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Modelling the Muscles of the Lower Extremity:

The Effect of Varying Joint Angles on Muscle Length

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Abstract

Polynomial regression was used to describe the relationship between lengths of the five muscles of interest and lower extremity joint angle(s). A difference between the genders was observed, so the male and female data were separated and five regression equations (one per muscle) were fitted to each data set.

In an attempt to build general regression equations normalization and transformation of the data was performed, but these manipulations of the data did not lead to predictive equations. Addition of leg segment length, for the monoarticular muscles, and height, for the biarticular muscles, as independent variables did significantly increase model fit.

The general regression model was quantitatively compared to the leg segment lengths and the actual observed values. It was also qualitatively compared to two other models. Results showed that while the general regression model is good at predicting muscle function, it is not a very accurate predictor of muscle length.

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Chapter 1
General Introduction

It is important to study the working of the muscles of the lower extremity to successfully model human motion and, more importantly, human locomotion. Whether it is a baby crawling, an athlete running or an older couple taking an evening stroll the muscles of the lower extremity play the most important role in propelling motion. While limits are placed on the role a muscle can play by the structure of the musculoskeletal system, the function of a muscle can only be determined if knowledge of how the muscle-tendon unit (hereby referred to simply as muscle) changes in length during motion is known. In addition, human locomotion occurs mostly in the sagittal plane. This means that flexion and extension motions dominate our movement repertoire. Therefore, to gain an increased understanding of how translation of the entire human body through space occurs, knowledge of how the leg muscles change in length as the sagittal plane angles of the ankle, hip and knee joints vary is required.

Muscle Function

The main purpose of this study was to construct a two-dimensional (sagittal plane), polynomial regression model that predicted muscle lengths of the lower extremity from changes in the angles of the ankle, knee and hip joints. Joint angles were chosen to be the independent variable as they are easy to measure and rotate (i.e., change position) with changes in muscle lengths. The model was built two-dimensionally in the sagittal plane as the sagittal plane motions, flexion and extension, dominate the human movement repertoire. The reason for choosing to build a polynomial regression model is that past researchers (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) have had success using polynomial regression to mathematically relate muscle lengths to joint angle(s). Hawkins and Hull (1990) have pointed out that this method of modelling benefits from being simple, while at the same time resulting in high regression coefficients.

The muscles of the lower extremity chosen for this study were the monoarticular soleus, vastus lateralis and gluteus maximus, as well as the biarticular gastrocnemius, rectus femoris and biceps femoris (Figure 1.1, 1.2 & 1.3). The rational for choosing these six muscles was as follows:

1) they are surface muscles,

2) they are prime movers of the joints they cross, and

3) they cross the ankle, knee and hip joints.

Table 1.1 describes the main actions of these muscles as defined by Moore (1992) and establishes when these muscle are functioning concentrically (shortening) and eccentrically (lengthening).

Table 1.1: The main actions of the six muscles of interest, as well as the situations in which they are functioning concentrically and eccentrically. Note that a muscle is contracting concentrically when performing its main action and eccentrically when the joint is moving in the opposite direction as the main action of the muscle would predict. For the monoarticular muscles the main action is defined by motion at a single joint. Conversely, for the biarticular muscles the main action is defined by motion at both joints the muscle crosses.

Muscle	Main Action	Concentric Function	Eccentric Function
Soleus	plantar flex ankle	plantar flex ankle	dorsiflex ankle
Gastrocnemius	plantar flex ankle & flex knee	plantar flex ankle & flex knee	dorsiflex ankle & extend knee
Vastus Lateralis	extend knee	extend knee	flex knee
Rectus Femoris	extend knee & flex hip	extend knee & flex hip	flex knee & extend hip
Biceps Femoris	flex knee & extend hip	flex knee & extend hip	extend knee & flex hip
Gluteus Maximus	extend hip	extend hip	flex hip

While it is easy to determine, from the information in Table 1.1, if a muscle is shortening or lengthening during motion at a single joint, it is impossible to predict the change in length of a biarticular muscle when motion is occurring simultaneously at both joints it crosses. For example,

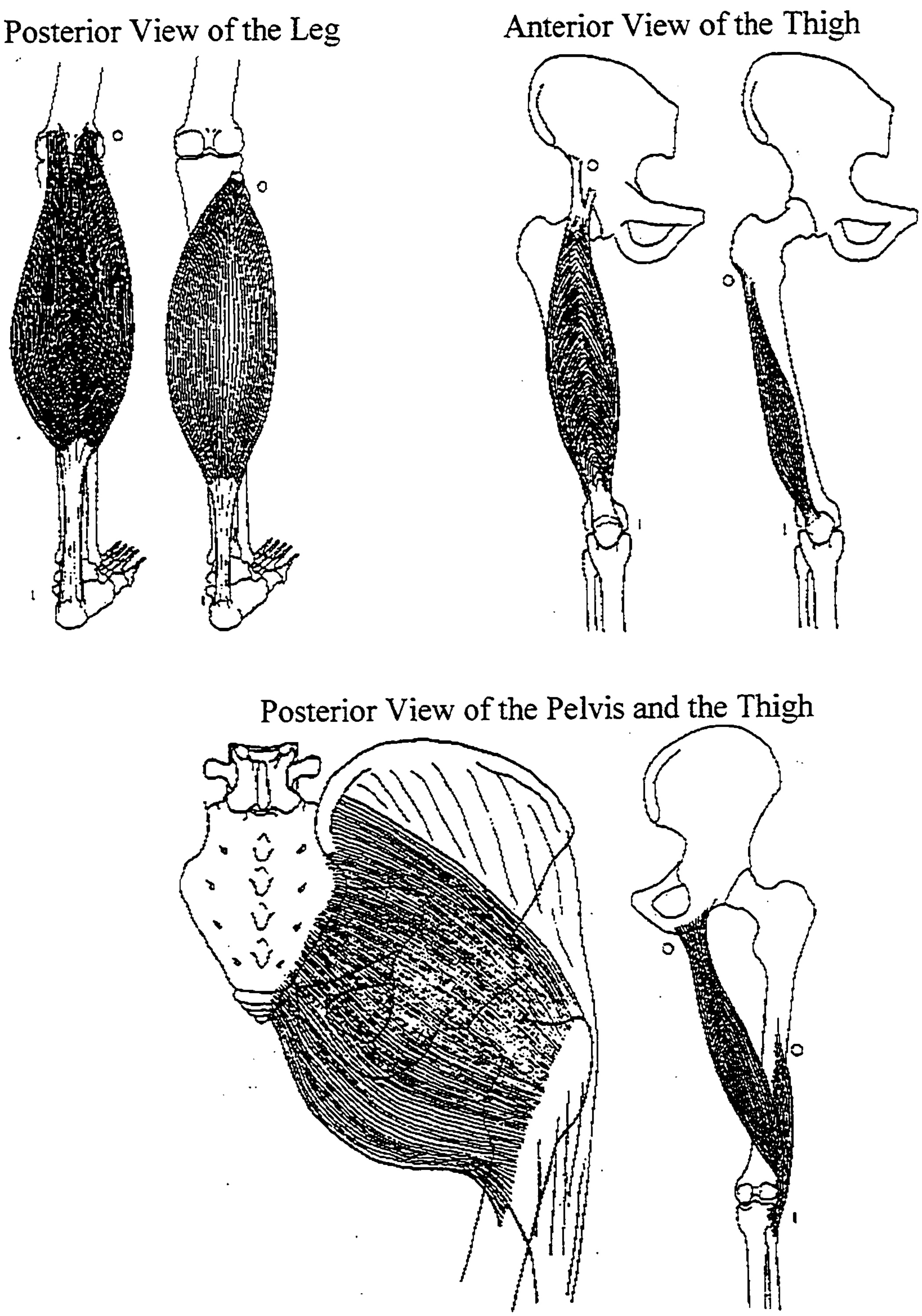


Figure 1.1: Images of the six muscles of interest showing the origin of the muscles, marked as "o", and the insertion of the muscles, marked as "i". Note that the biceps femoris has two origins, each on different bones. It is the long head which inserts on the pelvis that is of interest in this study.

simultaneous flexion at the ankle, knee and hip joints (i.e., squatting) would cause the rectus femoris to act eccentrically at the knee and concentrically at the hip. Does this mean that there was no change in length of the rectus femoris muscle during the squatting motion, or did the action at one of the joints dominate? Research has indicated that the length of the rectus femoris is affected more by motion at the knee than by motion at the hip (Hawkins & Hull, 1990; Visser et al., 1990). Thus, the rectus femoris should be lengthening when both the hip and knee joints undergo flexion.

Other muscles also pose this dilemma. During squatting, the biceps femoris would act concentrically at the knee and eccentrically at the hip and the gastrocnemius would act concentrically at the knee and eccentrically at the ankle given the information in Table 1.1. According to research (Hawkins & Hull, 1990; Visser et al., 1990), the length of the biceps femoris is most affected by the motion at the hip joint, while the length of the gastrocnemius is most affected by motion at the knee joint. Therefore, the biceps femoris should lengthen and the gastrocnemius should shorten during simultaneous flexion of the three major joints of the lower extremity. For a model predicting muscle length to be useful, not only must it accurately predict the proper change in length that a muscle undergoes during motion at a single joint, it must also reflect the unique, and highly unpredictable, changes in length that biarticular muscles undergo during multiarticular motion.

Polynomial Regression Models

Three research teams (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) have built polynomial regression models, relating the lengths of muscles of the lower extremity to joint angles. Their work forms the basis for the muscle length model developed in this study. All three research teams used a common method for measuring muscle lengths at set joint intervals and then applied regression analysis of increasing polynomial degree until no significant difference in degree was observed. This process gave mathematical equation that related muscle lengths to joint angles. In these studies, consisting of eight or fewer cadavers/subjects, the muscles of interest were considered to be straight line segments, connecting the origins of the muscles to the insertions, and the measured lengths were normalized (i.e., divided) by the leg segment length (shin or thigh). Some important differences exist between the three models and they are outlined in the following brief reviews of the papers.

Grieve and colleagues' (1978) model, based on cadaver muscle length measurements taken using spring calipers, predicted the change in length of the gastrocnemius as a function of ankle and knee joint angles. While one of the joints was stabilized the other was manipulated and muscle length measurements were taken at ten degree intervals. This formed the data upon which the model was built using the mathematical procedure described above. It was determined that a second degree polynomial was the equation of best fit for the gastrocnemius muscle at both the ankle and knee joints. The overall length of the gastrocnemius, for any position of the lower limb, was determined to be the algebraic sum of the length change caused by each individual regression joint displacement (Appendix A).

Visser and colleagues (1990) also used cadavers to measure muscle length changes in relation to changes in knee and hip joint angles. Muscle length measurements were taken at every five degrees of joint motion using Vernier calipers. Data collected for the rectus femoris, biceps femoris and gastrocnemius were fitted, using the polynomial regression method previously described, with a second-degree polynomial. The regression equation obtained in this study (Appendix A) was identical in form to that obtained by Grieve and colleagues (1978). As well, both studies ascertained that biarticular muscle lengths could be determined from the algebraic sum of the lengths predicted individually for each joint.

Hawkins and Hull's (1990) muscle length model related the length of sixteen muscles of the lower extremity to changes in angle of the ankle, knee and hip joints. Anthropometric measurements from six male subjects were input to a computer program that predicted muscle lengths from simulated combinations of joint angles varied in fifteen-degree intervals. Results indicated that linear equations best described the relationship between muscle lengths and joint angles, except for the monoarticular muscles crossing the knee which were better described by second degree polynomials (Appendix A). No mathematical interaction of the joint variables was observed for the biarticular muscles. Subsequently, these researchers used the developed muscle length equations to determine muscle kinematics and moment arm lengths (Hawkins 1992).

It was decided for this study that the polynomial regression equations would be used to predict muscle lengths instead of changes in muscle length. The reason for this was two folds. First, when predicting changes in muscle length there must be some preset muscle length value from which the predicted change length is added or subtracted to obtain the current length of the muscle. How to define the muscle length (i.e., resting length) to which changes in length are added or subtracted can be difficult and open to criticism. As well, it requires one more muscle length measurement and one more calculation, which can introduce more error into the determination of muscle length.

Second, the Biomech software used in Chapter 4 requires the lengths of muscles to perform biomechanical analysis of digitized data and produce graphs of muscle velocity versus time. This software is unable to deal with percent changes in muscle lengths without additional programming.

The design of this present, empirical study improves upon that of the three previously described polynomial regression models (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) using:

1) live subjects,

2) a larger number of subjects,

3) both male and female subjects, and

4) a more precise, and three-dimensional, measuring device.

The goal is to produce a polynomial regression model relating muscle lengths to joint angles that is highly predictive of changes in muscle lengths and applicable to all healthy, normal adult subjects. The previously described models (Grieve et al, 1978; Hawkins & Hull, 1990; Visser et al, 1990) were based on data obtained from cadavers or computer simulations and therefore may not be predictive of change sin length in live subjects. It is important to note that this model will not be able to predict changes in muscle length with respect to joint angles for people whose joints are malformed even slightly or whose rotation about the axis has been affected by a recent injury.

Many assumptions must be made when modelling the human form. This aids in simplifying the body into a manageable system to which polynomial regression analysis can be applied. These assumptions were required in this study to collect the data to which the empirical model was fit. The assumptions made in this paper are as follows:

1) muscle length was considered to be the straight line segment between the origin and insertion points (Jensen & Davy, 1972; Grieve et al., 1978; Dostal & Andrews, 1981; Brand et al, 1982, Andrews & Hay, 1983; Hawkins & Hull, 1990; Visser et al., 1990),

2) effective points of origin and insertion (false muscle insertions used as the better define the true line of action of the muscle) were used for muscles which curve or are pennate in nature (Brand et al., 1982; Andrews & Hay, 1983; Hawkins and Hull, 1990),

3) broad attachment areas were represented as points (Andrew & hays, 1983; White et al., 1989; Lu et al., 1998), and

4) all joints were considered to be frictionless joints with one degree of freedom (Andrews & Hay, 1983; Andrews,1985; Hawkins and Hull, 1990).

The polynomial regression model built in this study may experience an effect of gender which was not a factor in the three models (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) outlined above. Males and females differ greatly in the structural anatomy of their lower extremity as the female pelvis is both wider and shallower than the male pelvis (Moore, 1992). This causes females to have more extreme (i.e., less vertical) angles at their hip and knee joints. Therefore, it is possible that the lower extremity muscle lengths of female subjects are unreliably predicted when using models based solely on male data.

Not only does the differences in pelvic anatomy affect the relationship between muscle length and joint angle of the two genders, but so does height. The average height of North American men is higher than that of North American women (Pheasant, 1988). The taller a person the longer the limbs and the longer the limbs the longer the muscles must be to span the limbs. Therefore, on average, men should have longer lower extremity muscles than women. The ratio of the femur to tibia length was constant across all subjects, regardless of gender.

Testing the Model

Ideally, a model relating muscle lengths to joint angles would be tested by comparing the lengths predicted by the model to the actual lengths of the muscles measured *in vivo*. The lower the residual mean square error (RMSE) between the predicted and actual observed lengths, the more reliable the model and as a result the more accurate the predictions. The RMSE is equal to the sum of the squares of the difference between the observed and the predicted value divided by the degrees of freedom within the model. Unfortunately, these steps were impossible to perform as it is considered unethical to perform medically unnecessary surgeries on humans. In the future it is likely that scans showing the lengths of muscles at different joint angles will become the accepted standard used to validate new muscle length models, as the availability of medical imaging techniques to researchers increases. Unfortunately, it is currently not feasible, due to expense and lack of availability, to use medical imaging devices.

Therefore, support for the newly developed model in this study was obtained by quantitatively determining the RMSE between the values predicted by the model and the actual observed values (measured externally), as well as by qualitatively comparing the predictions of the new model to those of published models. Unfortunately, measuring muscle lengths externally is more susceptible to errors than doing measurements internally or using scans. Since external measurements were the best representation of actual muscle length values available for this study, they were used as the standard to which the muscle length values predicted by the polynomial regression model were compared. The smaller the RMSE between the observed and the predicted values, the better the model

Qualitative comparison between different models predicting muscle lengths have been used in the past to support newly developed models. For example, Hawkins and Hull (1990) compared the results predicted from their muscle length model to the results obtained using Bobbert and colleagues' (1986a) model, as well as the model developed by Grieve's research team (1978). The consistency seen across the models increased the odds that Hawkins and Hull's (1990) predicted muscle length values were reflective of actual muscle lengths. While this consistency lent support to the model, it in no way guaranteed it's reliability, as Hawkins and Hull (1990) only compared their muscle length model to other models based on regression analysis (Grieve et al., 1978; Bobbert et al., 1986a). It was possible that although the results were consistent, there was a fatal flaw present in all of the regression models that led to the prediction of very inaccurate muscle lengths.

Therefore, the regression model built in this study will have its results compared to those obtained using Frigo and Pedotti's (1978) triangle based model. Consistency between these two models, based on different mathematical principles, will provide increased support for muscle length models built using regression analysis.

Frigo and Pedotti (1978) used geometry and trigonometry to examine changes in length of eleven muscles of the lower extremity with respect to joint angles. The lower limb was reduced to a three-link system consisting of the thigh, leg and foot, with three angular coordinates representing the hip, knee and ankle joints. Determination of the instantaneous lengths of the muscles required the recording of the three angular coordinates over time. The origin and insertion points of the muscles were approximated and the lengths of the muscles were estimated using straight-line segments. From this data, geometry and trigonometry were used to create functional triangles from which muscle lengths could be predicted. Unfortunately, discontinuities were observed in this model when a change over between triangles occurred.

