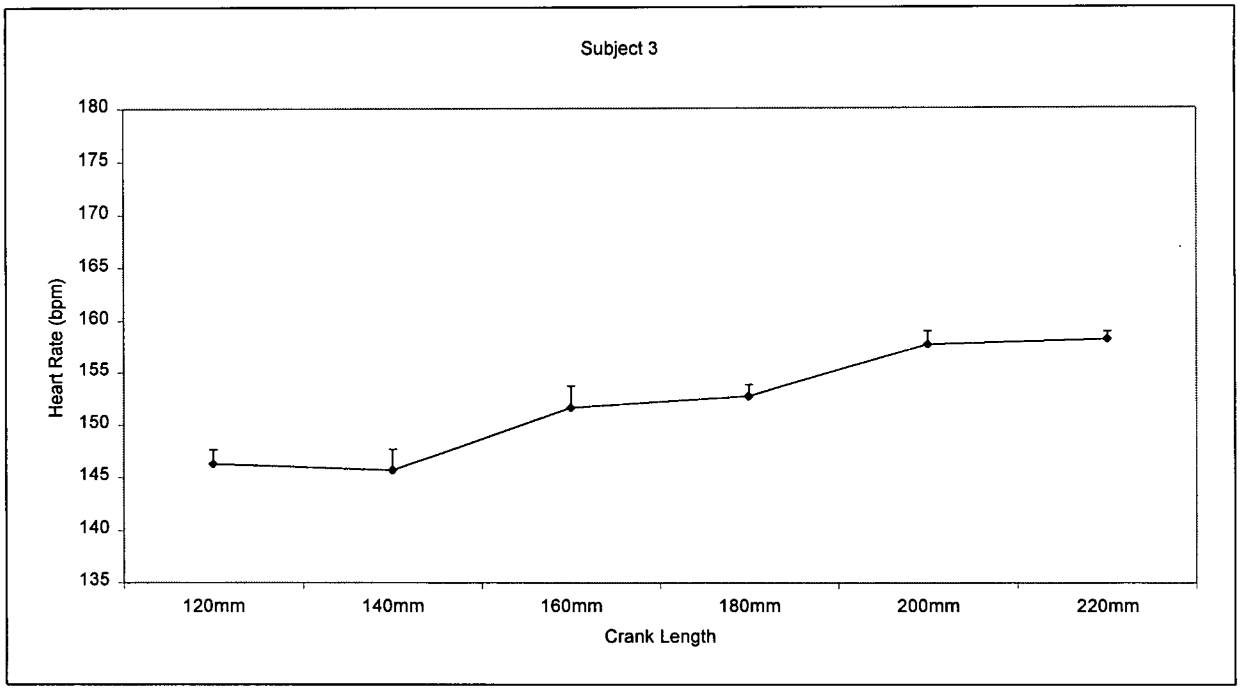
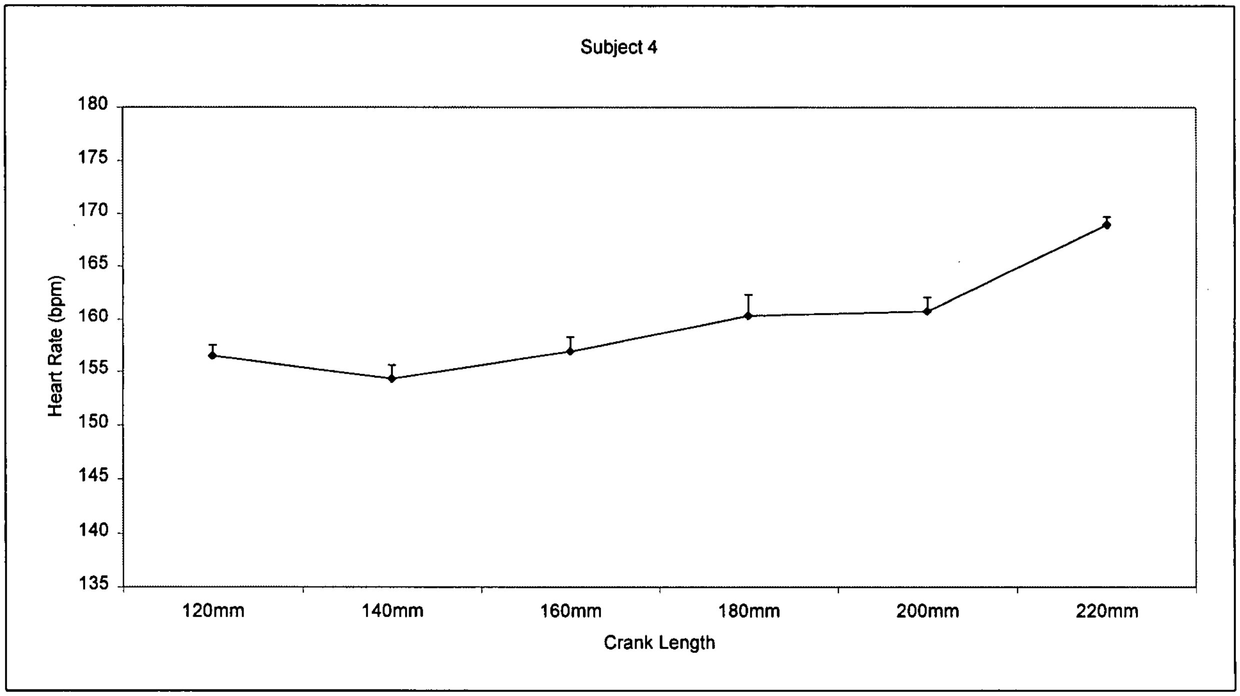
200mm
220mm

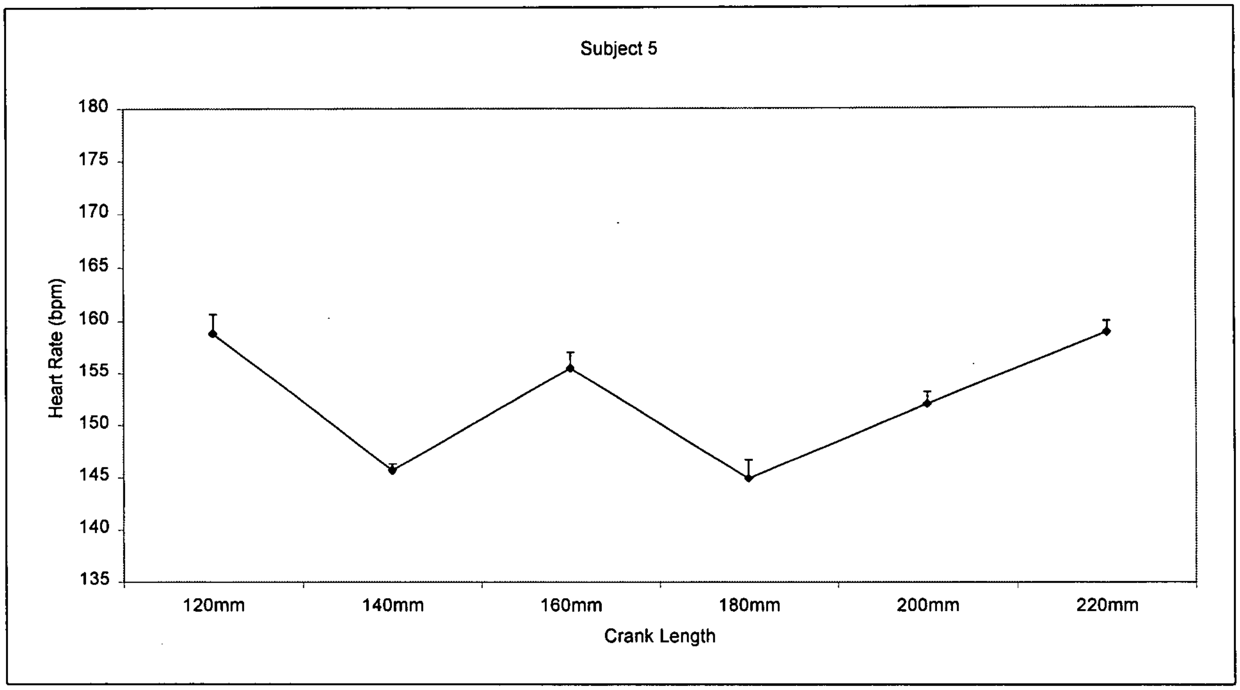
Appendix C2: Individual Heart Rate Response to Crank Length (+ 1 S.D. error bars)

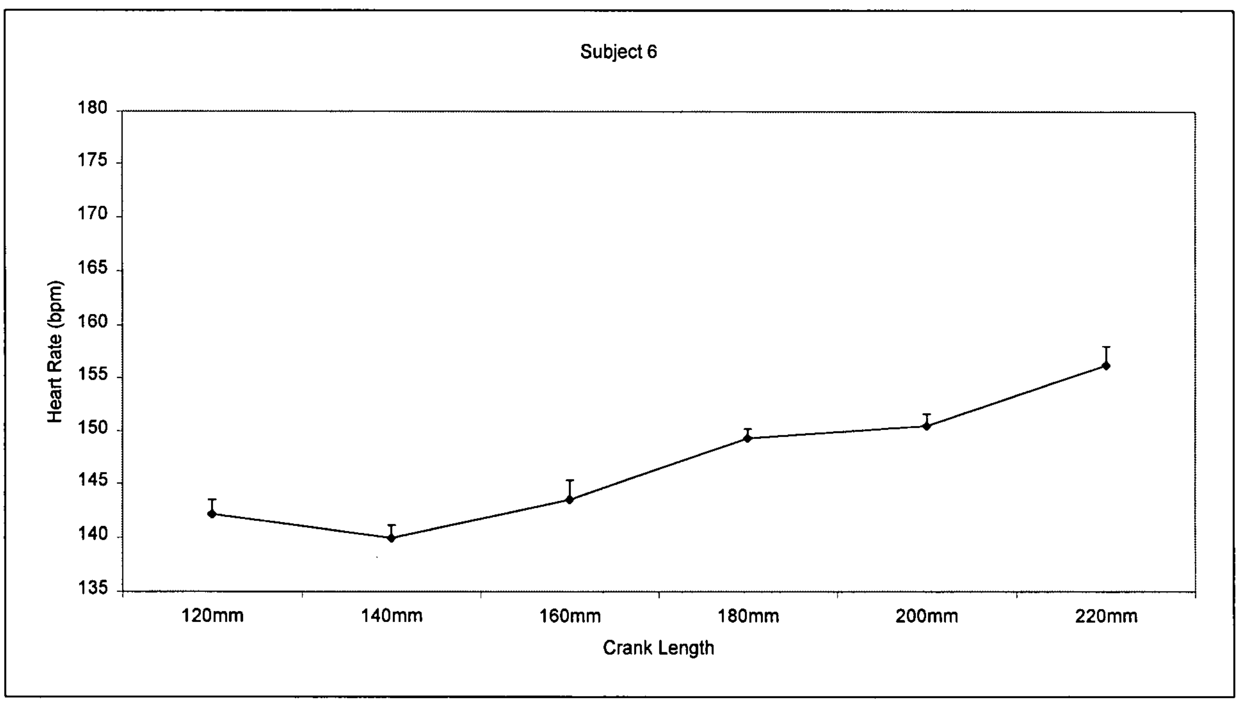

Subject 1
180
175
170
165
160
155
150
145
140
135
Heart Rate (bpm)
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length

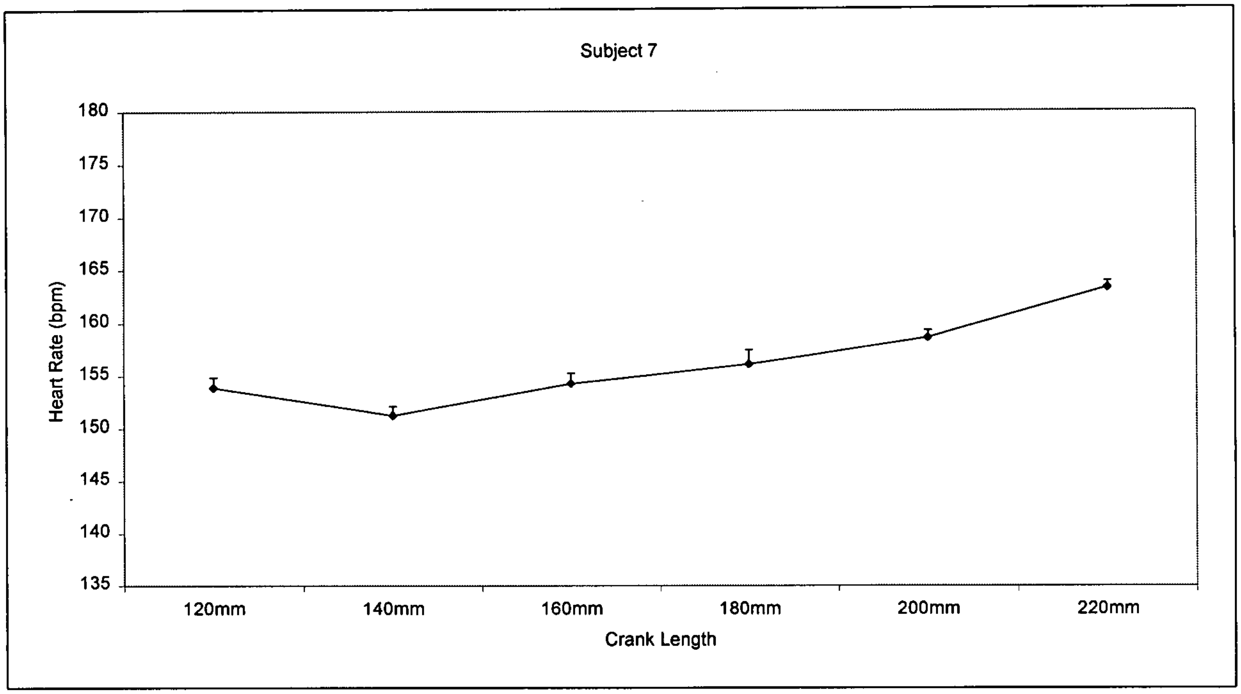

Subject 2
180
175
170
165
160
155
150
145
140
135
Heart Rate (bpm)
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length

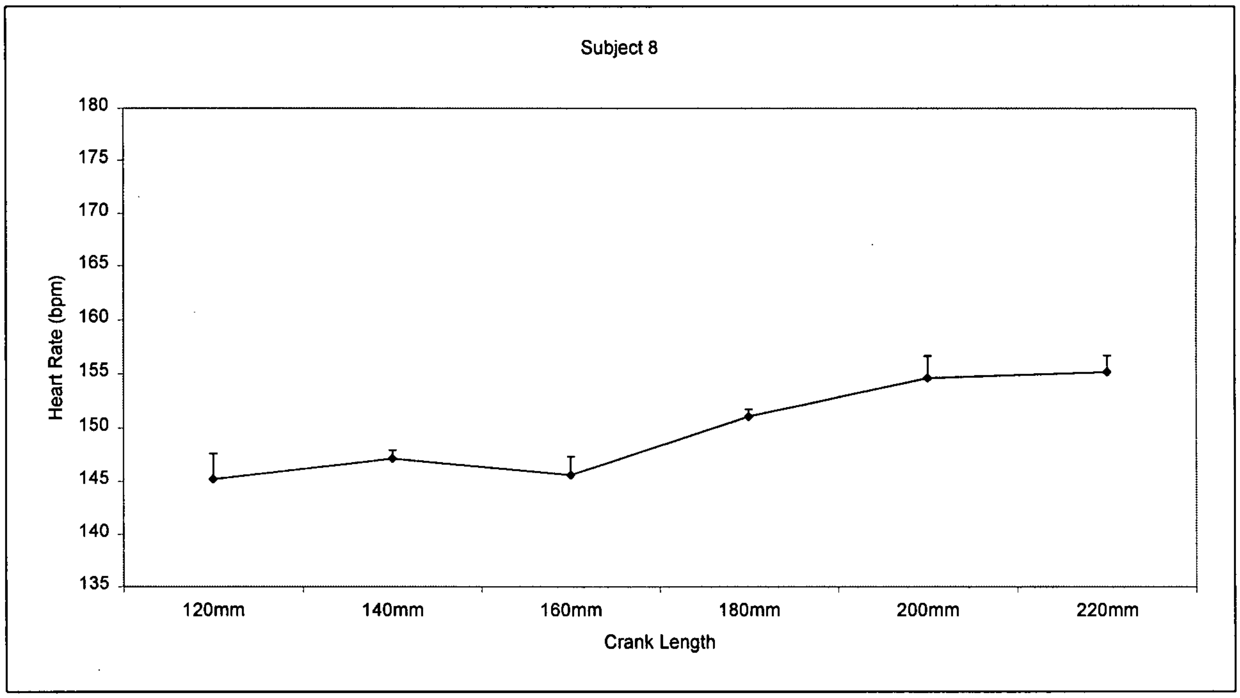

Subject 3
180
175
170
165
160
155
150
145
140
135
Heart Rate (bpm)
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length

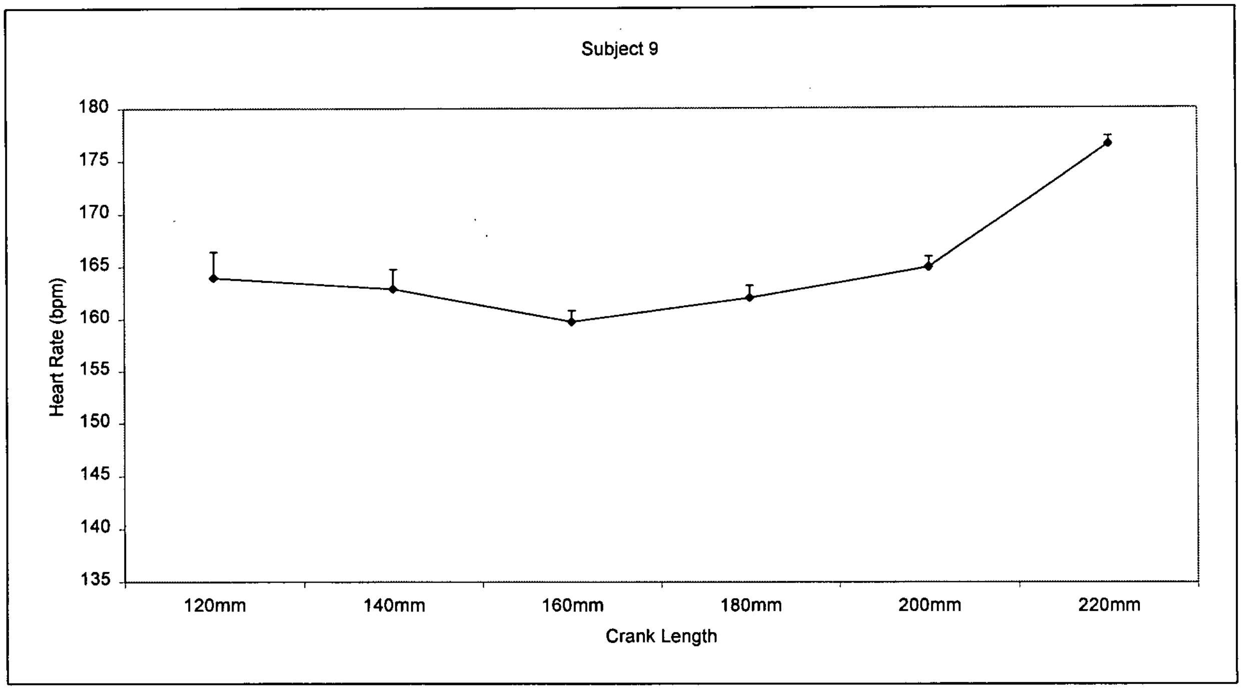

Subject 4
180
175
170
165
160
155
150
145
140
135
Heart Rate (bpm)
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length


Subject 5
Heart Rate (bpm)
180
175
170
165
160
155
150
145
140
135
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length

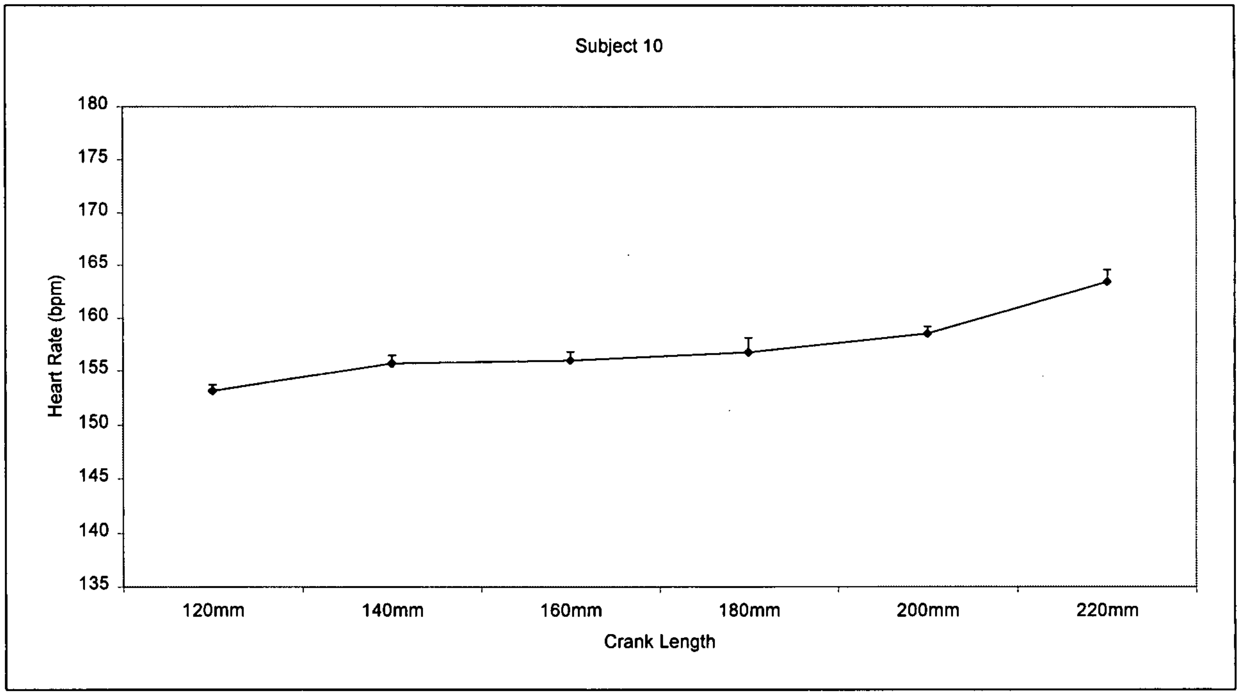

Subject 6
Heart Rate (bpm)
180
175
170
165
160
155
150
145
140
135
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length


Subject 7
Heart Rate (bpm)
180
175
170
165
160
155
150
145
140
135
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length

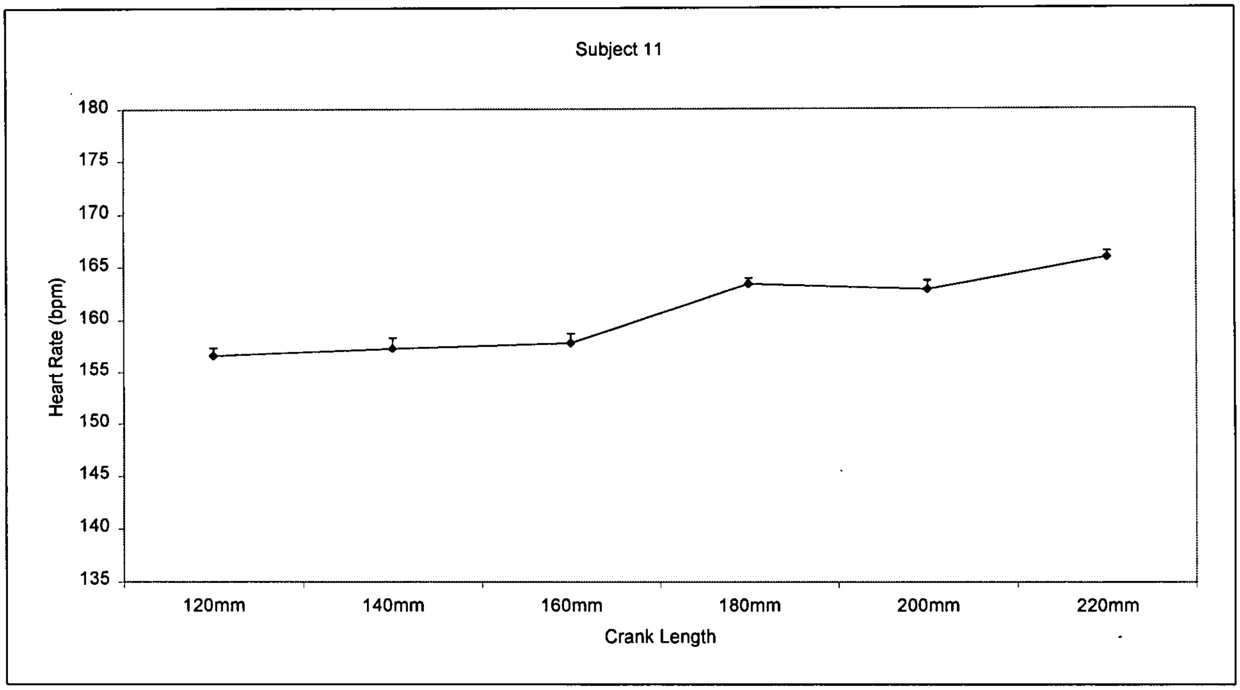

Subject 8
Heart Rate (bpm)
180
175
170
165
160
155
150
145
140
135
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length



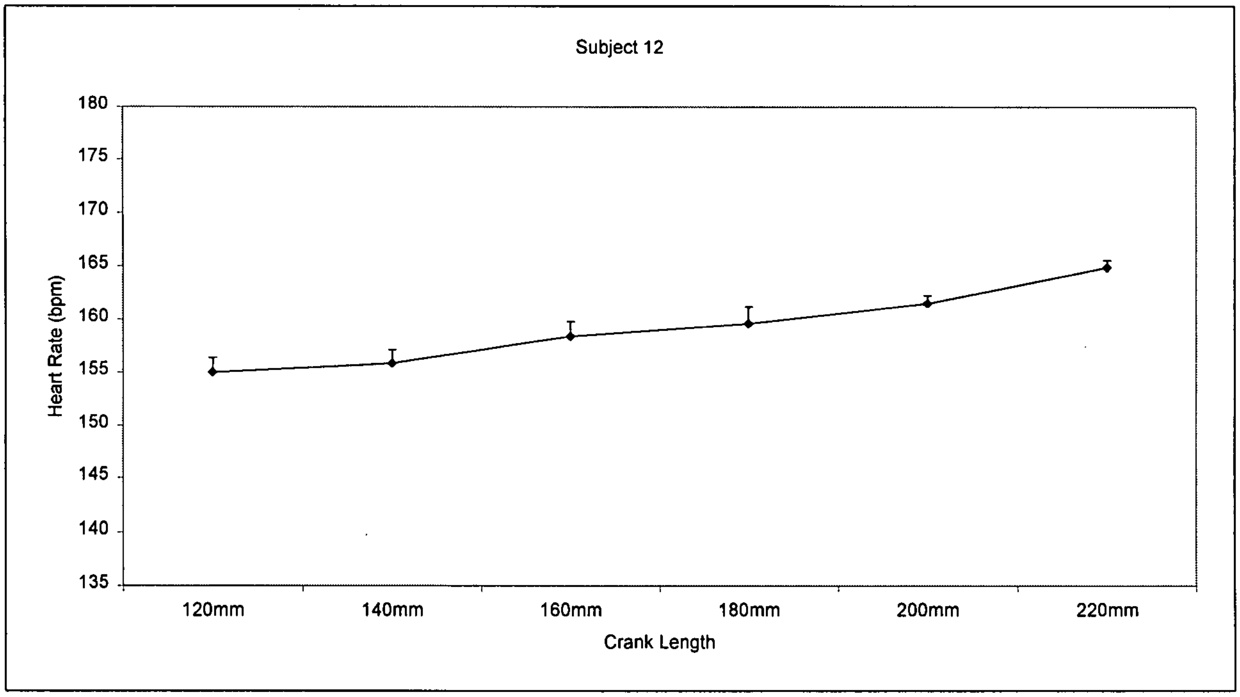
Subject 9
180
175
170
165
160
155
150
145
140
135
Heart Rate (bpm)
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length



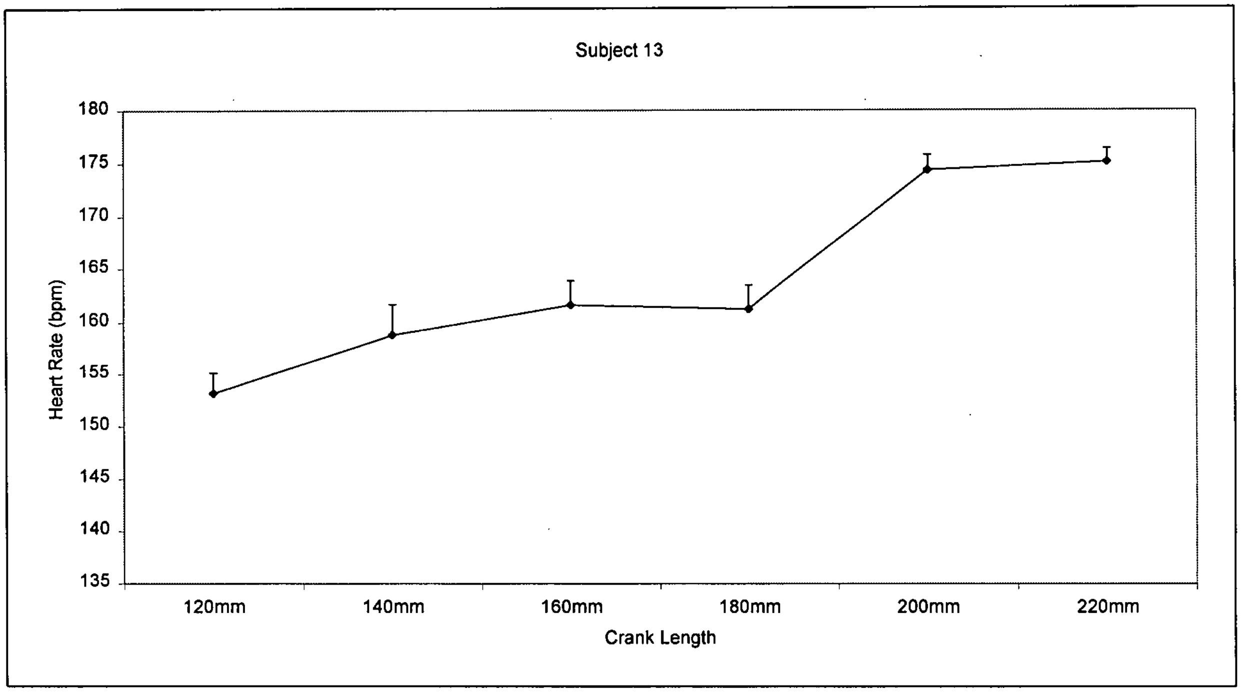
Subject 10
180
175
170
165
160
155
150
145
140
135
Heart Rate (bpm)
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length



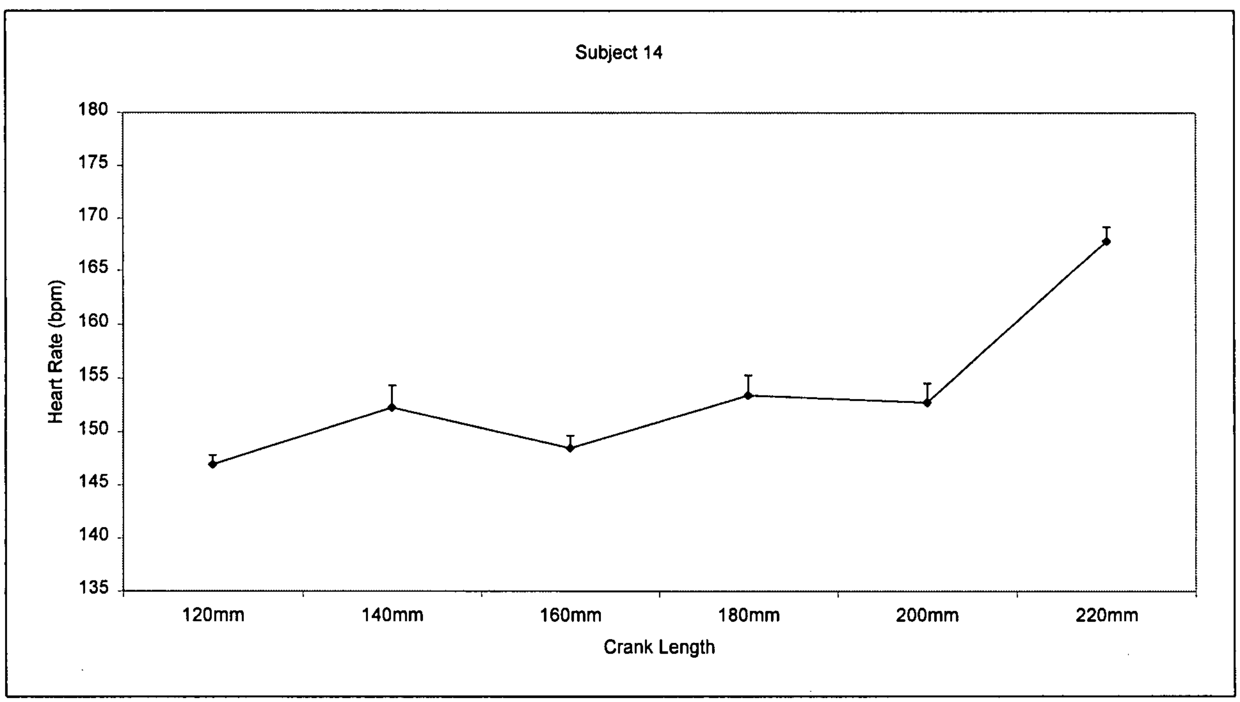
Subject 11
Heart Rate (bpm)
180
175
170
165
160
155
150
145
140
135
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length



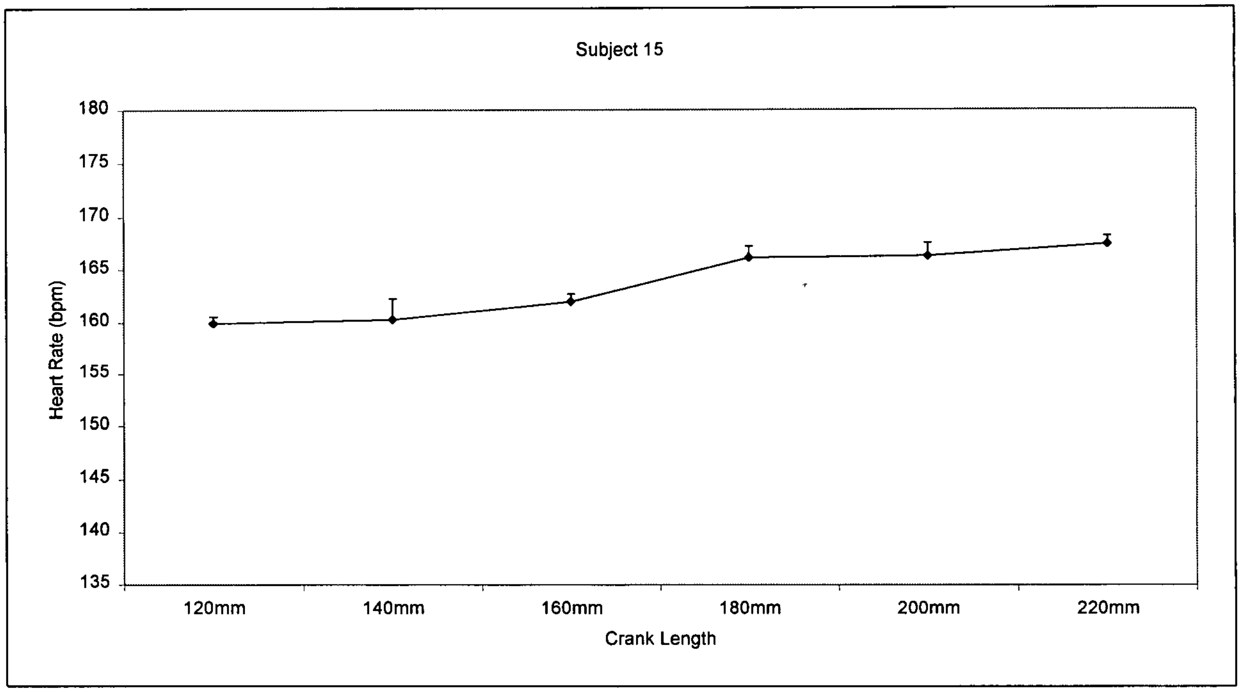
Subject 12
Heart Rate (bpm)
180
175
170
165
160
155
150
145
140
135
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length

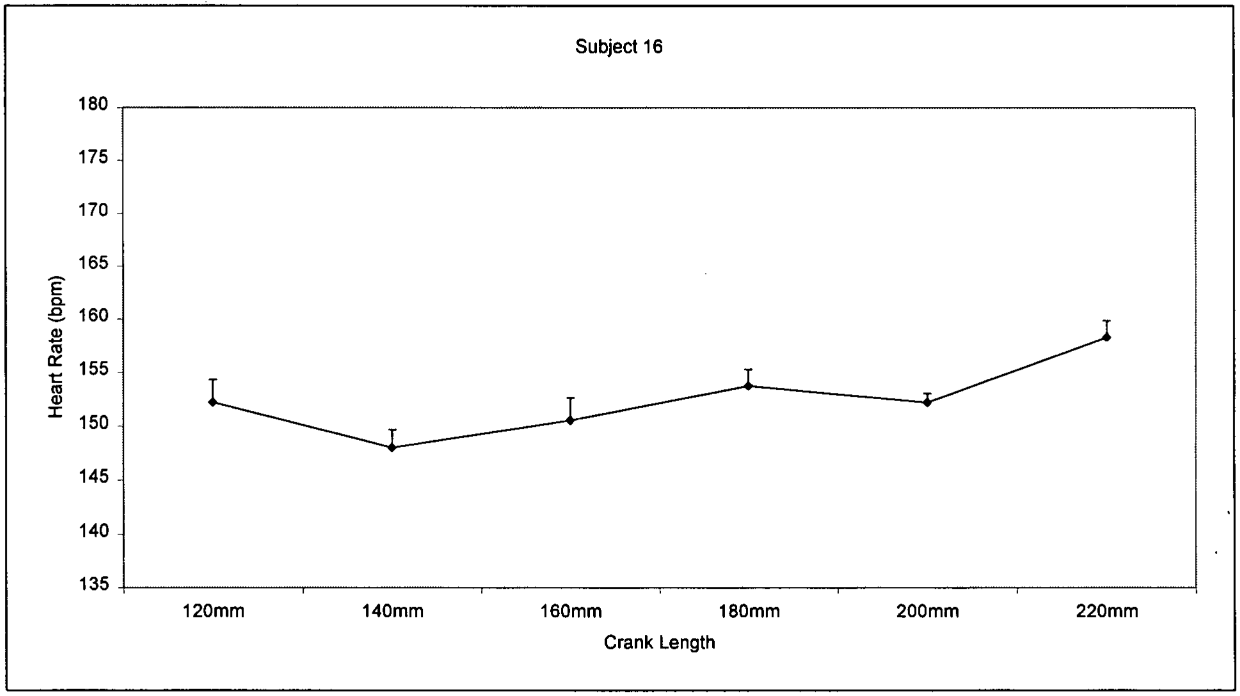


Subject 13
180
175
170
165
160
155
150
145
140
135
Heart Rate (bpm)
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length

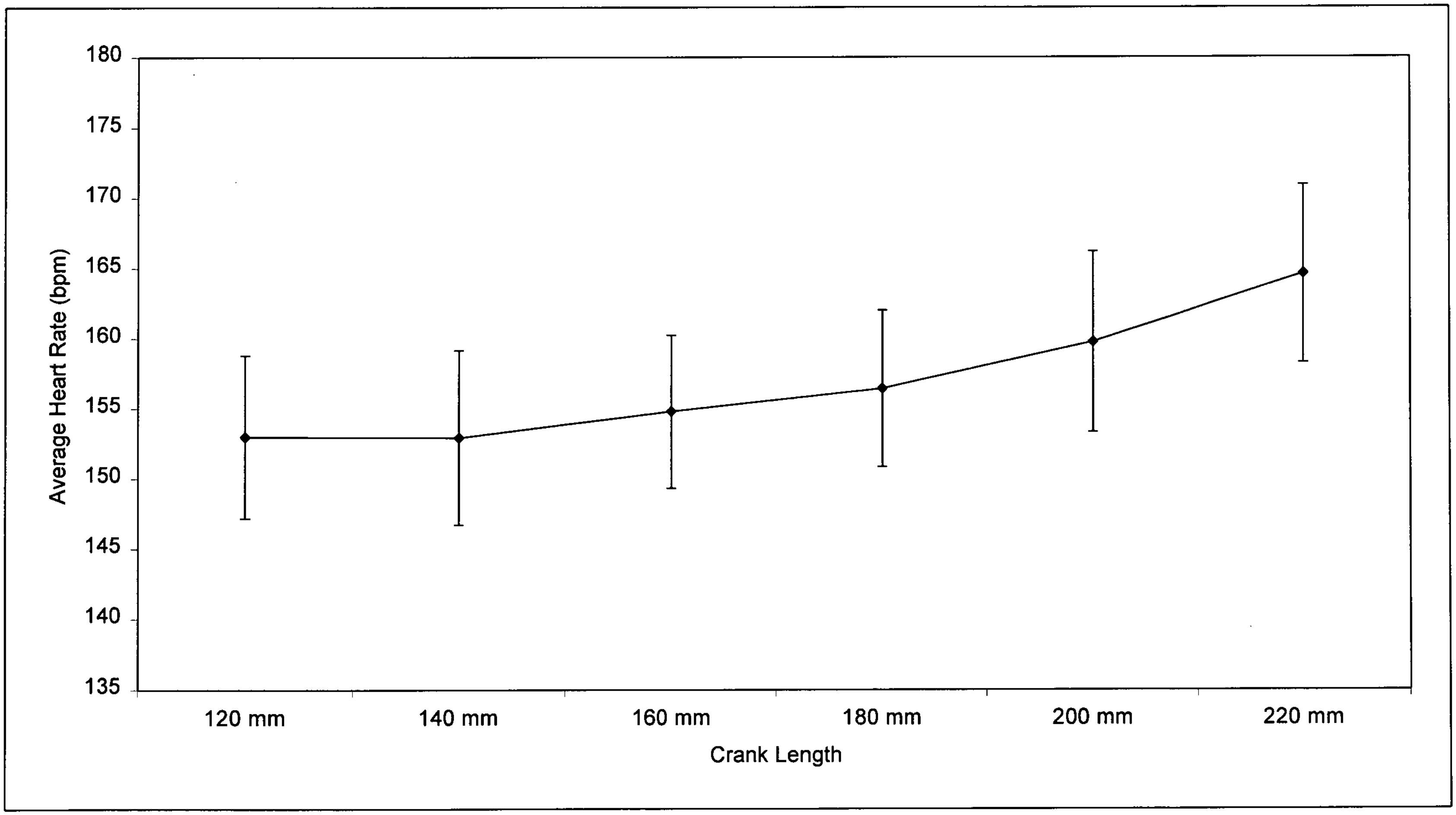


Subject 14
180
175
170
165
160
155
150
145
140
135
Heart Rate (bpm)
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length


Subject 15
Heart Rate (bpm)
180
175
170
165
160
155
150
145
140
135
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length


Subject 16
Heart Rate (bpm)
180
175
170
165
160
155
150
145
140
135
120mm
140mm
160mm
180mm
200mm
220mm
Crank Length

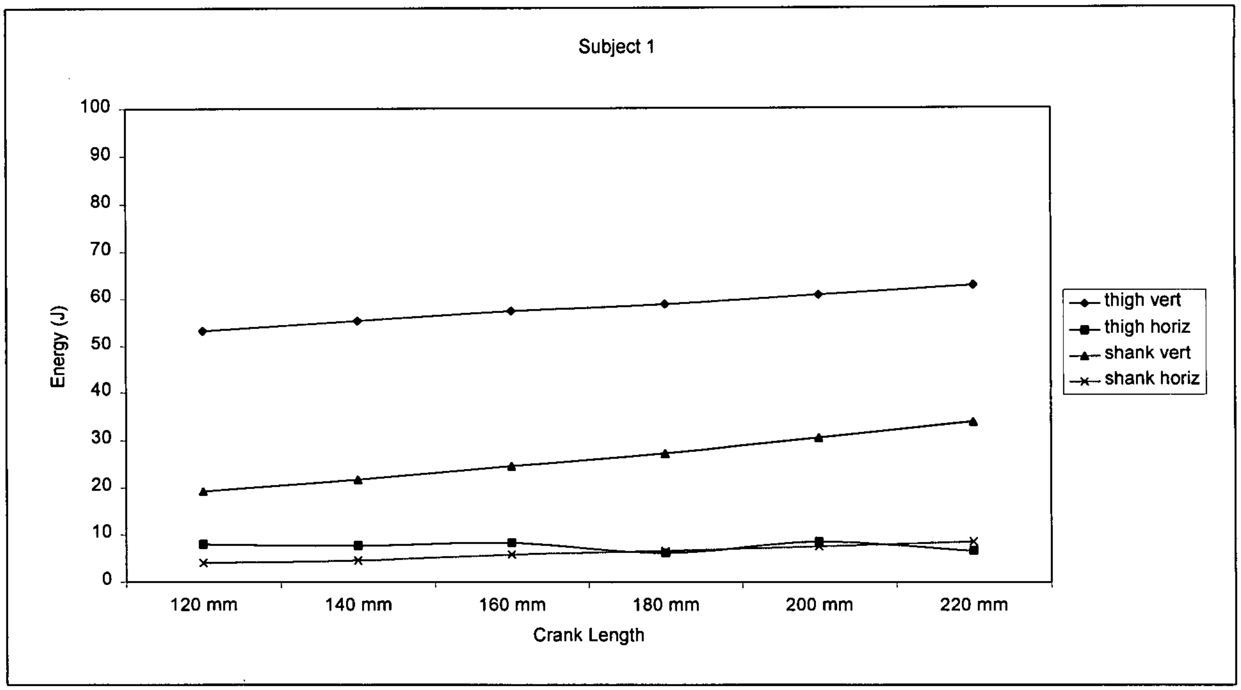
Appendix C3: Average Heart Rate Response to Crank Length for all Subjects (+ 1 S.D. error bars)

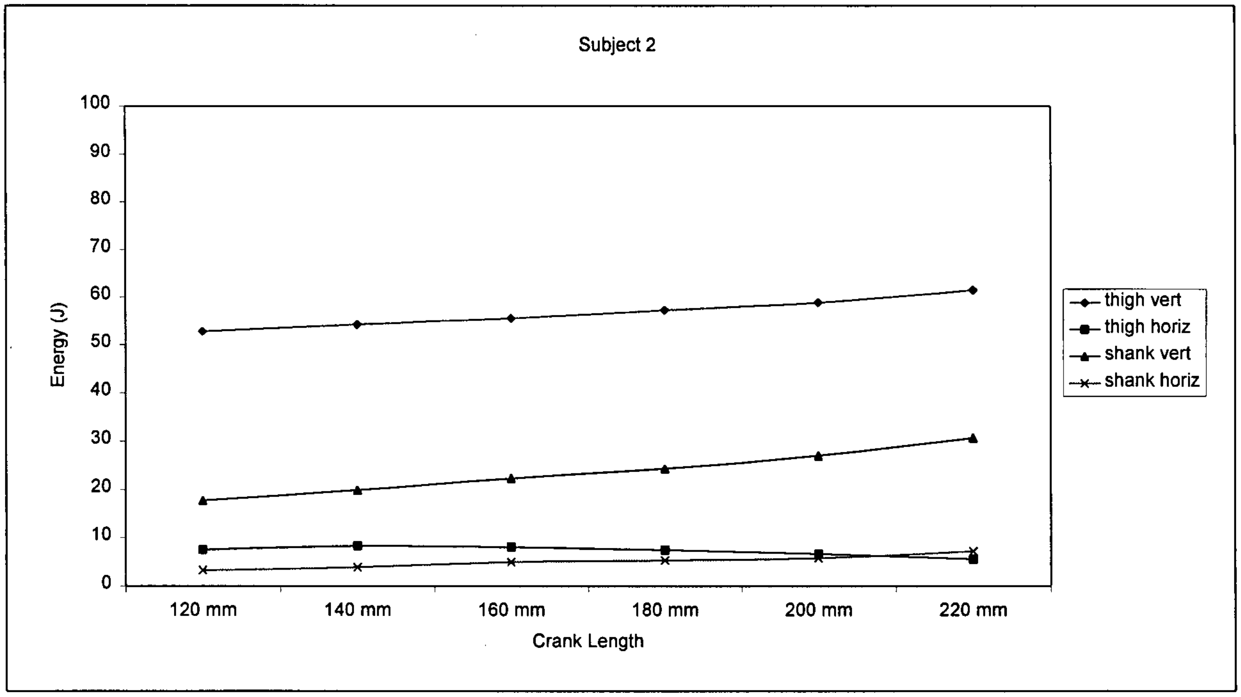


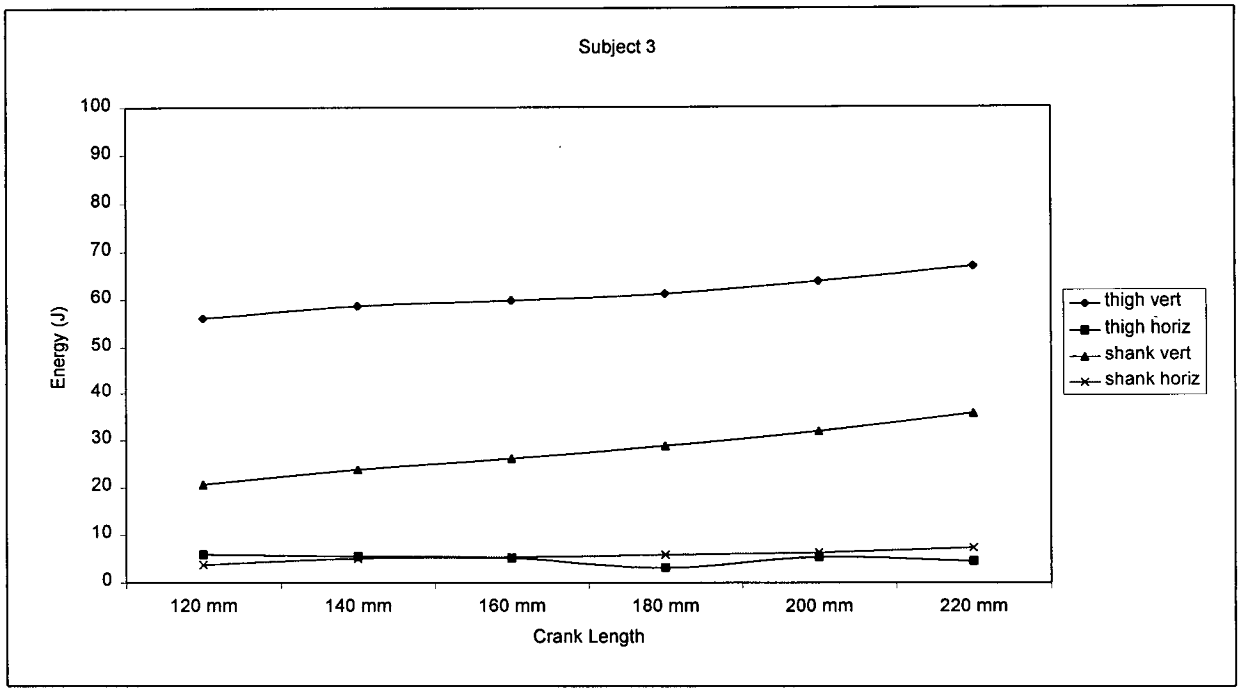
Appendix C4: Individual Segmental Energy Responses to Crank Length

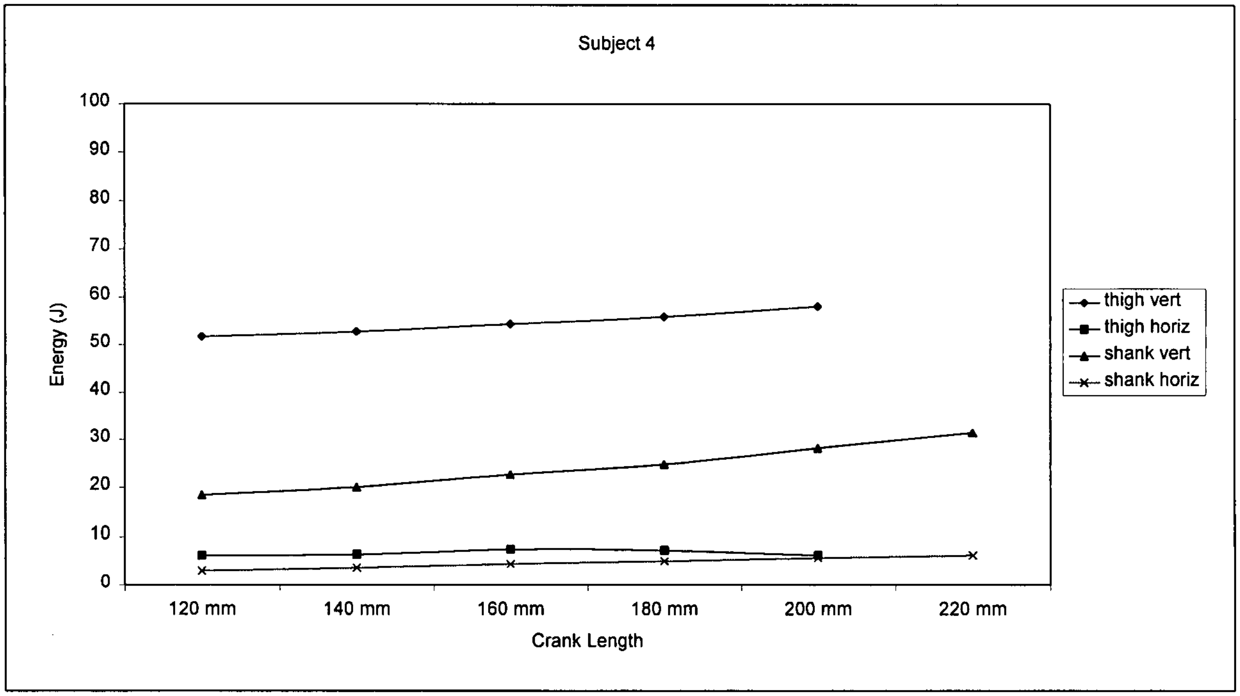
(includes total energy for the thigh and shank in both the vertical and horizontal directions)

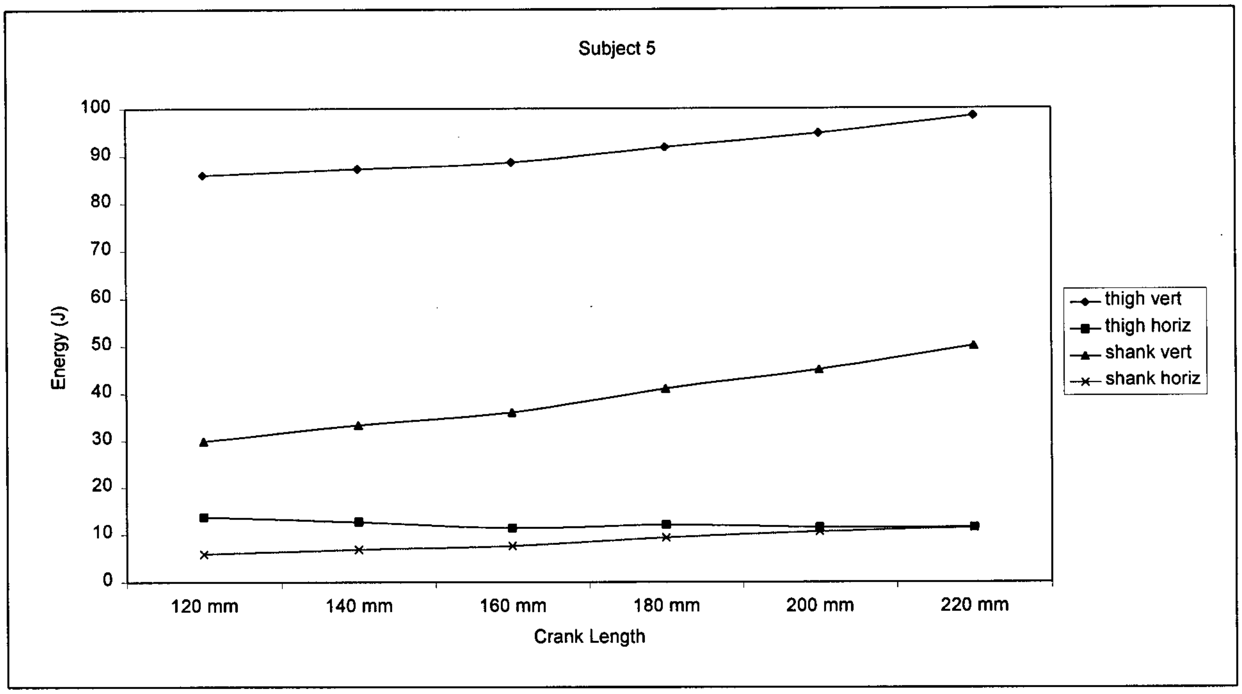
Note: Missing data is due to the inability to digitize certain markers.

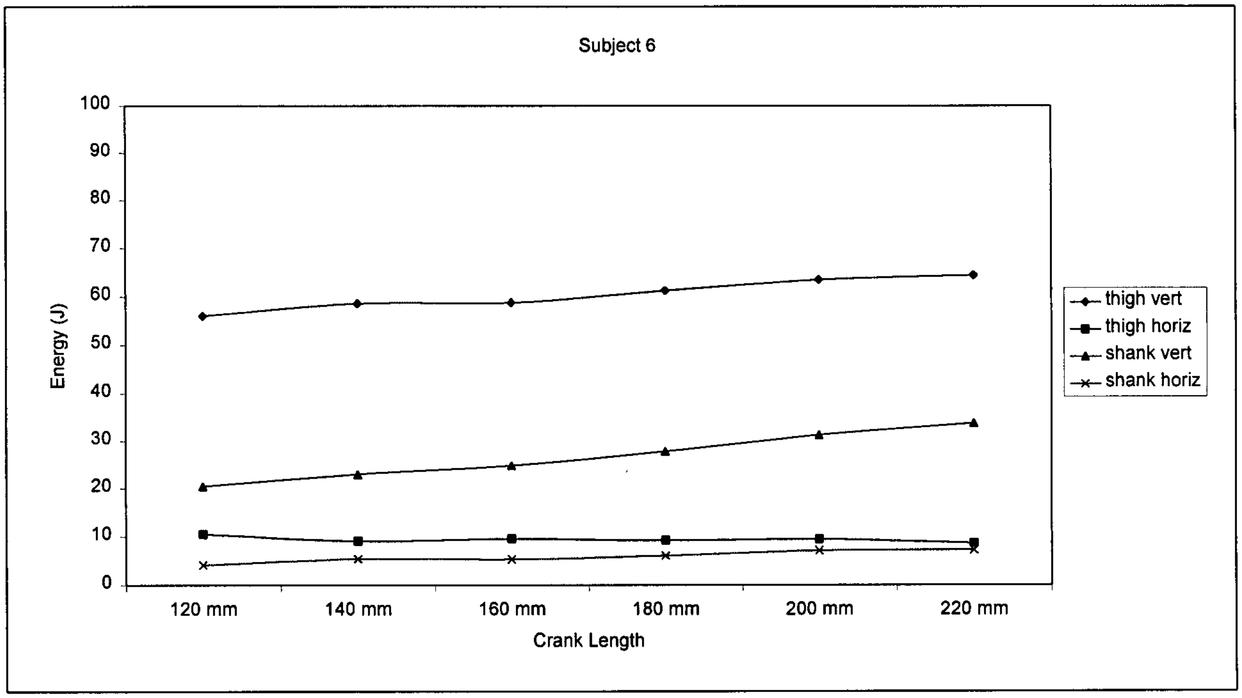

Subject 1
Energy (J)
100
90
80
70
60
50
40
30
20
10
0
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz

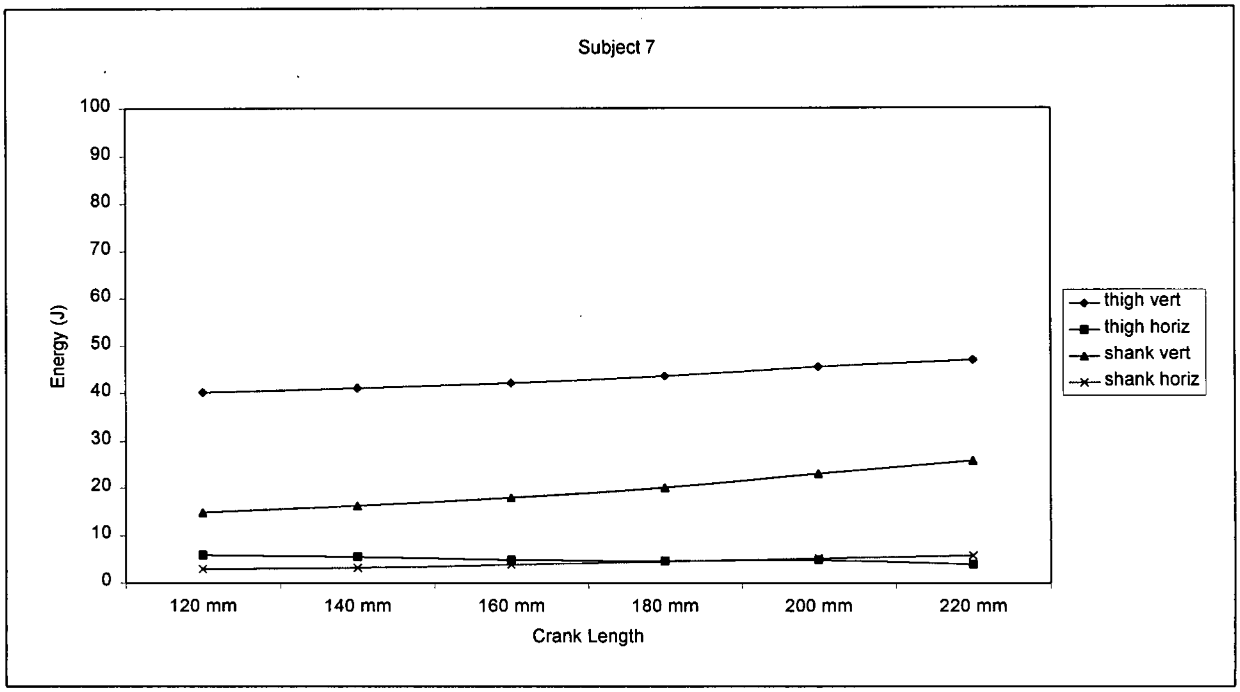

Subject 2
Energy (J)
100
90
80
70
60
50
40
30
20
10
0
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz


Subject 3
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz

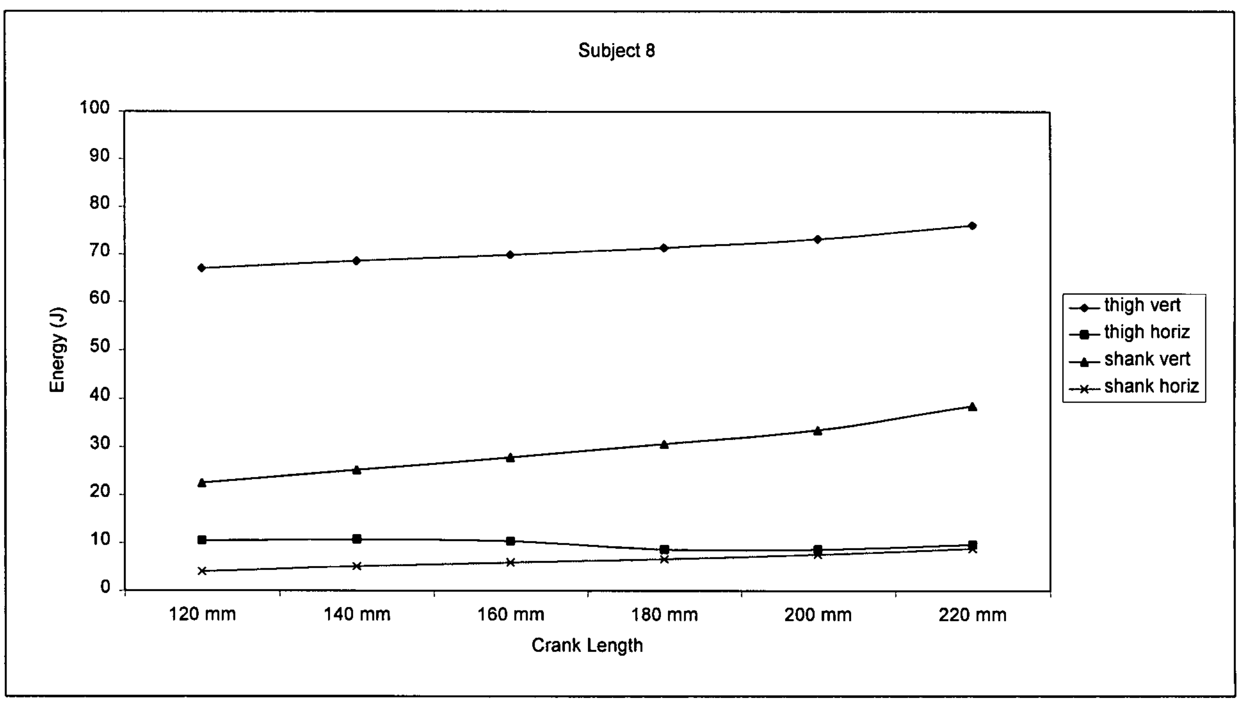

Subject 4
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz


Subject 5
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz

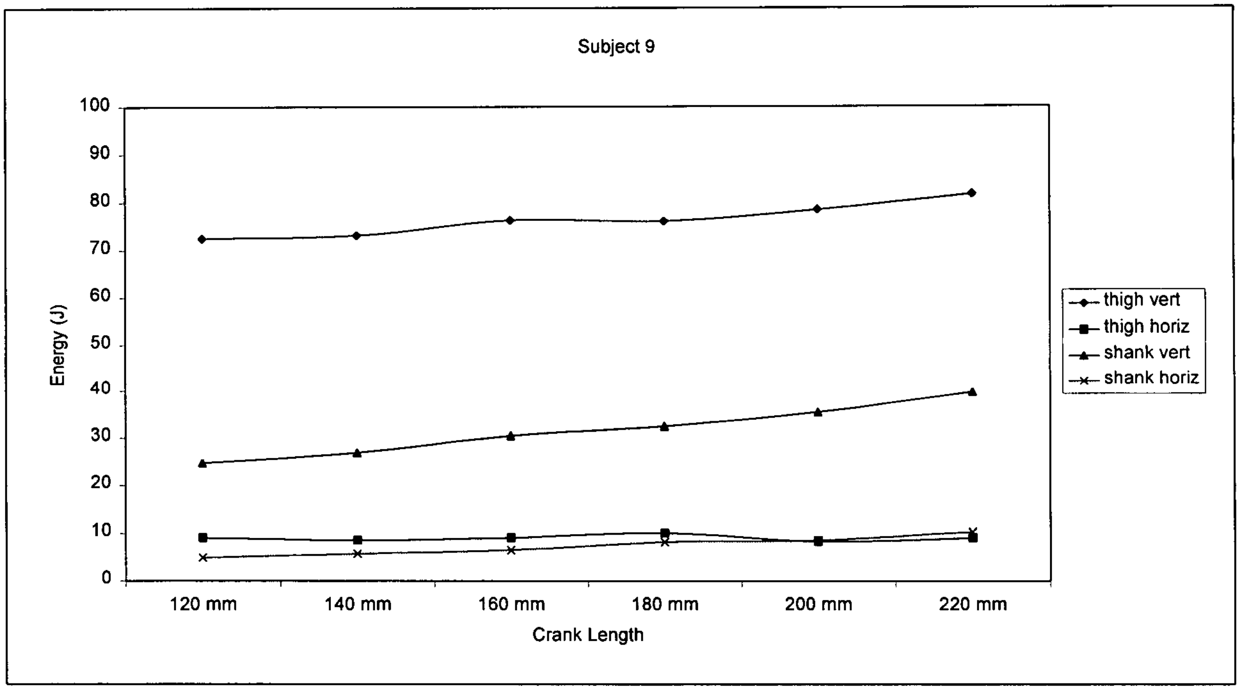

Subject 6
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz

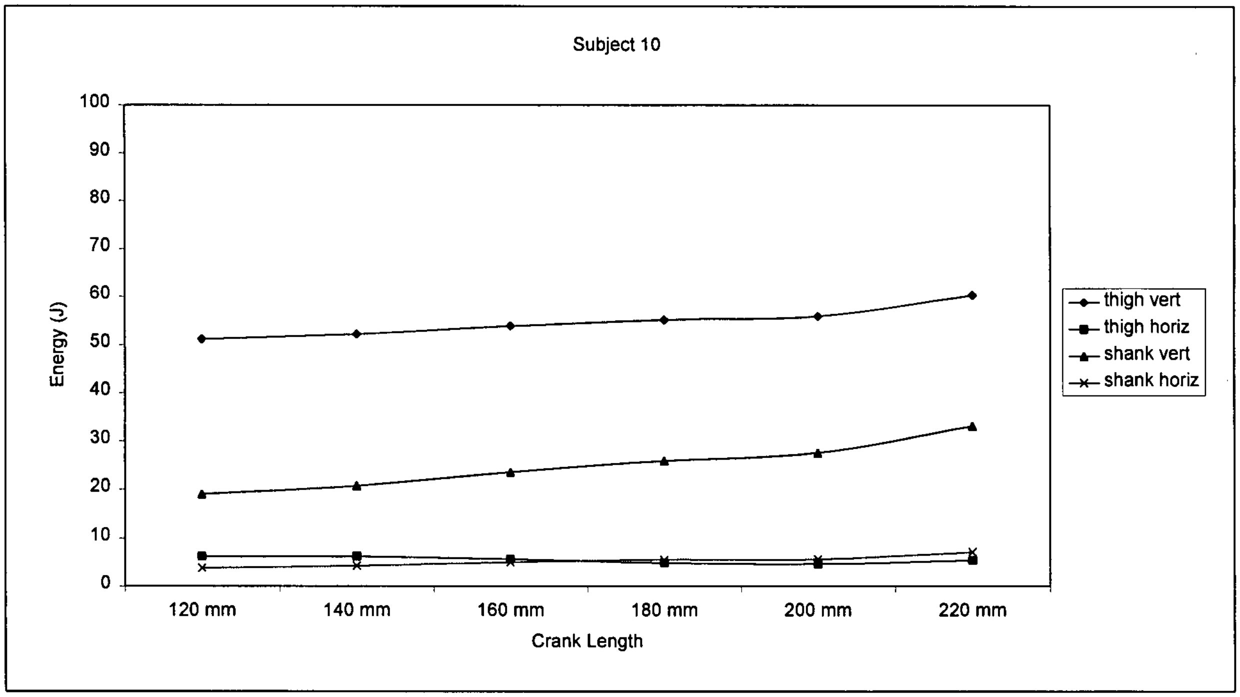


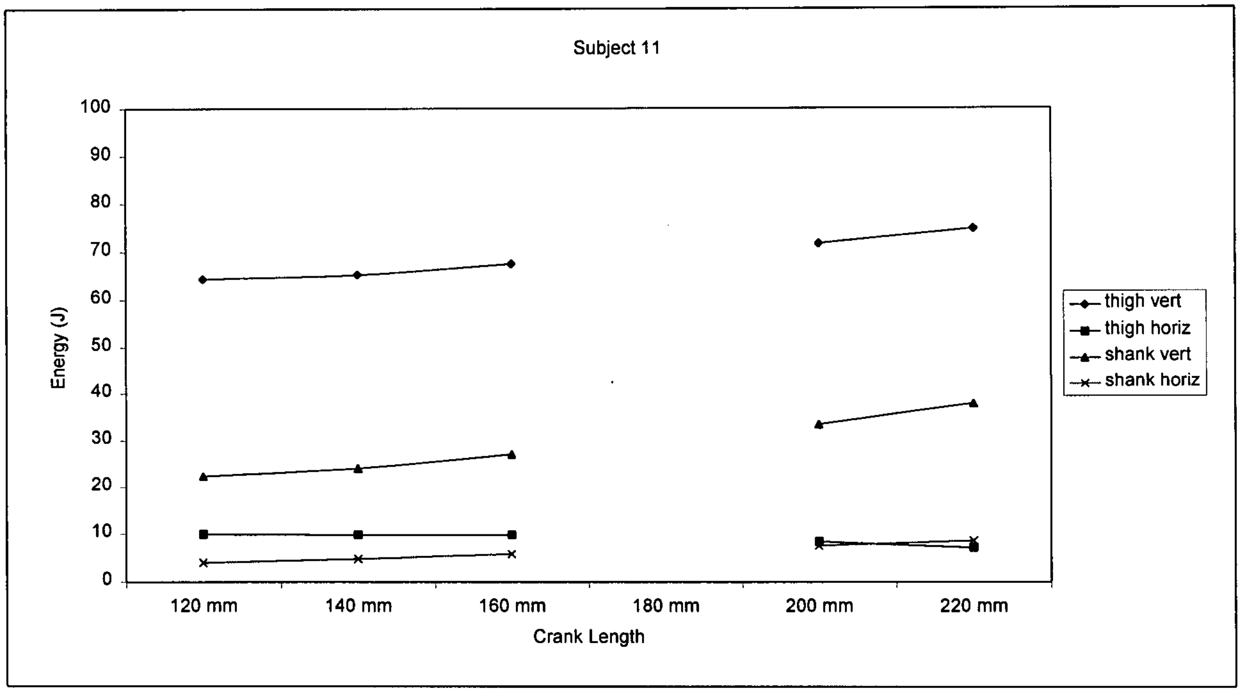
Subject 7
Energy (J)
100
90
80
70
60
50
40
30
20
10
0
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz



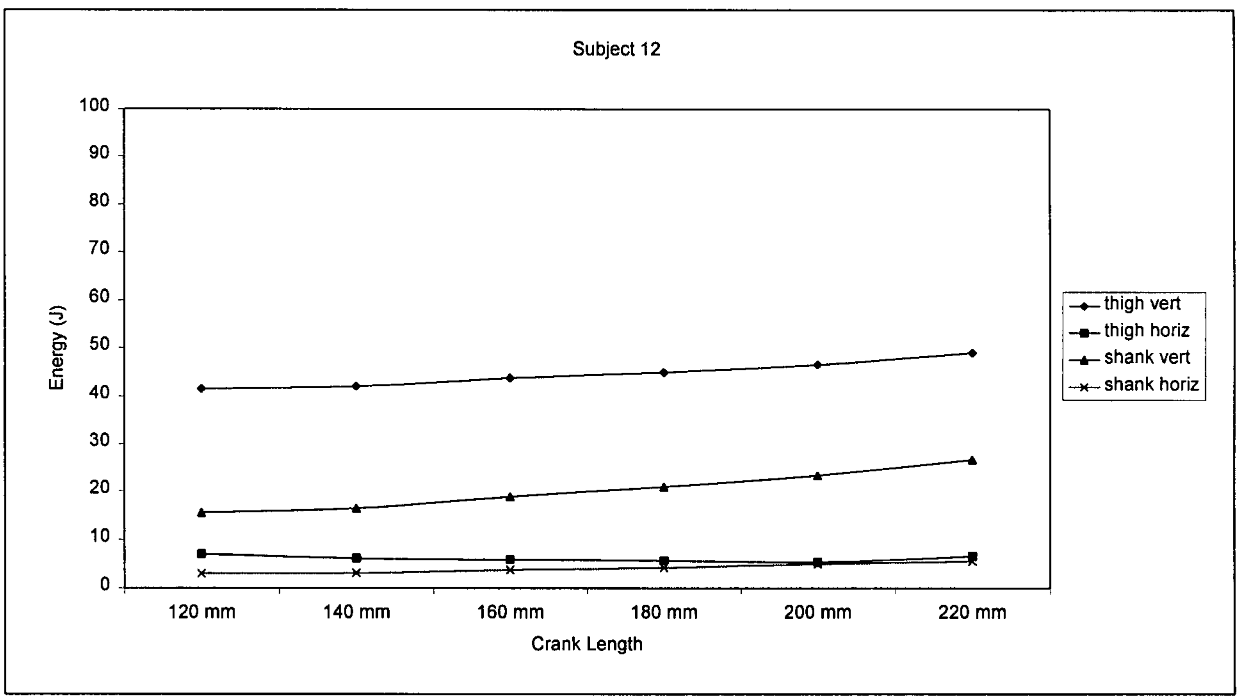
Subject 8
Energy (J)
100
90
80
70
60
50
40
30
20
10
0
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz


Subject 9
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz

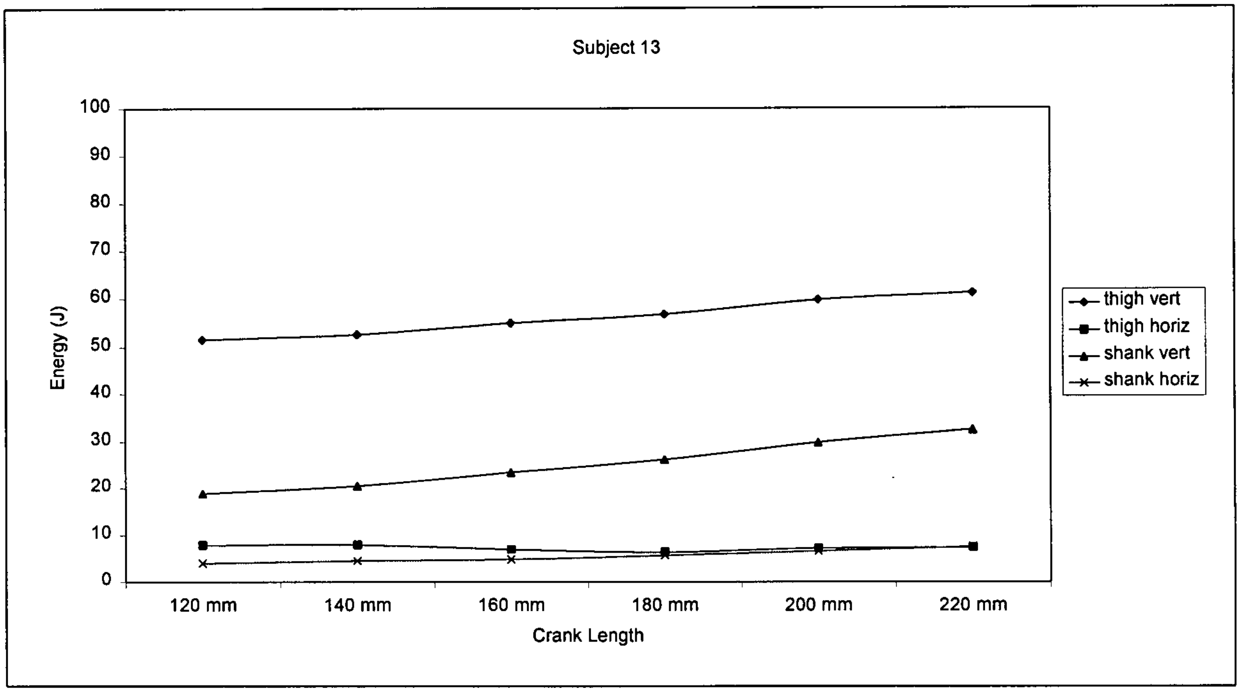

Subject 10
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz

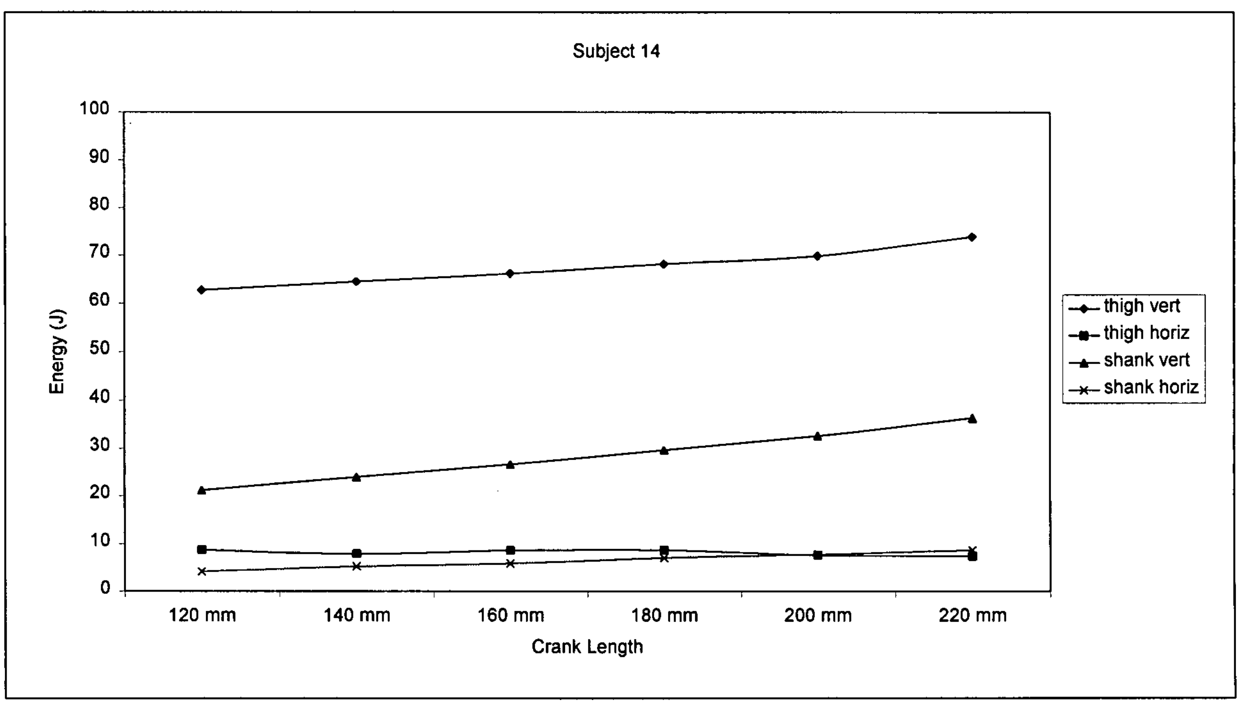


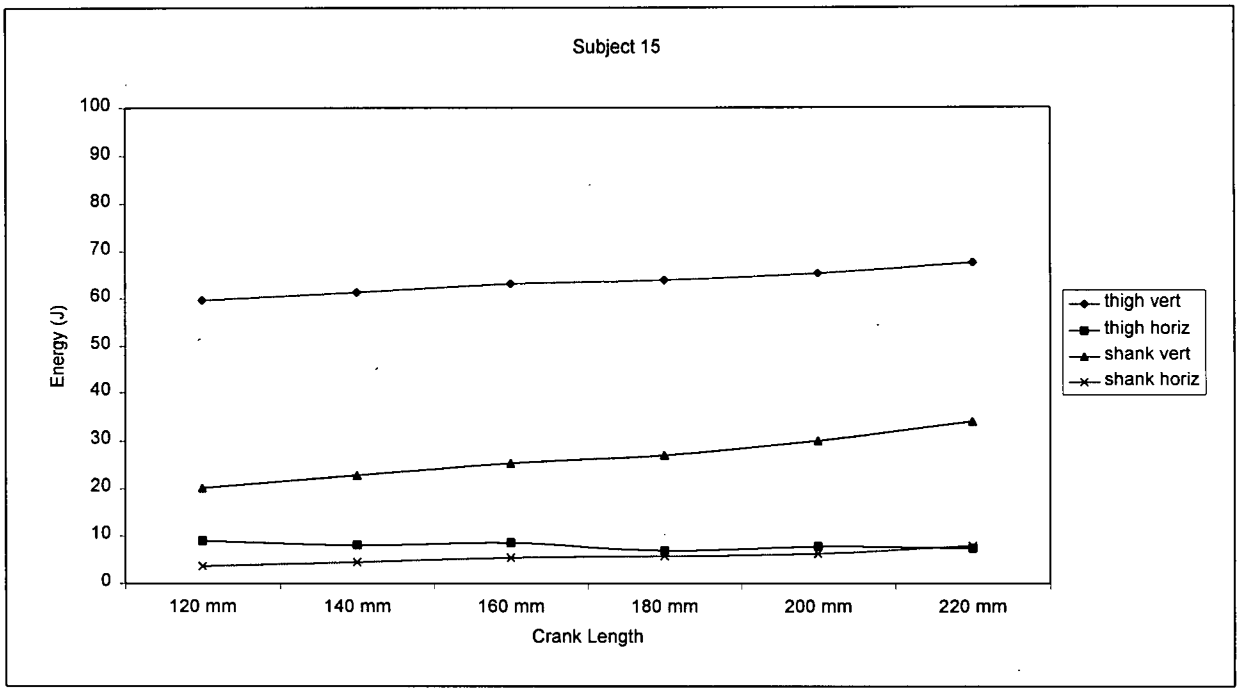
Subject 11
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz



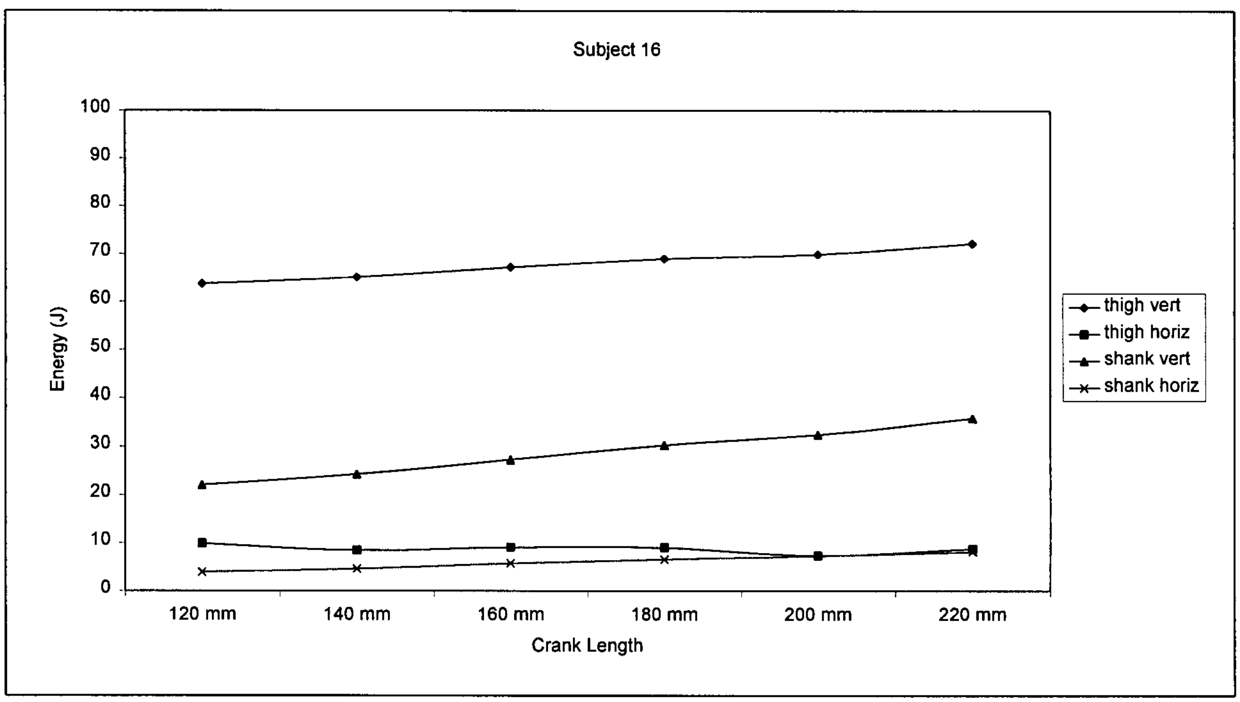
Subject 12
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz


Subject 13
Energy (J)
100
90
80
70
60
50
40
30
20
10
0
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz


Subject 14
Energy (J)
100
90
80
70
60
50
40
30
20
10
0
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz



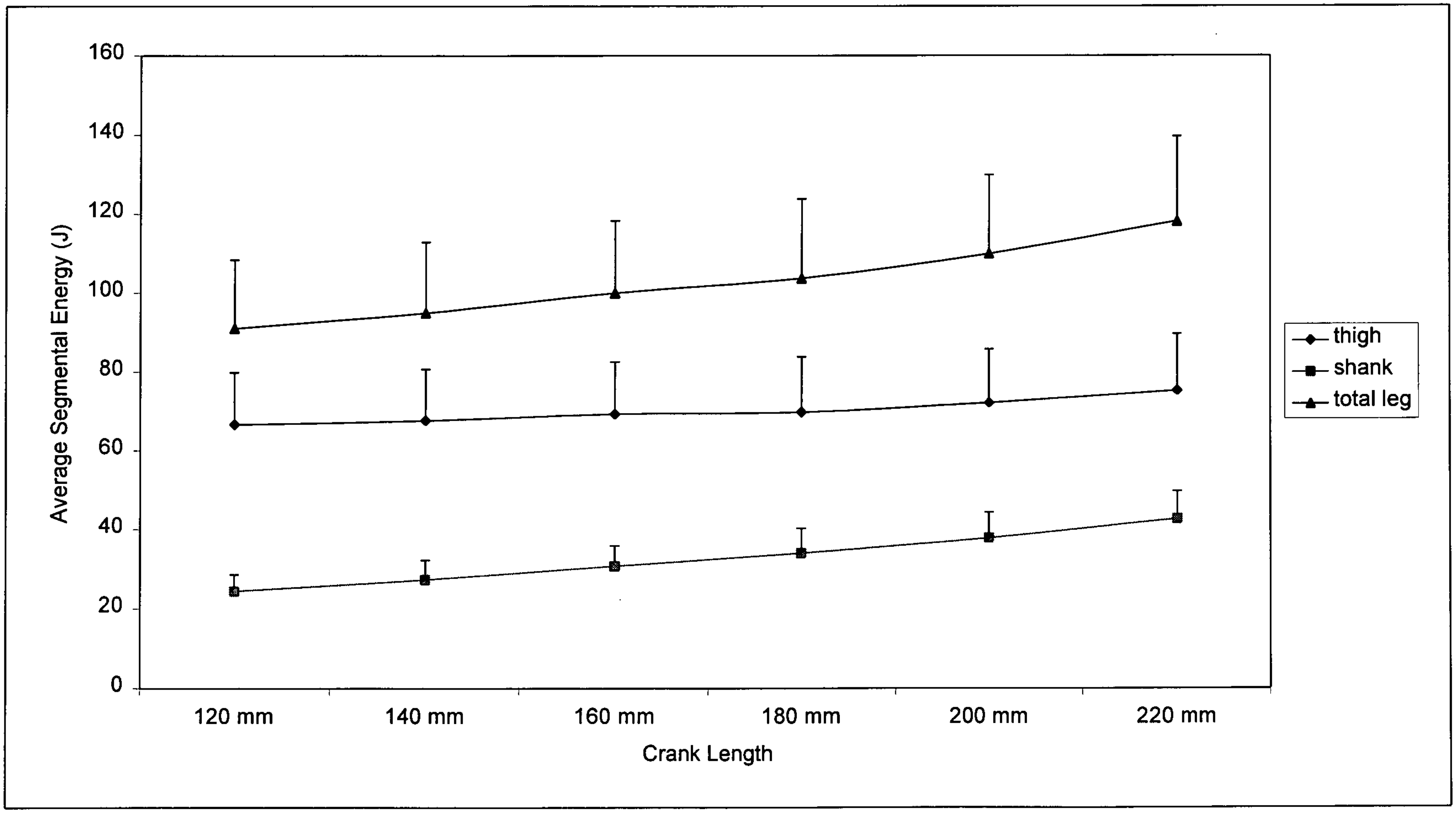
Subject 15
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz



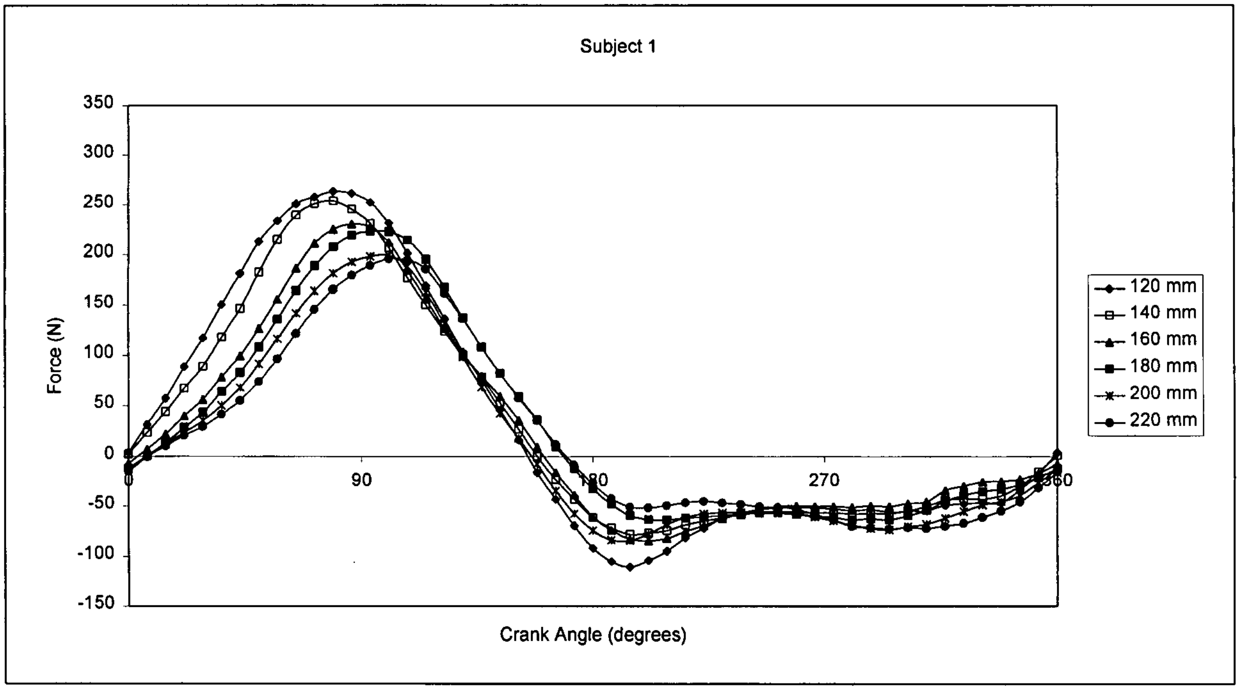
Subject 16
100
90
80
70
60
50
40
30
20
10
0
Energy (J)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm
Crank Length
thigh vert
thigh horiz
shank vert
shank horiz

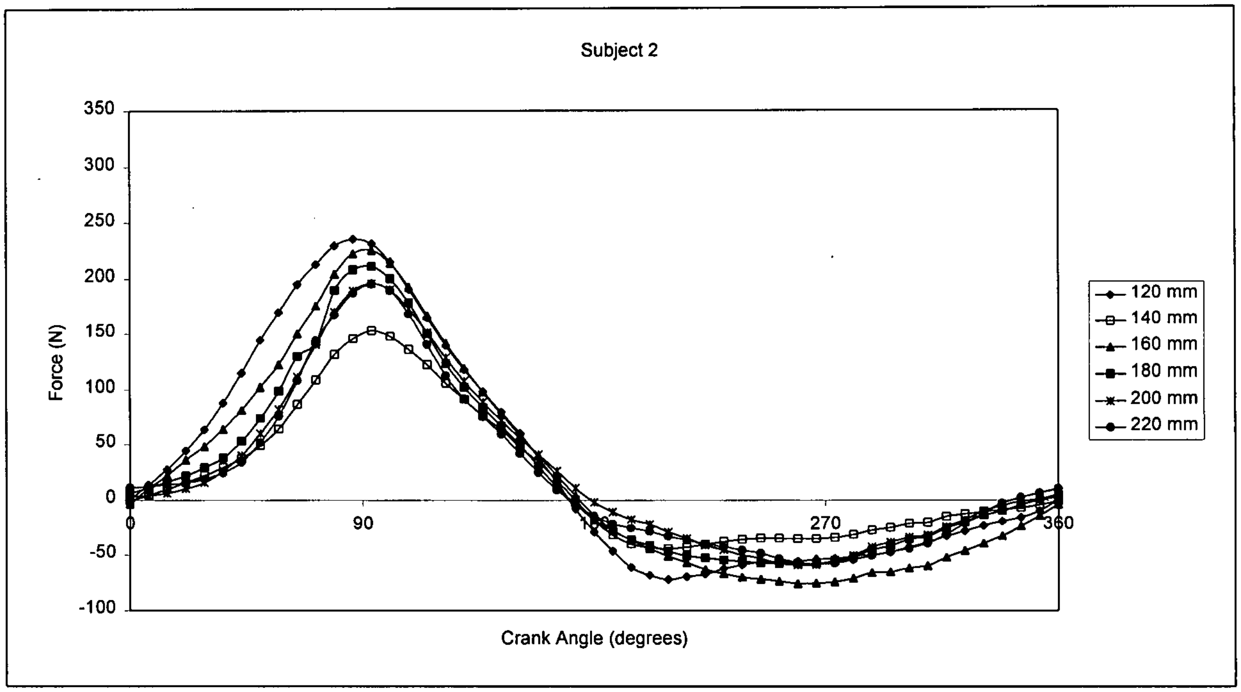
Appendix C5: Average Segmental Energy Response to Crank Length for all Subjects (+ 1 S.D. error bars)

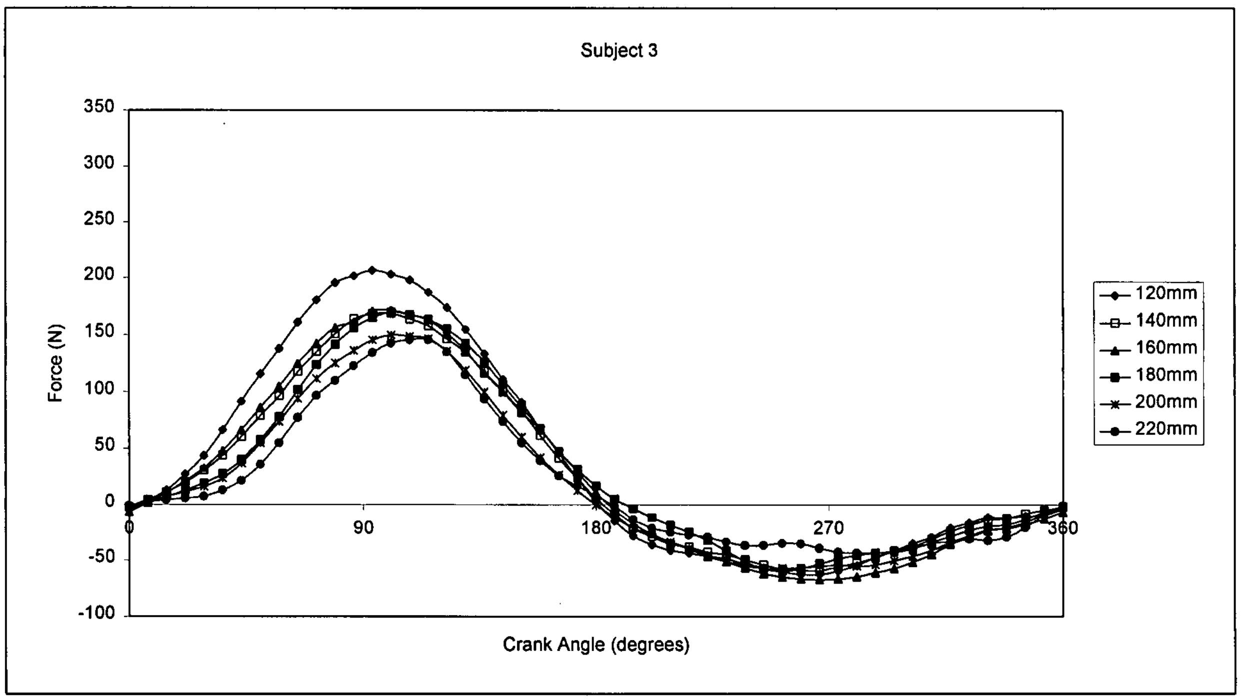
(note: data for 15 subjects were used to calculate averages for segmental energies at the 180 mm and 220 mm crank lengths)

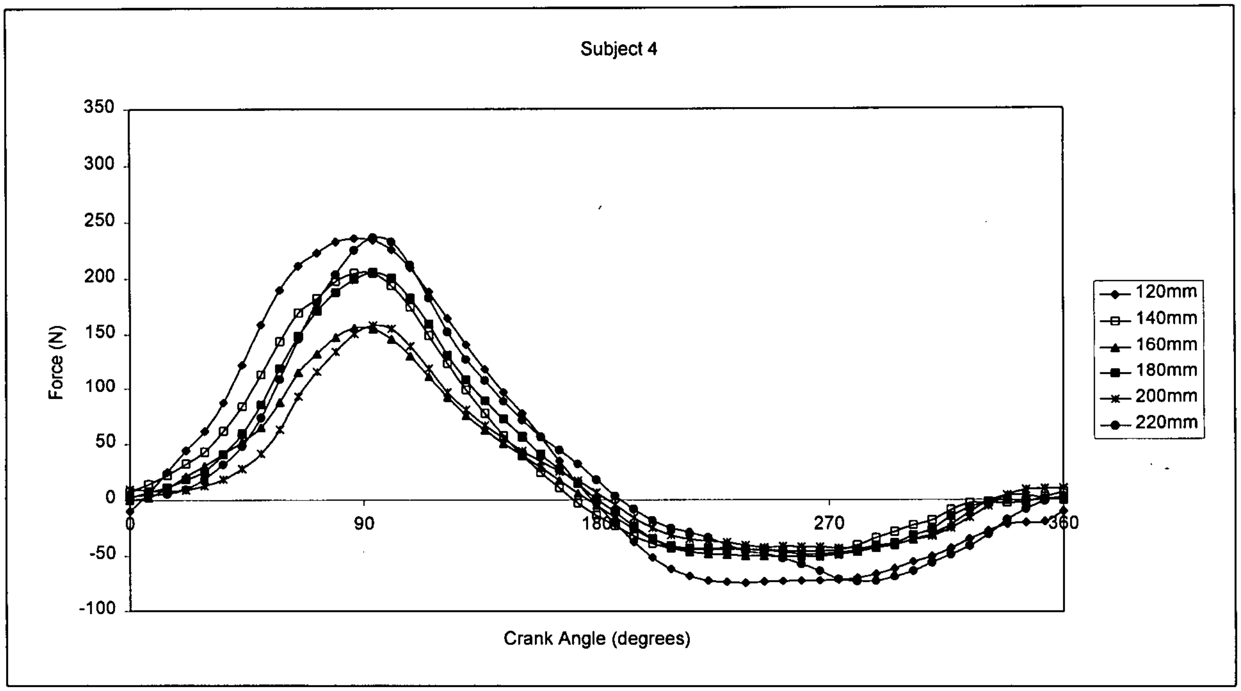


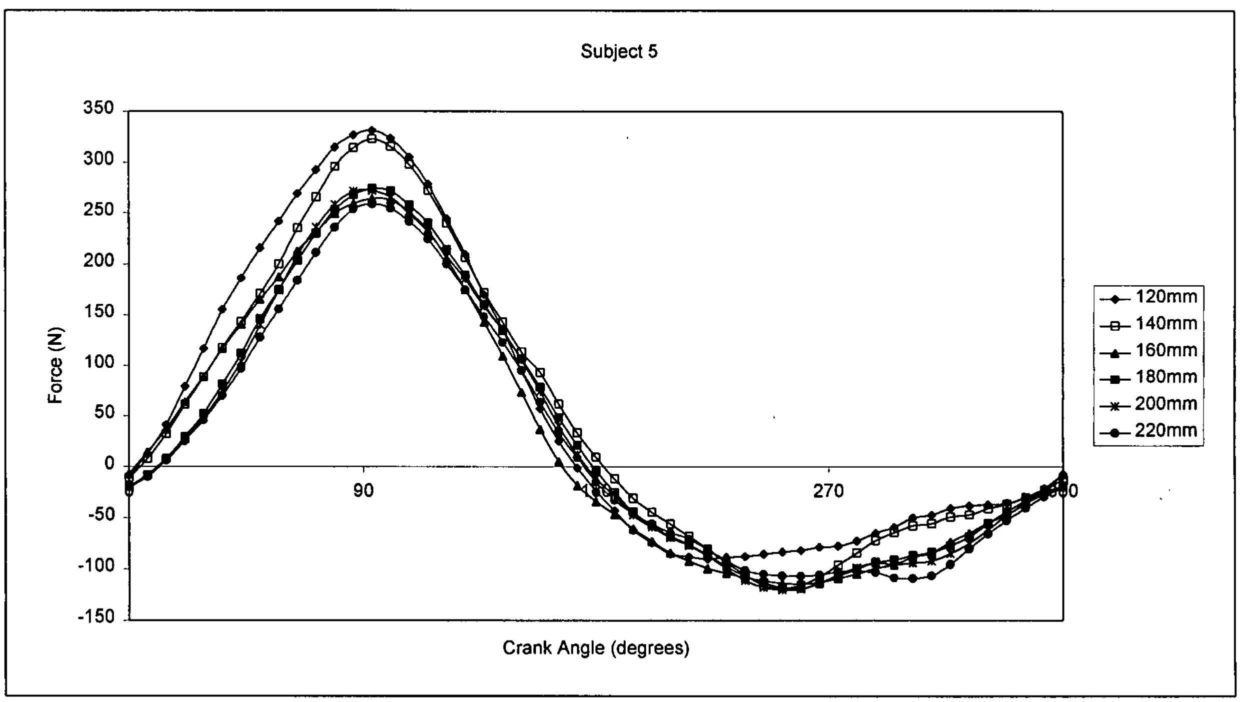
Appendix C6: Individual Effective Force Responses to Crank Length

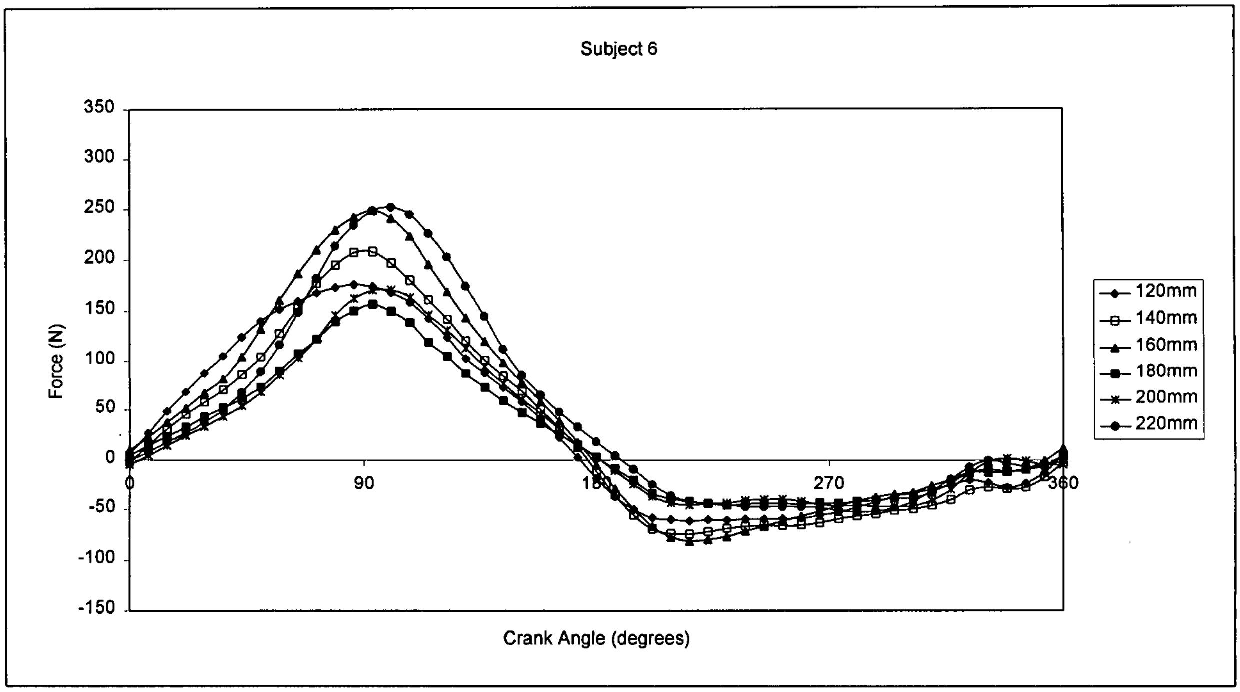


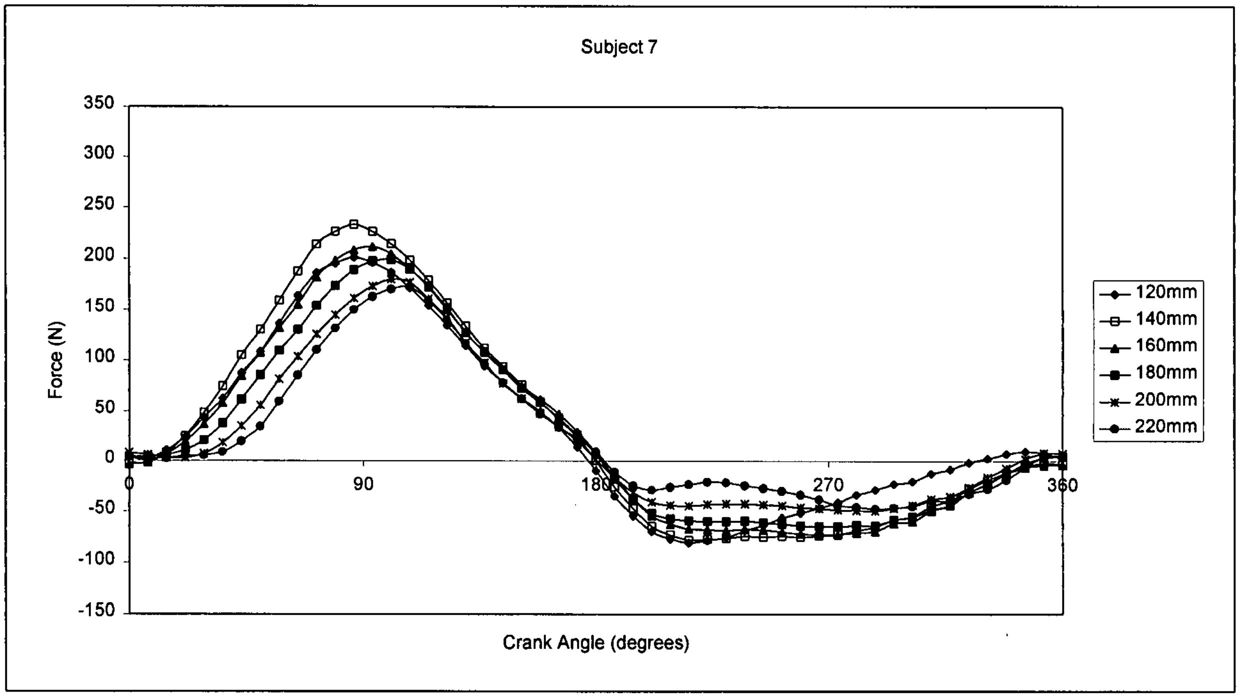

Subject 2
350
300
250
200
150
100
50
0
-50
-100
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

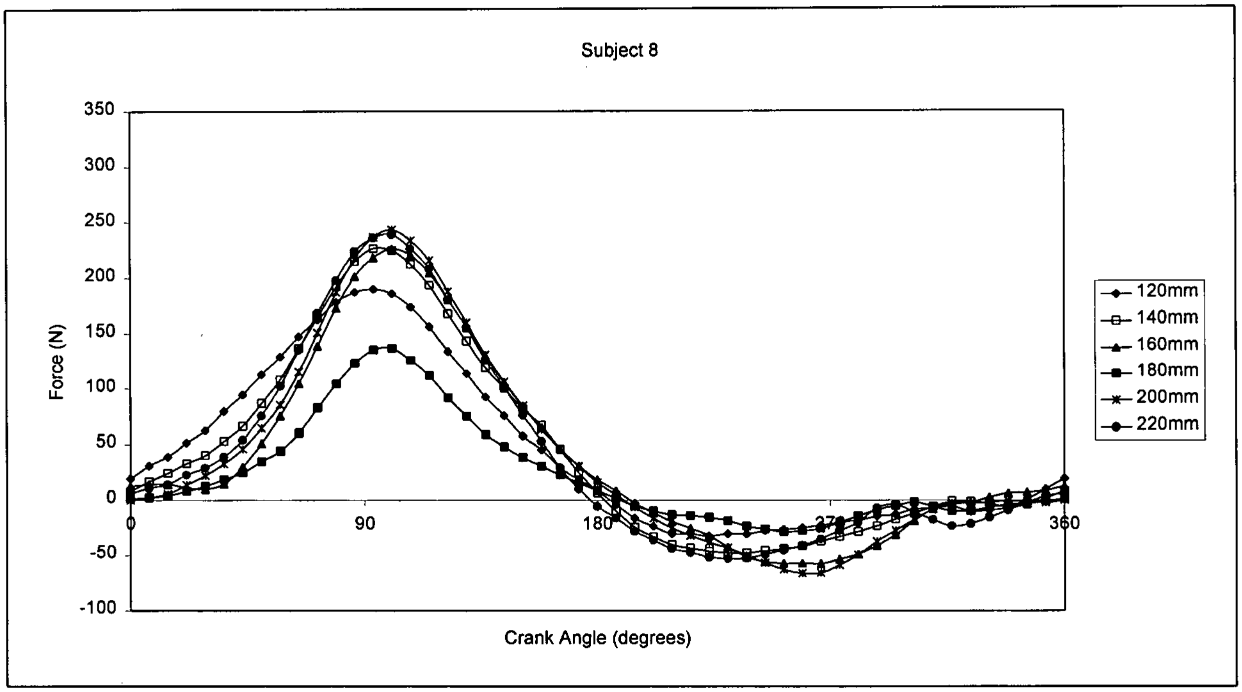

Subject 3
350
300
250
200
150
100
50
0
-50
-100
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