A study performed by Pierrynowski and Morrison (1985) provided support for both Frigo and Pedotti's (1978) triangle based model and Grieve and colleagues' (1978) regression model. The results of this study indicated that the muscle lengths predicted from the triangle based model and from the regression model were comparable. It also provided additional support for muscle length models built using polynomial regression analysis.

Objectives

A model relating height-normalized muscle lengths to joint angles was built in Chapter 2. This model was constructed using the method of polynomial regression analysis of increasing degree until no significant difference in degree, as determined using an ANOVA, was observed. This was the same methodology used in past work performed by Grieve and colleagues (1978), Hawkins and Hull (1900) and Visser and colleagues (1990). The only change in methodology was the use of height as the factor for normalization. Height was substituted for leg segment length as these two anatomical variables were highly correlated, but height was easier to define and measure. As well, the effect of gender on the relationship between muscle length and joint angle(s) was also examined. It was predicted that the relationship between muscle length and joint angle(s) would be greater in order than first-degree and that there would be an observed difference between the genders.

Chapter 3 compared model fit (i.e., R^2 values) using height-normalized, leg segment length-normalized, and individual regression data sets. As leg segment length was highly correlated to height, it was predicted that normalization by leg segment length would not improve model fit (i.e., higher R^2 values) above that obtained using normalization by height. If this was the case, then other anthropometric variables would be tested to see if they were better variables to be used for normalization (i.e., increase the R^2 values). If normalization was completely unsuccessful in increasing model fit, then transformation of the data would be attempted.

At this point, the methodology of the study deviated from that of the past studies (Grieve et al, 1978; Hawkins & Hull, 1990; Visser et al, 1990) on which it was based, as transformation of the data was never required. If transformation of the data was also unsuccessful, then it could be concluded that linearization of the data was impossible. The solution to this problem would be to apply forward selection polynomial regression, coupled with transformation and the addition of anthropometric variables to the right hand side of the equations, in an attempt to increase the predictability of the equations.

Chapter 4 quantitatively and qualitatively examined the newly built polynomial regression model. These equations were used to predict the muscle length of one male and one female subject. First, the muscle lengths predicted from the polynomial regression equations were compared to the length of the leg segment they span. If the predicted length was much longer or shorter than the leg segment length the prediction was considered to be anatomically impossible and the corresponding equations were discarded.

Next, the predicted muscle curves of the newly developed polynomial regression model were qualitatively compared to those obtained using the individual regression equations and Frigo and Pedotti's (1978) triangle based model to determine if the muscle were performing their proper function throughout the motion. Further quantitative comparison was then performed as the RMSE between the predicted and the actual observed muscle lengths was calculated.

Justifications

Researchers, coaches and health care professionals use mathematical models to help them simplify, analyze, describe and understand complex human motions. A model must be general enough to be useful in different situations and to be applied to different subjects. It also must be simple enough that it is easy for the user to understand and apply. This must be accomplished without sacrificing the too much of the reliability of the model and the accuracy of its predictions. Therefore, it is a balance between generality and accuracy the must be attained for a model to be useful.

A model able to determine whether a major muscle of the lower extremity is lengthening, shortening or remaining the same length aids in determining the role that particular muscle plays during motion. The information provided by this type of model is useful to researchers analyzing human motion as it allows them to classify and define muscle function. From this, a greater understanding of how muscles contribute to human movement can be attained. Increased knowledge of the musculoskeletal system can lead to the development of new knowledge and theories with more practical applications.

In addition, a model defining changes in muscle lengths can have many direct and practical applications. It can be used by coaches and trainers to analyze an athlete's technique. Variances from proper technique and muscle inefficiencies can then be detected and changes implemented, which in turn lead to improved athletic performance. More importantly, a model of this type can be used in rehabilitative centres to analyze the gait patterns of patients having difficulty walking (e.g., accident victims, stroke patients and persons suffering from cerebral palsy). A comparison of muscle function during abnormal gait to normal gait provides the health care professional with information as to the nature of the problem, as well as the changes required to improve (i.e., make more efficient) the walking pattern.

A model predicting muscle lengths from joint angles based on muscle lengths measured externally will never be as exact as one which is based on muscle lengths measured using imaging techniques. Unfortunately, imaging techniques are not widely available for nonmedical research at this time. So although the ideal is not currently available, the necessity for and the wide spread usage of such a model makes the development of the most predictive model based on the most current equipment justified. In other words, it is preferable to have the best model available at the time based on external measurements then to do without until the ideal can be achieved.

Chapter 2
Building the Model

Introduction

Human motion results from changes in muscle lengths that cause joints to rotate about their axes. This leads to the translation of body segments through space. While changes in joint angles during motion are readily visible, and therefore easily measured, muscle lengths are impossible to measure directly without the use of invasive techniques. However, muscle lengths can be determined indirectly (i.e., noninvasively) by relating muscle lengths to joint angles through the application of equations developed using polynomial regression analysis. More specifically, mathematical equations were developed using least squares polynomial regression analysis of increasing degree until an analysis of variance shows no significant difference with the increase in polynomial degree.

Research (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) using polynomial regression analysis to build muscle length models has indicated the relationships between lower extremity muscle lengths and joint angles are either linear or quadratic in nature. Grieve's research team (1978) examined the gastrocnemius muscle of cadavers and determined the relationship between muscle length and joint angles to be quadratic. A second degree polynomial was also determined to be the best fit for the gastrocnemius, rectus femoris and biceps femoris muscles according to the trends observed in cadavers studied by Visser and colleagues (1990). It is important to note that when using polynomial regression the anatomical and/or physiological significance of the higher order terms (i.e., greater that first-order) is generally not known.

In contrast, Hawkins and Hull's (1990) study using computer simulations, based on the anthropometric data of male subjects, there was found to be a linear relationship between muscle length and joint angle for the gastrocnemius, rectus femoris, biceps femoris, soleus and vastus lateralis muscles. More generally, a linear equation was determined, by these two researchers (Hawkins & Hull, 1990), to be the best fit for all muscles of study, with the exception of the monoarticular muscles crossing the knee joint. The regression equations developed in these three studies (Grieve et al, 1978; Hawkins & Hull, 1990; Visser et al, 1990) are outlined in Appendix A.

Hawkins and Hull's (1990) finding that linear equations were adequate in describing the relationship between lower extremity muscle lengths and joint angles may have resulted from these researchers measuring muscle lengths at every fifteen degrees throughout the range-of-motion (i.e., over fitting). In comparison, the other two research teams (Grieve et al., 1978; Visser et al., 1990), who took measurements at smaller joint intervals, determined these same relationships to be second degree polynomials. It is possible that the large joint intervals used by Hawkins and Hull (1990) did not allow for enough sensitivity for a higher order polynomial to be detected when in fact it really did exist.

By decreasing the joint interval size, (i.e., number of degrees the joint is manipulated between measurements) Grieve's (1978) and Visser's (1990) research teams increased the number of measurements. This provided for a greater number of points to be plotted and, therefore, was likely to provide a more reliable representation of the relationships between muscle lengths and joint angles. In other words, by decreasing the joint interval, the sample size, and thus the resolution increased, and in this manner the researchers (Grieve et al., 1978; Visser et al., 1990) increased their ability to detect nonlinear effects if there were in fact present.

The present study used polynomial regression equations to relate muscle lengths to joint angles and built upon its predecessors (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) in the following ways:

1) live subjects were used,

2) a larger number of subjects were used,

3) both male and female subjects were used, and

4) more precise, and three-dimensional, measuring equipment was used.

Errors were introduced into these past studies (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) by using cadavers and computer simulations that ignored the effect of gravity/muscle tone and interindividual regression differences, respectively. This, combined with the low number of cadavers/subjects used in the studies, increases the chances that the developed equations are not truly representative of the population at large. In addition, calipers precise to 1 mm were used to measure the lengths of the muscles. It is predicted that with the use of live subjects, of both genders, and a more sensitive measuring instrument (the Microscribe, precise to 0.23 mm) improvements can be made upon these models, while still applying the same methodologies.

Hypothesis

1) The human body is a complex machine and very few biological and/or physiological relationships are linear in nature. More specifically, muscle length is not linearly related to the active tension that can be developed in a muscle (Wilmore & Costill, 1994). The active tension increases with muscle length up to resting length and then the tension decreases as this resting length is surpassed. Muscle length is strongly correlated to both tension and joint angle. Since the relationship between muscle length and tension is not linear, then it was hypothesized that the relationship between muscle length and joint angle(s) was also not linear.

Prediction

1) It is predicted that the relationship between muscle length and joint angle(s) will be best described by a polynomial greater than first degree (i.e., linear).

The lower extremity of males and females differ greatly due to gender differences in the anatomy of the pelvis and differences in height. Women have wider hips, thus the coronal angles at their hip and knee joints are more extreme than those of men (Moore, 1992). This means that the lower extremity muscles of males and females have different lines of action. As well, males tend to be taller than females, thus their lower extremity leg segments, and as a result their lower extremity muscles, will be longer than those of females. Therefore, it was expected that different equations would be required to describe the relationship between muscle length and joint angle of males and females.

The polynomial regression equations were built upon data that had been normalized by height. This means that for each subject the dependent variable (i.e., muscle length) was divided by the subject's height. Normalization was performed in an effort to put all subjects, regardless of height, on the same scale for direct comparisons. The reason for choosing height as the anatomical variable for normalization was the ease with which it can be defined and measured, as well as its relationship with muscle length. The taller a person, the longer their muscles must be to span the joints.

Materials and Methods

Subjects

Twelve volunteer subjects participated in this study, six males (ages 23-31) and six females (ages 21-27). Since joint range-of-motion decreases in adults during the normal aging process, young adults were used for this study to ensure that muscle length measurements could be taken over a large range of joint motion.

The male subjects ranged in height from 173.5 cm to 184.0 cm with a mean of 177.25 cm and a standard deviation of 4.01 cm. Their weight varied from 70.2 kg to 90.7 kg with a mean of 78.7 kg and a standard deviation of 7.6 kg. According to Pheasant's (1988) anthropometric measurements for American populations, all of the male subjects fell within the fifth and ninety-fifth percentile for height and weight.

The females ranged in height from 152.0 cm to 171.30 cm with a mean of 161.58 cm and a standard deviation of 9.23 cm. Their weight ranged from 50.3 kg to 80.7 kg with a mean of 65.8 kg and a standard deviation of 12.3 kg. Again, the height and weight values fell within the fifth and ninety-fifth percentile of the height and weight of American female adults (Pheasent, 1988). Subjects who had heights and weights within the fifth and ninety-fifth percentile were used to ensure that the developed regression equations represented the normal population and not the extremes.

The subjects all resided in the Ottawa area and exercised at least three times a week for a minimum of 30 minutes. All subjects were free of pathological and neurological problems in their lower extremities and none had experienced an injury to the left lower limb in the past two years. Each subject read and signed a consent form, approved by the Ethics Board at the University of Ottawa, prior to the commencement of data collection (Appendix B).

Pre-Test

Subjects were tested one at a time in the laboratory. The subject's height and weight were measured and recorded. Styrofoam markers were placed on the origin and insertion points of the six muscles of interest, as well as at the centre(s) of rotation of the ankle, knee and hip joints (Table 2.1 & 2.2). The markers had an ink dot located in the middle and this point was positioned over the centres of attachment of the muscles and the centre(s) of rotation of the joints. The distance between the lateral markers placed on the joint centre(s) of rotation was measured using an anthropometric measuring device to obtain the length of the leg and thigh segments. Only one leg was marked and measured as Hawkins and Hull (1990) determined there was no difference between right and left side measurements when building their regression model.

Table 2.1: Anatomical location of the origin and insertion points of the six muscles of interest. Note that effective attachment points were used for origin of the gastrocnemius, as well as the origin and insertion of the gluteus maximus.

MUSCLE	ORIGIN	INSERTION
Soleus	fibular head	calcaneus
Gastrocnemius	midway between femoral condyles	calcaneus
Vastus lateralis	lateral greater trochanter	tibial tuberosity
Rectus femoris	caudal anterior inferior iliac	tibial tuberosity
Biceps femoris	ischial tuberosity	fibular head
Gluteus maximus	mid sacrum lateral edge	lateral greater trochanter

Table 2.2: Anatomical location of the centres of rotation of the three joints of interest. The ankle and knee were considered hinge joints with the centre of rotation defined both laterally and medially. The hip was considered a ball and socket type joint with only one centre of rotation located at the midpoint of the ball of the femur. All three joints were provided only one degree of freedom.

JOINT	TYPE	POINT 1	POINT 2
Ankle	Hinge	lateral malleolous	0.5 cm below medial malleolous
Knee	Hinge	midway between lateral condyles	midway between medial condyles
Hip	Ball	1 cm anterior to the tip of the greater trochanter	

Testing

Data collection for this stage was divided into six sections named: Ankle, Knee1, RF & BF, Knee2, GA and Hip. For all sections, the passive mode of the KinCom machine (an isokinetic dynamometer) was used to monitor changes in joint angle during lower extremity flexion and extension. The Microscribe, an articulated three-dimensional measuring device precise to 0.23 mm within a 1.27 m diameter volume, was placed on a tripod and used to digitize the location of the muscles' origins and insertions, as well as the joints' centres of rotation. An image of the KinCom and the Microscribe can be found at the following Web site: www.health.uottawa.ca/biomech/lab/equip.htm.

It is important to point out that it is the complete muscle-tendon unit that is being measured and not just the length of the muscle itself. The reason for this is twofold. First, tendons experience virtually no change in length throughout the normal range of motion, unless a heavy load is applied (Nordin & Frankel, 1989). As motion in this study took place within the normal range under a situation of no loading, then it can be assumed that no change in tendon length occurred. Therefore, the difference between the length of the muscle-tendon unit at two different joint positions is a direct result of the change of length of the muscle. Secondly, it is easier to palpate tendon insertions on bones than tendon insertions on muscle. By using the muscle-tendon unit there is a decreased chance of erroneously marking the points of attachments.

Subjects were asked to perform the required flexion/extension movements within their comfortable range-of-motion. This ensured that the muscles were not stretched or compressed to the point where their physiological integrity was compromised. Active tension in a muscle is produced when the actin and myosin filaments dynamically interact in a process called cross bridge cycling (Nordin & Frankel, 1989). At muscle lengths much less than resting length the overlap of the actin and myosin filaments interferes with the cross bridge cycling required to produce tension. Cross bridge cycling is also adversely affected at muscle lengths much longer than resting length where there is little overlap of the filaments. Therefore, when considering active tension alone, the amount of force generated by a muscle increases as it approaches resting length and then decreases as it moves away from resting length.

However, the relationship between muscle length and tension is not this simple as this as the muscle also has noncontractile components and connective tissue, both of which passively contribute to force production (Nordin & Frankel, 1989). At muscle lengths greater than resting length the passive tension of the muscle increases. Passive tension results from the stretching of the series and parallel elastic components that include the tendons/ligaments and the noncontractile portions of the muscle respectively. The net result of the active and passive tension is the maintenance of and then increase of total tension following resting length.

Monoarticular muscles are not usually stretched to the point where passive tension contributes greatly to total tension. On the other hand, passive tension contributes greatly to the total tension of biarticular muscles (Nordin & Frankel, 1989). For example, when the hip is flexed and the knee extended the hamstrings muscles are so stretched that the passive tension causes the knee to flex if the hip is moved further into flexion. Therefore, when measuring the biarticular muscles the position of stabilized joint (i.e., the joint whose angle does not change) can effect the range of motion through which the second joint can move.

Based on the results of a pilot study, measurements were taken for every 5° of motion at the ankle and hip, and every 10° of motion at the knee. For muscles crossing the hip joint, or the hip and knee joints, the ankle's centres of rotation were digitized at one joint position only, while the centres of rotation of the hip and knee were digitized at each joint position. Conversely, for muscles crossing the ankle joint, or the ankle and knee joints, the hip's centre of rotation was digitized at one joint position.

Ankle

A modified ankle plantar/dorsiflexion attachment was fitted to the load cell on the lever arm of the KinCom. The subject was required to sit on the right seat of the KinCom with the backrest in the upright position. Their left foot was strapped into the attachment while their right foot rested gently on the console between the machine and the lever arm. The subject was instructed to hold the panic button for all sections of testing and to press it if they felt uncomfortable or nervous at any time. Pressing of the panic button would cause the KinCom machine to shut down.

Ankle testing began with the joint positioned at full extension (plantar flexion) and this start angle was measured using a hand held goniometer. Following the defining of the reference plane used by the Microscribe, the origin and insertion points of the soleus and gastrocnemius were digitized, as well as the location of the centres of rotation of the three joints. The ankle angle was then decreased by 5° and the above anatomical landmarks, with the exception of the hip centre of rotation, were digitized again. This was repeated every 5° throughout the range-of-motion with the experimenter aiding the subject in moving their joint between the desired angles. Testing ended when full ankle flexion was reached.

Kneel

The shin pad attachment was connected to the load cell on the KinCom's lever arm. A rigid foam tag with an indented marker was attached to the point of origin of the biceps femoris. This indented marker, placed 200 mm and at an angle of 35° from the origin of the biceps femoris, represented the actual attachment point on the ischial tuberosity, which was unreachable in the sitting position. The subject sat on the right side of the KinCom machine and had their left leg strapped to the shin pad. Again, the right foot rested on the KinCom console and their back rested firmly against the backrest in the upright position (100°).

The start position for this section was the greatest degree of knee flexion the subject could attain comfortably while sitting on the KinCom. This angle was measured using a hand held goniometer. The plane of the Microscribe was defined followed by the digitization of the origin and insertion of the vastus lateralis, rectus femoris and the biceps femoris, as well as the centres of rotation of the knee and hip joints. The knee angle was successively increased in 10° increments and these anatomical landmarks were digitized at each joint angle until full extension was reached. In this position the centres of rotation of the ankle joint were also digitized.