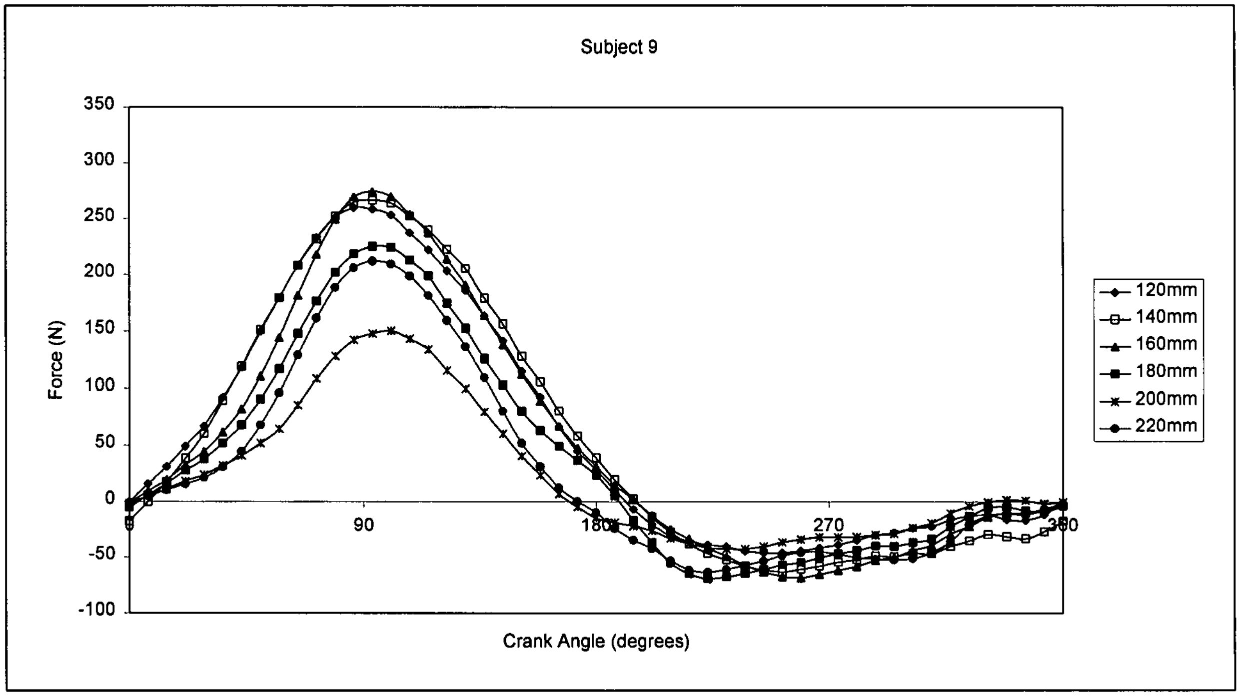

Subject 4
350
300
250
200
150
100
50
0
-50
-100
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

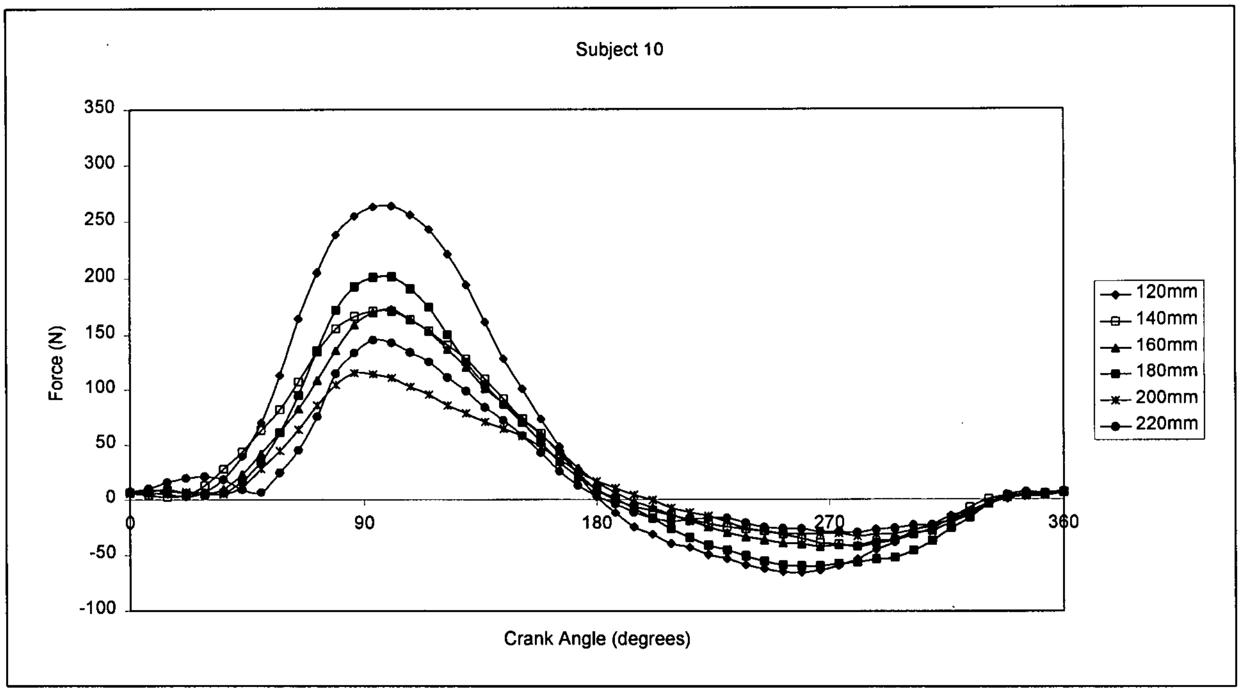

Subject 5
350
300
250
200
150
100
50
0
-50
-100
-150
Force (N)
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

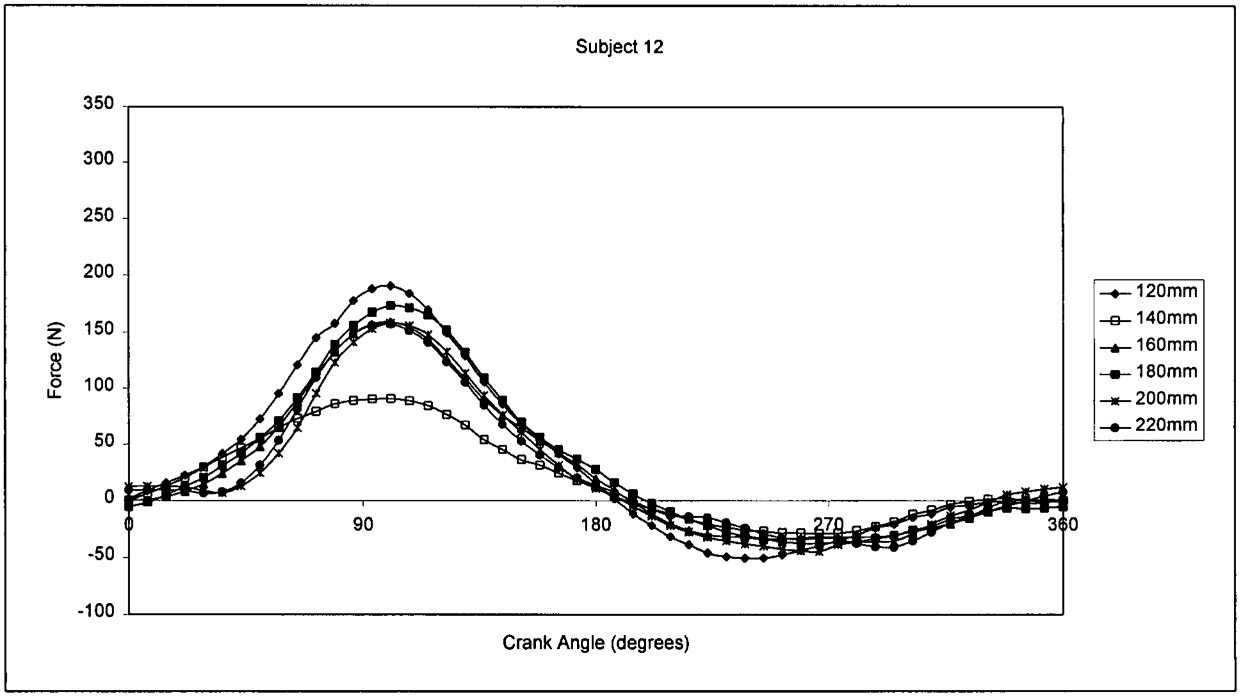

Subject 6
350
300
250
200
150
100
50
0
-50
-100
-150
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

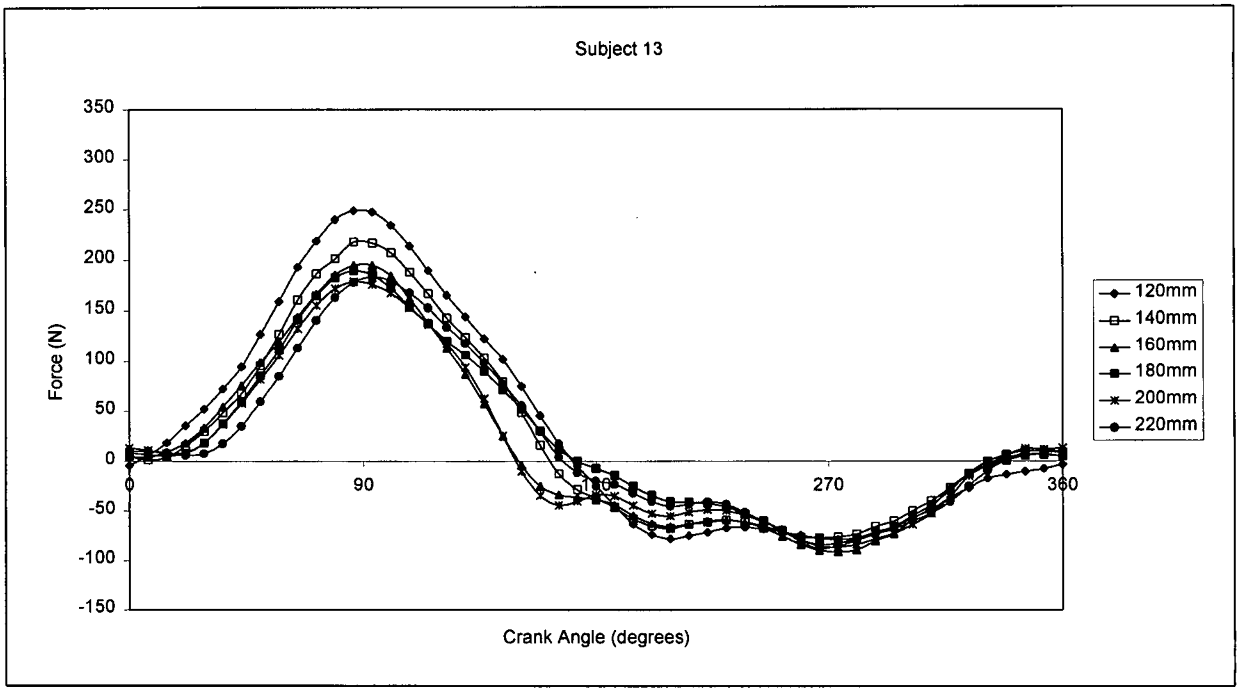

Subject 7
350
300
250
200
150
100
50
0
-50
-100
-150
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

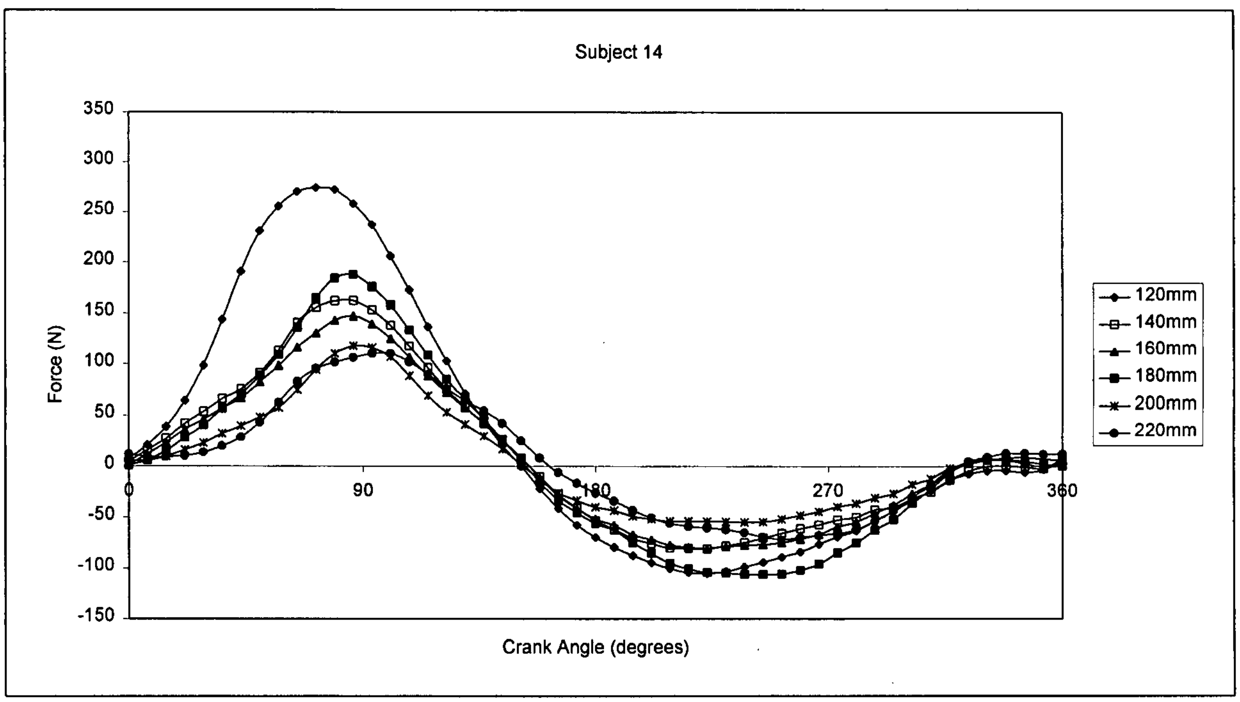

Subject 8
350
300
250
200
150
100
50
0
-50
-100
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

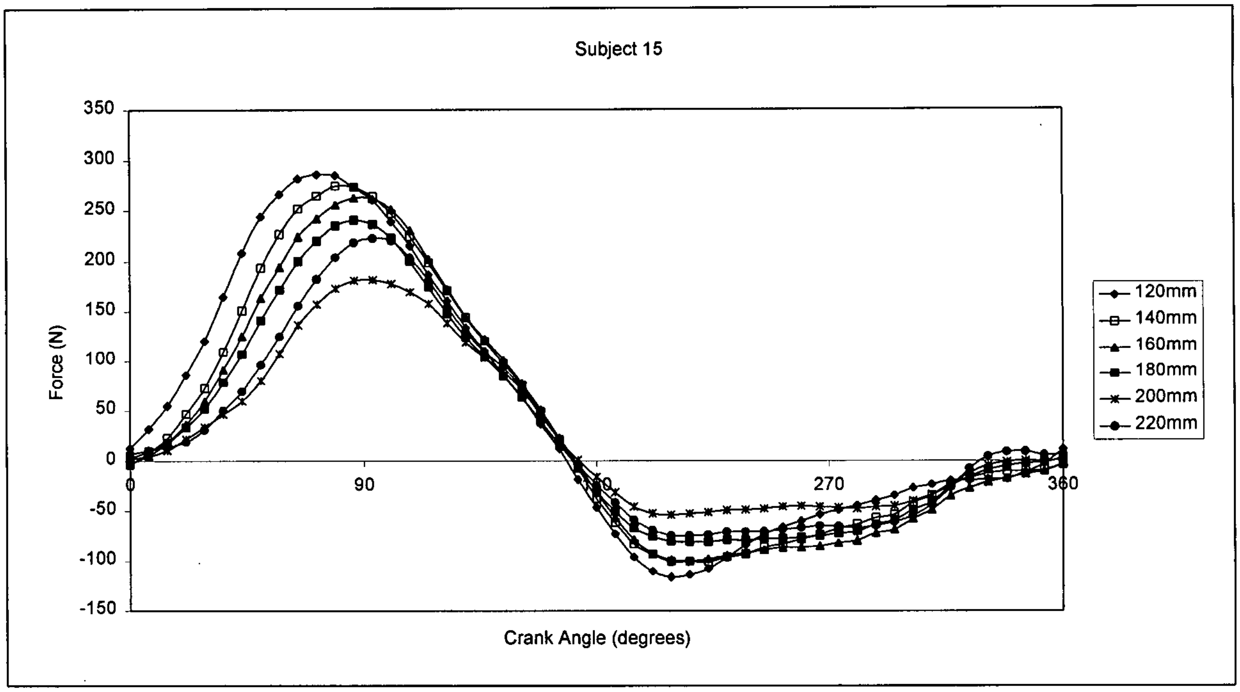

Subject 9
350
300
250
200
150
100
50
0
-50
-100
Force (N)
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

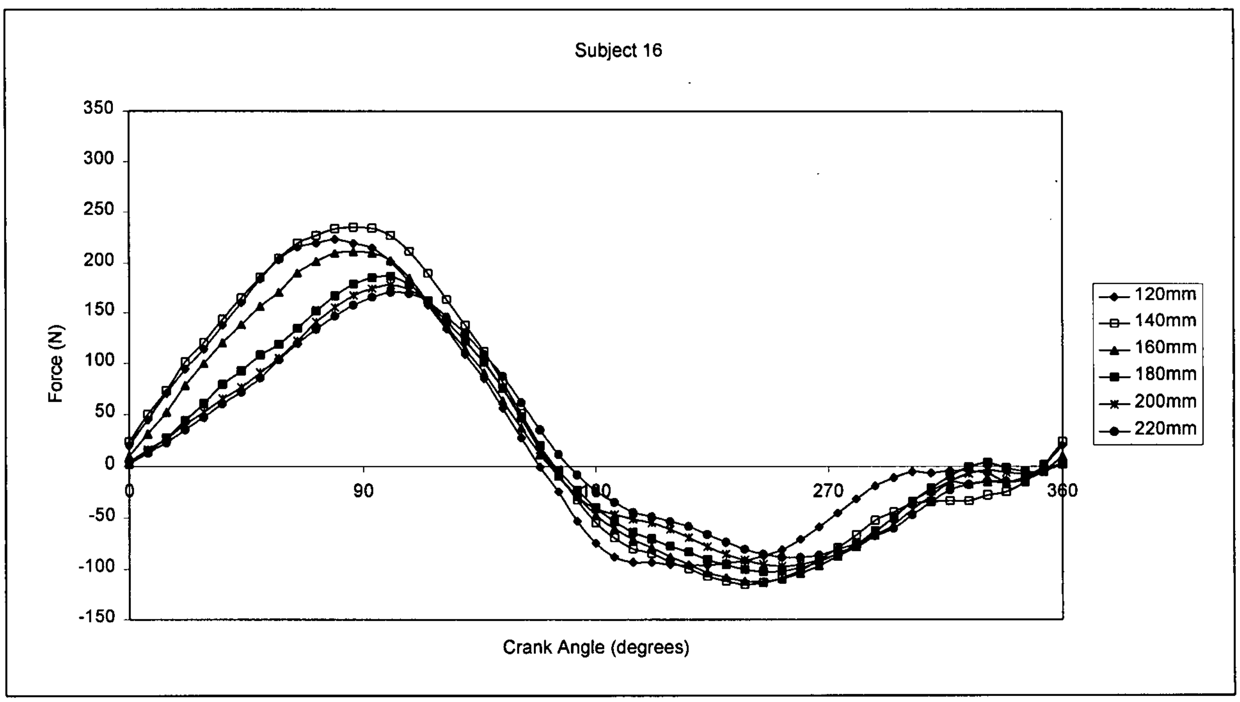

Subject 10
350
300
250
200
150
100
50
0
-50
-100
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm


Subject 12
350
300
250
200
150
100
50
0
-50
-100
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

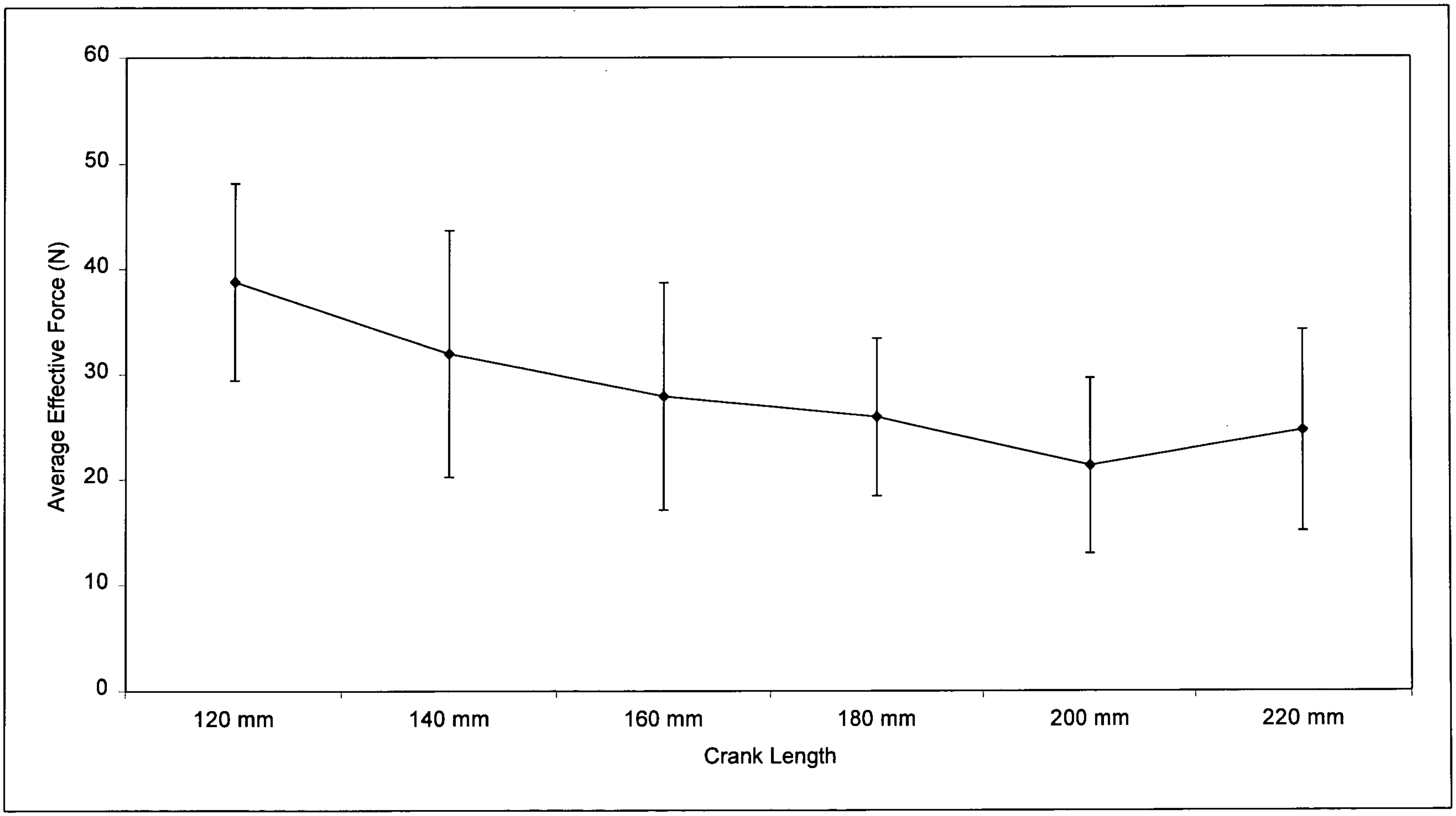

Subject 13
350
300
250
200
150
100
50
0
-50
-100
-150
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm


Subject 14
350
300
250
200
150
100
50
0
-50
-100
-150
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

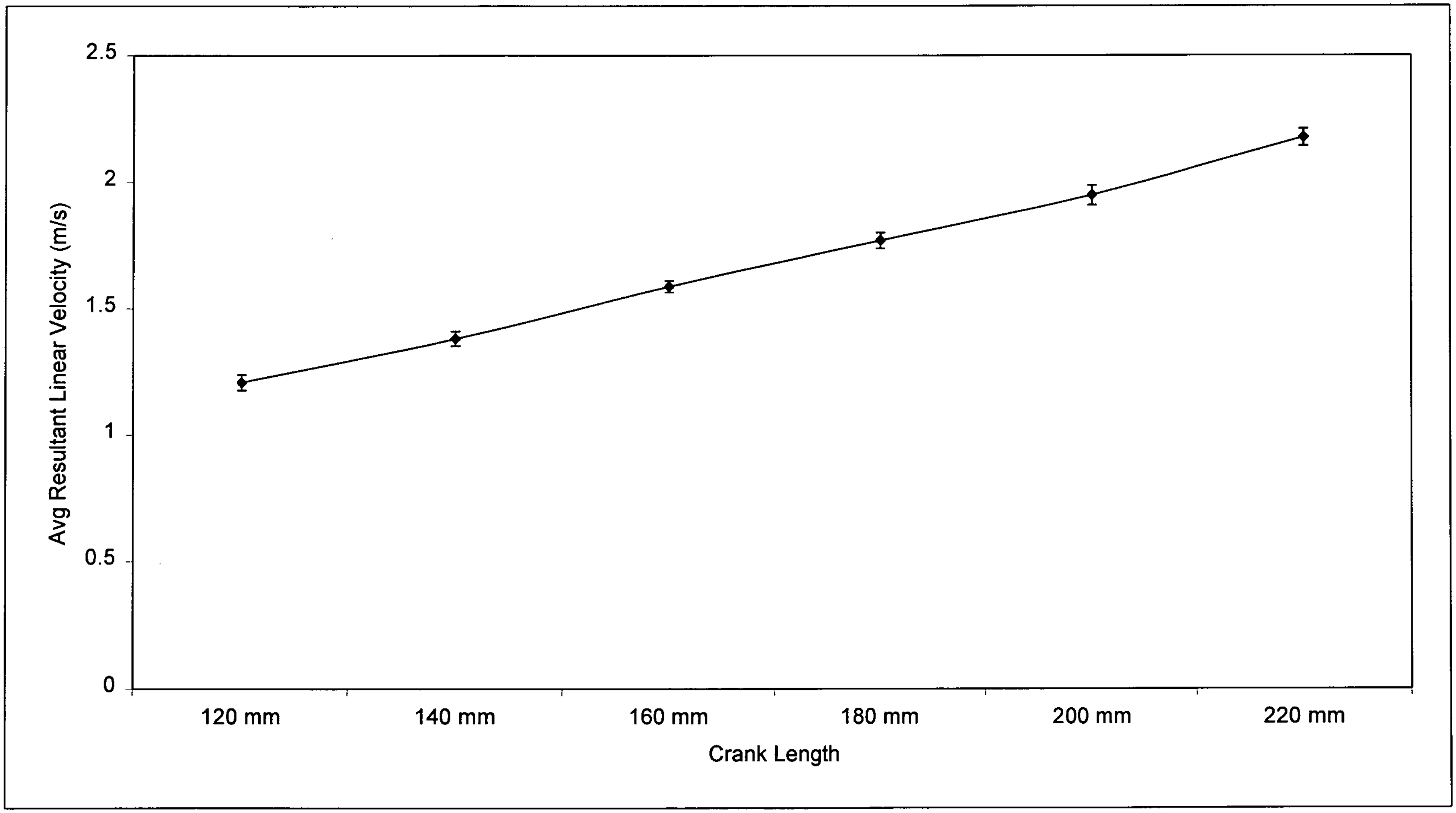

Subject 15
350
300
250
200
150
100
50
0
-50
-100
-150
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm


Subject 16
350
300
250
200
150
100
50
0
-50
-100
-150
Force (N)
0
90
180
270
360
Crank Angle (degrees)
120mm
140mm
160mm
180mm
200mm
220mm

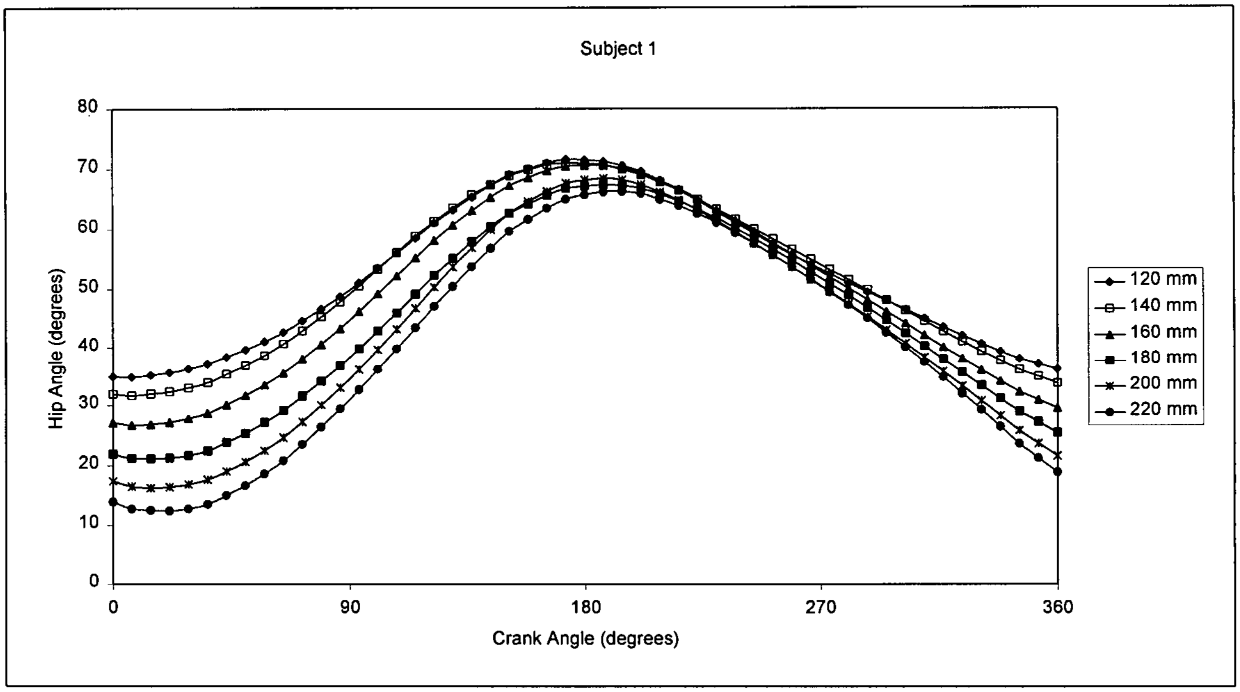
Appendix C7: Average Effective Force Response to Crank Length for all Subjects (+ 1 S.D. error bars)

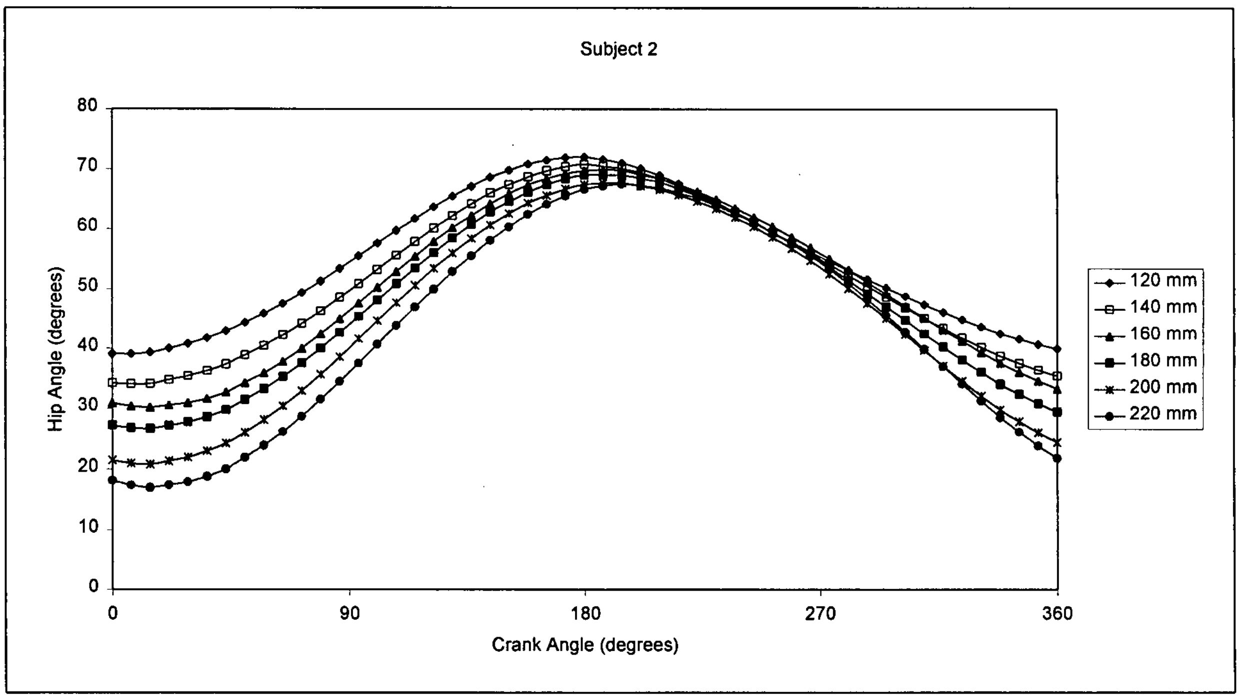


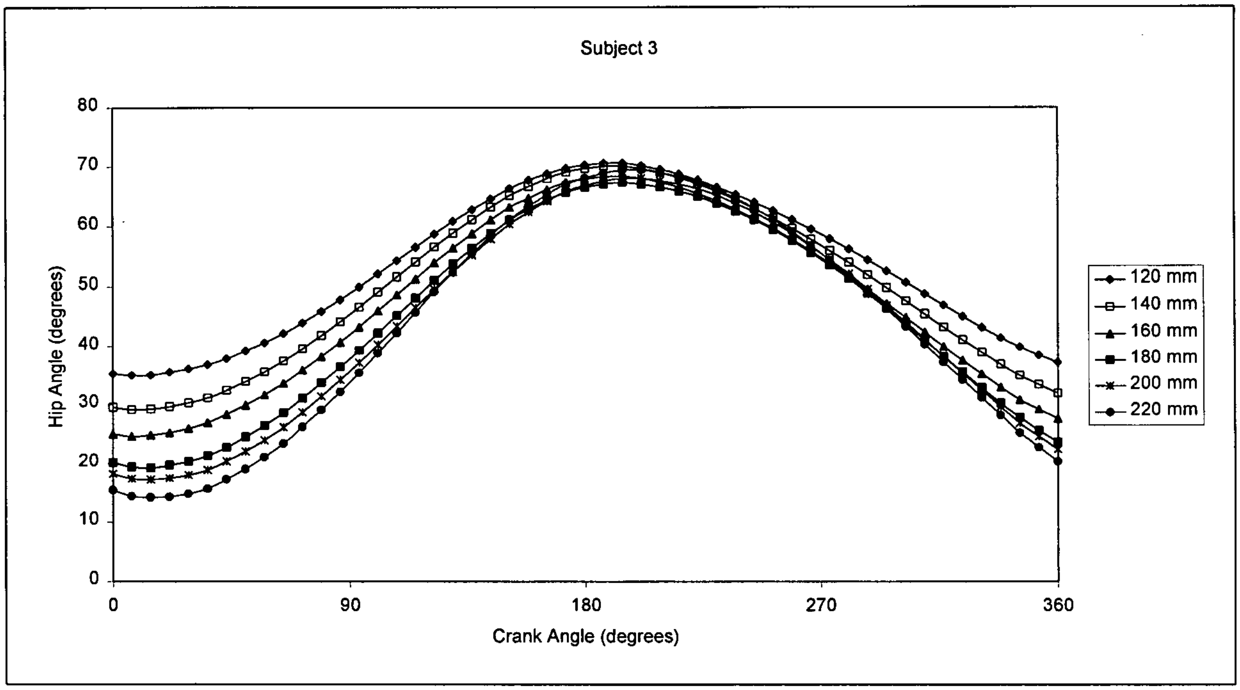
Appendix C8: Average Resultant Linear Velocity of the Foot Response to Crank Length for all Subjects (± 1 S.D. error bars)

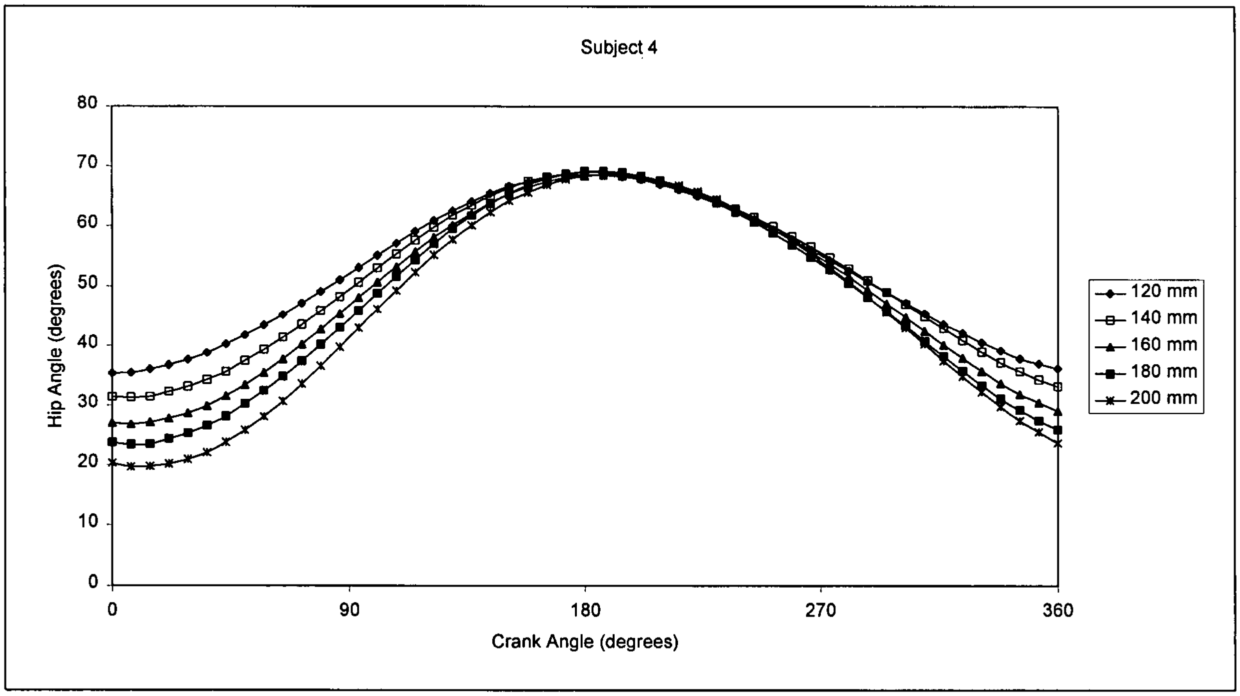


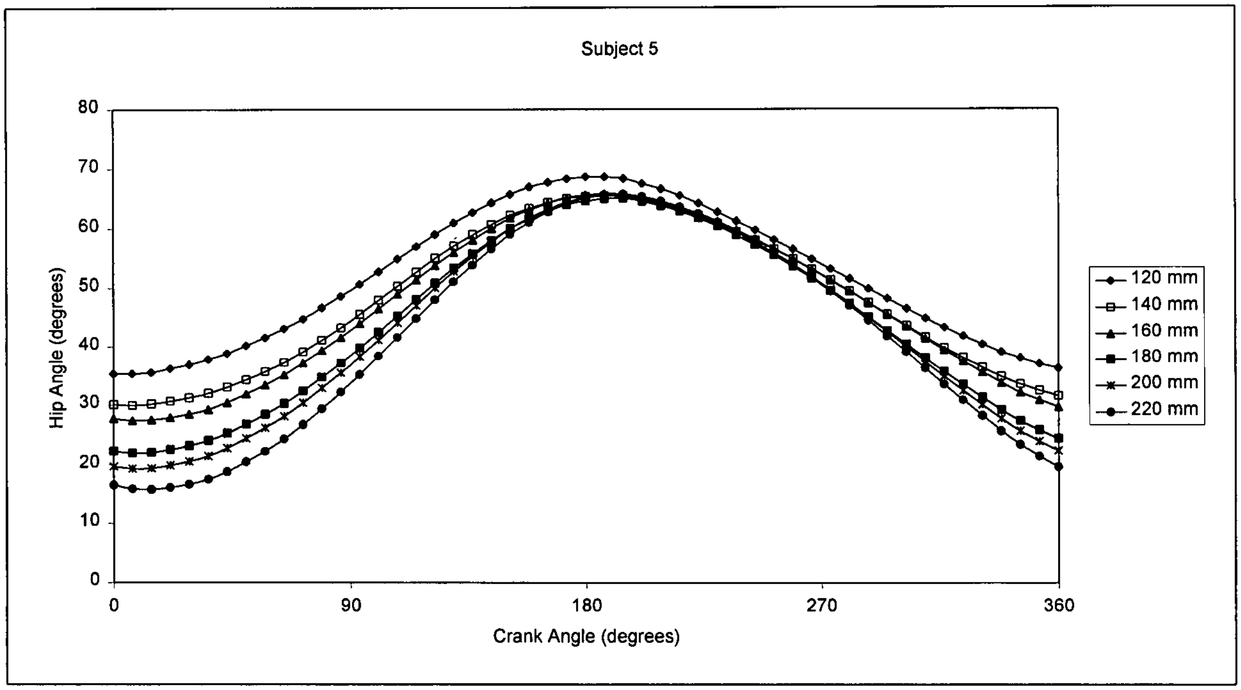
Appendix C9: Individual Hip Angle Responses to Crank Length

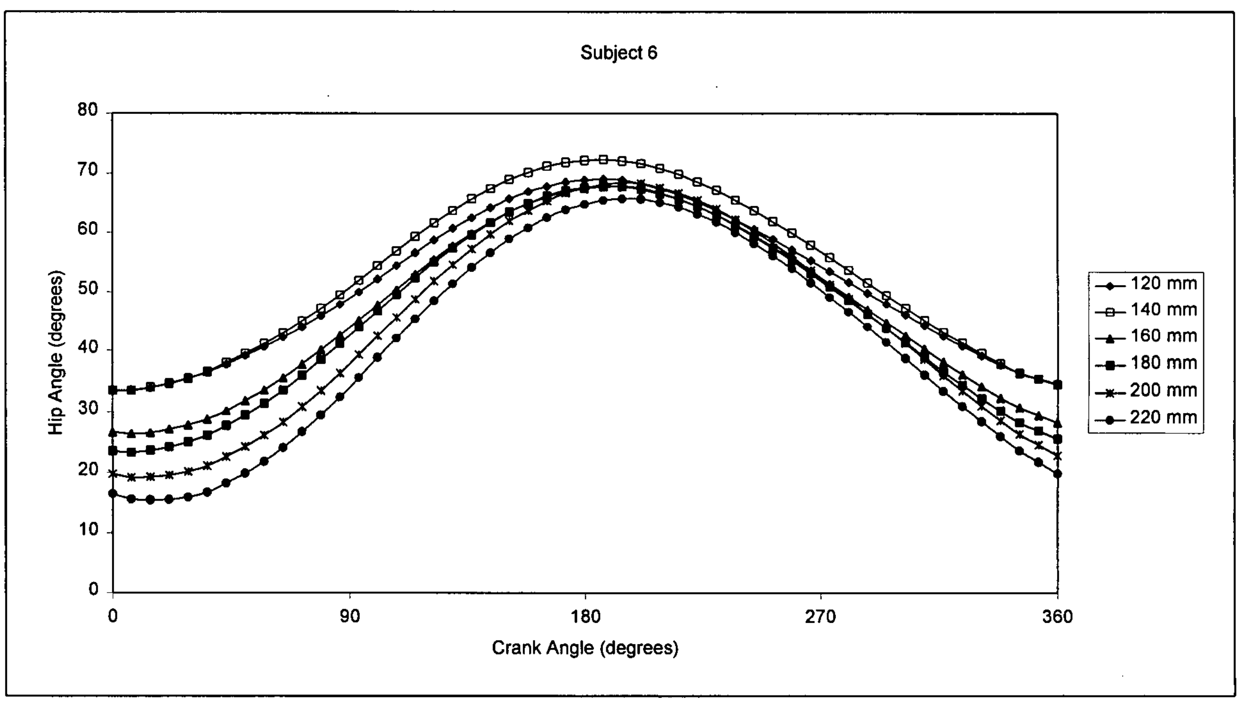

Subject 1
Hip Angle (degrees)
80
70
60
50
40
30
20
10
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

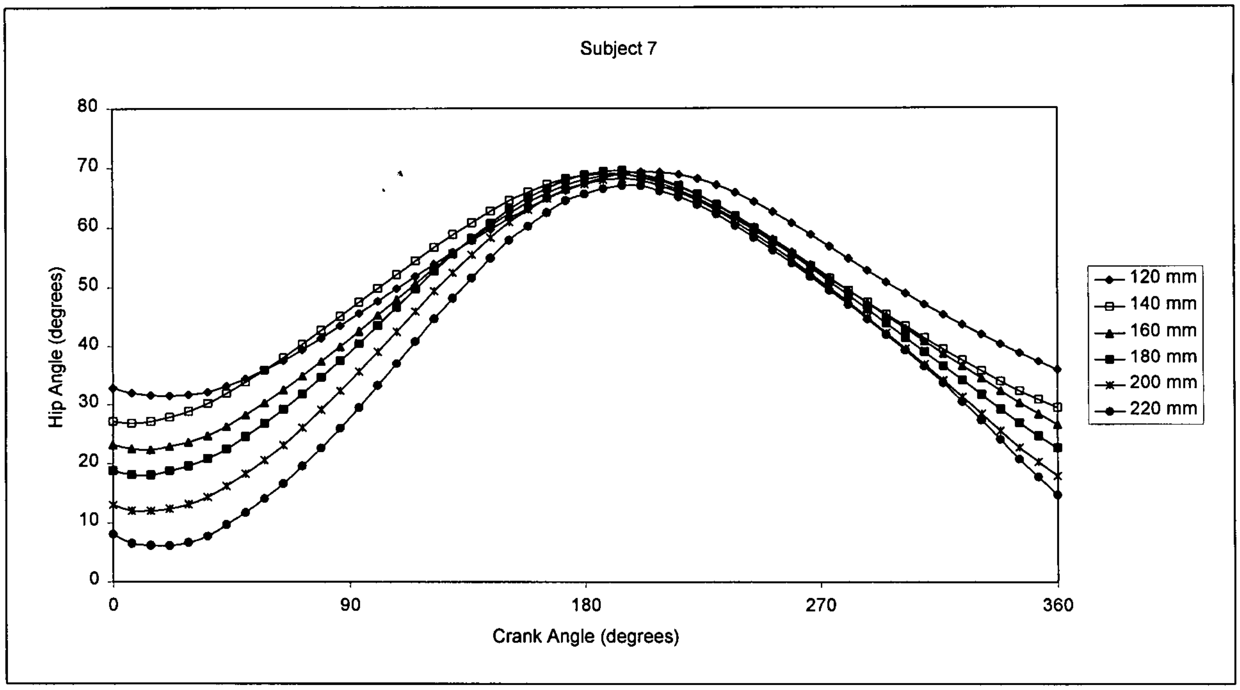

Subject 2
Hip Angle (degrees)
80
70
60
50
40
30
20
10
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

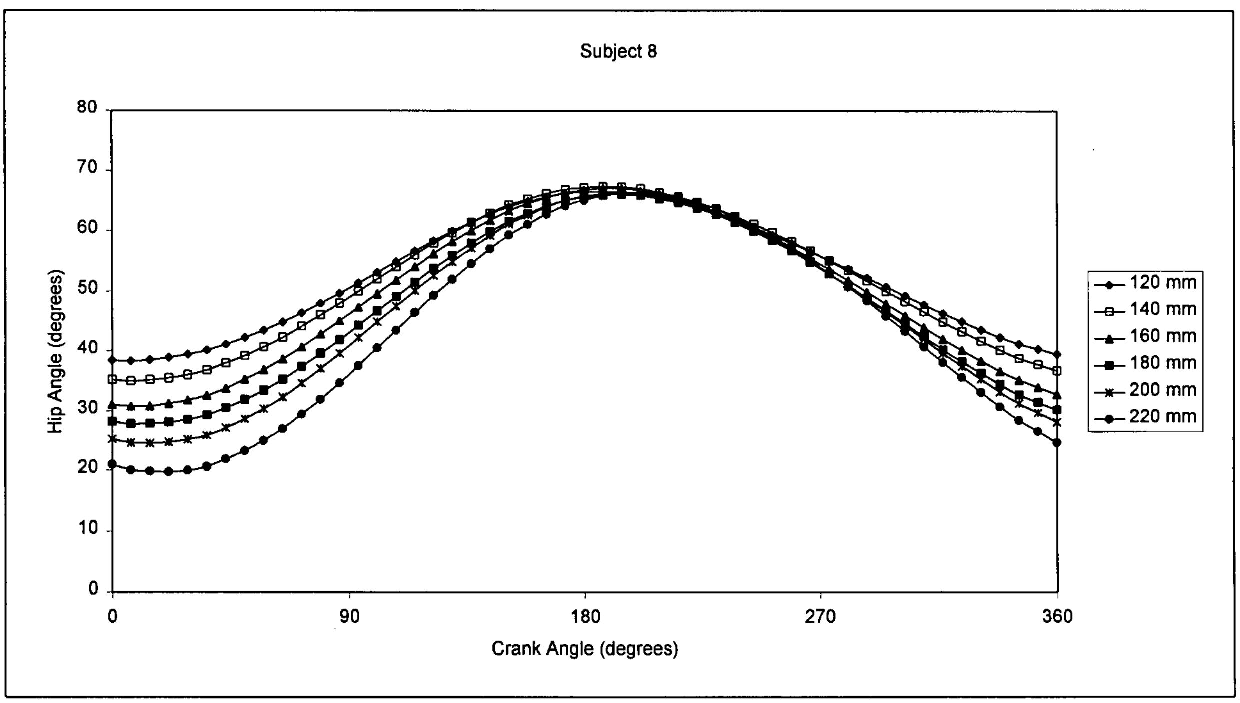

Subject 3
Hip Angle (degrees)
Crank Angle (degrees)
0
10
20
30
40
50
60
70
80
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

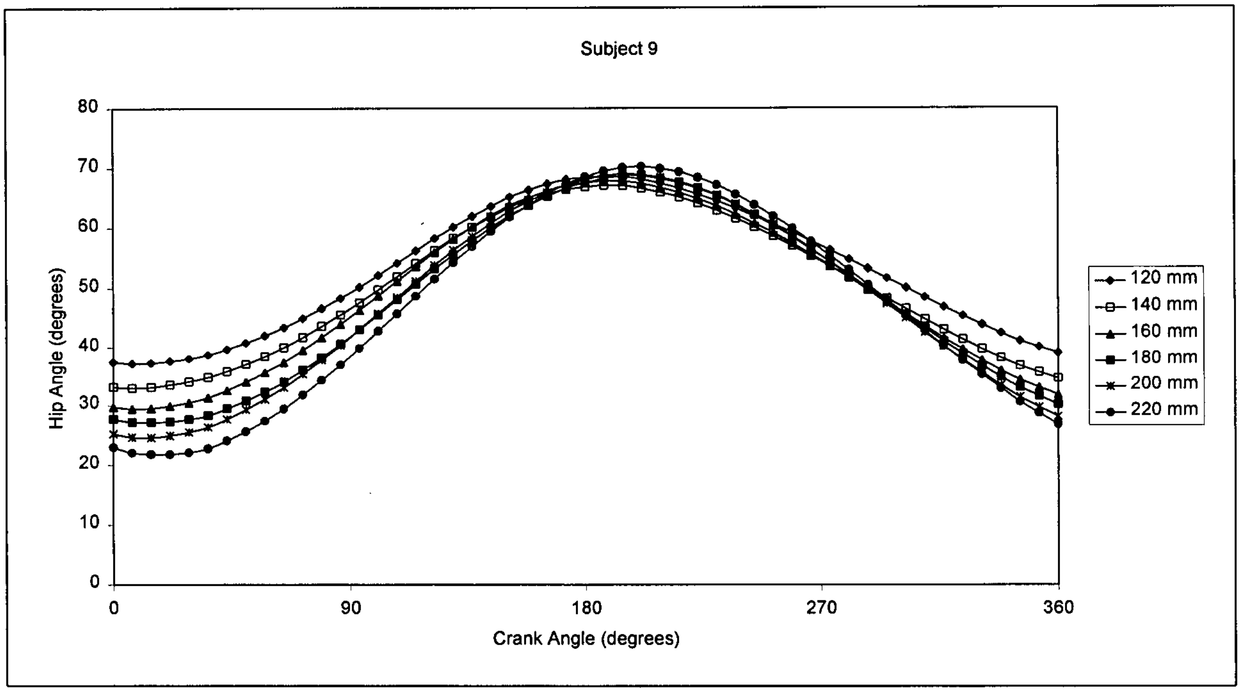

Subject 4
Hip Angle (degrees)
Crank Angle (degrees)
0
10
20
30
40
50
60
70
80
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm

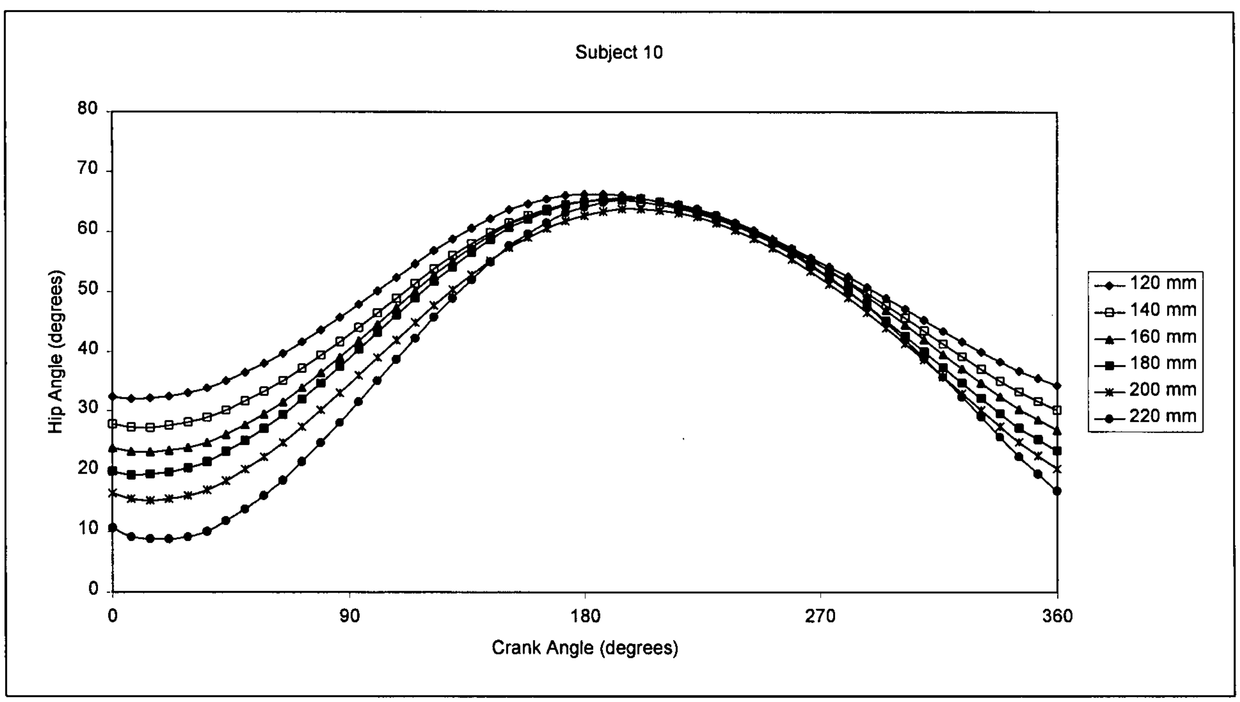

Subject 5
Hip Angle (degrees)
Crank Angle (degrees)
0
10
20
30
40
50
60
70
80
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

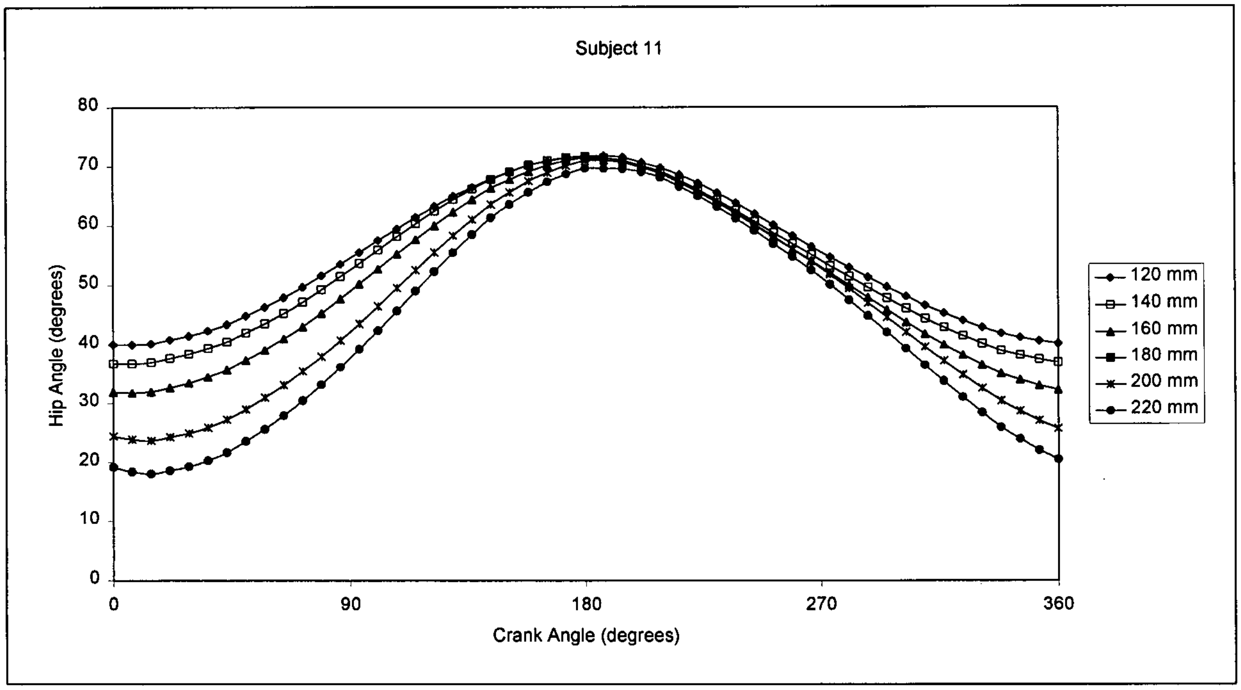

Subject 6
Hip Angle (degrees)
Crank Angle (degrees)
0
10
20
30
40
50
60
70
80
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

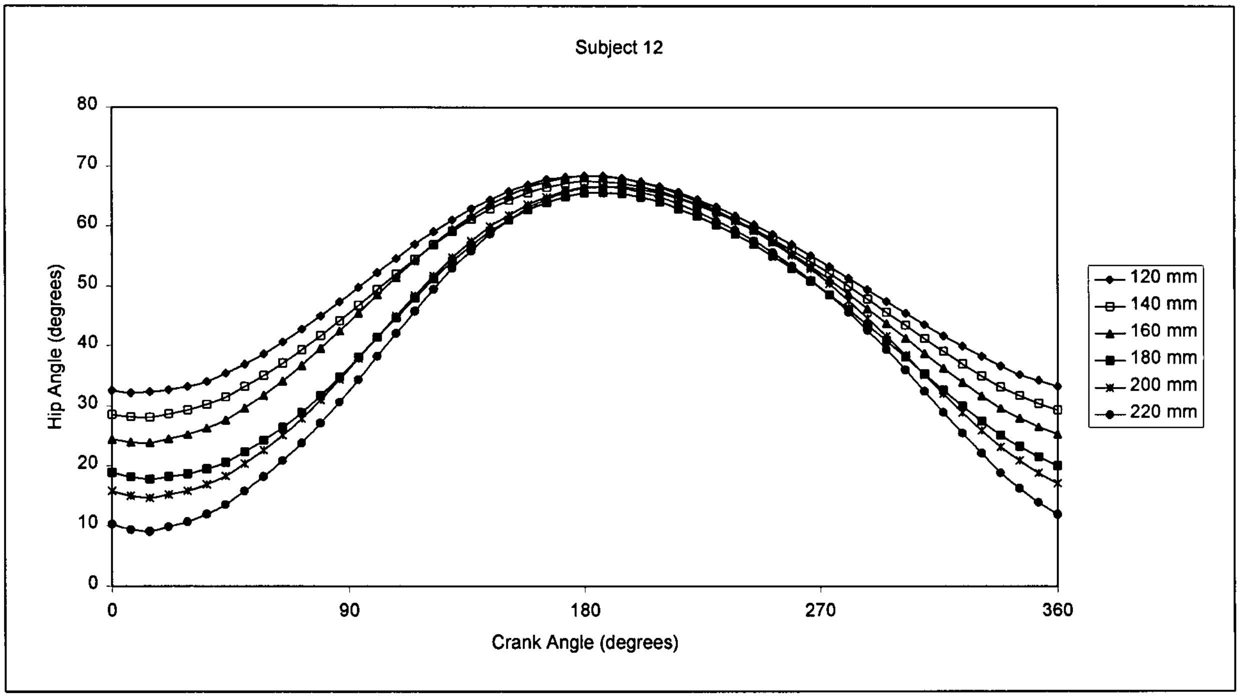

Subject 7
Hip Angle (degrees)
80
70
60
50
40
30
20
10
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

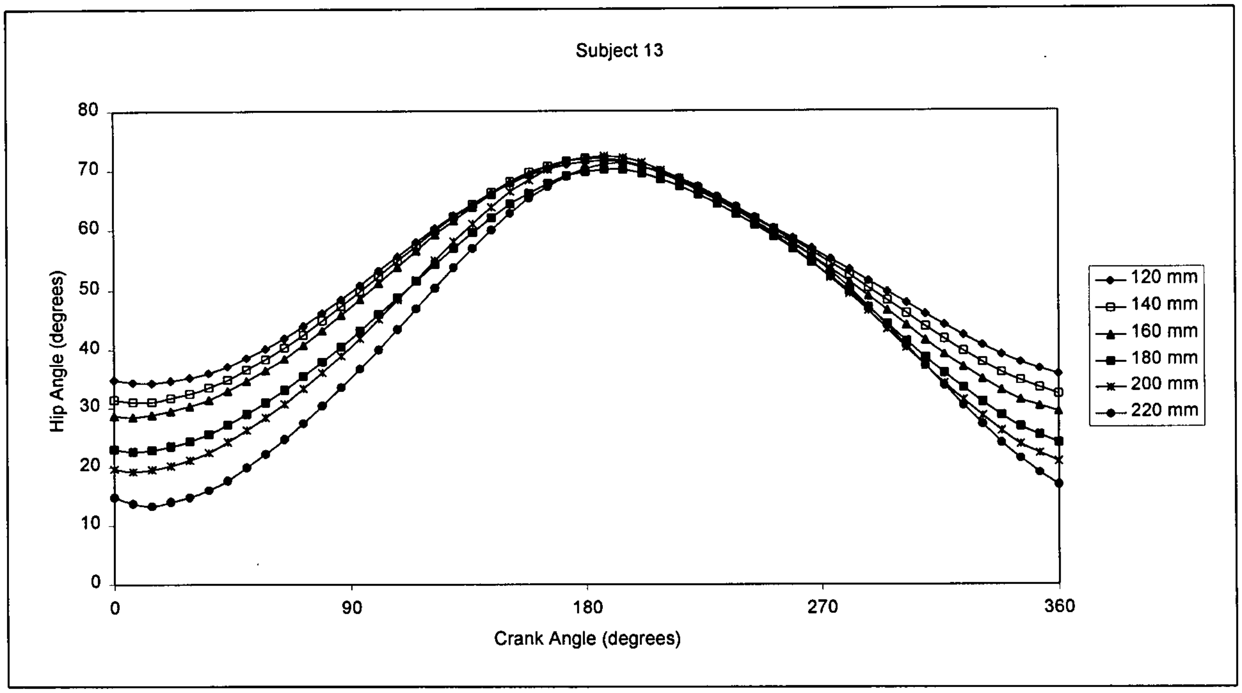

Subject 8
Hip Angle (degrees)
80
70
60
50
40
30
20
10
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

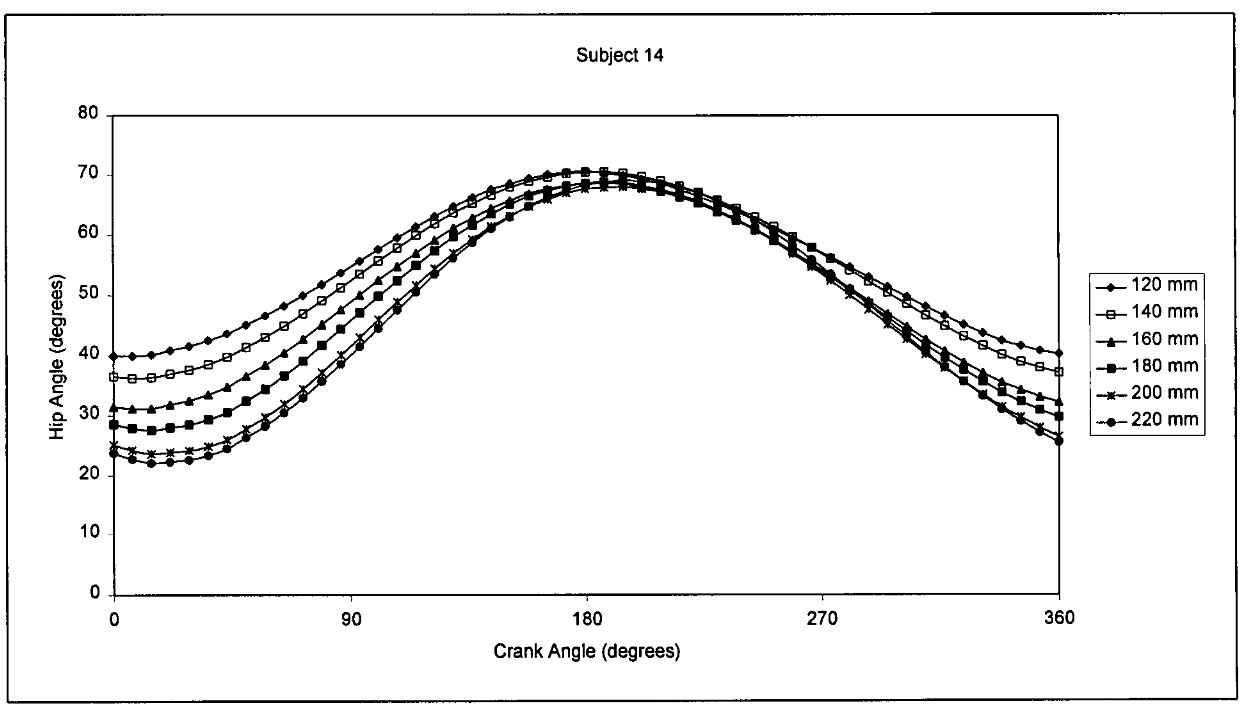

Subject 9
Hip Angle (degrees)
Crank Angle (degrees)
0
10
20
30
40
50
60
70
80
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

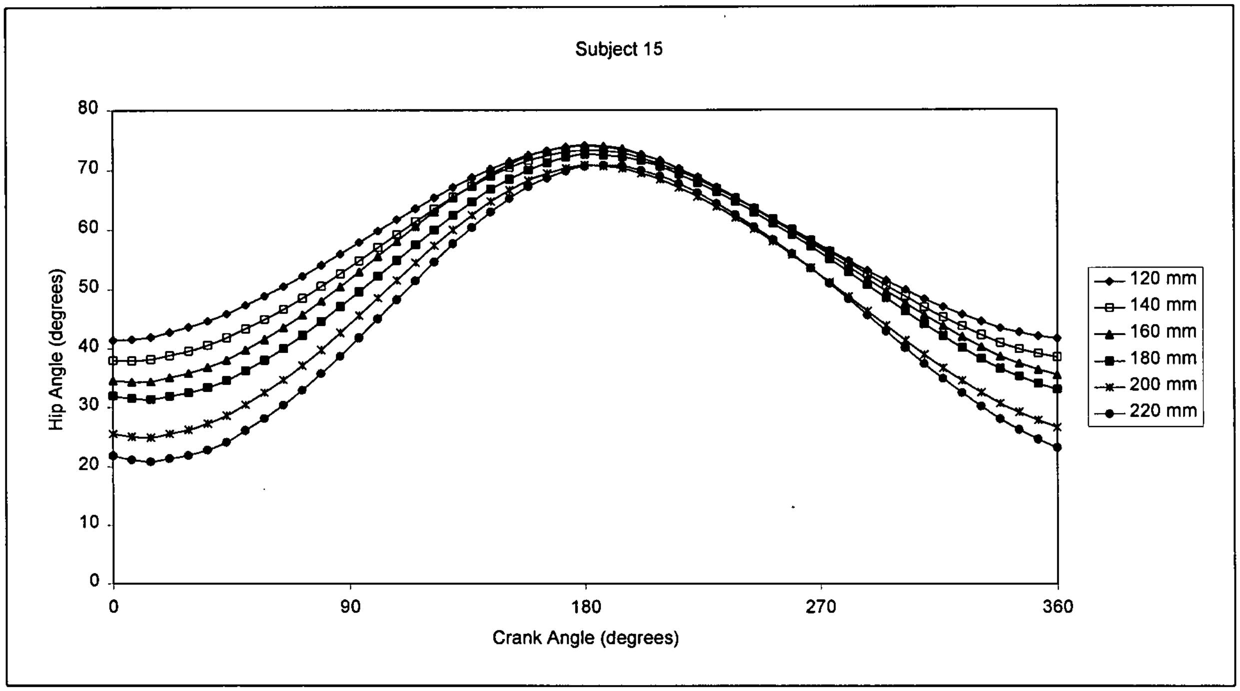

Subject 10
Hip Angle (degrees)
Crank Angle (degrees)
0
10
20
30
40
50
60
70
80
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 11
80
70
60
50
40
30
20
10
0
Hip Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

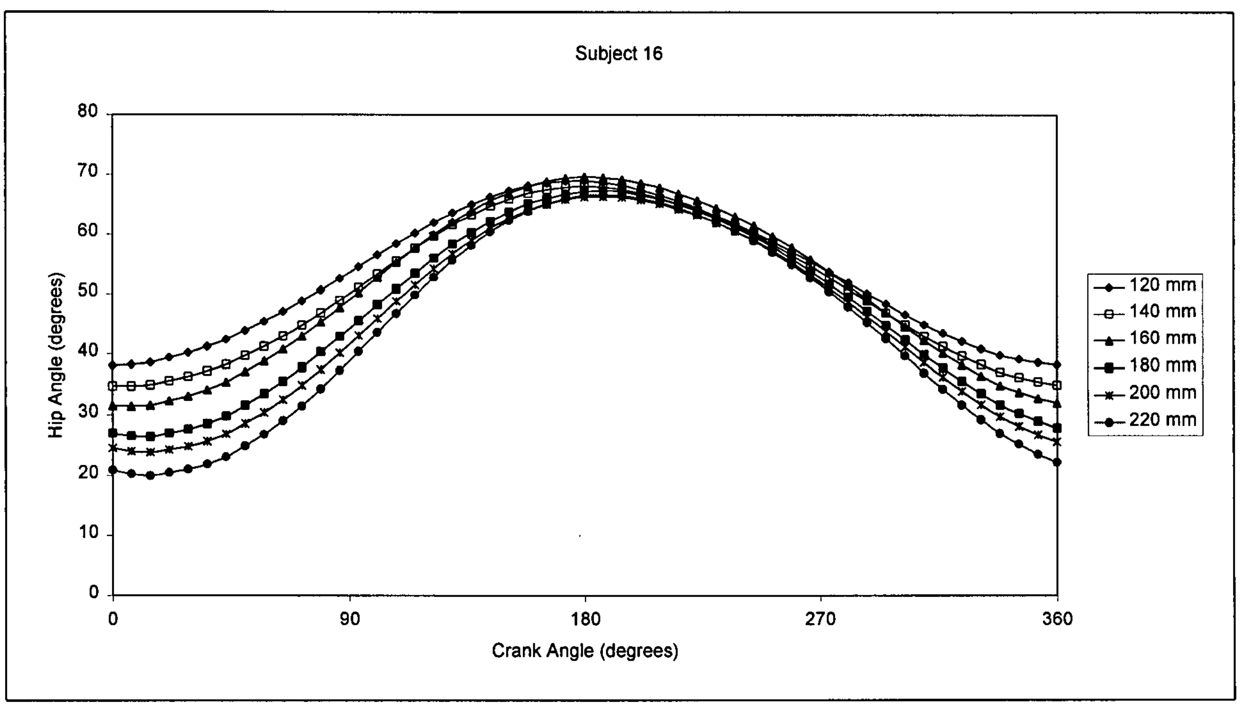

Subject 12
80
70
60
50
40
30
20
10
0
Hip Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 13
80
70
60
50
40
30
20
10
0
Hip Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 14
80
70
60
50
40
30
20
10
0
Hip Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