RF&BF

The subject remained seated on the Kin Com machine in the same position as described in the Knee1 section. The only change was a foam pad placed between the subject's back and the backrest of the KinCom that decreased hip angle from 100° to 85°. The subject then moved their knee through the same range-of-motion (from flexion to full extension) as before and all points were again digitized. The only exception was the origin and insertion points of the vastus lateralis, which were excluded, as this muscle does not cross the hip joint. This process of digitizing at increasing knee angles was repeated three more times with the seat reclined at angles of 115°, 135° and 180°. As there was no change in the starting, or ending, knee angle used in this section and the previous section (Knee1), the centres of rotation of the ankle in the end position was assumed the same for all hip positions.

Knee2

The subject remained sitting on the KinCom in the same position as described in the Knee1 section. The knee was moved through its previously determined, comfortable range-of-motion with digitization still taking place at every 10°of motion. The ankle remained relaxed and this angle was measured in the starting position with a hand held goniometer. For this section, the origin and insertion of the gastrocnemius, along with the ankle and knee joints' centres of rotation, were digitized at each joint position. After the knee had been moved through its full range-of-motion the leg was returned to the start position and the plane of the Microscribe was redefined to digitize the hip's centre of rotation.

GA

The procedure used for this section was exactly the same as that used for the Knee2 section, except at each knee angle all anatomical points of interest were digitized with the ankle in full extension and then in full flexion. These two ankle angles were measured using a hand held goniometer. The subject did not change positions between the Knee2 and GA sections so the centre of rotation of the hip was assumed the same.

Hip

For this section, the subject stood facing away from the KinCom seat with the shin pad positioned on the front of their thigh. The subject lifted their knee from a starting position of 180° (measured with a hand held goniometer) into the air causing the hip angle to decrease. The location of the origin and insertion of the gluteus maximus, rectus femoris and biceps femoris, as well as the centres of rotation of the hip and knee joints, were digitized at every 5° of hip motion. At the end angle the Microscribe was moved and its plane redefined to digitize the ankle's centres of rotation.

Results

General Trends

For the biarticular rectus femoris and biceps femoris, it can be observed that as knee joint angle increased the length of the rectus femoris decreased and the length of the biceps femoris increased for any hip angle (Appendix C - I, II, III & IV). As the hip angle increased the rectus femoris increased in length and the biceps femoris decreased in length for any knee angle. The gastrocnemius, the third biarticular muscle of study, increased in length as the knee joint angle increased for any ankle angle and decreased in length as ankle joint angle increased for any knee angle (Appendix C - V & VI).

All other relationships in this study examined the change in lengths of muscles as a result of varying the angle of only a single joint. Increasing ankle joint angle decreased the length of the soleus and the gastrocnemius muscles (Appendix C - VII, VIII, IX & X). However, two female subjects (1F & 3F) and one male subject (3M) did not exhibit this trend for the gastrocnemius. A retest was performed on a female subject and the results confirmed that as ankle joint angle increased the length of the gastrocnemius decreased. In contrast to the effect of the ankle on the gastrocnemius, increasing the angle of the knee led to an increase in the length of the gastrocnemius (Appendix C - XI & XII).

Other muscles crossing the knee joint were inspected. Increasing the knee joint angle caused a decrease in the length of the vastus lateralis and the rectus femoris of the female subjects only (Appendix C – XIII & XV). The male subjects showed an initial increase in the length of these two muscles followed by a decrease in length as knee joint angle increased (Appendix C – XIV & XVI). A retest confirmed this was the observed pattern for the male subjects. Only one female subject (5F) exhibited this peak shape, but all of the female subjects showed a plateau prior to the decrease in muscle length.

The observed relationship between the angle of the knee joint and the length of the vastus lateralis and the rectus femoris was anatomically impossible. No constant decrease in muscle length during knee flexion was observed as expected. The reason for this was the breakdown of the straight-line approach being used in this study. As outlined in the introduction, it was assumed that all muscles act in a straight line between their points of origin and insertion. However, this causes a problem for muscles crossing the anterior of the knee where the patella acts as a pulley around which the muscles curve. This curvature causes the straight-line approach to become ineffective, especially as flexion increases.

To obtain a more true reflection of how the vastus lateralis and rectus femoris change length with knee joint angle, a modified version of the patella pulley model was applied (Brand et al., 1982). The patella pulley model (Brand et al. 1982) is a three-dimensional model based on internal anatomical measurements performed on cadavers. It assumes that the muscles crossing the anterior of the knee slide over the patella as if it were a frictionless pulley. The line of action of a muscle once it has crossed the patella is circular in nature. At small joint angles the effect of the patella is much less than at larger degrees of flexion.

As this study was two-dimensional and did not use cadavers to obtain muscle length measurements, a modified version of the patella pulley model was applied. The length between the middle of the patella and the tibial tuberosity was subtracted from the total length of the muscle. In its place the calculated length of the arc between the mid-patella and the tibial tuberosity was added (Appendix D). Although a deviation from the straight-line approach, it appeared to give a more reliable reflection of the changes in length of the vastus lateralis and rectus femoris during knee extension as observed by the constant decrease in length during knee extension. As a result, it was decided that the modified patella pulley model would be used for the remainder of this study (Appendix C – XVII, XVIII, XIX & XX). Application of the modified patella-pulley model removed the plateaus seen in the female data and the peaks seen in the male data, creating a more constant decrease in the lengths of the muscles as the knee joint extended.

The modified patella pulley model was also applied to the length of the rectus femoris when being examined biarticularly. Although it had no effect on the general trends observed at the hip and knee joints that were previously described, it provided a more reliable representation of the relationship between the muscle length and knee angle at each hip position (Appendix C – XXI & XXII).

The relationship between biceps femoris length and knee joint angle was much less complicated, as there was no patellar effect. However, as the actual origin point of the biceps femoris could not be digitized (the subjects were sitting on their ischial tuberosities) a point on a semi-rigid foam pad, at a known distance and angle from the real origin, was digitized instead. The real length of the biceps femoris was calculated from this measured length using the sine law (Appendix E). The results showed that the biceps femoris increased in length as the angle of the knee increased, for both the male and female subjects (Appendix C – XXIII & XXIV).

There was no trend observed between changes in hip joint angle and gluteus maximus length. This muscle seemed to fluctuate randomly as hip joint angle increased (Appendix C - XXV & XXVI). The use of effective attachment points was not enough to enable the straight-line approach to reliably describe the length of this pennate muscle. Therefore, the gluteus maximus was removed from the study.

Obvious trends between hip joint angle and muscle length were observed for the rectus femoris, which increased in length with increasing hip joint angle, and the biceps femoris, which decreased in length with increasing hip joint angle (Appendix C – XXVII, XXVIII, XXIX & XXX).

Jackknife Analysis

Jackknife analysis, which is a resampling procedure, was performed to ensure that the chosen joint intervals did not lead to over-fitting of the regression equations. What the jackknife did was repeatedly refit the regression model to the data set while removing a single datum each time. The newly obtained regression coefficients were then compared to the 95% confidence interval. If the coefficients fell within the 95% confidence interval, the result was considered acceptable and no over-fitting of the data was thought to have occurred. However, if the regression coefficients fell outside the 95% confidence interval over-fitting of the data was a potential problem.

If over-fitting of the data were observed it would mean there was a possibility that a linear regression equation was fitted to the data, when in fact a second degree polynomial was the better fit. This would have resulted from data being collected at joint intervals that were too large (i.e. resolution was too large) to detect a difference between polynomial orders.

To perform the jackknife analysis the following steps were carried out:

- Fit a General Linear Model (GLM) to the data with muscle length as the dependent variable and joint angle as the independent variable,

- Use code received from the GLM output to code for the jackknife and specify that the regression coefficients be saved, and
- Open saved regression coefficients and compare to the 95% confidence intervals.

For each of the ten subjects jackknife analysis was performed eight times, once for each situation where a muscle crossed a joint. The end result was that jackknife analysis was applied once to monoarticular muscles and twice to biarticular muscles, once at each joint they crossed. Next the 95% confidence intervals for the coefficients obtained from the jackknife analyses were calculated. Only in three of the eighty cases (3.75%) were over-fitting of the data observed. Therefore, over-fitting was not a severe problem in this study and the joint intervals used to collect the data were of sufficient size to detect the difference between a linear and quadratic relationship.

Polynomial Order

For each subject, graphs were created relating monoarticular and biarticular muscle length to a single joint angle. Up to sixth-degree polynomials were fitted to each individual regression subject's data sets for each muscle length-joint angle relationship and observed R^2 values were recorded. In an effort to preserve simplicity, the best polynomial equation was considered to be the lowest order at which no increase in degree caused a significant increase in the R^2 value.

As the assumptions for an analysis of variance (ANOVA) were not met, a nonparametric ANOVA ($\alpha = 0.05$) on the ranked R^2 values obtained from the polynomial regressions of each individual regression subject was performed. A nonparametric ANOVA, also called a Kruskal-Wallis ANOVA, uses the ranked values of the dependent variable instead of the actual values. It is particularly useful in situations; such as exist in this study, where sample size is small.

Following the nonparametric ANOVA, a Tukey's *post hoc* showed there to be no difference

($p>0.05$) between the linear and quadratic equations for the muscles crossing the hip and ankle joints. This means that the increase in polynomial from first to second degree did not lead to a significant improvement in model fit. Conversely, the same Tukey's *post hoc* showed a significant difference ($p<0.05$) between the first and second degree polynomial at the knee, with the second degree polynomial being the better fit (i.e., higher R^2 values). There was no improvement in fit when increasing the degree from second to third. Therefore, the relationships between muscle lengths and joint angles were determined to be linear for the muscles crossing the ankle and hip joints, and quadratic for the muscles crossing the knee joint (Table 2.3). The only exception to this trend was the biceps femoris, which exhibited a linear relationship at the knee joint.

The biarticular muscles, when affected by dual joint manipulation, required the testing of more complicated equations, based on polynomial regression with backwards selection, as their length is affected by two variables:

1) $\text{length} = a + b(\text{joint1}) + c(\text{joint1})^2 + d(\text{joint2}) + e(\text{joint2})^2 + f(\text{joint1}*\text{joint2})$
2) $\text{length} = a + b(\text{joint1}) + c(\text{joint1})^2 + d(\text{joint2}) + e(\text{joint2})^2$
3) $\text{length} = a + b(\text{joint1}) + c(\text{joint1})^2 + d(\text{joint2})$
4) $\text{length} = a + b(\text{joint1}) + c(\text{joint2}) + d(\text{joint2})^2$
5) $\text{length} = a + b(\text{joint1}) + c(\text{joint2})$

Where a = constant

b, c, d, e, f = regression coefficients

joint 1 = knee joint angle in degrees

joint 2 = hip or ankle joint angle in degrees

The rectus femoris and gastrocnemius exhibited quadratic relationships at the knee and linear relationships at the hip and ankle, respectively. For each subject's data these two muscles were fitted with equations that examined the interaction of the two joints, both variables as second degree polynomials, and the knee as a second degree polynomial with the hip/ankle variable expressed linearly (equations 1, 2 & 3). In comparison, the biceps femoris exhibited linear relationships at both spanned joints (hip and knee). This lead to the possibility that both joint variables could be expressed linearly and therefore all five of the above equations were fitted to this muscle for each subject's data.

A nonparametric ANOVA ($\alpha = 0.05$) on all of the subject's ranked R^2 values followed by a Tukey's *post hoc* indicated for the rectus femoris and gastrocnemius that there was no significant difference ($p>0.05$) in fit between the three equations tested. Therefore, in an effort to preserve simplicity, Equation 3 was chosen as the model of best fit. The same statistics were performed on the biceps femoris and again there was no statistical difference ($p>0.05$) observed between any of the equations tested. Using the principle of simplicity, Equation 5 was chosen as the model of best fit (Table 2.3).

Table 2.3: Polynomial order of the regression equations relating muscle lengths to joint angles. The biarticular muscles are listed three times; once at the proximal joint, once at the distal joint and finally at both joints. When listed at both joints the polynomial order is defined first at joint 1 and then at joint 2. The monoarticular muscles are listed only once.

Muscle	Joint 1	Joint 2	Polynomial Order
Soleus	ankle		linear
Gastrocnemius	ankle		linear
Gastrocnemius	knee		second degree
Vastus Lateralis	knee		second degree
Rectus Femoris	knee		second degree
Biceps Femoris	knee		linear
Rectus Femoris	hip		linear
Biceps Femoris	hip		linear
Rectus Femoris	knee	hip	second degree/linear
Biceps Femoris	knee	hip	linear/linear
Gastrocnemius	ankle	knee	linear/second degree

In addition to polynomial equations, logarithmic, power and exponential equations were also fitted to the individual regression data sets. Although all four types of equations provided a reasonable fit, the polynomial equation, either linear (Appendix F) or quadratic (Appendix G) was always the best fit. The next best fit was the exponential equation. The power and logarithmic equations were a slightly worse fit and this fact was emphasized with the increase in polynomial order from first to second. These results, coupled with the fact that past researchers have worked with polynomial equations (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990), lead to the continuation of the use of polynomial equations throughout this study. In future work it may be interesting to examine the effect of using exponential equations to describe the relationship between muscle length and joint angle(s).

Effect of Gender

One male and one female subject were removed from the study at this point. They were removed so that their data could be used later on to test the general polynomial regression equations being built upon the other ten subjects' data. The two subjects were selected out of the group of twelve for two reasons. First, they had no trials that needed to be discarded due to anatomically impossible trends (i.e., muscles observed not to be constantly increasing or decreasing). Second, these subjects were available to return to the lab for additional testing.

Once the general polynomial regression equations were determined, they were applied to these two subjects data without a bias, as the general equations were not based on the data from these subjects. It was then possible to compare the muscle lengths predicted for these two subjects using the equations to the actual muscle lengths measured using the Microscribe. The RMSE between the predicted and measured lengths could then be calculated to determine how well the general model predicts the length of muscles in the population outside of the sample group.

The two nonparametric ANOVAs previously discussed also tested for the effect of gender on polynomial order. No difference in polynomial order between the genders was detected ($p>0.05$), except for the effect of hip joint angle on the length of the biceps femoris muscle. Here a statistical difference was observed so the order of the polynomial was determined separately for each gender. Results showed the relationship between biceps femoris length and hip joint angle was linear for both males and females.

A second ANOVA ($\alpha=0.05$) was performed to determine if gender has an effect on muscle length. A statistical difference ($p<0.05$) between the genders was observed, with males having longer muscle lengths than females. This intuitively makes sense as the males in this study have a larger mean height than the females and height and muscle length are anatomical variables that were strongly correlated.

All data were normalized by subject height and then grouped according to gender. Polynomial regression equations relating muscle lengths to joint angles for each gender were determined for the following five relationships:

1) effect of the ankle on the soleus,
2) effect of the ankle and knee on the gastrocnemius,
1) effect of the knee on the vastus lateralis,
2) effect of the knee and hip on the rectus femoris, and
3) effect of the knee and the hip on the biceps femoris.

It was deemed acceptable to express the length of the biarticular muscles using only the equation relating muscle length to both joint angles. Past research has shown that the results obtained using this method is the mathematical equivalent of that obtained through the combination of the two equations that determine biarticular muscle length based on a single joint angle (Grieve et al., 1978;

Hawkins & Hull, 1990; Visser et al., 1990). In other words, for biarticular muscles it is unnecessary to use two equations and add the results together, when one single equation with multiple variables (i.e., two joints) can produce the same result.

From a statistical point of view, a multiple regression model is more realistic and general than two regression models, each with a single independent variable. The multiple regression model built in this study was based on polynomial regression. Since polynomial terms are strongly correlated there is a decrease in precision with increases in the order of the terms. Fortunately, the highest order used in the study is second degree so the effect on precision should be low.

In addition, equations relating biarticular muscle length to a single joint angle are only of use if the joint not being manipulated is in the same position it was in when the data upon which the equation was built collected. Therefore, not only do equations relating biarticular muscle length to joint angles cut down on the number of calculations performed, they also are applicable in a greater number of situations.