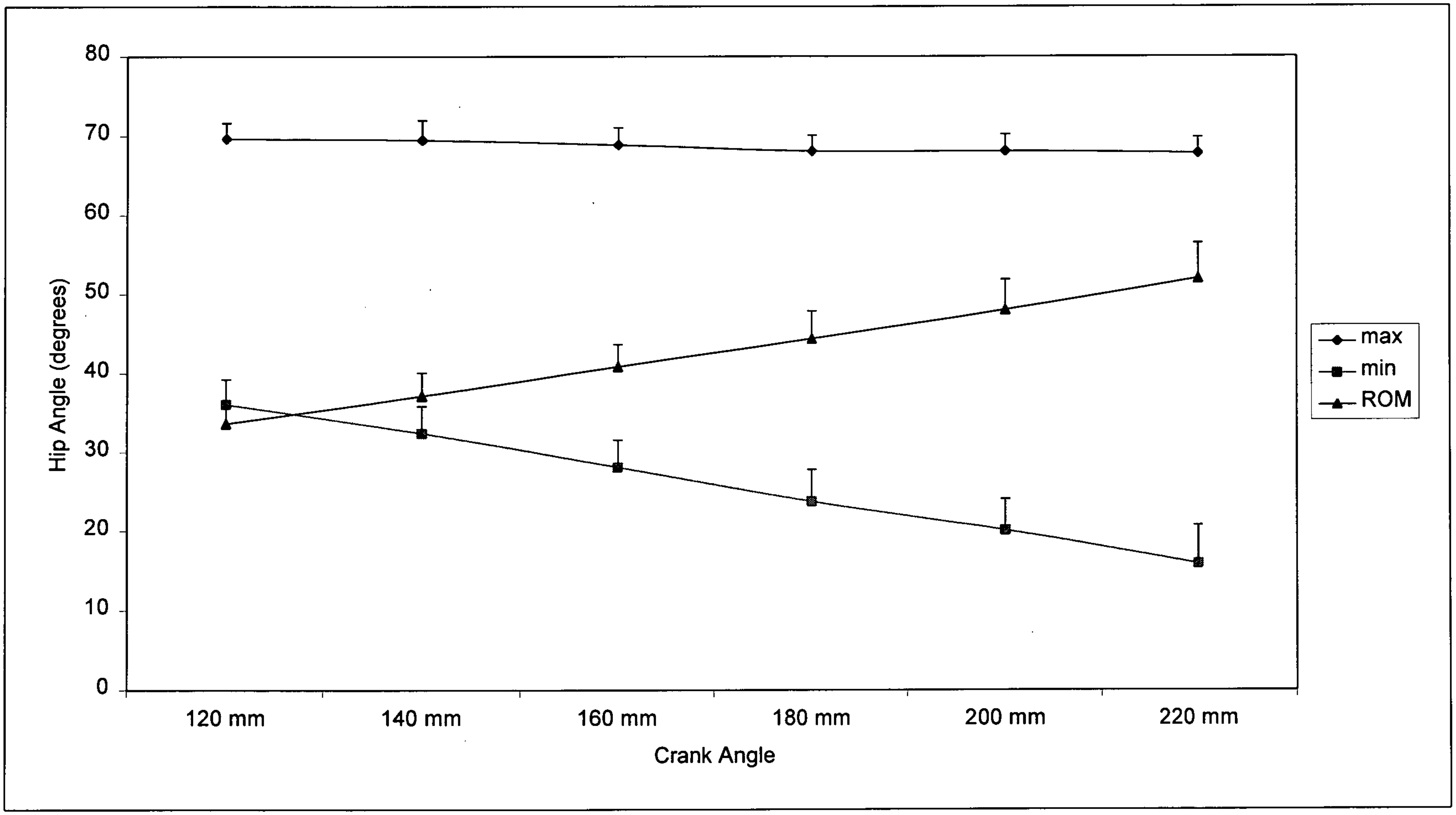


Subject 15
Hip Angle (degrees)
80
70
60
50
40
30
20
10
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

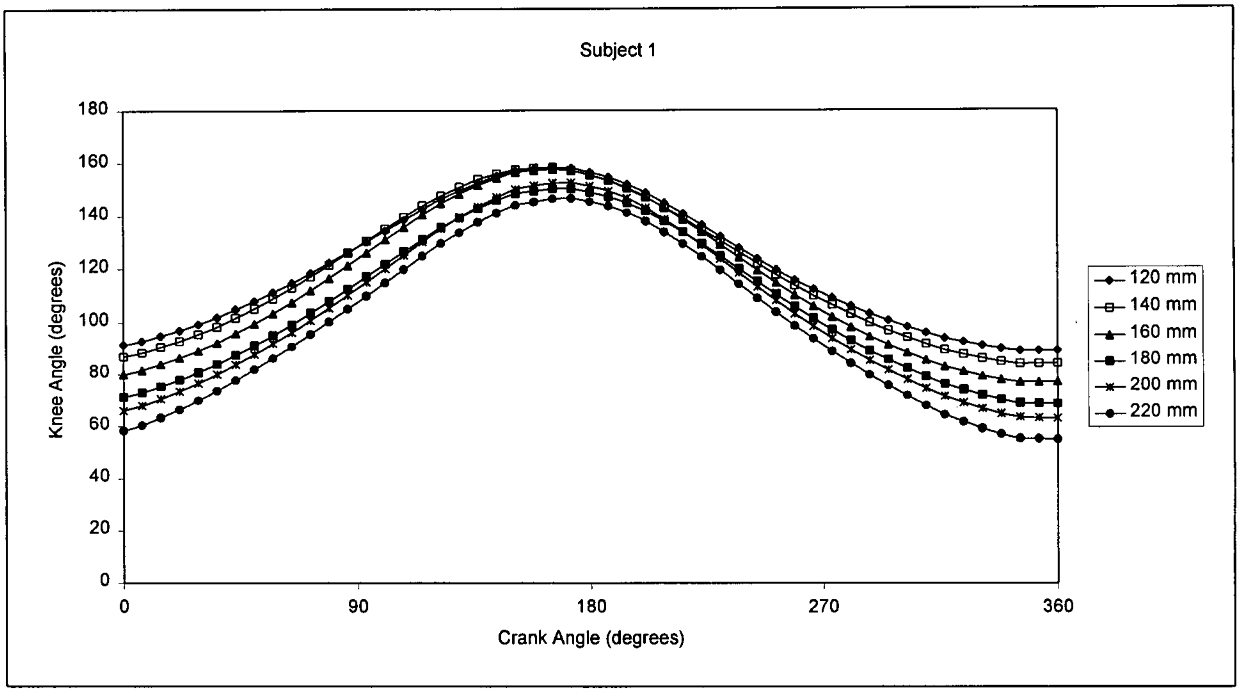


Subject 16
Hip Angle (degrees)
80
70
60
50
40
30
20
10
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

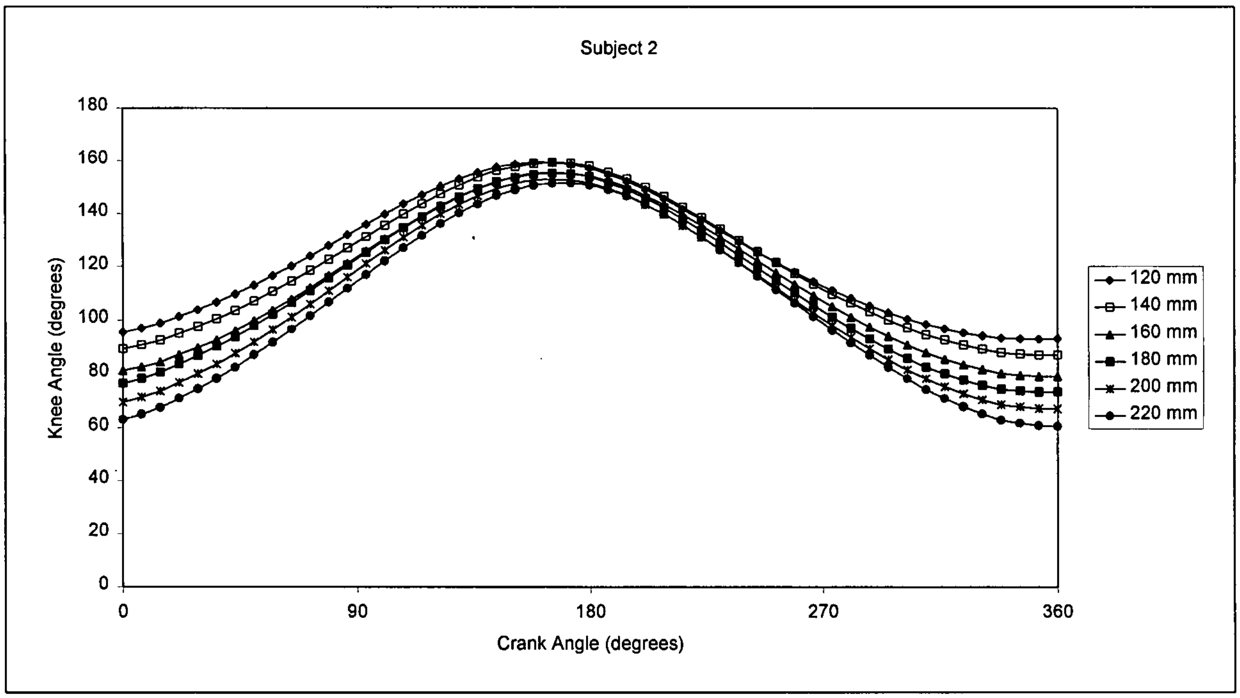
Appendix C10: Average Hip Angle Response to Crank Length for all Subjects (+ 1 S.D. error bars)



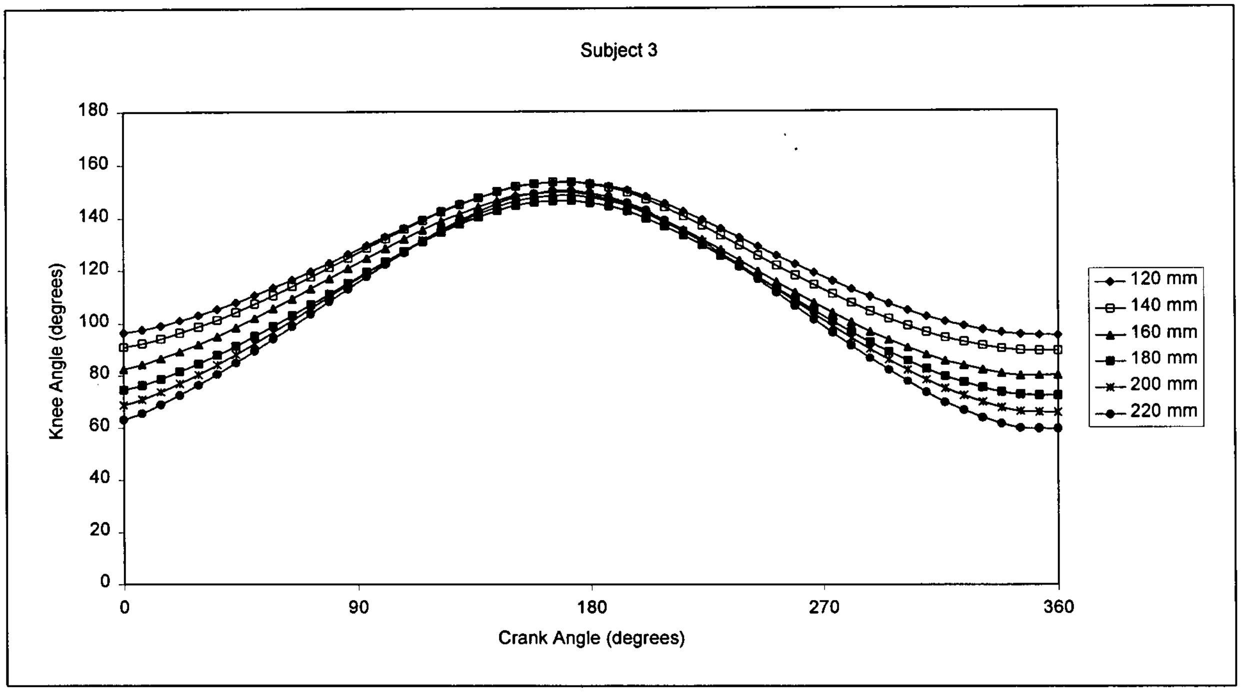
Appendix C11: Individual Knee Angle Responses to Crank Length



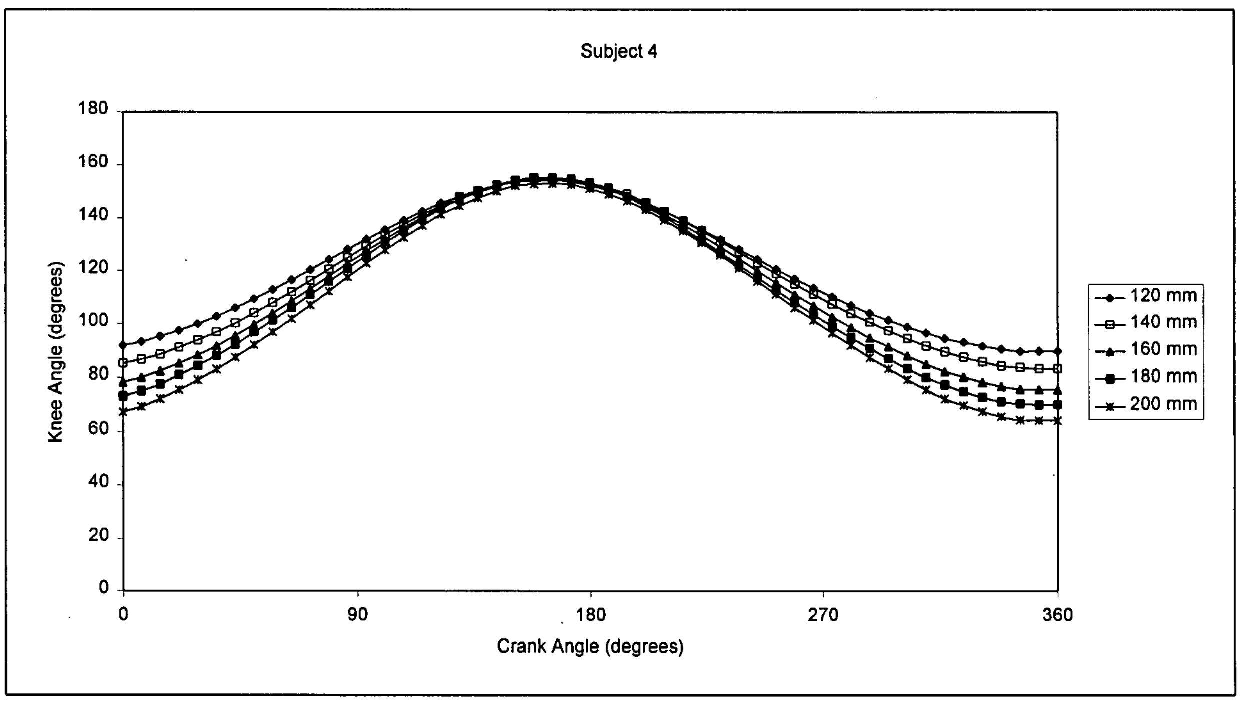
Subject 1
180
160
140
120
100
80
60
40
20
0
Knee Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm



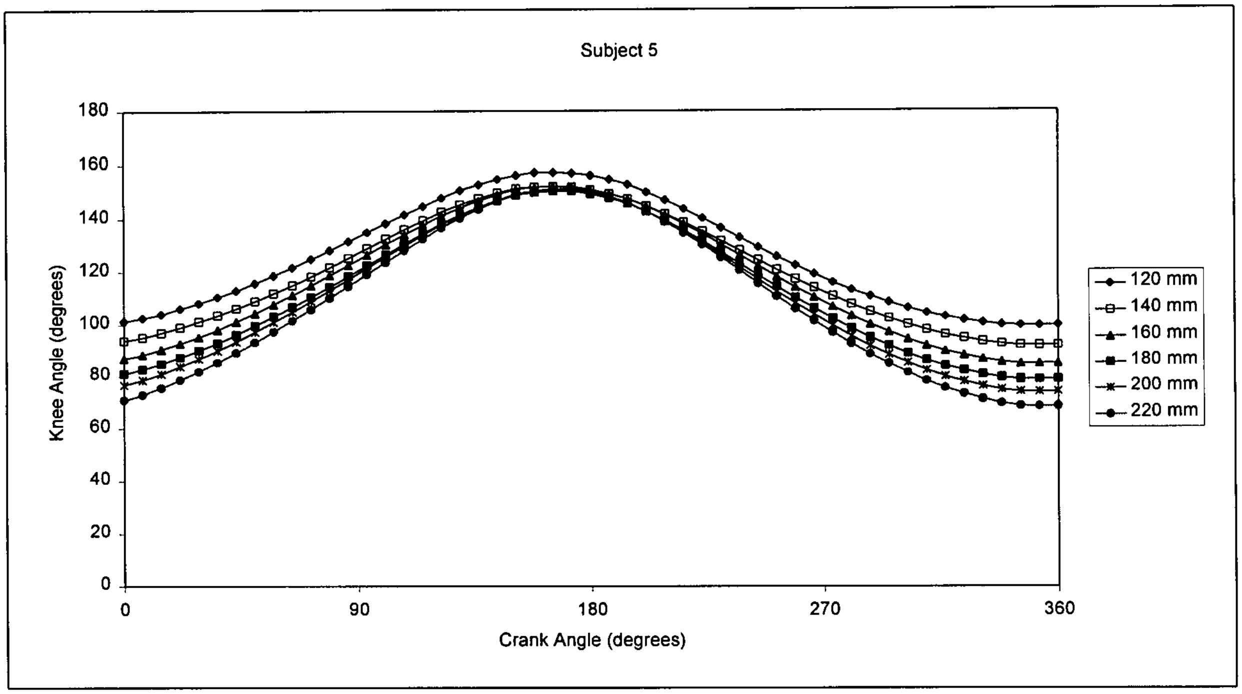
Subject 2
180
160
140
120
100
80
60
40
20
0
Knee Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm



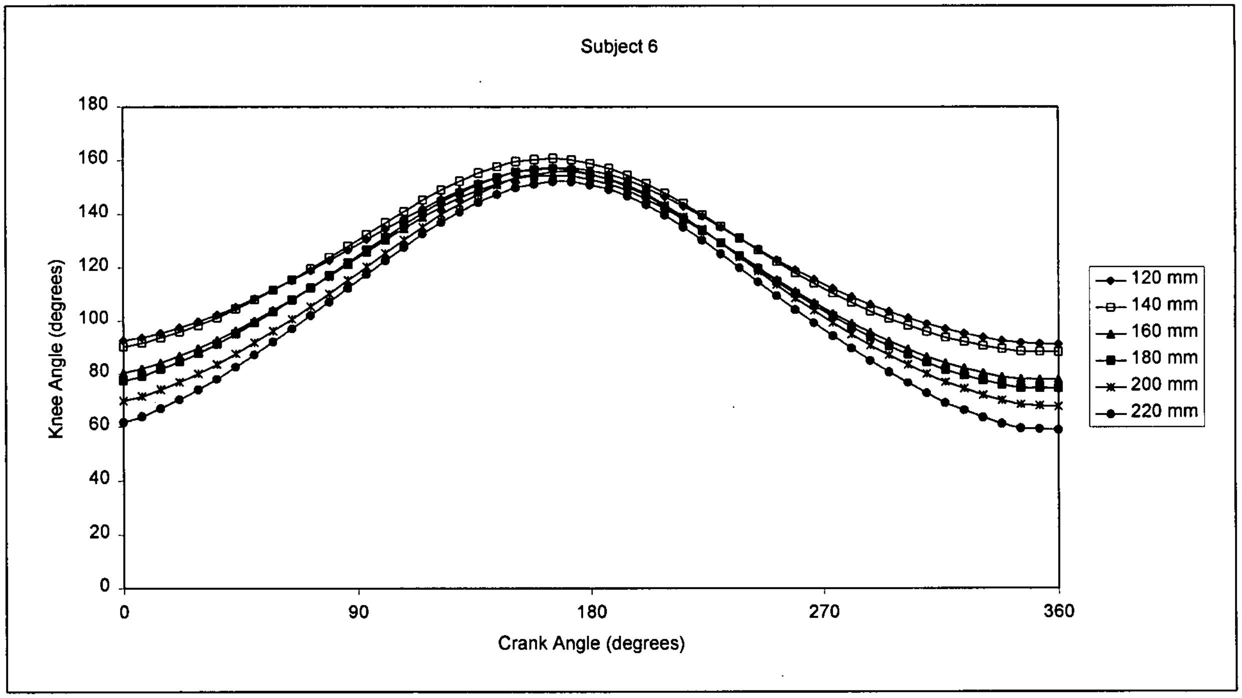
Subject 3
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm



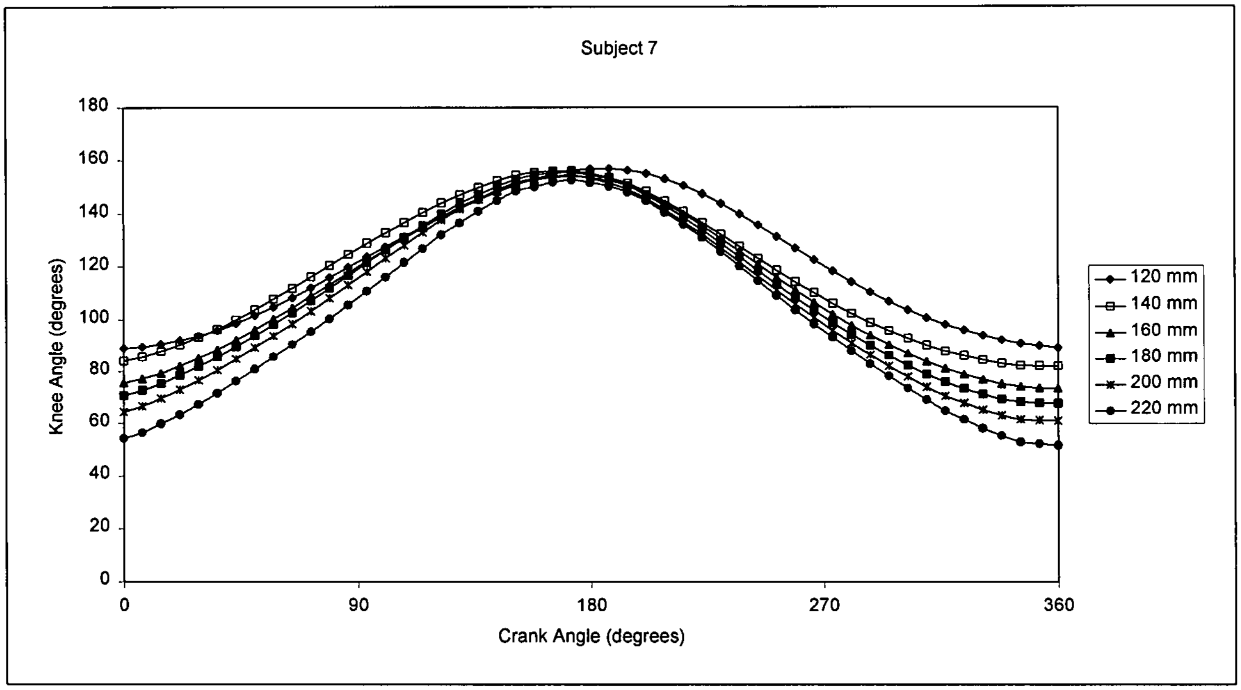
Subject 4
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm

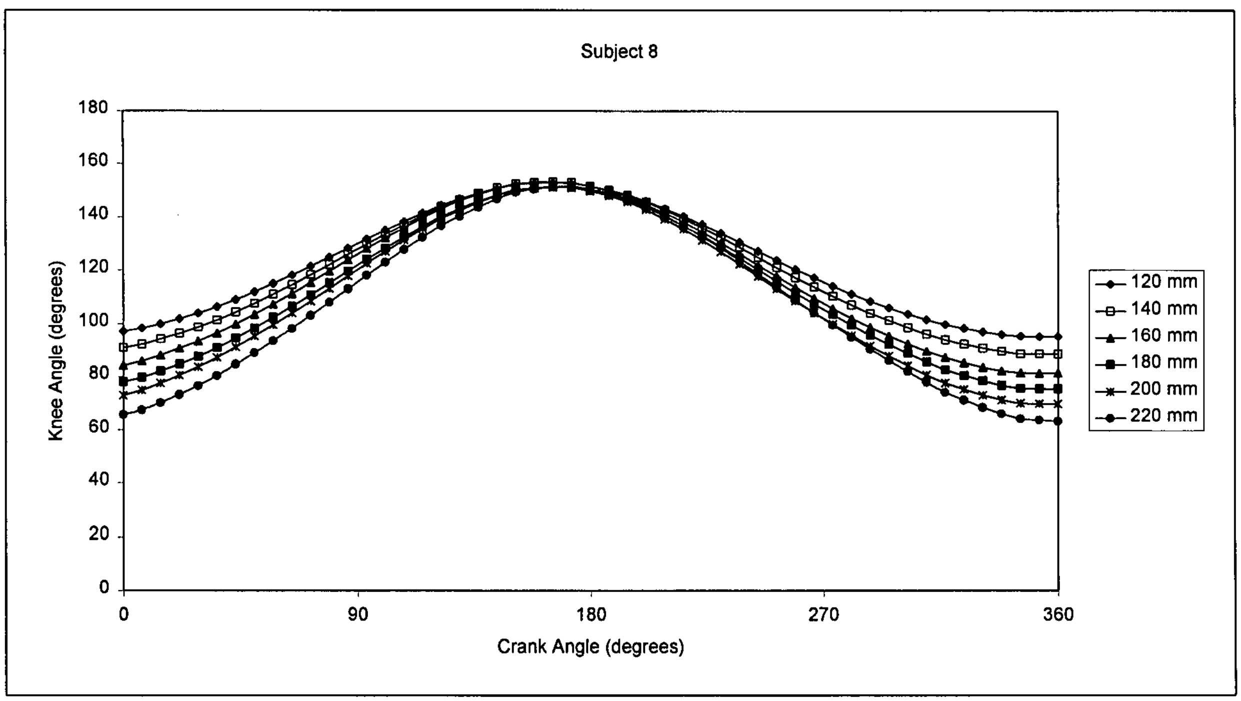


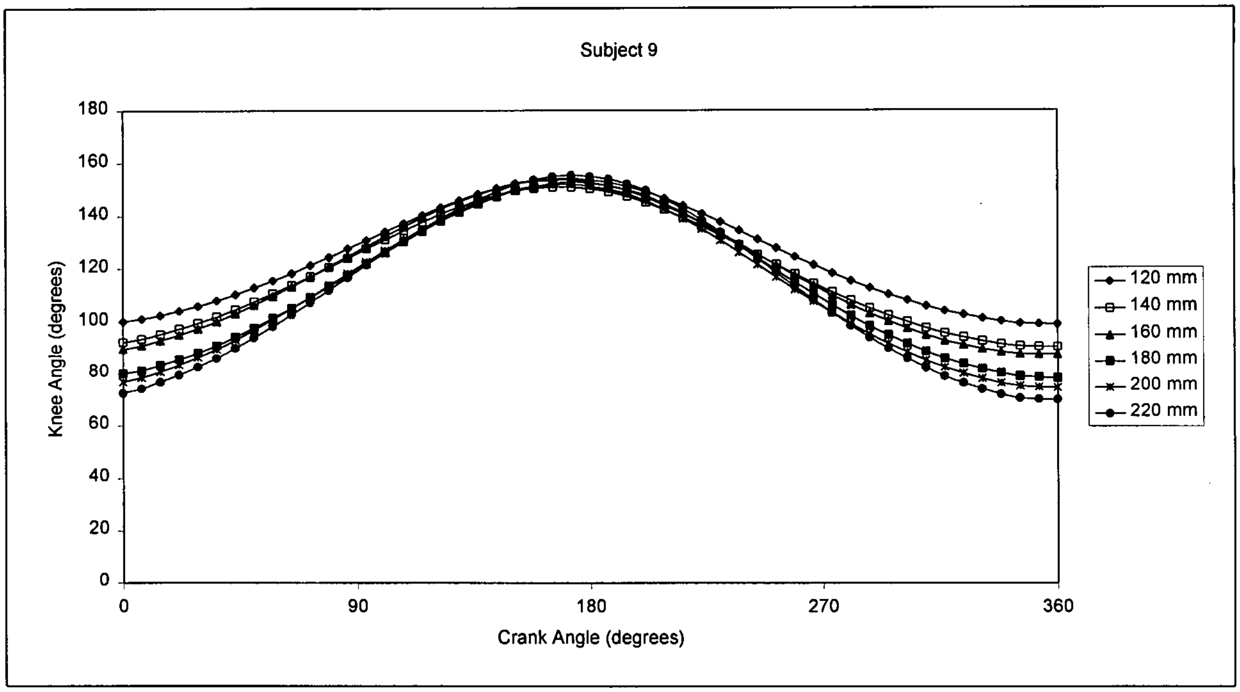
Subject 5
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

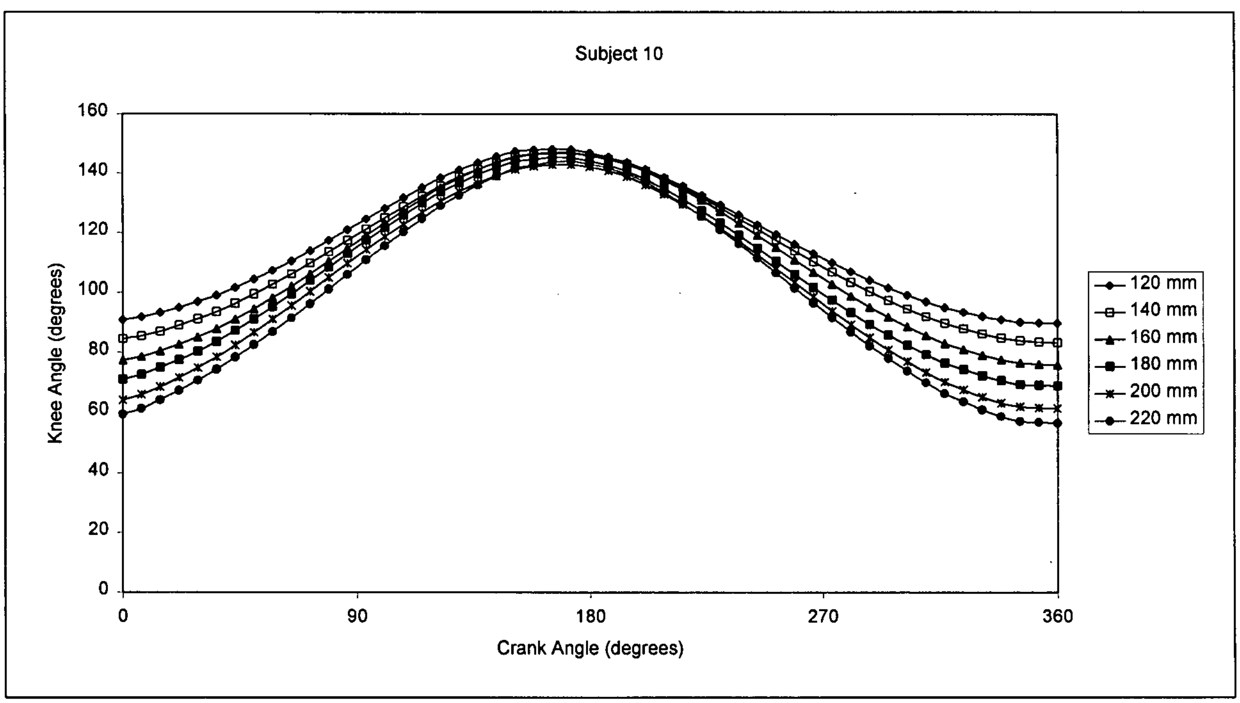


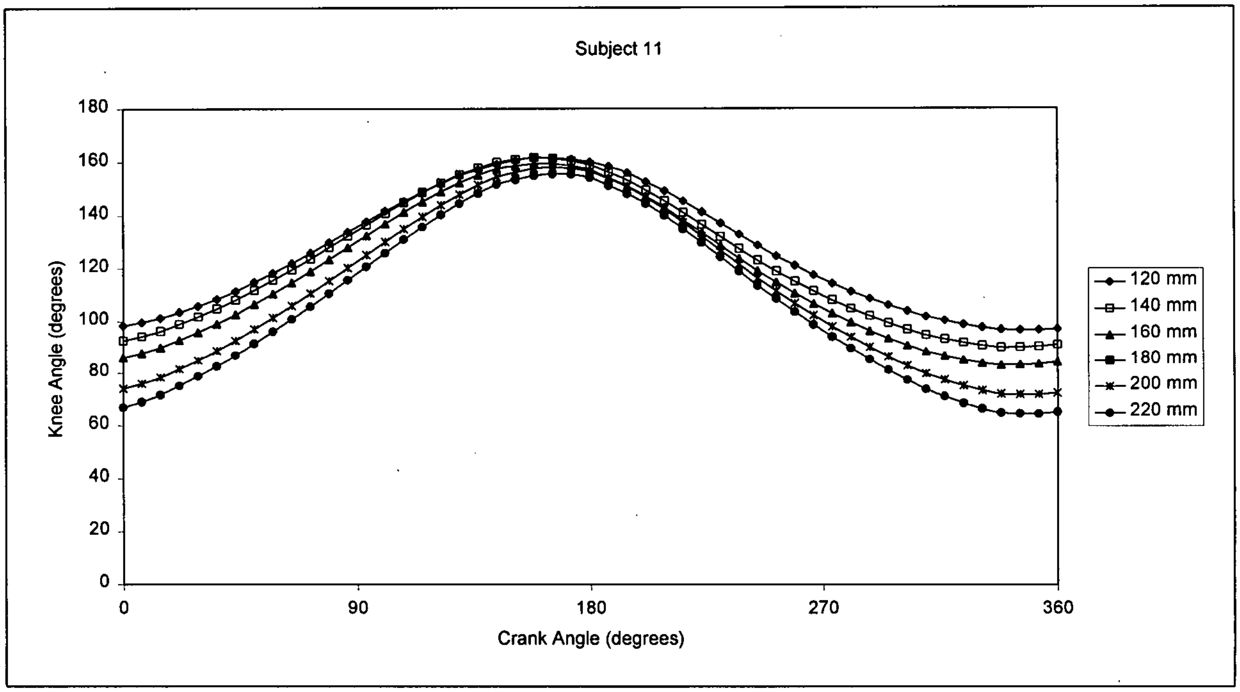
Subject 6
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

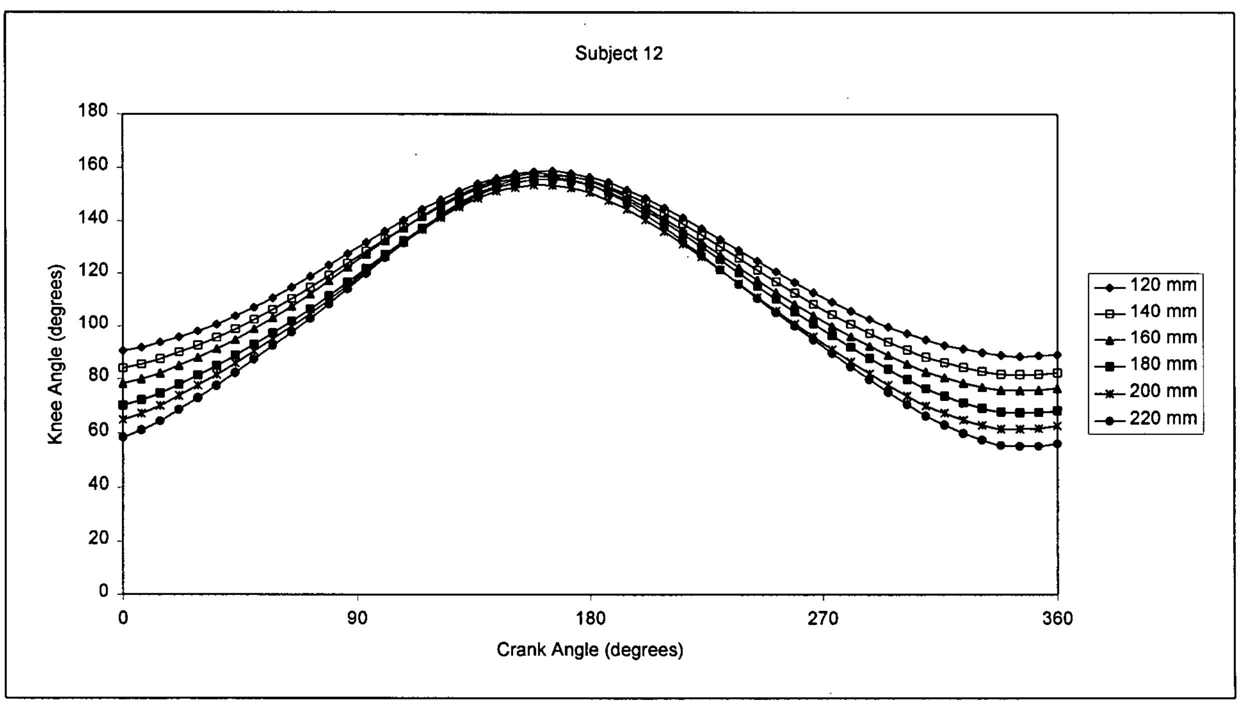

Subject 7
180
160
140
120
100
80
60
40
20
0
Knee Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

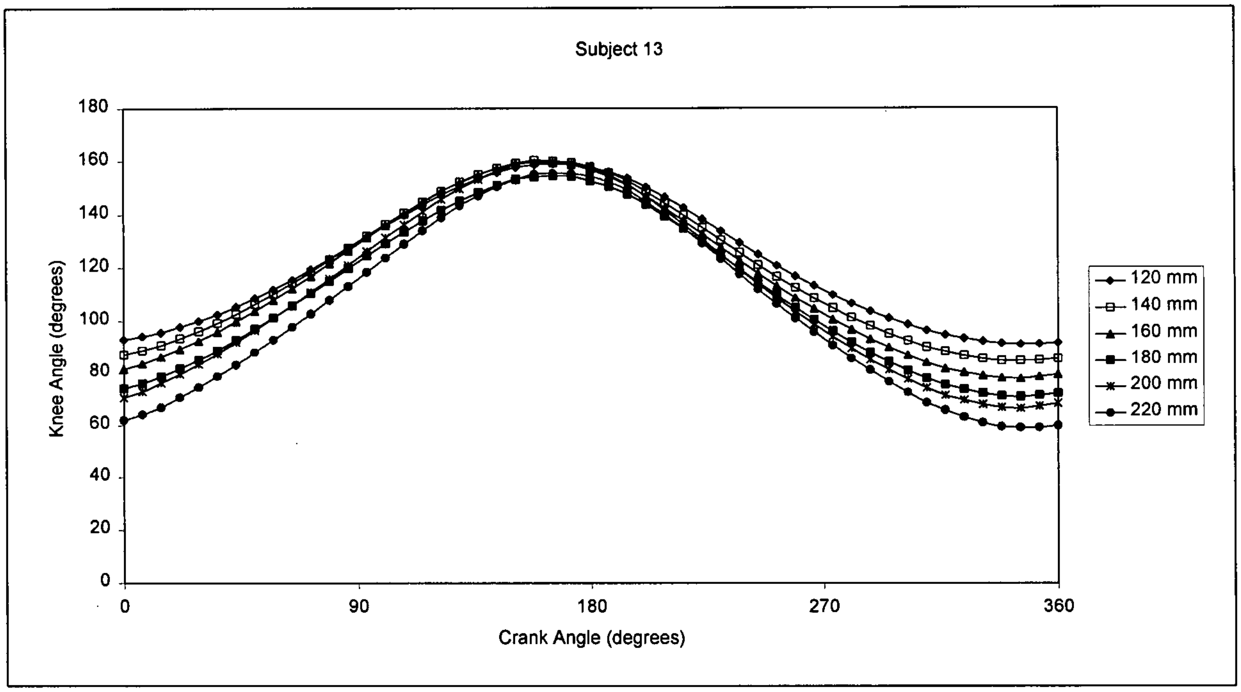

Subject 8
180
160
140
120
100
80
60
40
20
0
Knee Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

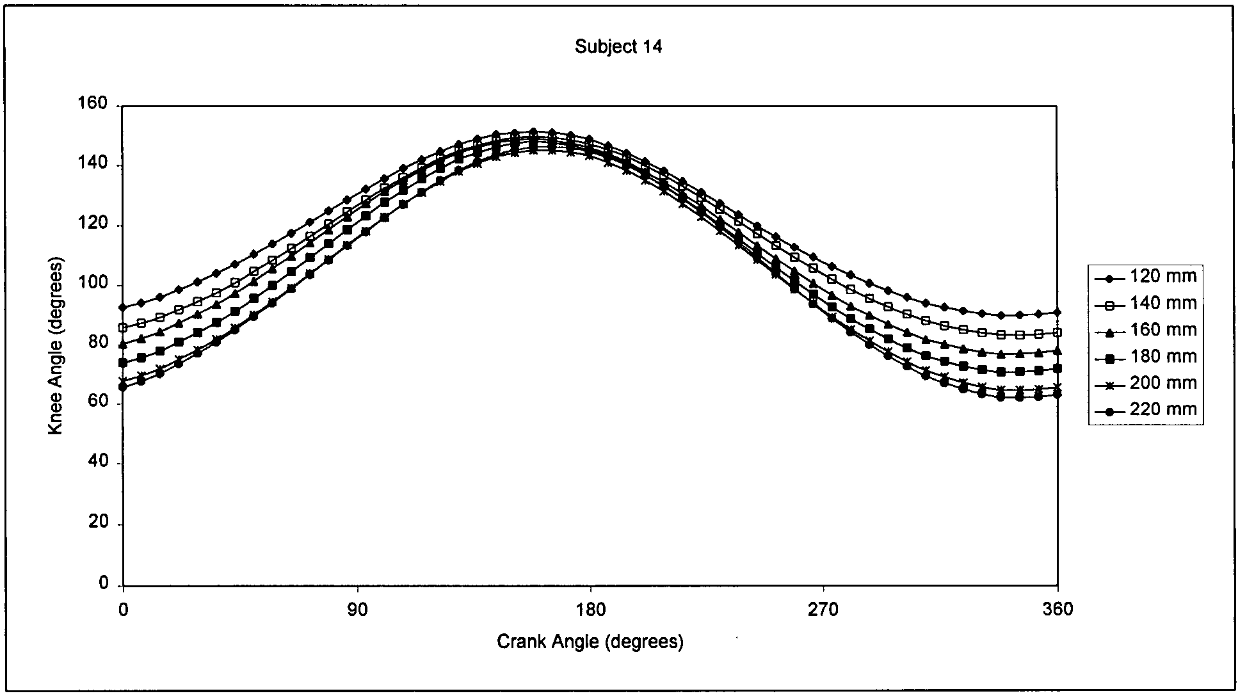

Subject 9
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

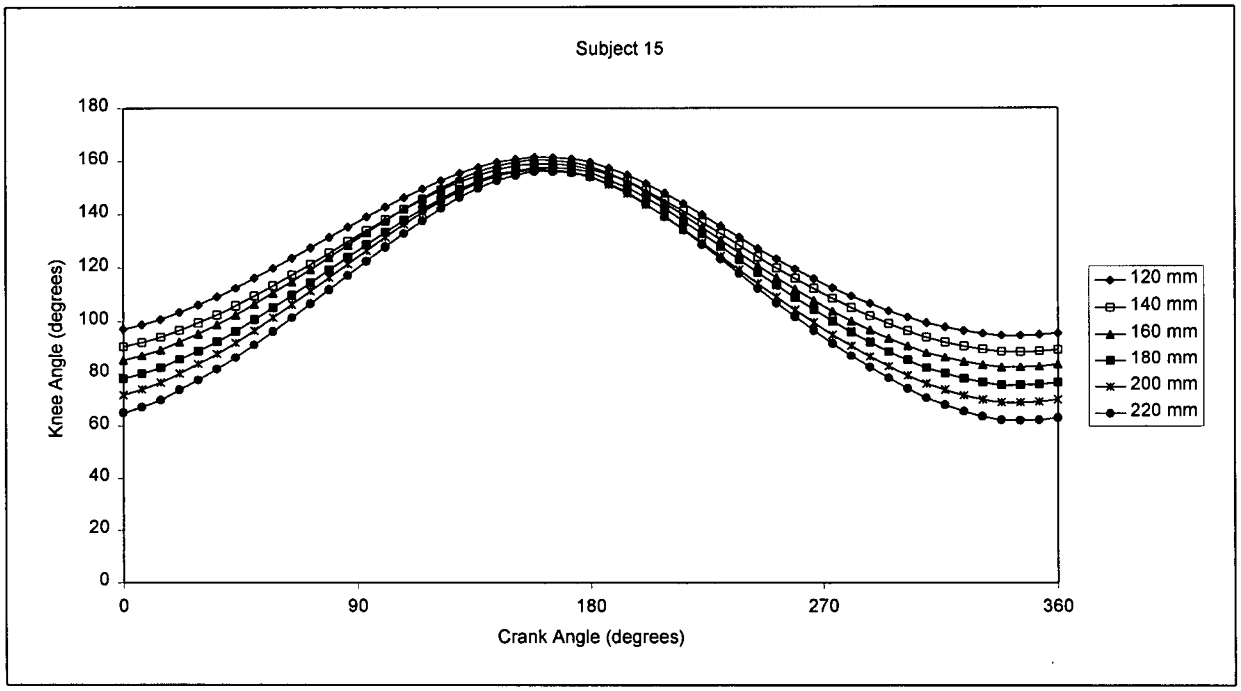

Subject 10
Knee Angle (degrees)
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

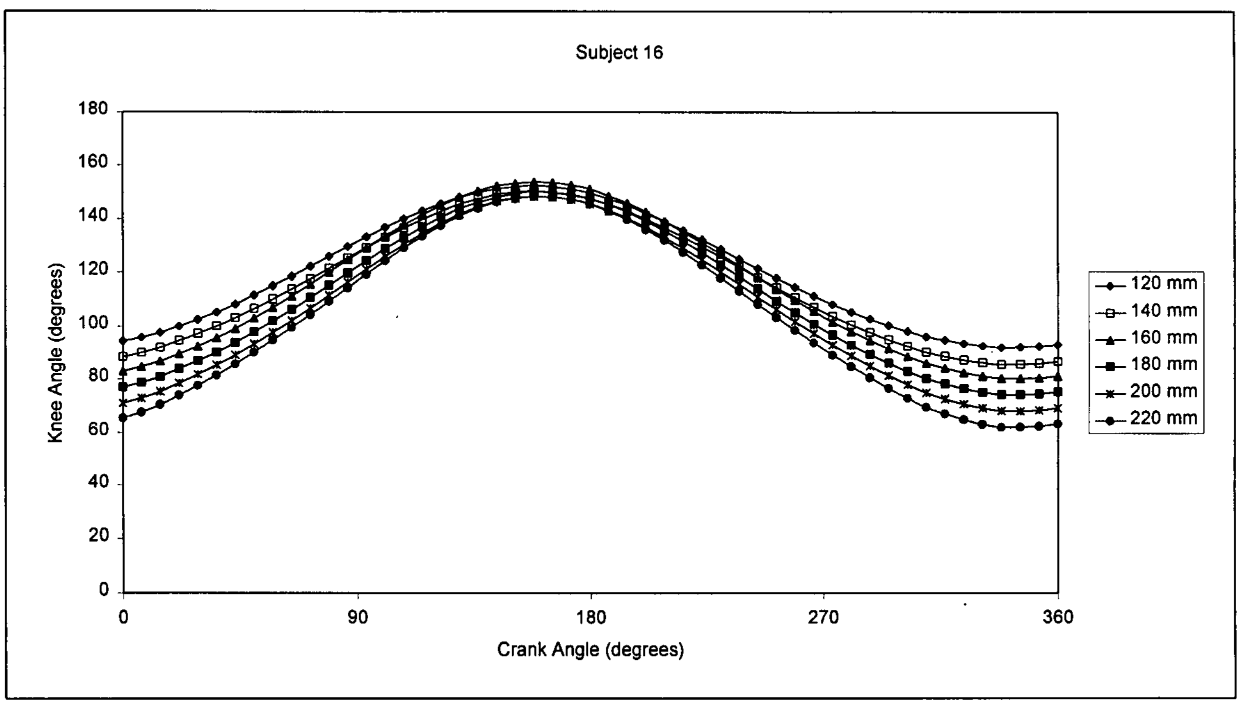

Subject 11
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 12
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

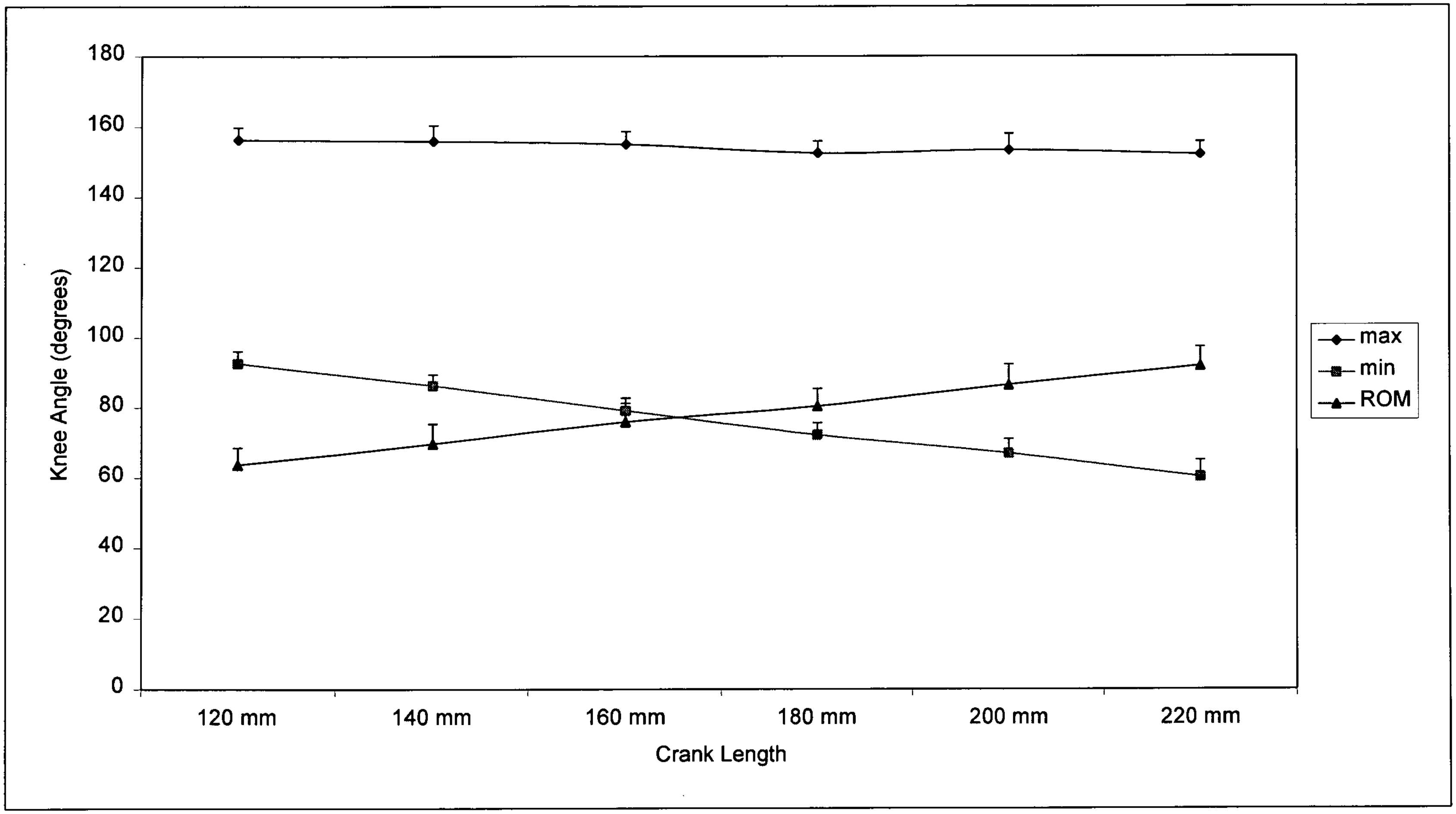

Subject 13
180
160
140
120
100
80
60
40
20
0
Knee Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 14
160
140
120
100
80
60
40
20
0
Knee Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

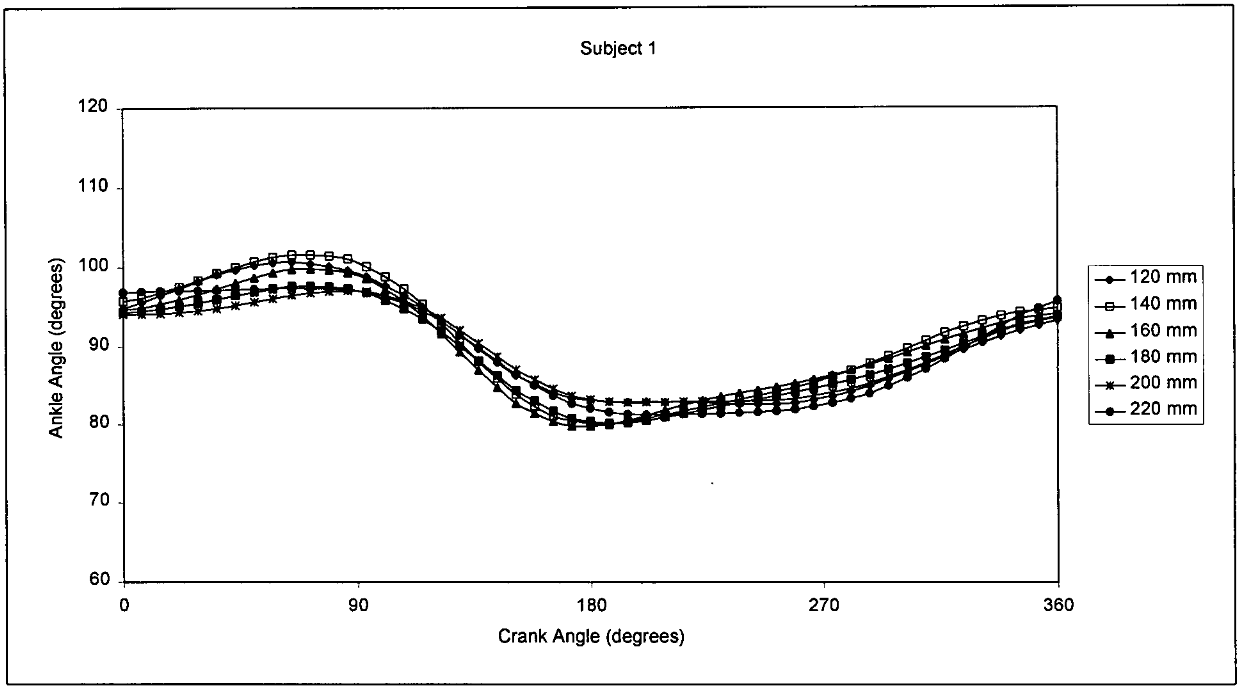

Subject 15
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 16
Knee Angle (degrees)
180
160
140
120
100
80
60
40
20
0
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

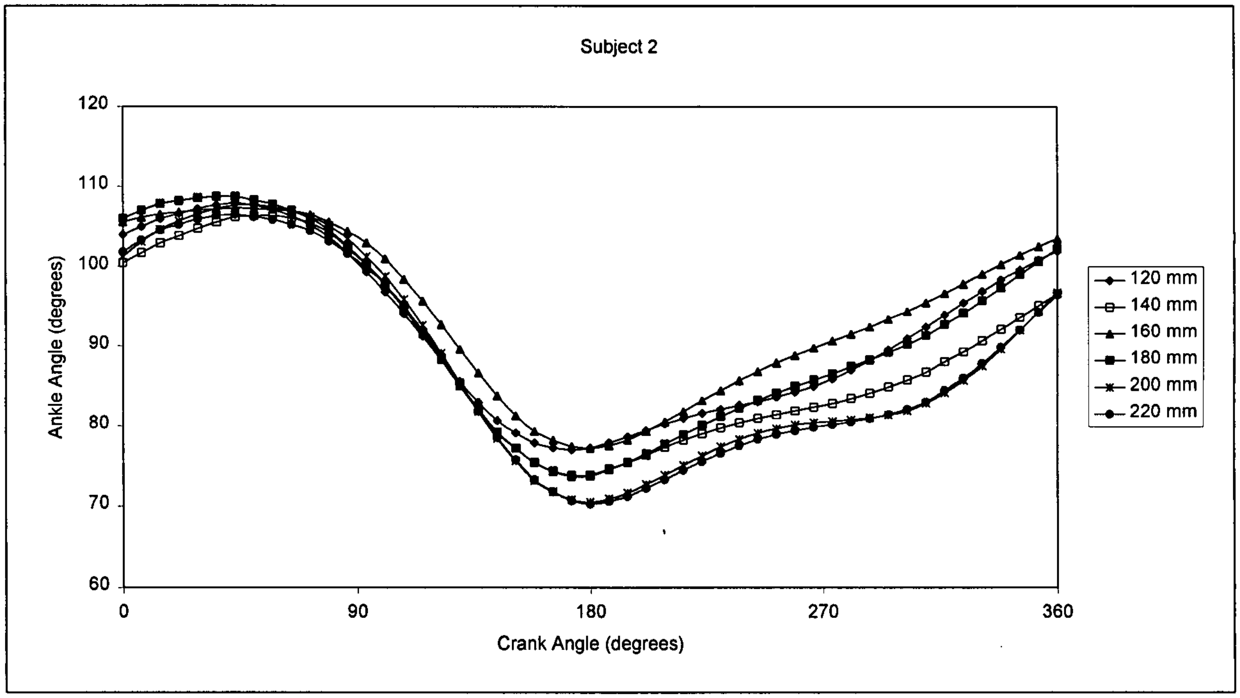
Appendix C12: Average Knee Angle Response to Crank Length for all Subjects (+ 1 S.D. error bars)



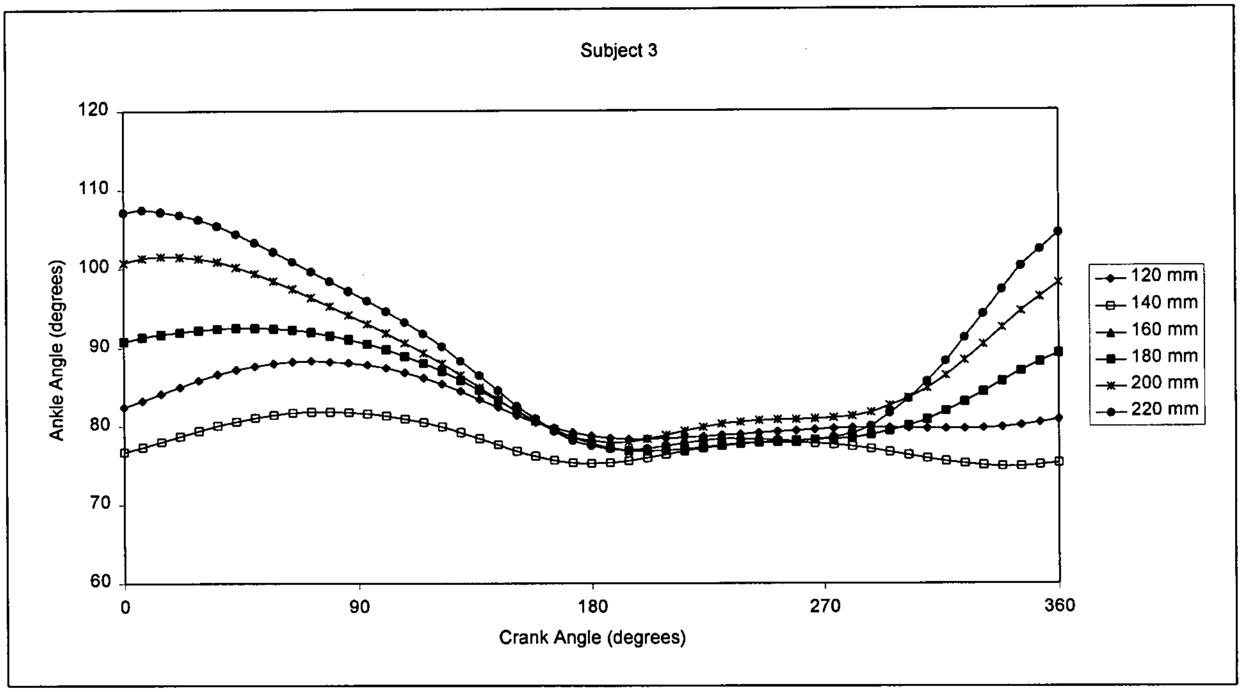
Appendix C13: Individual Ankle Angle Responses to Crank Length



Subject 1
120
110
100
90
80
70
60
0
90
180
270
360
Ankle Angle (degrees)
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm



Subject 2
120
110
100
90
80
70
60
0
90
180
270
360
Ankle Angle (degrees)
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm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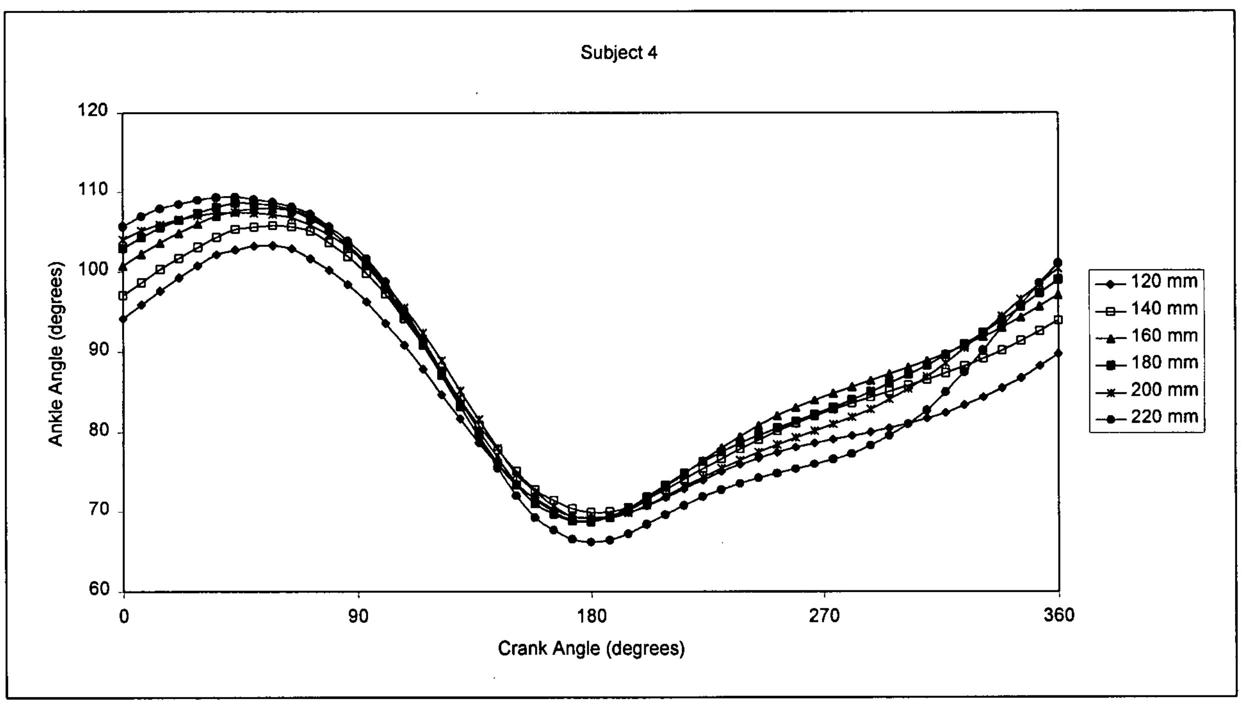
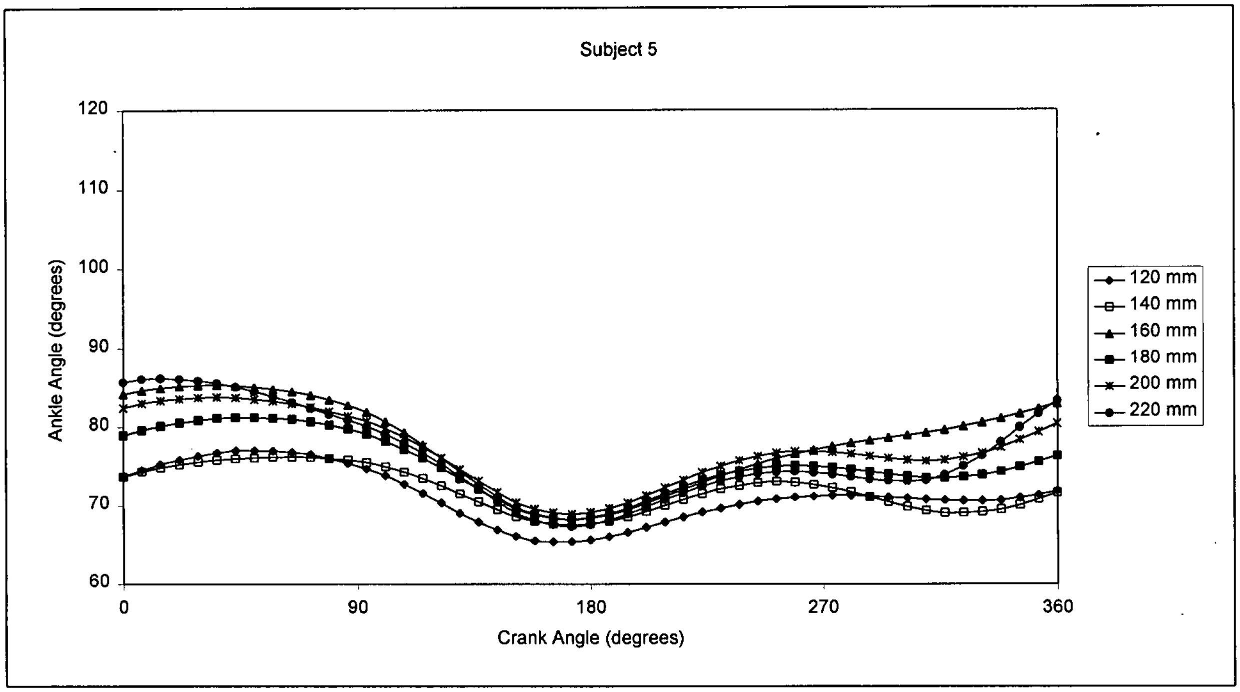
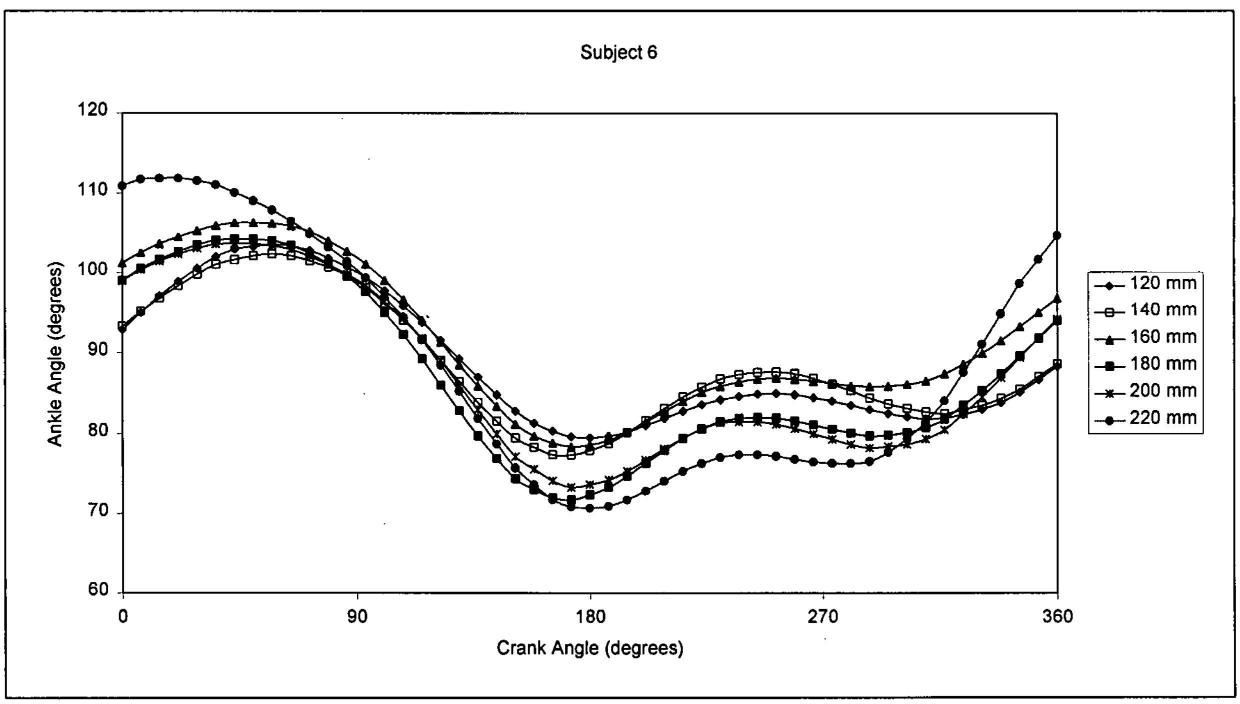
120
110
100
90
80
70
60
0
90
180
270
360
Ankle Angle (degrees)
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 4
120
110
100
90
80
70
60
0
90
180
270
360
Ankle Angle (degrees)
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 5
120
110
100
90
80
70
60
Ankle Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm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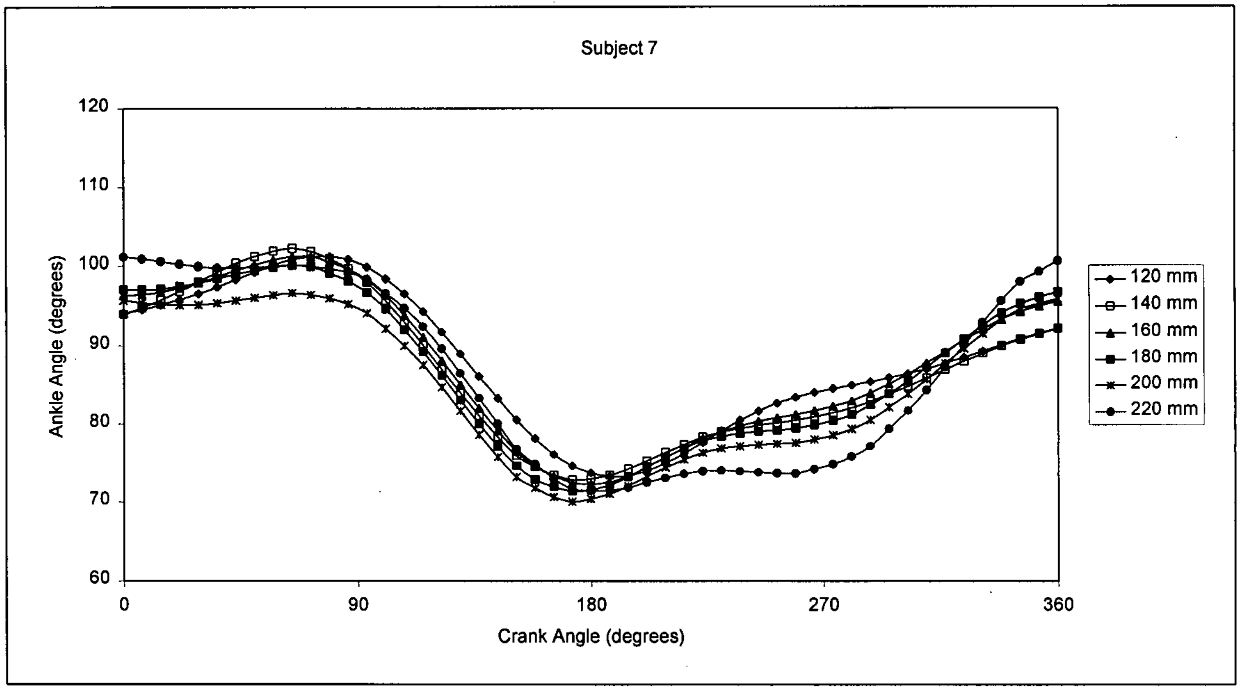
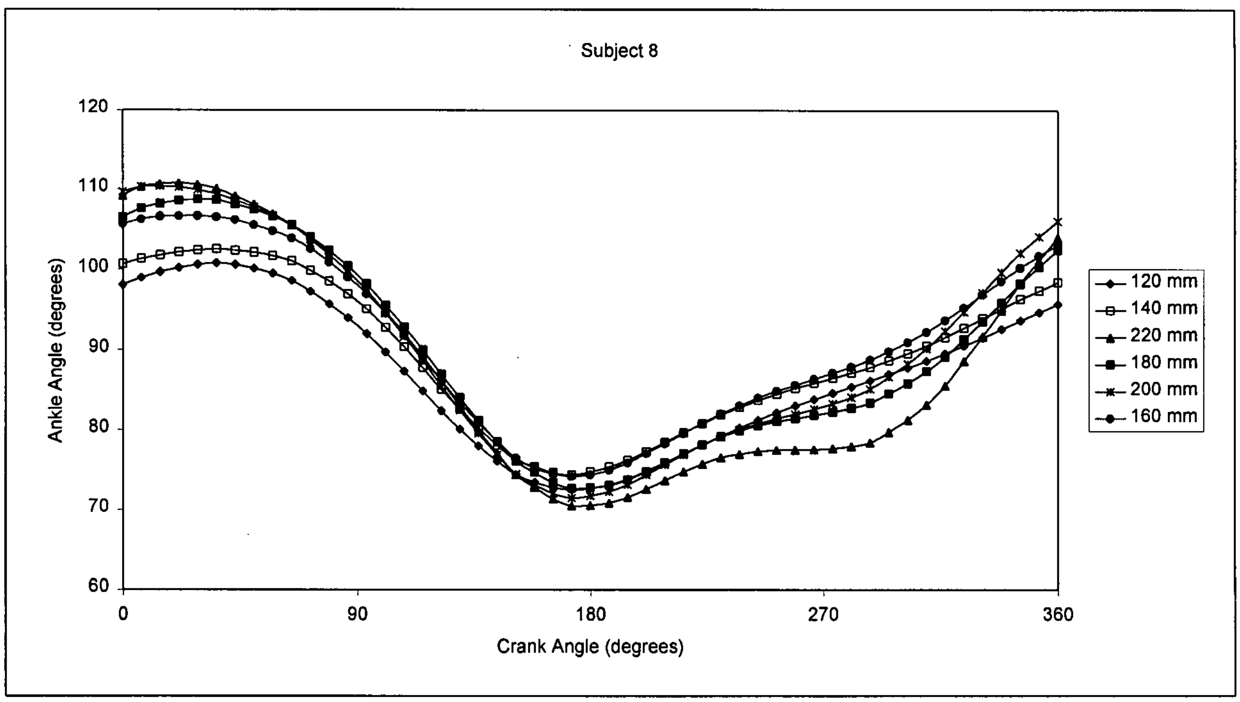
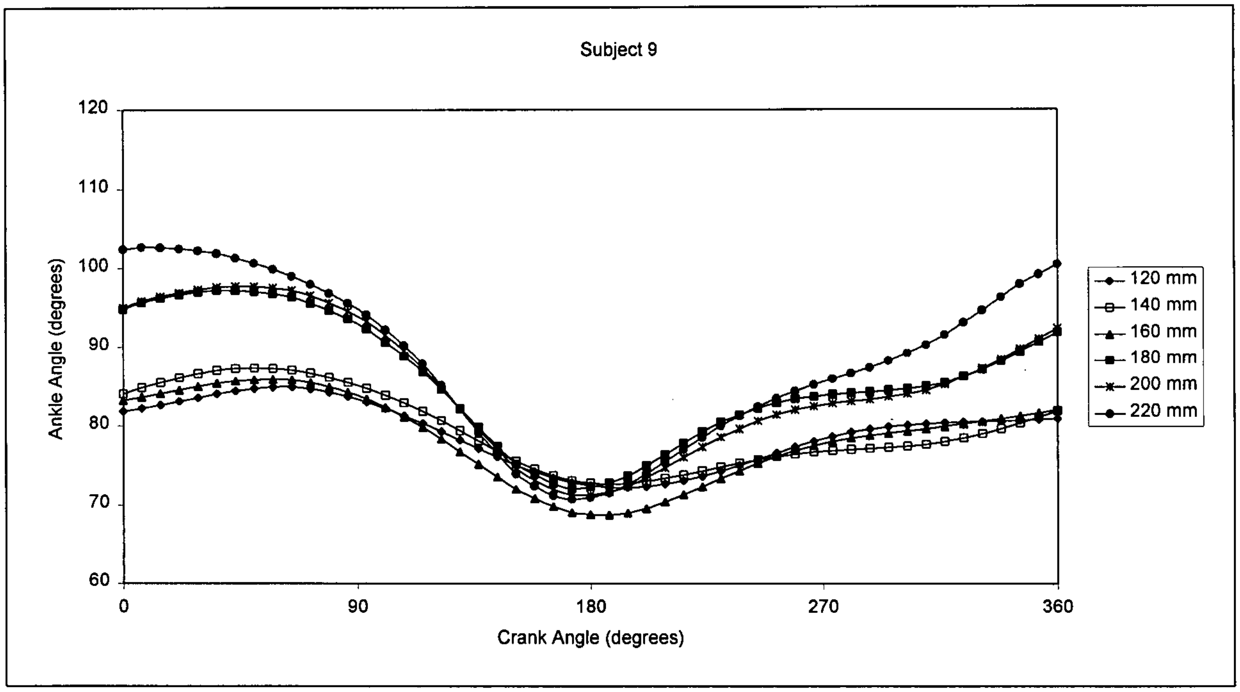
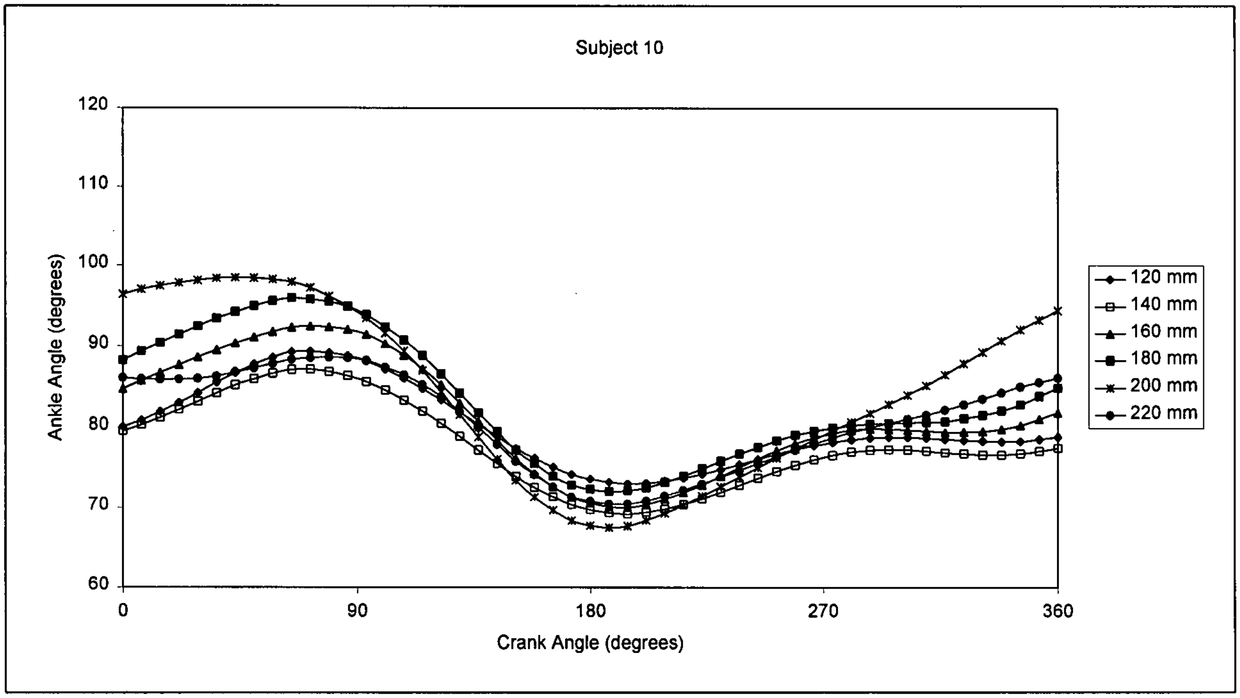
110
100
90
80
70
60
Ankle Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 7
Ankle Angle (degrees)
Crank Angle (degrees)
120
110
100
90
80
70
60
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