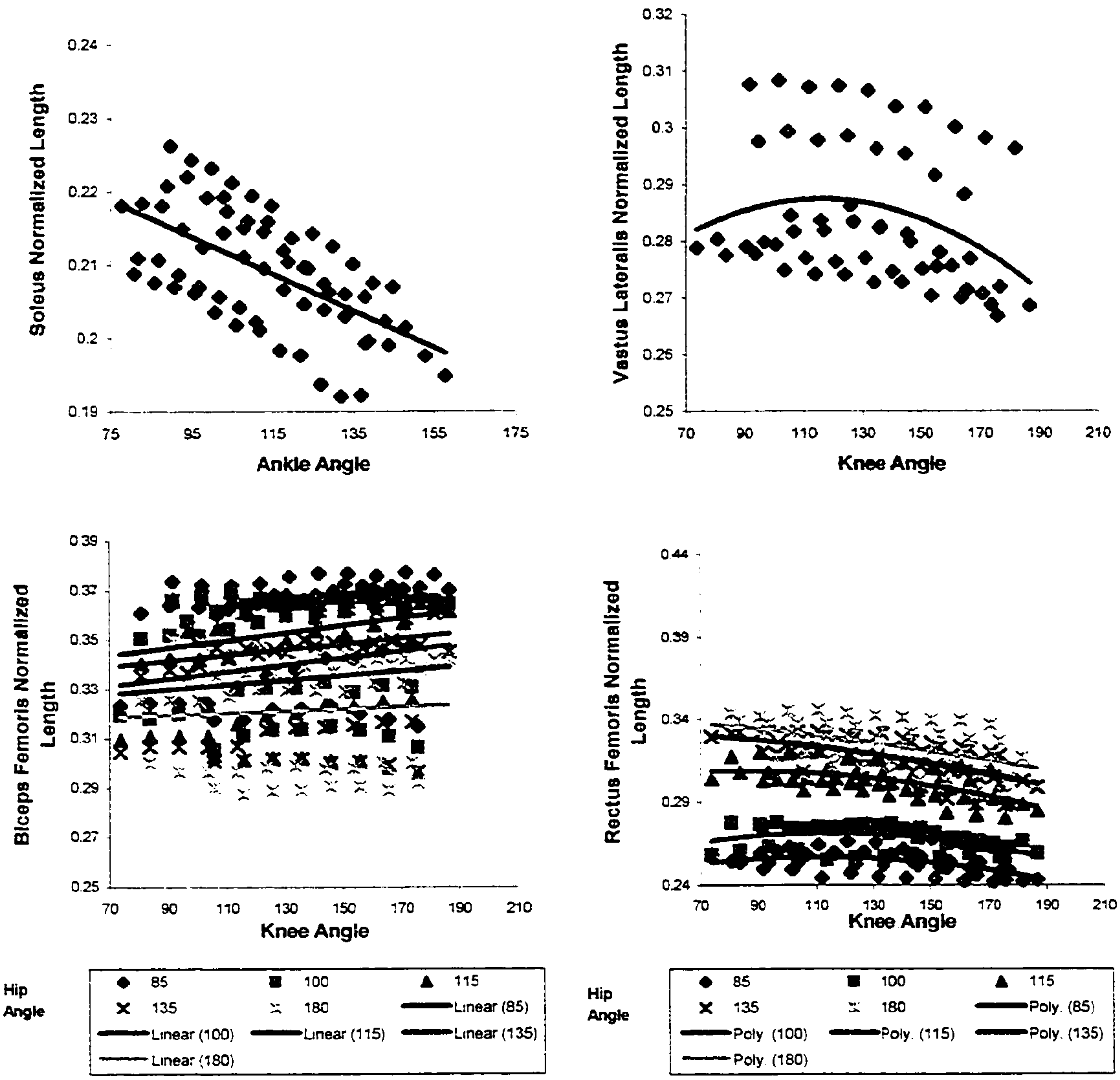
For the monoarticular soleus and vastus lateralis muscles, where the relationship between muscle length and joint angle was determined to be linear and quadratic, respectively, regression based on the principle of least squares was applied to the male and female data sets separately to determine the equation of the line of best fit for each gender (Table 2.4 & 2.5). Least squares regression was also performed on the separated male and female data for the biarticular muscles and Equations 3, 5 and 3 were fitted to the rectus femoris, biceps femoris and gastrocnemius muscles data sets, respectively (Table 2.4 & 2.5). Graphical representation of these relationships is displayed in Figure 2.1 and 2.2.

Table 2.4: Regression equations relating muscle lengths to joint angles for female subjects. For the biarticular muscles, the "x" variable in the expression is the angle of the knee joint while the "z" variable is the hip joint angle for the rectus femoris and biceps femoris and the ankle joint angle for the gastrocnemius.

Muscle	Joint(s)	Equation	R^2 Value
Soleus	Ankle	$y = -0.0003x + 0.2379$	0.3778
Gastrocnemius	Knee & Ankle	$y = 0.00159x - 0.00016z + 0.11206$	0.8357
Vastus Lateralis	Knee	$y = 0.007x + 0.2472$	0.0919
Rectus Femoris	Knee & Hip	$y = 0.00051x + 0.00072z + 0.185040$	0.7137
Biceps Femoris	Knee & Hip	$y = 0.00024x - 0.00033z + 0.33571$	0.2023

Table 2.5: Regression equations relating muscle lengths to joint angles for male subjects. For the biarticular muscles, the "x" variable in the expression is the angle of the knee joint while the "z" variable is the hip joint angle for the rectus femoris and biceps femoris and the ankle joint angle for the gastrocnemius.

Muscle	Joint(s)	Equation	R^2 Value
Soleus	Ankle	$y = -0.001x + 0.2305$	0.1035
Gastrocnemius	Knee & Ankle	$y = 0.00207x - 0.00022z + 0.10471$	0.5837
Vastus Lateralis	Knee	$y = 0.00006x + 0.2777$	0.0026
Rectus Femoris	Knee & Hip	$y = 0.0003x + 0.00042z + 0.2312$	0.5782
Biceps Femoris	Knee & Hip	$y = 0.00088x - 0.00005z + 0.33335$	0.1538



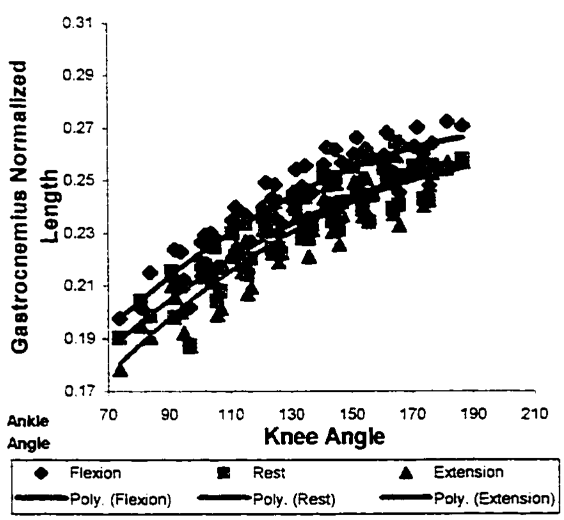
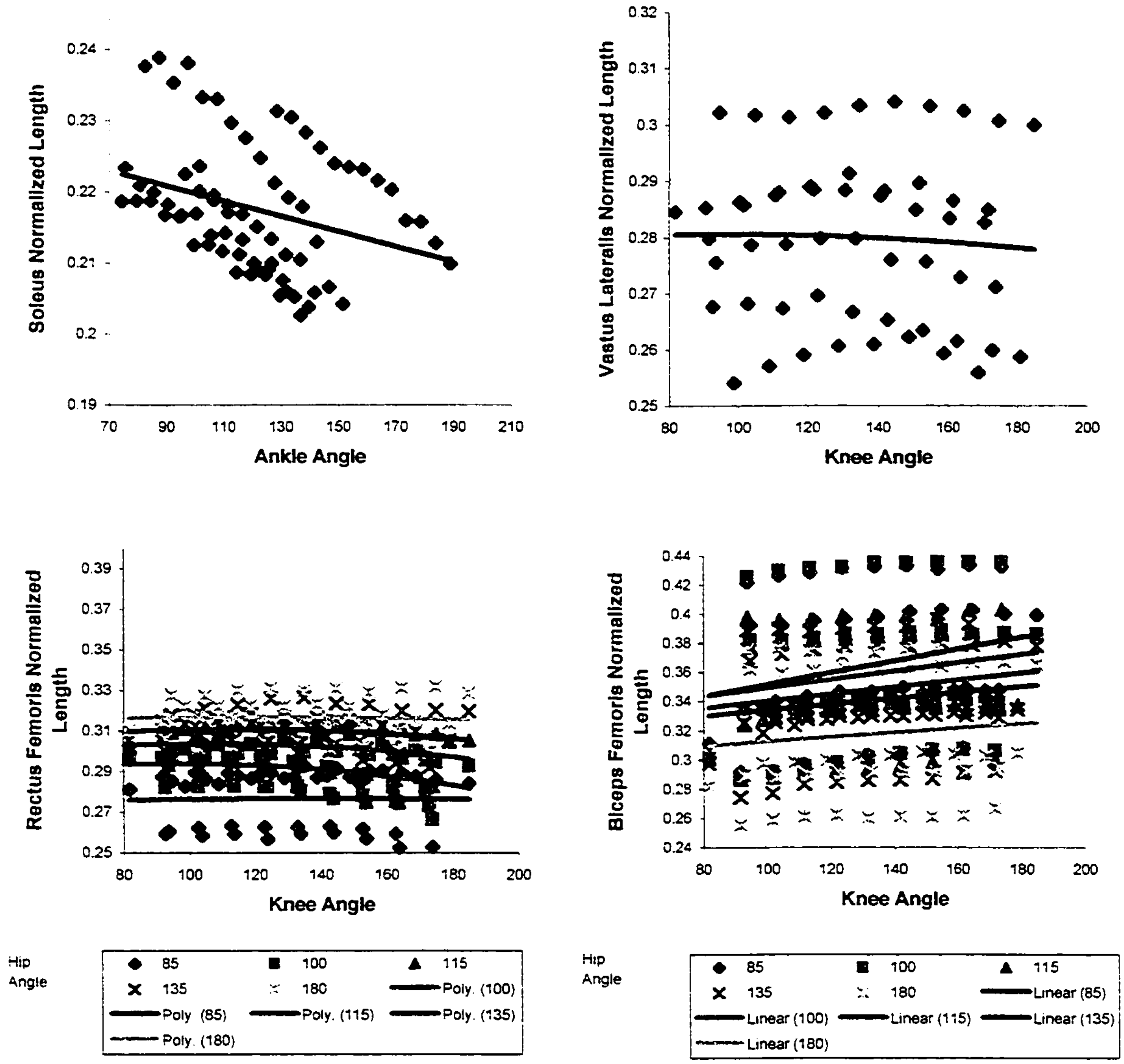


Figure 2.1: Grpahs depicting the effect of joint angle(s) on height normalized muscle lengths for female subjects. The soleus and vastus lateralis are monoarticular muscles and have only one line of best fit. The remaining muscles are biarticular and have multiple lines as muscle length is being effected by two joint angles.



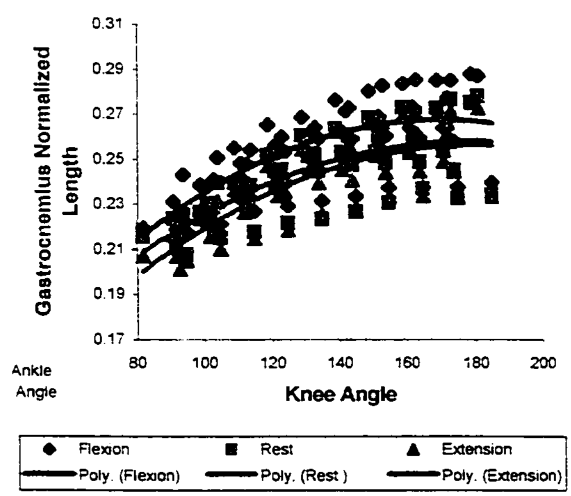


Figure 2.2: Grpahs depicting the effect of joint angle(s) on height normalized muscle lengths for male subjects. The soleus and vastus lateralis are monoarticular muscles and have only one line of best fit. The remaining muscles are biarticular and have multiple lines as muscle length is being effected by two joint angles.

Overall, the general formula of the regression equation relating muscle lengths to joint angles can be expressed as follows:

$$L = \alpha + \beta_1(\theta_1) + \beta_2(\theta_2)^2 + \beta_3(\theta_2) + \beta_4(\theta_3)^2$$

Where L = length

α = constant

β = regression coefficients

θ_1 = ankle angle

θ_2 = knee angle

θ_3 = hip angle

In situations where the muscle is not affected by one or more of the joint angles, the angle is entered as zero to remove the effect of the noncontributing joint(s).

Discussion

General Trends

As the joints of the lower extremity move into extension, the muscles crossing the top of the joints shorten, while the muscles running underneath lengthen. This allows for muscles to be defined as concentric (shortening) or eccentric (lengthening) contractors. During extension (plantar flexion) of the ankle both the soleus and gastrocnemius shorten. In comparison, the gastrocnemius lengthens during knee extension, as does the biceps femoris. At the same time, the rectus femoris and the vastus lateralis are shortening. The roles of the rectus femoris and biceps femoris become reversed at the hip where they function eccentrically and concentrically, respectively, during extension. These are the patterns which should be observed during normal extension according to Moore (1992) (Table 1.1).

In general, the trends observed in this data set (Appendix C- I-XXVI) reflected the anatomical occurrences outlined by Moore (1992). During increasing flexion, or extension, the muscle were observed to be smoothly lengthening, or shortening, according to their main action. As the direction of motion did not vary (i.e., change from flexion to extension or *vice versa*) during the collection of data, all of the muscles should have been observed to be acting entirely in a concentric, or eccentric, nature throughout the motion. However, there were some instances where muscles (not the gluteus maximus) were observed to be fluctuating between concentric and eccentric behaviour. In the seven situations where the data exhibited these anatomically impossible fluctuations the data was discarded from all future analyses

All data sets for the gluteus maximus were discarded due to their anatomically impossible fluctuating, and thus uninformative, nature. Most likely these fluctuations arose from the definition of the "effective" origin and insertion points of the muscle. Effective attachment points were required as the gluteus maximus is a pennate muscle with very broad areas of origin and insertion. For this study, the origin was defined as a point midway on the lateral border of the sacrum and the insertion was located at the greater trochanter. However, motion at the hip joint seemed to cause the greater trochanter to move in a circular arc about the hip joint. The point of origin of the gluteus maximus also remained a relatively constant distance from the hip joint. This caused there to be no constant increasing or decreasing trend for gluteus maximus length with respect to hip joint angle since the length of the muscle was considered to be a straight line between the origin and insertion points, but in fact it's line of action was circular. Dostal and Andrews (1981) also found that the straight-line approach does not work well for the gluteus maximus muscle.

Future studies should measure length changes of the gluteus maximus from the same origin on the sacrum to a new insertion below the buttocks; to this, the arc length from under the buttocks to the greater trochanter should be measured and added. Alternative solutions would be to model the gluteus maximus as a two-segment straight-line muscle (Nemeth & Ohlsen, 1985), to use three points of origin and one insertion point (Brand et al., 1982) or to use finite elements (Au & Christiano, 1993).

Polynomial Order

The relationship between the length of the muscles in this study and the joints which they cross were sometimes best described by linear equations, while at others times quadratic equations were determined to be the line of best fit (Table 2.3). This does not confirm the prediction put forth in the introduction, which stated that, the relationship between muscle lengths and joint angles would be of a higher polynomial order than first degree.

A general trend emerged from the data sets of both the monoarticular and biarticular muscles acting at a single joint. It was observed that muscles spanning the ankle and hip joints were expressed linearly, while muscles spanning the knee joint were best described by quadratic equations (Table 2.3). Therefore, it would appear that the order of the regression equations was determined by the physical properties of the joints, not the muscles. The knee is a more complex, and less stable joint, than the ankle and hip joints (Nordin & Frankel, 1989) and these two factors may be contributors to the increase in degree observed in the equations expressing the length of a muscle as a function of knee joint angle.

The only exception to the previously described trend was the biceps femoris, which was expressed linearly at the knee (Figure 2.1 & 2.2). It is possible that this relationship was in fact quadratic and similar in order to the other equations in this study relating muscle lengths to knee joint angles. There is a good chance that accuracy in the length measurements of the biceps femoris was lost through the use of a foam pad marker to represent the origin of the biceps femoris. Although semi-rigid, the foam pad would have become distorted (stressed) according to Poisson's ratio (Beer & Johnston Jr., 1992), thus introducing error into the measurement. A rigid pad would not have experienced this distortion, but would have caused the subjects extreme discomfort during the long sitting period required for testing. This discomfort would have lead the subjects to shift their weight in an effort to decrease pressure, introducing a different source of error to the measurement. The best solution to this problem would have been to measure the length of the biceps femoris with the subjects lying on their stomach, but this option was not possible given the physical design of the KinCom machine.

When examining the biarticular muscles during dual joint manipulation, the regression analysis became more complex as muscle length was related to two variables (i.e., joints). However, things became simplified when statistics showed that the joint trends observed when the muscles were examined at a single joint were carried over to two-joint motion (Table 2.3). For example, the rectus femoris was expressed quadratically at the knee and linearly at the hip when being examined monoarticularly (i.e., one joint held stationary while the other joint is manipulated). When the rectus femoris was expressed mathematically as a biarticular muscle the knee joint variable was still expressed as a second-degree polynomial. To this the linear expression of the hip joint variable and a constant were added. The same pattern existed for the regression equations of the biarticular gastrocnemius and biceps femoris. The gastrocnemius was expressed quadratically at the knee and linearly at the ankle, while the biceps femoris was expressed linearly at both the knee and hip joints.

No interaction between the joints was observed for any of the regression equations relating biarticular muscle length to the angle of both joints it crosses. This lack of interaction was also observed by past research groups (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) performing similar types of studies.

Effect of Gender

After determining the order of the regression equations the data were normalized by height and grouped by gender. Eliminating the equations relating biarticular muscle length to a single joint reduced the number of regression equations. These equations were deemed extraneous as the biarticular equation could be used even when the muscle was acting at a single joint. During monoarticular motion created by the action of a biarticular muscle, the biarticular equation would be applied by holding the variable for the nonmoving joint constant, while the other joint variable changed with motion. The monoarticular equations for the biarticular muscles would only be of predictive value if the nonmoving joint was in the exact same position as during data collection on the Kin Com

The five regression equations were fitted to both the male and female data sets (Tables 2.4 & 2.5). Although there was no difference in the order of the equations between the gender, a difference in the value of the coefficients of the equations was observed. Male and female pelvic anatomy differs greatly as the female pelvis is much wider and shallower. This causes females to have more extreme coronal plane angles at the hip and knee joints. As well, the males in this study had a taller average height than the females. It would appear that these two differences in anatomy between the genders do not affect the order of the mathematical relationship between the lengths of the muscles of study and joint positions in the sagittal plane, but do effect the value of the coefficients.