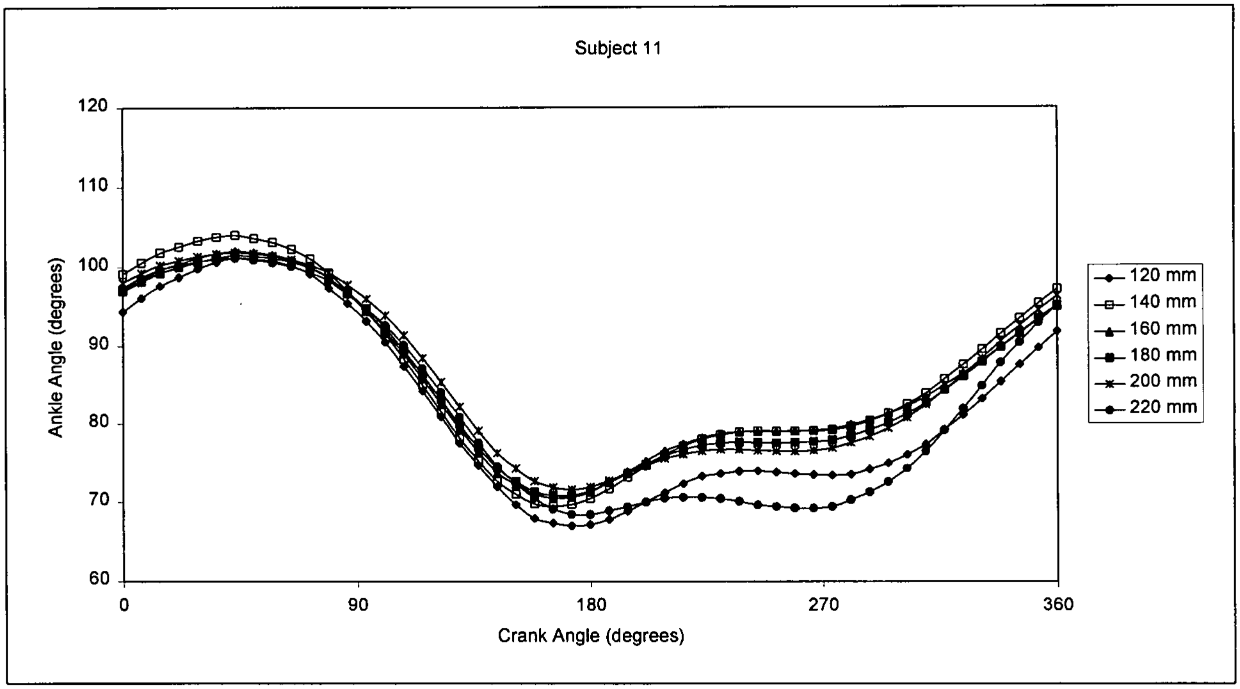

Subject 8
Ankle Angle (degrees)
Crank Angle (degrees)
120
110
100
90
80
70
60
0
90
180
270
360
120 mm
140 mm
220 mm
180 mm
200 mm
160 mm

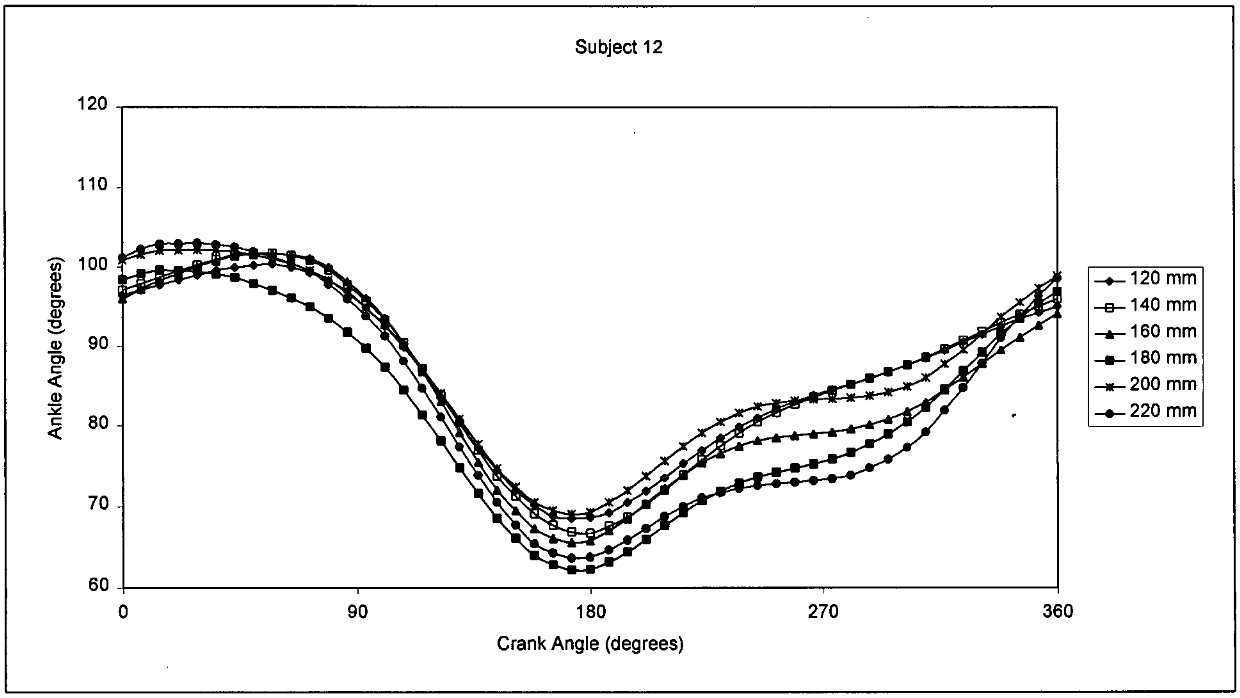


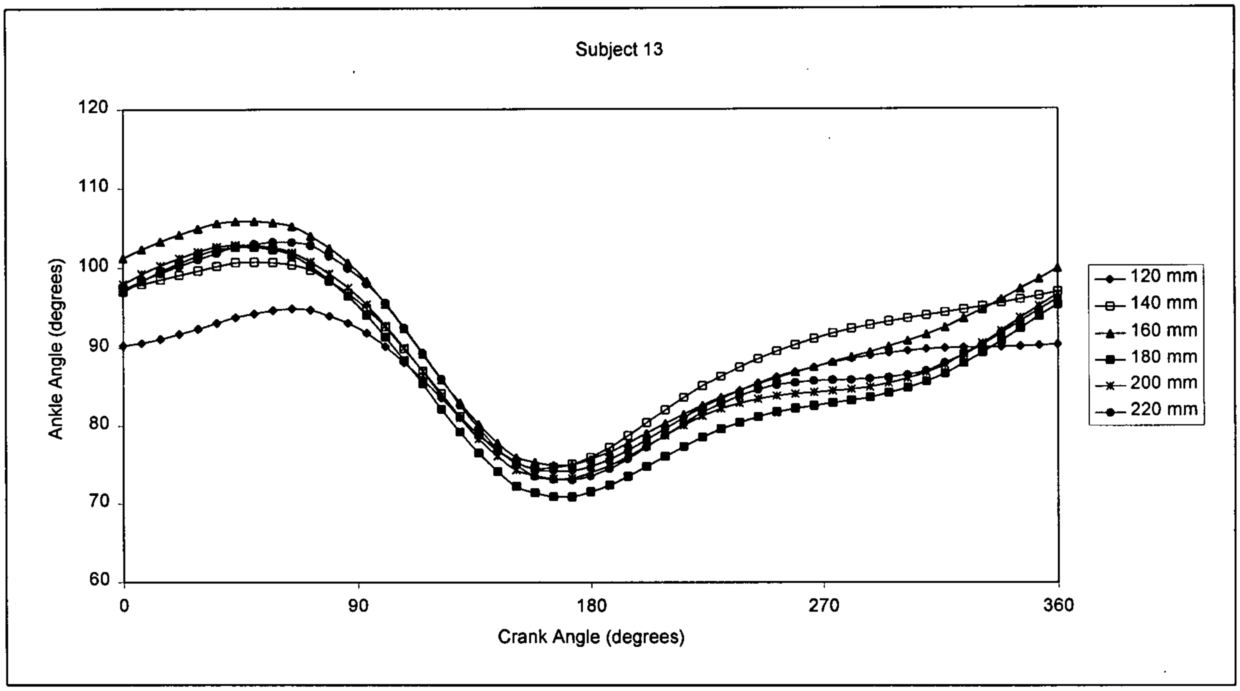
Subject 9
Ankle Angle (degrees)
120
110
100
90
80
70
60
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

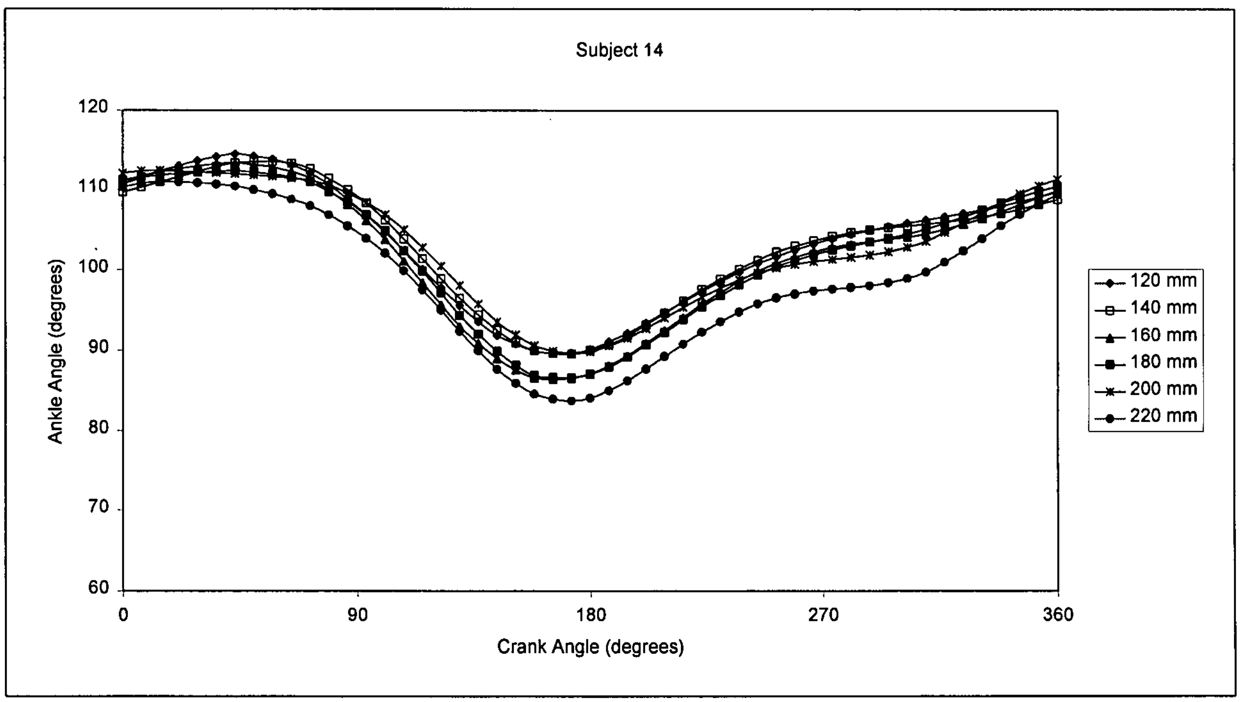


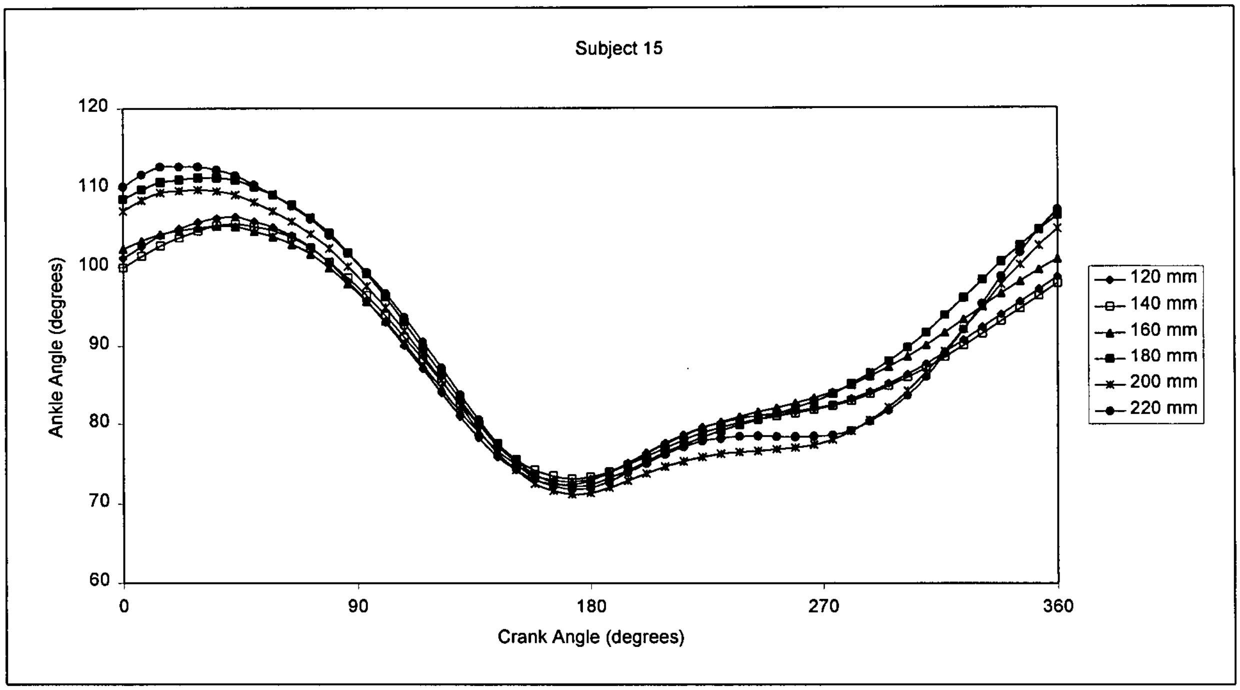
Subject 10
Ankle Angle (degrees)
120
110
100
90
80
70
60
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 11
120
110
100
90
80
70
60
Ankle Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

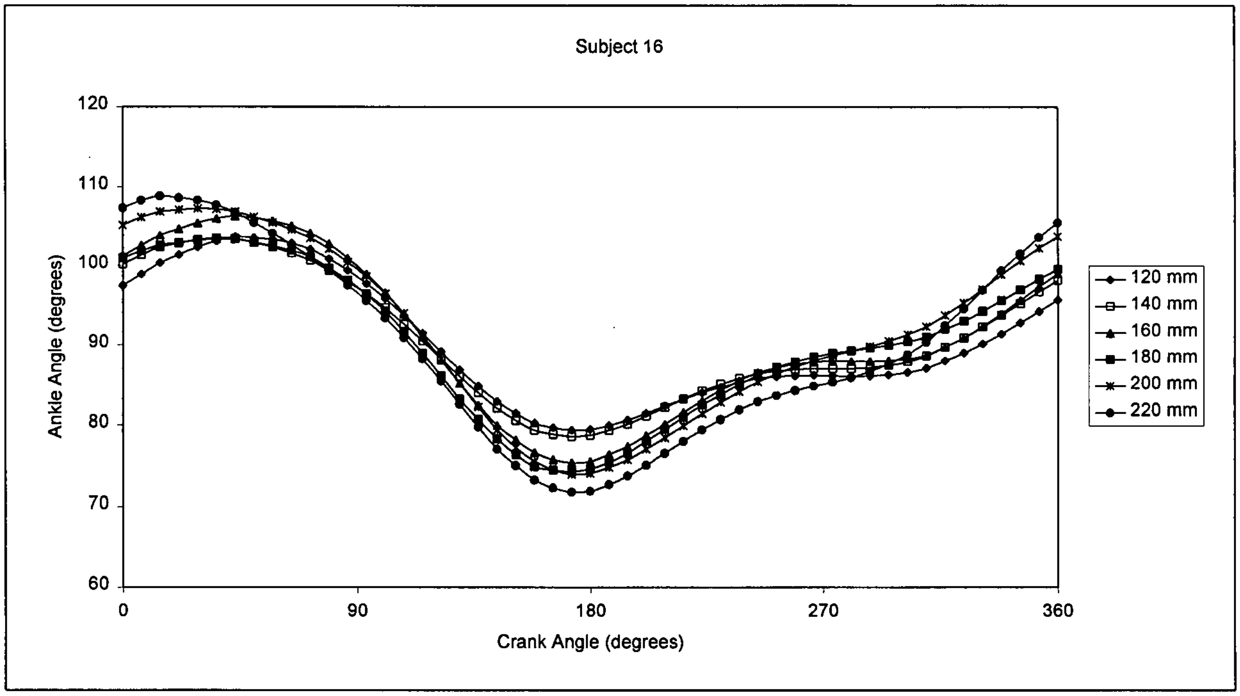

Subject 12
120
110
100
90
80
70
60
Ankle Angle (degrees)
0
90
180
270
360
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 13
Ankle Angle (degrees)
Crank Angle (degrees)
120
110
100
90
80
70
60
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm


Subject 14
Ankle Angle (degrees)
Crank Angle (degrees)
120
110
100
90
80
70
60
0
90
180
270
360
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

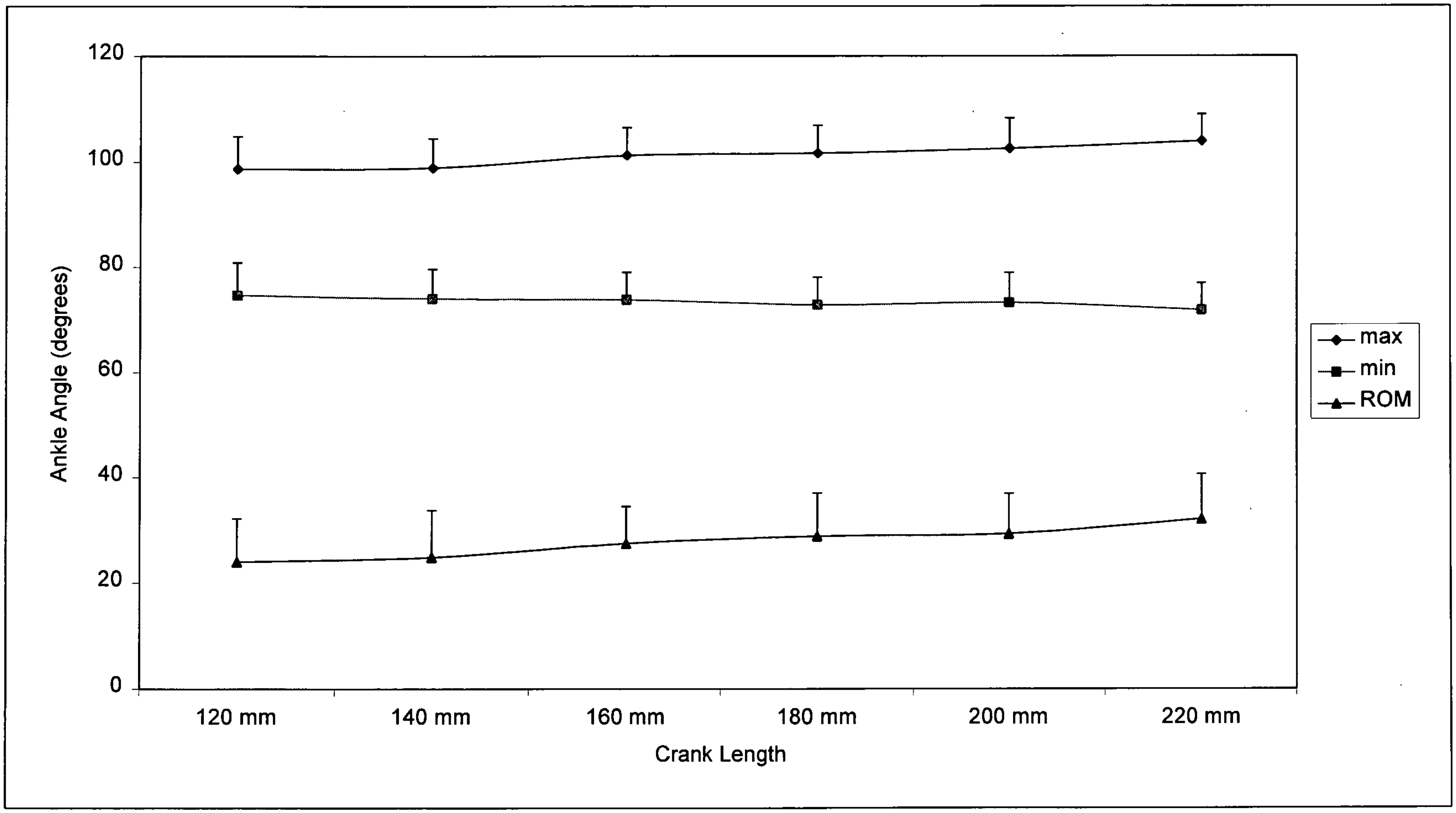


Subject 15
120
110
100
90
80
70
60
0
90
180
270
360
Ankle Angle (degrees)
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

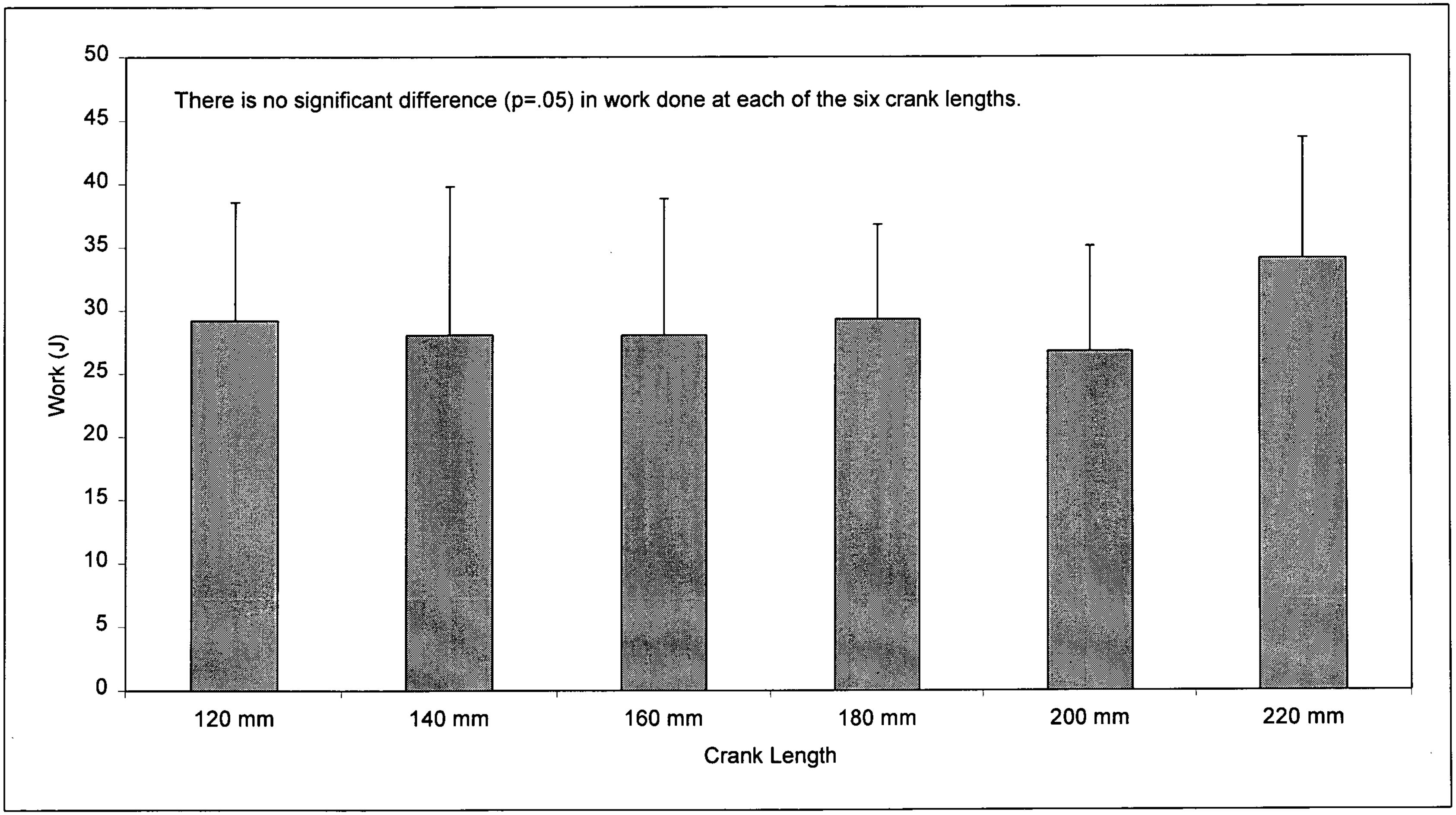


Subject 16
120
110
100
90
80
70
60
0
90
180
270
360
Ankle Angle (degrees)
Crank Angle (degrees)
120 mm
140 mm
160 mm
180 mm
200 mm
220 mm

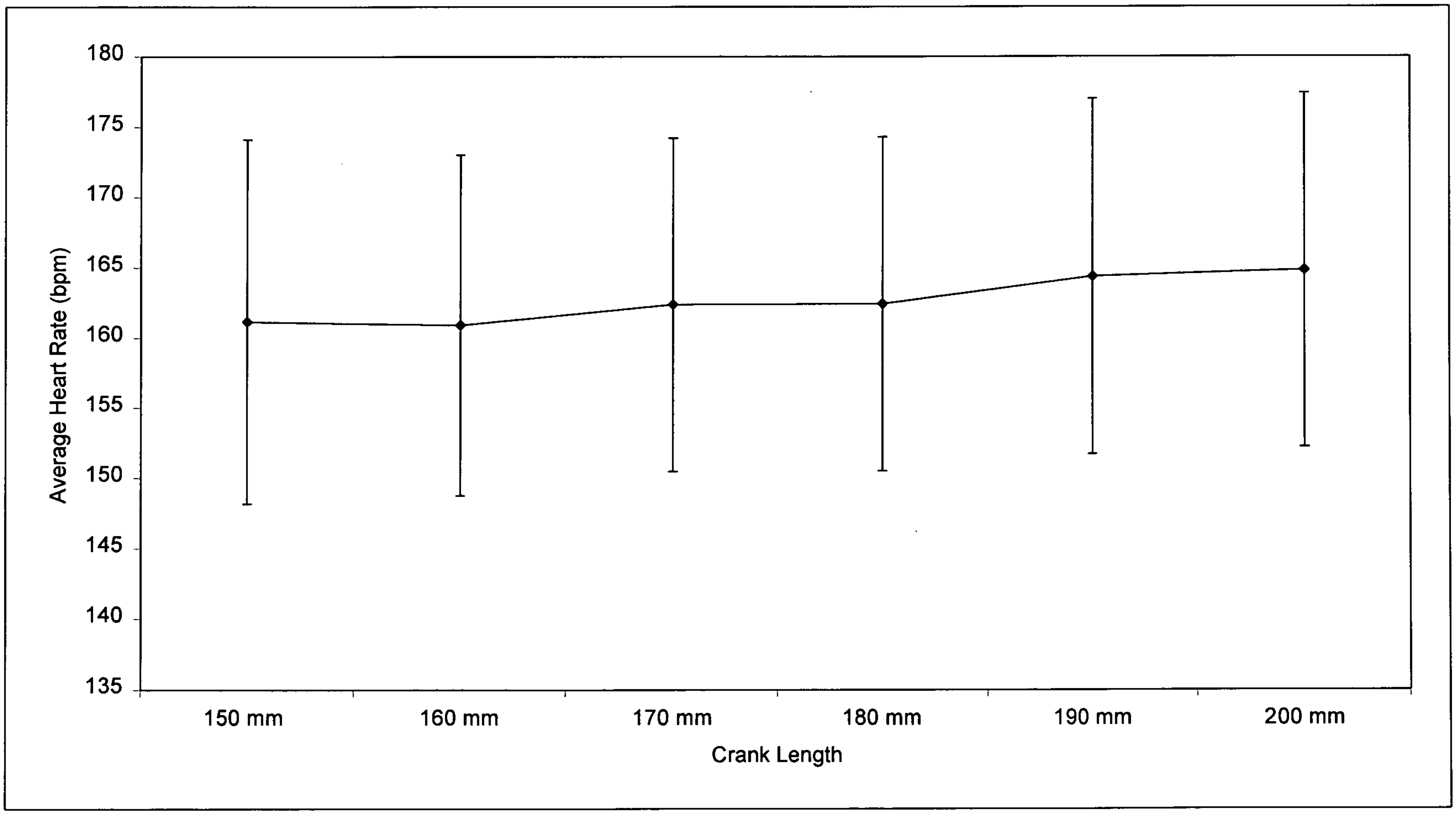
Appendix C14: Average Ankle Angle Response to Crank Length for all Subjects (+ 1 S.D. error bars)



Appendix C15: Average work done per crank cycle for each of the six crank lengths (+ 1 S.D. error bars)



Appendix C16: Average Heart Rate Response to Crank Length – data collected by Carmichael (1981) (+ 1 S.D. error bars)



set-up (seat height, reach, saddle fore-aft position) for the size of the rider according to current practices.

There will be six criterion rides that will be conducted over two visits to the lab. Each subject will ride at 150 watts and 90 rpm three times during each session. Each of the criterion rides will employ cranks of a different length: 140 mm, 150 mm, 160 mm, 170 mm, 180 mm and 190 mm. Each ride will last approximately 10 minutes with a sufficient recovery period between each of the criterion rides and a warm-up at the beginning of each testing session. The total time for subject involvement will be approximately **4 hours**.

Anthropometric measurements will be collected on the first visit to the lab. Trochanteric height, standing height, thigh length and shank length will all be determined using a measuring tape. Heart rate will be collected continuously during each criterion ride via a portable heart rate monitor. A transmitter continuously picks up the heart's electrical impulses and then wirelessly transmits this information to a wrist receiver in the form of a watch. The remainder of the data collection, that being surface EMG, kinematic data and kinetic data will take place for 8 seconds at the end of each 10 minute ride. EMG activity will be collected via surface bi-polar electrodes attached to the skin overlying the vastus lateralis. Kinematic information for the left leg will be collected by videotaping the subject while riding with reflective markers placed on the above-mentioned sites. A specially constructed pedal dynamometer will record pedal forces, pedal orientation and crank orientation.

Heart rate data will be examined to determine the relationship between crank length and heart rate. The videotape will be analysed by digitizing the position of the reflective markers using a computer system. This will enable the investigator to determine the changing positions of the joints of the lower limb during cycling. Differences in the maximum and minimum joint angles between trials will then be recorded as a function of crank length to observe the effects of crank length on the kinematics of the lower limb. Pedal forces and EMG activity will also be analysed to determine how they change when crank length is altered.

Confidentiality: All information regarding subject identification, during and after this study, will be kept strictly confidential. Data files will be coded so that only the principle investigator and co-investigator will have subject

Appendix E: Adjustable Crank Arms

A set of 170mm alloy cotterless cranks was modified in order to produce two cranks that were adjustable in 20 mm increments from 120 mm to 220 mm. A 5.5 cm piece was cut out of each of the original cranks, approximately 2.0 – 2.5 cm above the centre of the hole tapped for the pedal. Each of the remaining four ends were then milled so that a tapered lap joint could take place with a tapered aluminum insert. Twelve inserts were then machined from a piece of aluminum alloy. The inserts were cut in six different lengths so that the six resulting left and right cranks were 120, 140, 160, 180, 200 and 220 mm long. The length of the crank was defined as the distance between the centre of the pedal axle and the centre of the bottom bracket axle. Each insert was milled in a tapered fashion so that a solid and secure tapered lap joint could be made with the two ends of the original cranks (the end tapped for the pedal and the end that slides onto the bottom bracket axle). Each end of the insert as well as each of the four original pieces of crank were drilled and tapped with two holes. Two sets of screws, lock washers and nuts per crank then held the three sections of crank together (for each crank, two old pieces of the crank with the crank insert in the middle). Please see Figures 4 and 5 for photographs of the adjustable cranks.

Figure 3: Photograph of the crank inserts and crank ends as well as one complete crank

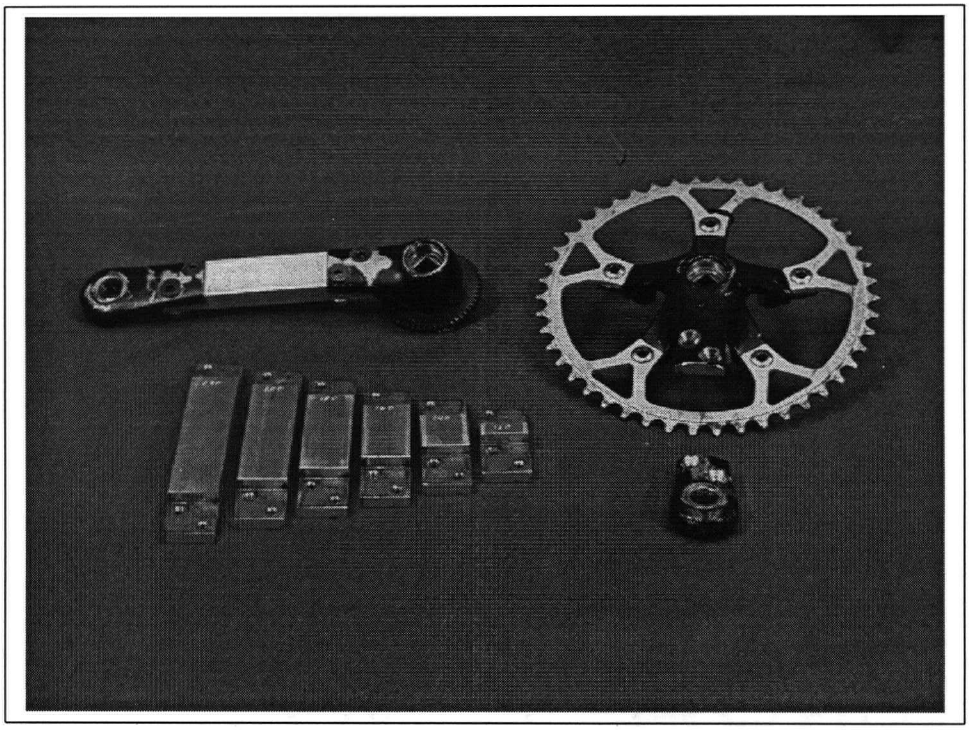


Figure 4: Photograph of one insert including bolts, washer and nut and one set of crank ends