Equations predicting muscle length from joint angle(s) for the height normalized male and female data sets were developed (Table 2.4 & 2.5). Unfortunately, the predictive value of these equations was low as indicated by the small R^2 values. Examination of the graphs (Figure 2.1 & 2.2) also demonstrated that normalization was ineffectual in eliminating intersubject variability. The data were very scattered and it was possible to pick out data sets for individual regression subjects based on the horizontal separation between sets of points. For normalization to be considered effective it must reduce all of these separate data sets into one set which is representative of all subjects. Based on the low R^2 values, data scatter and separation of data sets it is concluded that the regression equations developed in this section of the report were of little or no predictive value in their present form.

Sources of Error

Upon completion of model building it is important to note there were possible sources of error in the method which could not be eliminated. It is virtually impossible to place the pin point of a marker consistently at the same location on the origin and insertion points. For example, the common insertion of the vastus lateralis and rectus femoris is the tibial tuberosity. This anatomical landmark is much larger than a pin point, thus rendering the goal of always marking the same position on this broad attachment point unattainable. According to Brand and colleagues (1982), this mismarking accounts for less than 10% of the overall error and occurs mostly in the direction of the long axis of the femur and tibia.

For this study, it was estimated that the marker was consistently placed within a circle of diameter 1-2 cm from the desired location--the larger the anatomical landmark, the greater the degree of error. Every effort was made to decrease this error by using the same two researchers to place the markers on the landmarks and by consulting a researcher in the physiotherapy department who is an expert in palpating the human body. In addition, subjects who were in good shape and not suffering from obesity were chosen to make the process of palpation easier. However, even with these precautions it is impossible to consistently place a pinpoint in the exact same location on an anatomical landmark that can range form the size of a tip of a finger to the size of an adult hand.

In addition, once a marker is placed on the skin it moves over the anatomical landmark, and away from its original position, as the skin stretches and compresses with motion. It is estimated that the amount of error attributable to this source ranges from 1-4 cm (White, 1989; Reinschmidt et al., 1997). The error is greatest at the hip where musculature is large and decreases from the knee to the ankle. As such, Reinschmidt and colleagues (1997) conclude that skin markers are relatively accurate when examining flexion and extension at the knee and ankle, but there is error introduced at the hip joint. In this study the subjects were moving slowly and in one dimension, therefore it is estimated that the markers on the skin moved over the anatomical landmark within a circle of diameter 1-4 cm. The marker movement did appear to be greatest at the hip and lowest at the ankle.

Other errors exist due to the use of effective attachment points and the failure to partition muscles into representative functional units. This results in deviations between the approximated length of the muscle and its actual length. In fact, use of effective origin and insertion points leads to an underestimation of the real length of the muscles (Dostal & Andrews, 1981). In addition, use of the straight-line approach also leads to an estimation of muscle length that is 1-12% less than that determined using the centroid method (Jensen & Davy, 1975). These errors, coupled with the differences that exist in skin and fat thickness between subjects, make it virtually impossible to precisely determine the length of a muscle using noninvasive methods.

Future Research

To avoid the previously described errors it is necessary to employ a type of imaging technique that exactly pinpoints the origin and insertion of muscles. Two types, which have been used in recent studies, are the CT scan (Nemeth & Ohlsen, 1985) and the MRI machine (Lu et al., 1997). Unfortunately, the expense of these machines, along with their wide spread use in the medical field, does not permit for their usage in nonmedical, academic settings in Canada. Hopefully, with advances in technology, new imaging devices will cause these two pieces of equipment to become obsolete in the medical field, thus increasing their availability to researchers. Use of the CT scan and MRI machine will permit for more reliable modelling of the musculoskeletal system, while still maintaining the advantage of being noninvasive.

Chapter 3
Improving Model Fit

Introduction

The regression equations relating muscle lengths to joint angles developed in Chapter 2 had low R^2 values and were, therefore, of very little predictive value. This indicated that normalization by height was unsuccessful in decreasing the scatter of the data and removing intersubject variability. As such, it became necessary to find an alternative method of manipulating the data that would decrease the amount of variability in the gender data sets and increase the predictability of the equations.

Typically, researchers (Grieve et al., 1978; Hawkins & Hull, 1990; Visser et al., 1990) building polynomial regression models relating muscle lengths to joint angles have normalized their data using the anatomical parameter of leg segment length (shin or thigh). Some researchers have found this method of normalization to be unsuccessful in eliminating the scatter in their data sets (Grieve et al., 1978). The explanation was the observed scatter reflected anatomical differences among specimens that could not be eliminated using normalization.

On the other hand, Visser's research group (1990) observed a tight cluster of data following normalization by leg segment length. Thus, it is impossible to state, based on past research, whether or not normalization by leg segment length is an effective way to decrease data scatter and remove intersubject variability.

Hypothesis

1) The taller the subject the longer the leg segment length (i.e., leg segment length and height are highly correlated).

Prediction

1) Normalization by leg segment length will be no more effective than normalization by height in decreasing the scatter in the data.

As the leg segment lengths and the height of the subjects were strongly correlated, it was unlikely that normalization by leg segment length would be any more successful than normalization by height when it came to improving model fit. If it was found that normalization by leg segment length did not increase the fit of the model, then other anthropometric variables would be tested to see if they were effective in normalizing the data.

If all attempts at normalization were ineffective, then alternative methods of removing intersubject variability would be needed. Transformation of the data was performed in an attempt to increase model fit. If this also was not effective, then forward selection polynomial regression, coupled with transformation and the addition of anthropometric variable(s) to the right hand side of the equations, was applied to the data in an effort to increase the predictability of the equations.

It is interesting to note that past researchers (Grieve et al, 1978; Hawkins & Hull, 1900; Visser et al, 1990) have not required anything beyond normalization of the data to increase the goodness of fit of their models relating muscle lengths to joint angles. One research group (Grieve et al, 1978) found that normalization was not completely effective in removing interindividual regression differences, but still applied this mathematical technique as it did increase the fit of the model. If use of data transformation and/or the addition of anthropometric variable(s) as independent variable(s) is required to obtain a highly predictive model, then possible reasons for this must be discussed.

Materials and Methods

Data were normalized by leg segment length and polynomial regression equations, of the order determined in Chapter 2, were fitted to the male and female data sets. The male and female data sets remained separated due to the discovery in the previous chapter that there was a difference in the regression coefficients of the genders. R^2 values obtained using normalization by height, normalization by leg segment length and individual regression data sets were compared using a nonparametric ANOVA ($\alpha = 0.05$). This was done to determine if a statistical difference existed between the normalization methods. No difference existed between the normalized data sets and both had very low R^2 values. Conversely, the equations based on individual regression data sets were significantly different and were highly predictive.

Since there was no statistical difference found between the two normalization methods (i.e., one method of normalization was no more predictive than the other), the following anthropometric parameters were also examined as possible anatomical variables to be used for normalization: thigh-to-shin ratio, weight, foot length, joint start angle, joint end angle and total range-of-motion. The correlation between muscle length and these variables was even lower than that observed between muscle lengths and height or leg segment length. Therefore, none of the aforementioned parameters were considered to be appropriate variables to be used for normalization.

As a result, an attempt was made to decrease the variability in the data by transforming the data using log, natural log (ln), square root reciprocal and exponential functions. Transformation was also not successful in improving model fit.

Since both data normalization and transformation were unsuccessful in decreasing the spread of the data, forward selection polynomial regression of increasing degree, coupled with data transformation and the addition of anthropometric variable(s) as independent variables, was performed. While the addition of independent variables increased the goodness of fit of the model, data transformation did not.

Results

The results of the nonparametric ANOVA indicated that normalization by leg segment length produced R^2 values that did not differ significantly from the R^2 values determined using normalization by height. Statistical analysis showed even lower correlation between the regression coefficients in the equations predicting the lengths of the five muscles of interest and any of the other anthropometric variables. This indicated that none of the variables would be successful in normalizing the data. The R^2 values for the individual regression data sets were significantly higher than those obtained by either methods of normalization (Appendix H).

Following the lack of success in normalizing the data and removing individual differences, the dependent and independent variables were transformed)using the functions outlined in the Materials and Methods section) but no combination of these transformed data sets was successful in decreasing the scatter in the data.

A last effort was made to obtain highly predictive equations for each gender by applying forward selection polynomial regression analysis of increasing degree. In this type of multiple regression analysis, the first-order variables were added into the model and then the second-order variables were added into the model. If the second-order variables increased the fit of the model then they remained and the next higher order was added. If the higher order variables did not increase the fit then they were removed. An acceptable increase in fit (i.e., one where the higher order variable would remain) was considered to be an increase of 0.02 in the R^2 value. The equation of best fit was defined as that which was statistically significant ($p<0.05$) with the highest R^2 value.

The subject's height or leg segment length, whichever produced the highest R^2 values, was added to the independent variables side of the equations to account for individual differences. These two variables were used as height and segment lengths were always better predictors of muscle length than any of the other anthropometric variables. Addition of a second anthropometric variable did in some instances increase the fit of the model, but the tolerances for these correlated variables was quite low. Therefore, it was decided that the increase in model fit that was sometimes observed when adding correlated variables was not worth the resulting multicolinearity problems.

For some muscles the addition of height as an independent variable lead to higher R^2 values and for other muscles the addition of leg segment length as an independent variable lead to more predictive equations. A general trend emerged from the data. For monoarticular muscles the addition of leg segment length led to the greatest improvement in model fit. The reverse was true for biarticular muscles where the addition of height caused the largest increase in R^2 values. In none of the equations did the transformation of the data lead to an increase in model fit. Table 3.1 lists the equations and the R^2 values that resulted from this analysis.

The male and female data were pooled and gender was added to the polynomial regression analysis as a categorical, dummy factor. Pooling the data and adding gender as an independent variable sometimes lead to higher R^2 values, sometimes to lower R^2 values and sometimes to very little change in R^2 values. This can partially be explained by the large differences in R^2 values between the genders for the same muscle equation. The best example is the vastus lateralis. The R^2 value of the equation for the males was much higher than that of the females. Therefore, when the data was pooled the resulting R^2 value increased for the females and decreased for the males. In light of this, it was decided that leaving the data for the genders separate was the best way to build the most predictive model.

Table 3.1: General equations, based on the data from ten subjects, relating muscle lengths of the soleus, vastus lateralis, gastrocnemius, biceps femoris and rectus femoris to joint angles for both the female and male subjects. Note that both joint angle(s) and either leg segment length or height are required to estimate muscle length. All relationship were statistically significant (p=0.00).

Gender Muscle	Muscle Length Equation	R^2 Value
Female Soleus	Length = 153.540 – 0.578(ankle) + 0.653(segment length)	0.798
Vastus Lateralis	Length = 569.968 – 1.141(knee) + 0.0496(segment length)	0.778
Biceps Femoris	Length = 148.874 + 0.254(knee) – 0.536(hip) + 0.263(height)	0.399
Gastrocnemius	Length = -36.323 – 0.00542(knee)^2 + 2.449 (knee) + 0.00585 (ankle)^2 – 1.707(ankle) + 0.187(height)	0.876
Rectus Femoris	Length = -398.351 – 0.00530(knee)^2 + 0.207(knee) – 0.0203 (hip)^2 + 6.465(hip) + 0.280(height)	0.848
Male Soleus	Length = 41.568 – 0.303(ankle) + 0.864(segment length)	0.756
Vastus Lateralis	Length = 178.388 – 1.181(knee) + 0.895(segment length)	0.913
Biceps Femoris	Length = 789.880 + 0.268(knee) – 0.822(hip) – 0.333(height)	0.857
Gastrocnemius	Length = -34.228 – 0.00887(knee)^2 + 3.366(knee) + 0.0110(ankle)^2 – 3.152(ankle) + 0.229(height)	0.865
Rectus Femoris	Length = -631.268 – 0.0111(knee)^2 + 1.853(knee) – 0.0121(hip)^2 + 3.992(hip) + 0.450(height)	0.720

Discussion

Normalization by leg segment length produced equations that were no more predictive than those normalized by height. Both types of normalized equations were significantly less predictive than equations based on individual subject's data sets. This supports the prediction that normalization by leg segment length would not account for, and reduce, the biological differences that existed between the subjects any better than normalization by height. Transformation of the data was also not successful in increasing the fit of the mathematical model. Only analysis on an individual subject basis was successful in producing statistically significant, and highly predictable, R^2 values.

These results suggested that the relationship between the length of the muscles of study and the joint angles they cross was unique to each individual regression and there was no one normalized and/or transformed equation that could be used to reliably represent all subjects. Although the order of the equations was identical across subjects, the regression coefficients and the constants differed between individuals. This supports the work of Grieve and Colleagues (1978) who determined that normalization by leg segment length does not decrease the scatter in the data created by individual, anatomical variation, and refutes the findings of Visser's research team (1990).

However, White and his research group (1989) provide a different explanation as to the reason data scatter is not removed by normalization. They stated that more error, and thus variability, is introduced into musculoskeletal modelling by simplifications and assumptions then by between subject biological differences. The sources of error cited were as follows:

1. representing broad attachment areas as points,
2. failure to partition muscles into functional units,
3. using the straight line approach to model muscles, and
4. use of effective attachment points.

These simplifications and assumptions were all used in this present study and are an alternative explanation as to why normalization and transformation of the data was unsuccessful in removing variability from the data.

Forward selection polynomial regression analysis was applied to the data for males and the data for females in an effort to produce general equations, which could be applied to individuals outside the sample group. To account for individual differences, the subject's height or leg segment length, depending on which lead to the greatest increase in model fit, were added to the independent variable side of the equations. The reason for choosing these two variables was they were strongly correlated to muscle length. Addition of height or segment length lead to general regression equations whose R^2 values were significantly higher than those obtained using either normalization or transformation techniques.

More than one anthropometric variable (ex. height and weight) was not added to the independent variable side of the equations to avoid problems with multicolinearity. Multicolinearity results when independent variables are correlated and therefore not truly independent. The consequences can include inflated standard errors for the regression coefficient and increased sensitivity to small changes. When using polynomial regression multicolinearity is always a concern as the different orders of a variable (e.g., x and x^2) are always highly correlated. Since multicolinearity all ready existed in the model due to the higher order polynomials, it was decided that multicolinearity in the remaining independent variables would be avoided in an effort to increase the power to detect the effect of the independent variables.

For monoarticular muscles, the addition of leg segment length as an independent variable produced equations, which explained the greatest amount of change in muscle length as an effect of changing joint angles. Conversely, for biarticular muscles the addition of height as an independent variable lead to the most predictive regression equations. For neither monoarticular or biarticular muscles did the transformation of the data lead to increased model fit.

The only exception to the above was the biceps femoris muscle. Even with the addition of height as an independent variable, the regression equations (female and male) had very low R^2 values. This means that the ability to predict biceps femoris muscle length as a function of joint angles is very low. In the previous chapter, it was pointed out that the biceps femoris muscle did not follow the trends observed in the other muscles. It was thought that this resulted from difficulties in accurately measuring the muscle. The findings in this chapter lent further support to the conclusion that the biceps femoris data is flawed.

When comparing the general equations developed in this chapter (Table 3.1) to those developed in the previous chapter (Table 2.4 & 2.5) the increase in R^2, from a range of 0.0026 – 0.8357 to range of 0.720- 0.913 respectively (ignoring the biceps femoris), indicates that the addition of height or leg segment length accounts for much of the individual differences. However, these new equations were not perfect predictors of muscle lengths. Possible sources of error and additional variables for consideration include:

- measurement errors (as outlined in Chapter 2)
- error introduced through assumptions (White et al, 1989)
- individual regression differences such as, different distances from the joint centre(s) of rotation to the point of attachments and different amounts of subcutaneous fat.

Another difference between the height normalized equations developed in chapter 2 and those built in this chapter were the polynomial order trends. From the results of chapter 2 it was concluded that the order of the regression equations relating muscle lengths to joint angles depended on the joint(s) the muscle cross. From the results of this chapter it appeared that the type of muscle determines the order of the equation. Monoarticular muscles were best described by linear equations, while biarticular equations were best described by second degree equations. Therefore the more joints a muscle crosses the more complicated the equation required to describe the relationship between joint angle(s) and muscle length. Since the equations developed in this chapter were more predictive than those built in chapter 2 it is very likely that muscle type determines polynomial order.

The only exception to this rule was the biarticular biceps femoris. This muscle was linearly related to both joints it crossed. However, it was pointed out earlier that the data from this muscle is most likely flawed due to difficulties in reaching the point of origin. Therefore, very little weight should be given to results obtained from the biceps femoris data.

Future Research

It is recommended for future research that possible independent variables be collected which are not correlated to height and/or leg segment length. For example, while the weight of a person is strongly correlated to height, the percent body fat of a person is not. Percent body fat can be determined from water immersion or skin fold tests and could possibly explain more of the individual differences that seems to exist between subjects. By testing as many potential, and uncorrelated, independent variables as possible, the amount of differences between subjects versus the amount of error introduced by assumption can more accurately be determined.

Chapter 4
Comparing Muscle Models

Introduction

Newly developed muscle length models need to be tested both quantitatively and qualitatively to determine if they are reliable. The general regression equations built in the previous chapter (Table 3.1) were quantitatively compared to both leg segments lengths and actual muscle length measurements. In addition, the muscle curves (velocity of the muscle versus time) produced from the general equations were qualitatively compared to the muscle curves produced from the individual regression equations and from the triangle based model (Frigo & Pedotti, 1978). The quantitative analysis tested to see if the equations predicted accurate values, while the qualitative analysis determined if the equations reliably determine muscle function.

Quantitative analysis of muscle length models required two steps. First, a comparison of the predicted muscle length to the leg segment length (measured using an anthropometric measuring device) was performed to ensure that the predicted muscle length was anatomically possible. The shin segment was defined as the distance from the lateral malleolous at the ankle to the midway point between the lateral condyles at the knee. The thigh segment was defined as the distance from the midway point between the lateral condyles at the knee to 1 cm anterior to the tip of the greater trochanter at the hip. More generally, the shin and thigh segment lengths are the length of the tibia and the femur respectively. If the predicted muscle length was much longer, or shorter, than the leg segment length then it was considered to be an anatomically impossible length.

In this study, the acceptable difference between muscle length and leg segment length was be set at +15cm at each joint for muscles crossing the knee and hip joints. This accounted for errors in mismarking (2 cm), marker movement (4 cm), measurement error (1 cm) and distance required to cross the joint (8 cm). For muscles crossing the ankle joint, the acceptable range was +10 cm as this joint is smaller than the hip and knee joint and marker movement in this area of the leg is minimal

(Reinschmidt et al, 1997). An acceptable difference of –10 cm was also allowed to account for measurement, marker placement and skin movement errors. For biarticular muscles an extra +/-5 cm was allowed for he crossing of the second joint.

The second step of the quantitative analysis involved the calculation of the RMSE. If the predicted muscle lengths were anatomically possible, then the RMSE was calculated to determine the difference between the observed (externally measured) values and the predicted (calculated) values. The lower the RMSE value, the better the model at accurately predicting muscle lengths. An acceptable RMSE value was defined in the same manner as the acceptable range (outlined in the above paragraph) to account for errors and joint width. Therefore, the acceptable RMSE for the soleus was 20cm, for the vastus lateralis was 15cm and for the gastrocnemius, rectus femoris and biceps femoris was 30cm.

In addition to the quantitative analysis, qualitative analysis was required to demonstrate that the general equations predicted the proper muscle functions. Comparison of the muscle curves produced from the general equations were compared to the muscle curves produced by Frigo & Pedotti's (1978) triangle based model and the individual regression equations. Since the individual regression equations were based solely on the data collected from the subject, they were considered to be a good reflection of the actual function (i.e., periods of lengthening and shortening) of the muscles.

Frigo and Pedotti's (1978) triangle based model was chosen for qualitative comparison as it is a model not based on polynomial regression analysis. It is a fairly simple model based on trigonometry and geometry, and it produces muscle curves that correctly predict the function of the muscles. The function of a muscle can only be determined if the length of the muscle is known. As such, if qualitative analysis showed that the muscle length curves describing muscle function produced from the general equations were similar to those produced using the triangle based model (Frigo & Pedotti, 1978), then support for the reliability of the general regression model will have been achieved. It also provides support for the method of applying polynomial regression analysis to determine the relationship between muscle length and joint angle(s), since the same results can be obtained using two different mathematical techniques.

Although Frigo and Pedotti's (1978) triangle based model predicted proper muscle functions, it had some minor downfalls. For instance, it was observed that as angular variation increased, the error in calculating muscle length increased. As well, the model was ineffectual if the origin and insertion points of a muscle were poorly chosen, or if the muscle did not act along a straight line between the points of attachment (Brand et al., 1982).

The above drawbacks, listed for the model based on triangles (Frigo & Pedotti, 1978), are pitfalls that are virtually impossible to eliminate in any type of muscle length model. It is common for a muscle length model to breakdown at the extremes of the range-of-motion, as it is in this region of the motion that the body starts to perform compensatory motions and/or physically breakdown. In addition, if a researcher applying a muscle length model defines the origins and insertion points poorly, it is impossible for the predicted muscle lengths to be accurate. No matter how good the model, if the reference points upon which the model is based are not proper representations of the body under study, then the final results will be flawed.

A study by Pierrynowski and Morrison (1985) lent support to both Frigo and Pedotti's (1978) triangle based model and Grieve and colleagues' (1978) polynomial regression model. However, Frigo and Pedotti's (1978) model had a major downfall; it exhibited muscle curve discontinuities in the regions where there was a changeover between triangles. This discontinuity was manifested in the muscle curves as breaks in an otherwise smooth curve. At the point of discontinuity a spike was observed where the estimated muscle length jumped, or fell, to levels that were anatomically implausible.

The general regression model and the individual regression equations developed in this study should not have produced any of the discontinuities (i.e., spikes) observed in the triangle based model (Frigo & Pedotti, 1978) Regression equations are continuous and therefore, by definition, cannot produce discontinuities. Only smooth muscle curves, with no change over points, should be observed when regression equations are applied. Qualitative analysis, based on visual inspection of muscle curves produced by the regression equations developed in this study and those produced by Frigo and Pedotti's (1978), were used to demonstrate this point.

It is important to note that the origin and insertion points of Frigo and Pedotti's model (1978) have been defined differently than the origin and insertion points in this study. This would cause the actual length of the muscles, and thus the rates of lengthening and shortening, to be somewhat different. However, the new general regression model, the individual regression equations and the triangle-based model (Frigo & Pedotti, 1978) should show lengthening and shortening of the muscles during the same periods of time. Greater discrepancies between the two regression models and Firog and Pedotti's (1978) may be seen with the biarticular muscles as research has been inconclusive in determining the exact role of biarticular muscles (Andrews, 1982; Gregoire et al., 1984; Andrews, 1985; Bobbert et al., 1986; Bobbert & van Ingen Schenau, 1988; Jacobs & van Ingen Schenau, 1992; Jacobs et al., 1993; van Ingen Schenau et al., 1994; van Ingen Schenau et al., 1995).

Materials and Methods

Two subjects, one male and one female, were chosen from the field of twelve to be used to test the two newly built regression models. (Note: As previously stated, the data from these two subjects were not used to build the general regression model). These subjects were chosen for two reasons. First, the subjects had no regression equations for any of the muscle-length, joint-angle relationships which had to be discarded due to anatomically impossible trends (i.e., random length fluctuations) observed in the data. This indicated that no extreme human or equipment error occurred during data collection that would have severely contaminated the quality of the data. Secondly, these two subjects were willing and readily available to return to the lab for further testing.

The subjects were required to dress in black from head to toe and were filmed performing the following simple movements in the sagittal plane:

1) ankle flexion,

2) knee extension,

1) hip extension, and

2) squatting (simultaneous flexion of all three joints).

Reflective markers were placed on the subjects' fifth metatarsal, fifth metatarsal-phalangeal joint, calcaneus, lateral malleolous, lateral knee joint, hip joint and shoulder joint. The distance between these points was measured using an anthropometric measuring device. The subjects were individually filmed performing the previously described motions with the camera placed perpendicular to the sagittal plane. A control board was also filmed to provide a frame of reference for the digitizing process. All filming took place at 60 frames per second.

The film data was digitized using the APAS system and then transferred to the Biomech system for analysis and animation. Kinematic, Muscle, Fourier and Noise analyses were performed on each individual movement. The results were then used to create muscle curves (i.e., graphs relating muscle velocity to time) based on Frigo and Pedotti's (1978) triangle based model.

The regression equations based on the individual data of the two subjects (Appendix H, subjects 6F and 6M) and the general regression equations built from the data of the other ten subjects

(Table 3.1) were programmed into Biomech in the following format:

$$\text{length} = \alpha + \beta_1(\theta_1) + \beta_2(\theta_2)^2 + \beta_3(\theta_2) + \beta_4(\theta_3) + \varphi_1(\text{height}) + \varphi_2(\text{foot segment length}) + \varphi_3(\text{shin length}) + \varphi_4(\text{thigh length})$$

Where α = constant

β = regression coefficients

φ = anthropometric coefficients

θ_1 = ankle angle in degrees

θ_2 = knee angle in degrees

θ_3 = hip angle in degrees

The constant and the regression coefficients of every muscle (gastrocnemius, soleus, rectus femoris, biceps femoris and vastus lateralis) were entered by hand for each subject. When no motion occurred at a joint, its regression coefficient was set to zero. As well, if height and/or any of the segment lengths were not required then the coefficient was entered as zero. It is important to note that for the biarticular gastrocnemius, rectus femoris and biceps femoris the equations were based on data obtained when both joints were simultaneously being manipulated.

Once the regression equations were defined, the Biomech Kinematic, Muscle, Fourier and Noise analyses were rerun on the digitized data of the sagittal plane. Graphs were produced depicting the muscle curves obtained through application of both the general and individual regression equations.

The muscle curves graphs obtained from the Biomech program plotted muscle velocity versus time. Muscle velocity is defined as the change in muscle length over time. In this manner muscle velocity and muscle length, the dependent variable, were directly related. When examining the muscle curve, a positive velocity indicates that the muscle is lengthening, while a negative velocity indicates that the muscle is shortening.

Plotting muscle velocity versus time produces a graph where the function of the muscle can easily be determined. Any velocity above the zero line means that the muscle is acting concentrically, while a velocity below the zero line means the muscle is acting eccentrically. In comparison a muscle length may be positive, but the muscle may be functioning eccentrically. By plotting muscle velocity versus time, instead of muscle length versus time it is easier to determine the function of the muscle.

Results

Quantitative Analysis – Part 1

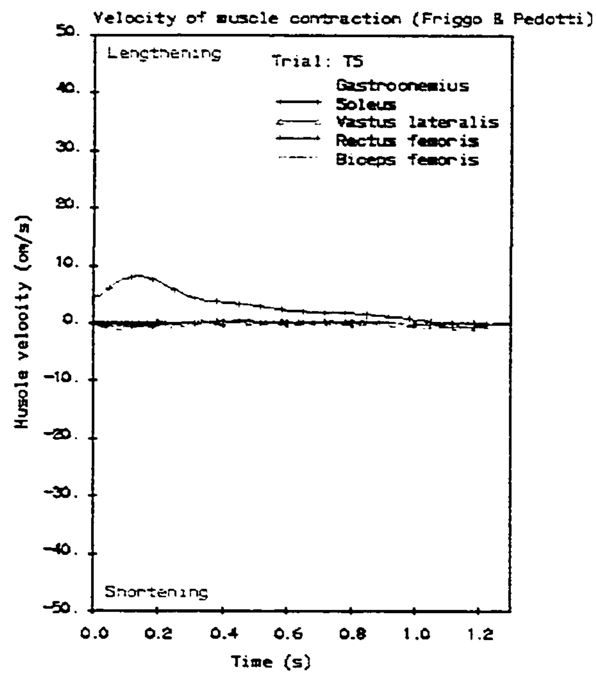
The maximum and minimum muscle lengths predicted from the triangle based model (Frigo & Pedotti, 1978), the individual regression equations and the general regression model were compared to the measured leg segment lengths of the subject (Table 4.1). For both the male and the female subjects, all of the muscle lengths predicted by the individual regression equations fell within the acceptable range. For the general regression model and Frigo & Pedotti's (1978) triangle based model, only the length of the male biceps femoris and the male vastus lateralis, respectively, were outside of the permitted range. As the individual regression equations were based on the subjects' own data sets it is not surprising that they were a slightly better at predicting muscle lengths than the general regression model and the triangle base model (Frigo & Pedotti, 1978) built on the data of a sample group.

Female Qualitative Analysis

During ankle dorsiflexion, (Figure 4.1a & b) all three models showed proper functioning of the five muscles of interest (as defined in Table 1.1). The soleus and gastrocnemius both lengthened, while the other three muscles showed little change in length. Some minor differences between the models were observed. Frigo and Pedotti's (1978) model predicted muscle velocities during

Table 4.1: Maximum and minimum predicted muscle length for the triangle based model (Frigo & Pedotti, 1978), the individual regression model and the logarithmic transformed regression model. Predicted muscle lengths and leg segment lengths are given for a male and female subject, in addition to the acceptable range within which the predicted muscle lengths must fall to be considered acceptable. The predicted muscle lengths which fell outside the acceptable range are highlighted.

Gender	Muscle	Segment Length/ Range (cm)	Value	Frigo & Pedotti	Individual	General
Female	Gastrocnemius	36.4	Max	46.198	42.64	38.891
Female	Gastrocnemius	21.4-56.4	Min	42.915	32.435	30.427
Female	Soleus	36.4	Max	35.259	37.459	35.221
Female	Soleus	26.4-46.4	Min	34.046	35.779	33.258
Female	Vastus Lateralis	41.2	Max	35.492	53.496	51.211
Female	Vastus Lateralis	31.2-56.2	Min	31.807	42.396	41.086
Female	Rectus Femoris	41.2	Max	45.866	52.411	47.553
Female	Rectus Femoris	26.2-61.2	Min	44.957	51.105	40.491
Female	Biceps Femoris	41.2	Max	37.537	58.07	52.743
Female	Biceps Femoris	26.2-61.2	Min	37.337	55.416	50.801
Male	Gastrocnemius	41.5	Max	48.528	44.464	43.904
Male	Gastrocnemius	26.5-61.5	Min	43.638	37.478	33.813
Male	Soleus	41.5	Max	36.245	44.078	37.865
Male	Soleus	31.5-51.5	Min	35.137	42.218	36.997
Male	Vastus Lateralis	47	Max	36.576	58.588	52.054
Male	Vastus Lateralis	37-62	Min	32.091	49.46	39.668
Male	Rectus Femoris	47	Max	47.266	55.9	45.139
Male	Rectus Femoris	32-67	Min	45.69	54.185	32.196
Male	Biceps Femoris	47	Max	40.274	73.142	24.180
Male	Biceps Femoris	32-67	Min	37.983	67.637	17.072



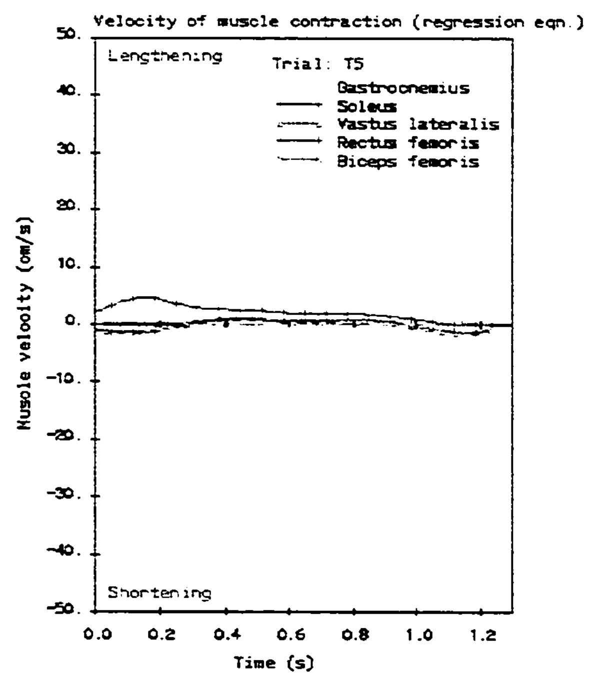


Figure 4.1a: Muscle curves showing the lengthening and shortening of the five muscles of study for the female subject during ankle flexion. Curves calculated using Frigo and Pedotti's (1978) model are displayed at top, while regression model curves are located in the bottom figure.

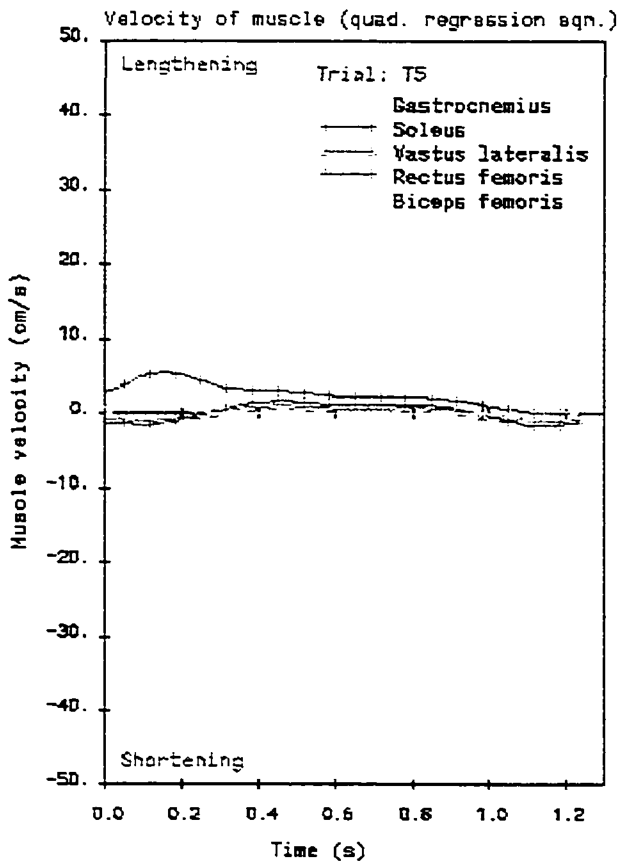


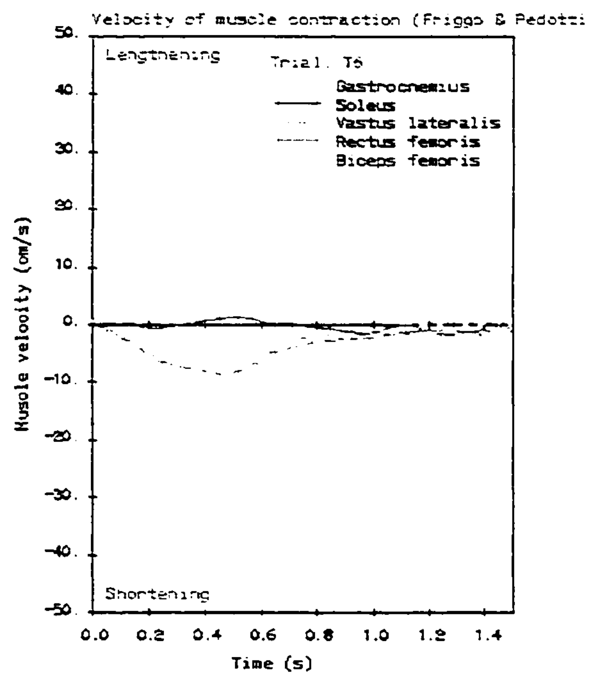
Figure 4.2b: Muscle curves showing the lengthening and shortening of the five muscles of study for the female subject during ankle flexion. The muscle curves were calculated using the general regression equations.

lengthening that were slightly higher than those of either regression models. As well, at the end of the range-of-motion (1.0-1.2s) the two regression models showed slight activity of the vastus lateralis, rectus femoris and gastrocnemius. Upon review of the animation, it was determined that during this period of time the subject was performing compensatory motions.

The three models also produced curves that showed all five muscles performing their proper function during extension of the knee (Figure 4.2a &b). The gastrocnemius and biceps femoris were lengthening, while the vastus lateralis and rectus femoris were shortening. The soleus, a muscle that does not cross the knee joint, showed little change in length throughout the range-of-motion. In contrast to the ankle flexion curves, in this case both regression models predicted higher muscle velocities than Frigo and Pedotti's (1978) model for knee extension.

Two major differences between the models were observed in the muscle curves obtained during knee extension. The first was the height of the biceps femoris curve. In Frigo and Pedotti's (1978) model, the rate of lengthening of the biceps femoris was higher than that of the gastrocnemius. Conversely, in both regression models the muscle velocity of the biceps femoris was at a level much lower than that of the gastrocnemius. The other major difference between the models was observed at 0.6 seconds where a spike (i.e., discontinuity) occurred in the curves of the biceps femoris and vastus lateralis muscles developed using Frigo and Pedotti's (1978) model. No such spikes were seen at any time in either of the regression models' curves of the biceps femoris and vastus lateralis muscles.

The muscle curves derived from all three models for hip extension showed the muscles performing their proper functions (Figure 4.3a&b). The rectus femoris was lengthening and the biceps femoris was shortening during the first 1.0 seconds of motion. During this same period of time the other three muscles showed little change in length. However, the second half of the trial (1.0-2.4 s) showed many peaks in the curves of all five muscles.



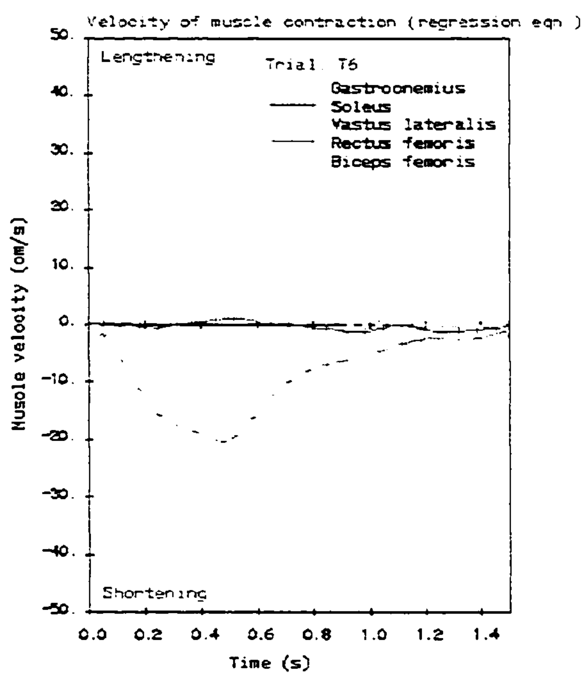


Figure 4.2a: Muscle curves showing the lengthening and shortening of the five muscles of study for the female subject during knee extension. Curves calculated using Frigo and Pedotti's (1978) model are displayed at top, while regression model curves are located in the bottom figure. Note the 2 spikes at time 0.6 seconds in the vastus lateralis and biceps femoris curves in the top graph.

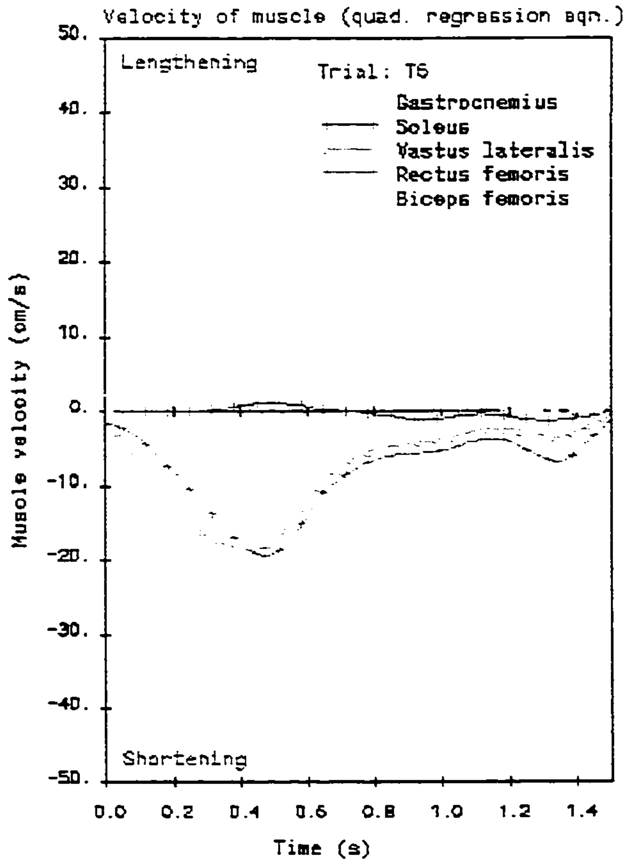


Figure 4.2 b: Muscle curves showing the lengthening and shortening of the five muscles of study for the female subject during knee extension. Muscle curves were calculated using the general regression equations. Note that no spikes are seen in the curves.

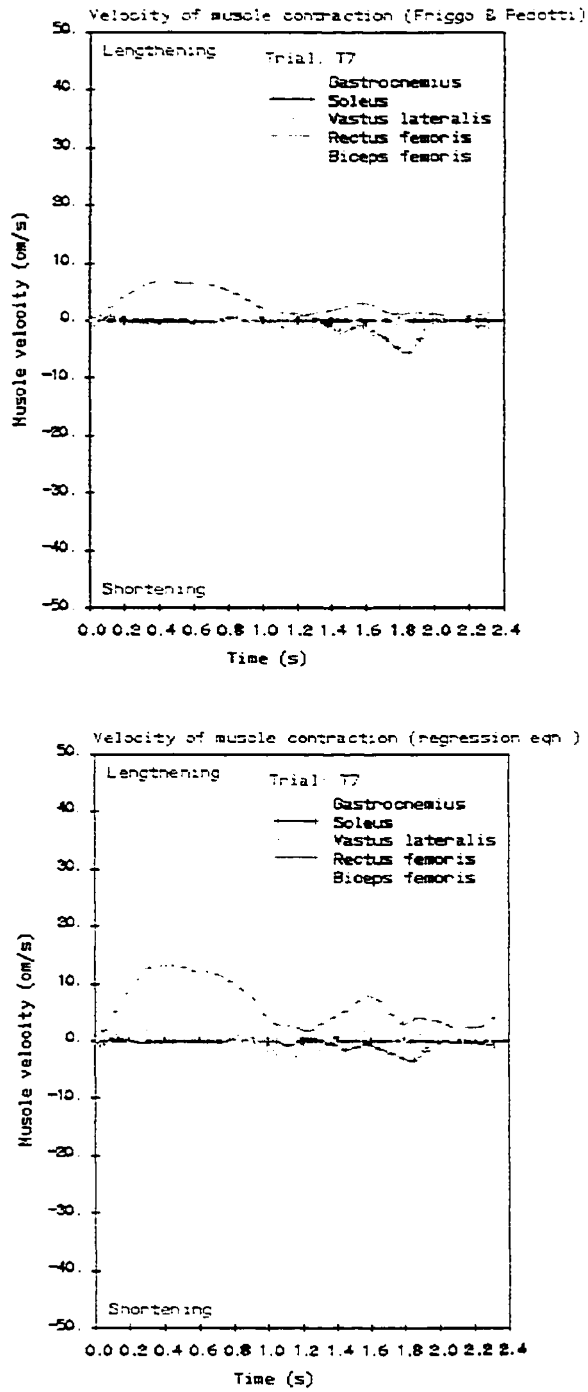


Figure 4.3a: Muscle curves showing the lengthening and shortening of the five muscles of study for the female subject during hip extension. Curves calculated using Frigo and Pedotti's (1978) model are displayed at top, while regression model curves are located in the bottom figure.

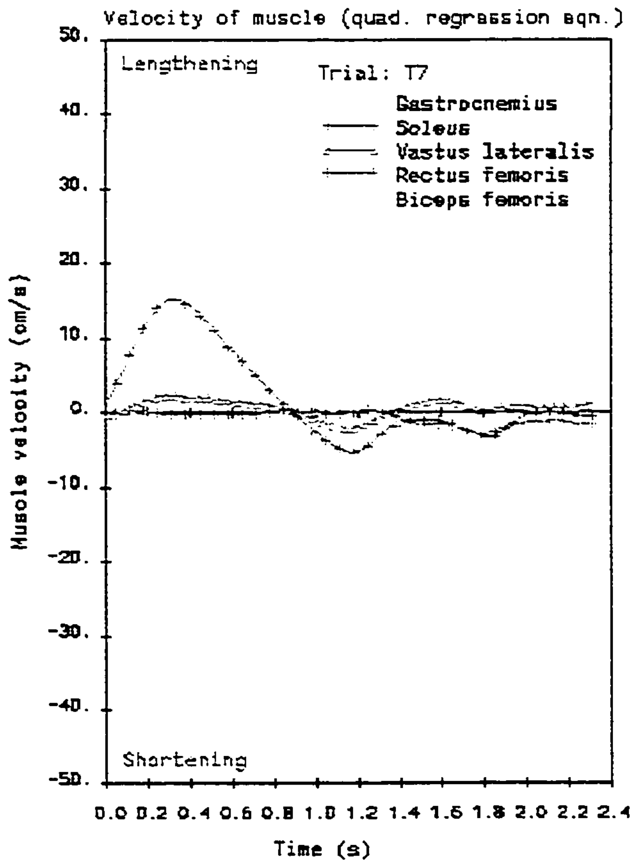
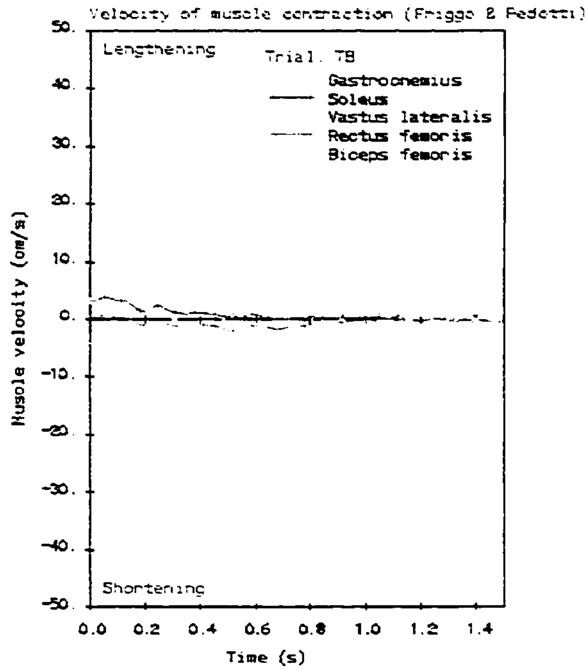


Figure 4.3b: Muscle curves showing the lengthening and shortening of the five muscles of study for the female subject during hip extension. Muscle curves were calculated using the general regression equations.

The activity observed in the second portion of the trial was greater for the two regression models than for Frigo and Pedotti's (1788) model. Analysis of the animated data showed that this activity, at the end of the range-of-motion of the hip joint, occurred during a time when the subject was performing compensatory motions.

In comparison to the simple motions occurring at a single joint, the squatting motion produced greater inconsistencies between the models (Figure 4.4a&b). The first major difference was observed in the functions being performed by the muscles. Frigo and Pedotti's (1978) model showed a lengthening of the vastus lateralis and soleus, and a shortening of the gastrocnemius. Little change in length was observed for the biceps femoris or rectus femoris. In comparison, the regression model showed a lengthening of the vastus lateralis, soleus and biceps femoris, and a shortening of the gastrocnemius. The rectus femoris was lengthening between 0-0.3 seconds, shortening between 0.4-1.02 seconds and then exhibited little change in length for the remainder of the motion. Overall, the muscle velocities were estimated to be higher using either of the regression based models.

A second major difference between the models was the timing of the events. Most muscle activity had stopped by 0.7 seconds according to Frigo and Pedotti's (1978) model, while muscle activity continued to 1.2 seconds in both of the regression model. Analysis of the animation showed that changes in joint angles were still occurring past the 0.7 second mark. The third, and final, difference was the two spikes observed between time 0-0.1 seconds in the muscle curves predicted using Frigo and Pedotti's (1978) model. Similar to the motion at the knee, the spikes were observed in the curves of the vastus lateralis and biceps femoris. No spikes were present in the muscle curves of the two regression models.



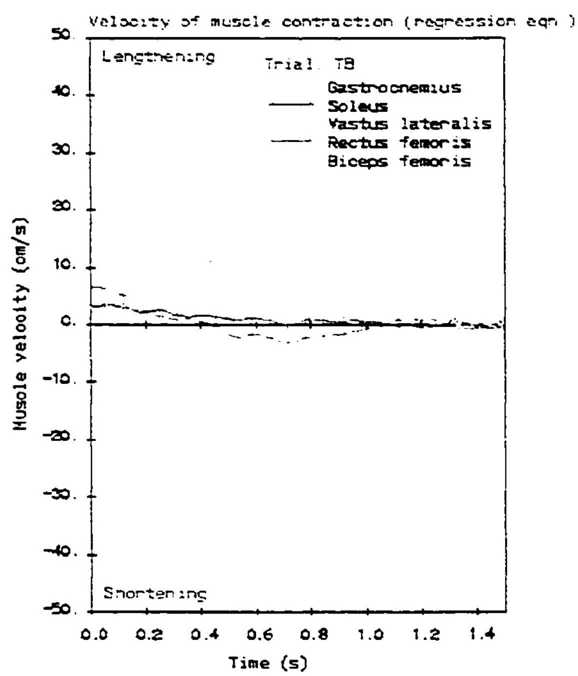


Figure 4.4a: Muscle curves showing the lengthening and shortening of the five muscles of study for the female subject during squatting. Curves calculated using Frigo and Pedotti's (1978) model are displayed at top, while regression model curves are located in the bottom figure. Note the2 spikes at time 0.1 seconds in the vastus lateralis and biceps femoris curves in the top graph.

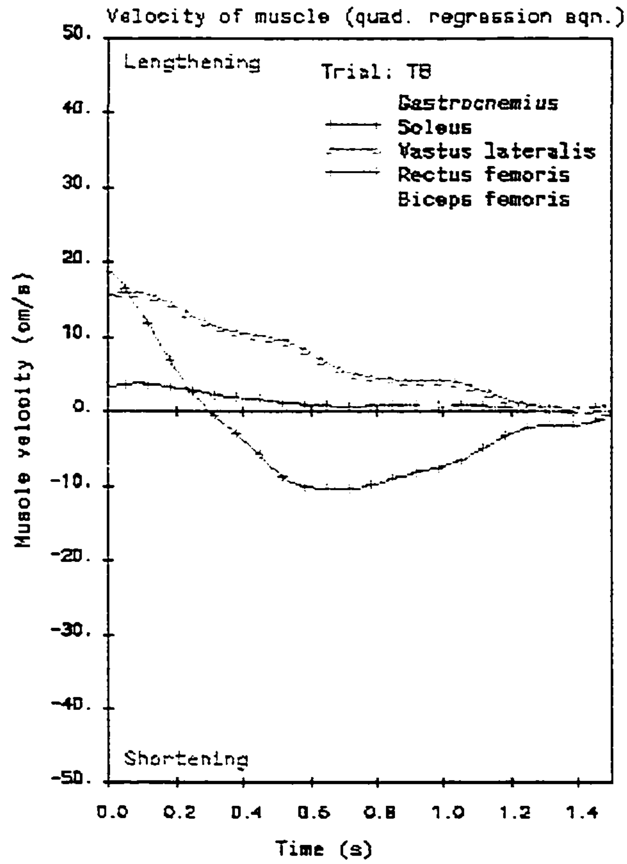


Figure 4.4b: Muscle curves showing the lengthening and shortening of the five muscles of study for the female subject during squatting. Muscle curves were calculated using the general regression equations Note the2 spikes at time 0.1 seconds in the vastus lateralis and biceps femoris curves in the top graph. Note that no spikes are seen in the curves.

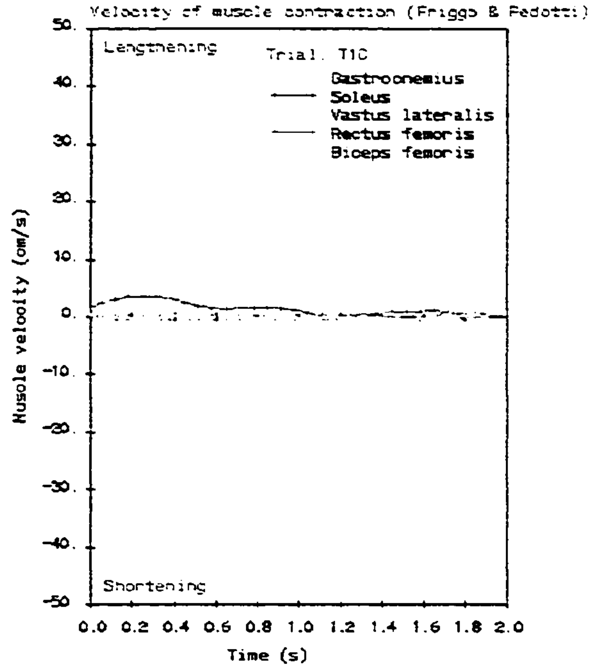
Male Qualitative Analysis

Very little difference was observed in the muscle curves produced by the three models for ankle dorsiflexion (Figure 4.5a&b). All muscles were performing their proper functions, as described in the female section. Frigo and Pedotti's (1978) model showed slightly higher muscle velocity values than the regression models.

The graphs depicting muscle velocities during knee extension showed a lengthening of the gastrocnemius and biceps femoris, and a shortening of the rectus femoris and vastus lateralis (Figure 4.6a&b). These four muscles were observed to be performing their proper function. However, the soleus, a muscle that does not cross the knee joint, and therefore should not change length, was observed to be undergoing random changes in length. These length changes resulted from the ankle wobbling, as it was not supported during extension of the knee.

Frigo and Pedotti's (1978) model had two discontinuities, exhibited as spikes, in the muscle curves of the biceps femoris and vastus lateralis at 0.9 seconds. These discontinuities were not observed in either of the regression models. Another contrast between the models was the muscle velocity of the biceps femoris. Although all three models showed the biceps femoris to be lengthening during knee extension, the triangle based model (Frigo & Pedotti, 1978) showed a much greater rate of shortening than the regression models. This discrepancy between the models was also observed in the knee extension data of the female subject.

The muscles performed their proper functions during extension of the hip joint (Figure 4.7a&b). During the first 0-1.0 seconds of hip extension the rectus femoris lengthened, the biceps femoris shortened and the other three muscles showed very little change in length. Following this time period the muscle length curves of the rectus femoris and biceps femoris began to fluctuate, and the



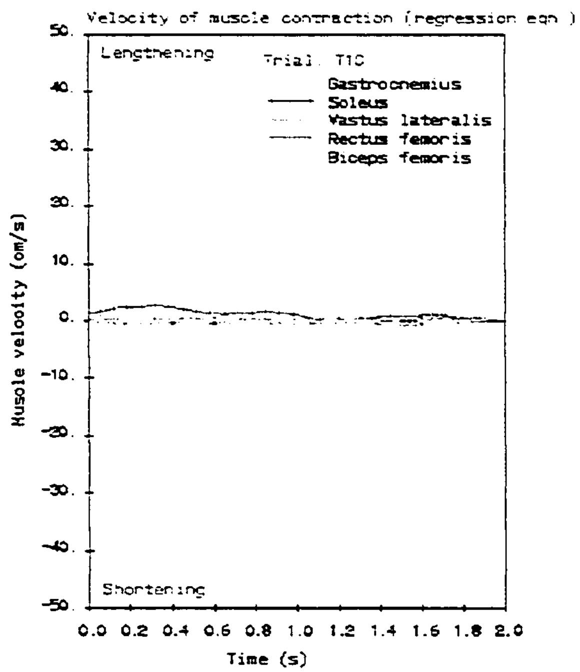


Figure 4.5a: Muscle curves showing the lengthening and shortening of the five muscles of study for the male subject during ankle flexion. Curves calculated using Frigo and Pedotti's (1978) model are displayed at top, while regression model curves are located in the bottom figure.

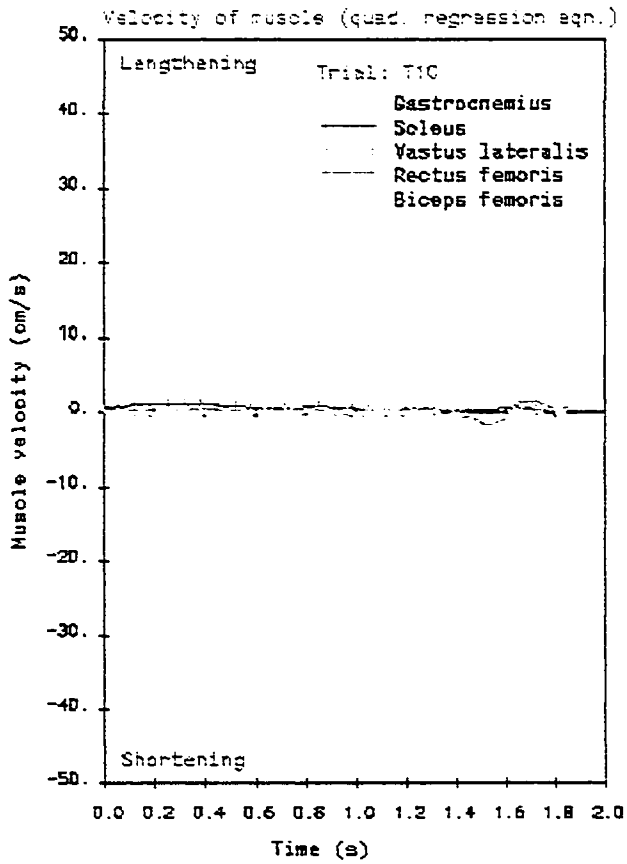
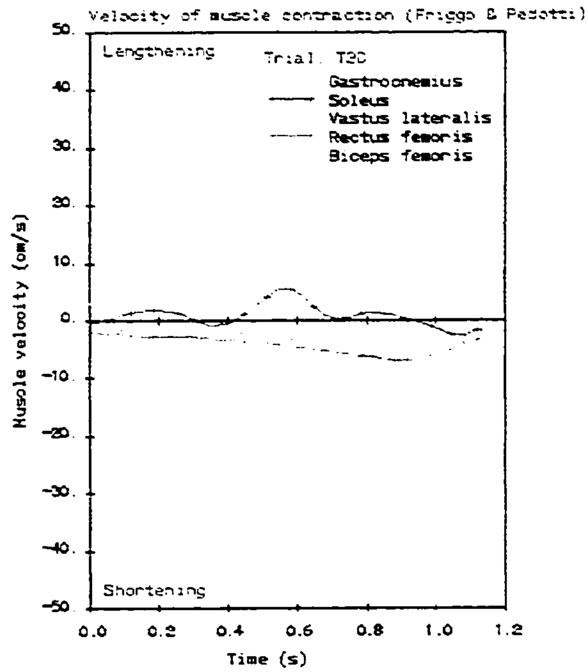


Figure 4.5b: Muscle curves showing the lengthening and shortening of the five muscles of study for the male subject during ankle flexion. Muscle curves were calculated using the general regression equations.



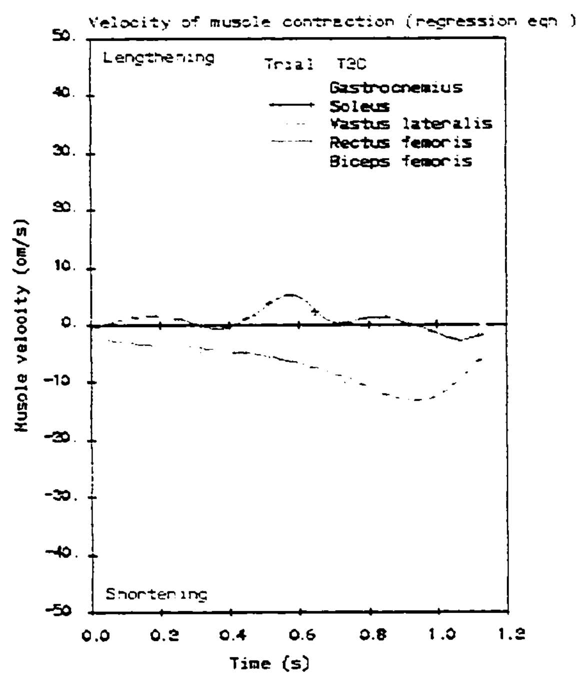


Figure 4.6a: Muscle curves showing the lengthening and shortening of the five muscles of study for the male subject during knee extension. Curves calculated using Frigo and Pedotti's (1978) model are displayed at top, while regression model curves are located in the bottom figure. Note the 2 spikes at time 0.9 seconds in the vastus lateralis and biceps femoris curves in the top graph.

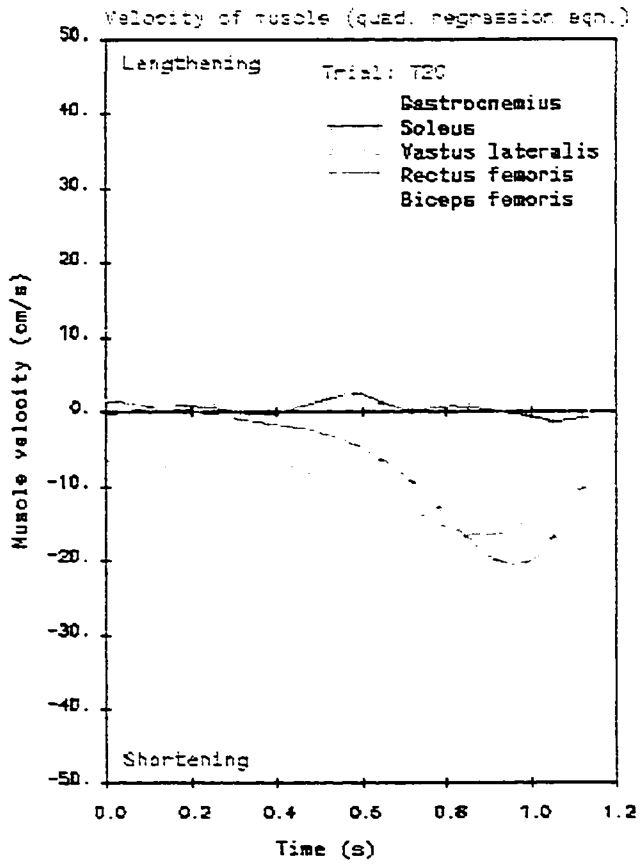


Figure 4.6b: Muscle curves showing the lengthening and shortening of the five muscles of study for the male subject during knee extension. Muscle curves were calculated using the general regression equations. Note that no spikes are seen in the curves.

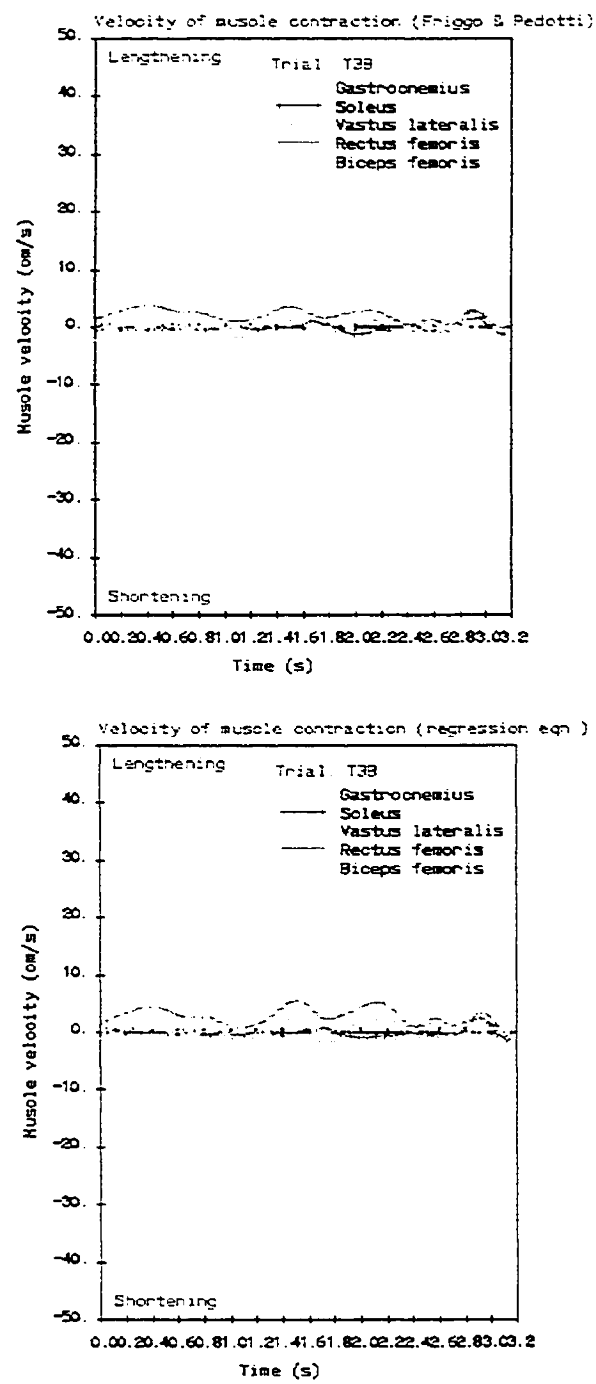


Figure 4.7a: Muscle curves showing the lengthening and shortening of the five muscles of study for the male subject during hip extension. Curves calculated using Frigo and Pedotti's (1978) model are displayed at top, while regression model curves are located in the bottom figure.

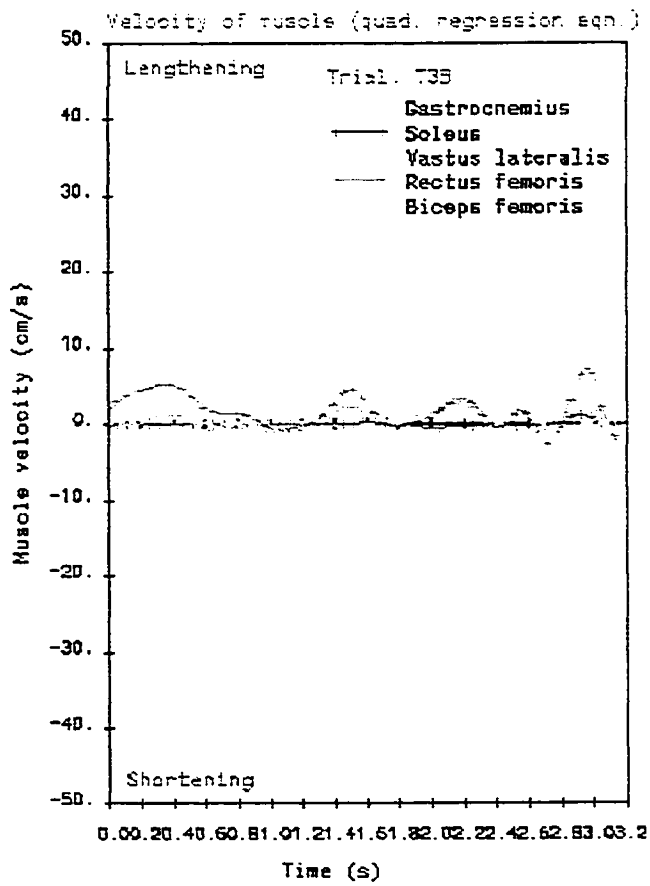


Figure 4.7b: Muscle curves showing the lengthening and shortening of the five muscles of study for the male subject during hip extension. Muscle curves were calculated using the general regression equations.

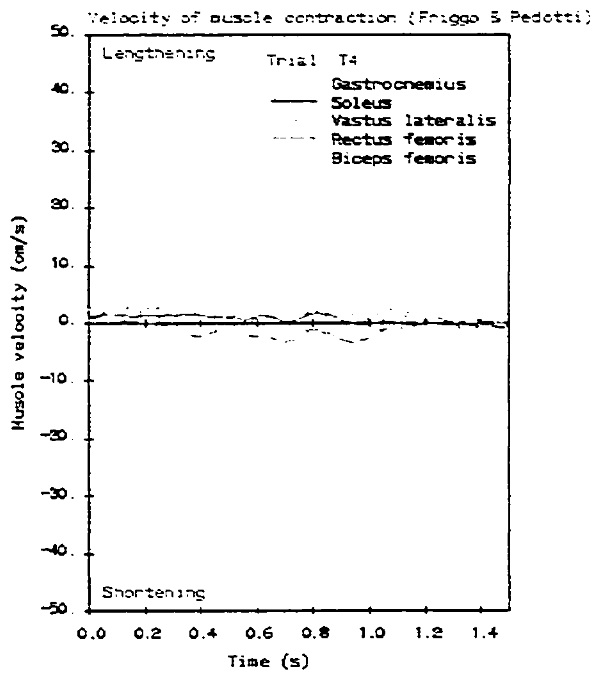
other muscles began to exhibit activity. Examination of the animation showed that compensatory motions were occurring during this later phase of hip extension. The amount of muscle lengthening and shortening during the compensatory motions were greater for the regression models than for the triangle based model (Frigo & Pedotti, 1978)

Similar to the female data, many differences existed between the three muscle length models when the male squatting motion was analyzed (Figure 4.8a&b). Different muscle patterns were seen in the muscle curves predicted from the models. Frigo and Pedotti's (1978) triangle based model showed a slow lengthening of the vastus lateralis, biceps femoris and soleus, and a shortening of the gastrocnemius. The rectus femoris exhibited a short period of lengthening at the start of the squatting motion (0-0.2 s), which was then followed by shortening of the muscle. In comparison, the regression models both showed a lengthening of the vastus lateralis, biceps femoris and soleus, and a shortening of the gastrocnemius. In both regression models the rectus femoris was lengthening for the first 0.6 seconds and then shortened for the remainder of the motion.

Two other differences between the models were observed for the squatting motion. Spikes were observed in Frigo and Pedotti's (1978) model at 0.3 seconds in the muscle curves of the vastus lateralis and biceps femoris. These spikes were not present in the muscle curves of either of the regression models. As well, the muscle velocities were higher for the regression models than for Frigo and Pedotti's (1978) model.

Quantitative Analysis – Part 2

The muscle lengths predicted from the general regression model and the corresponding joint angles were both included in the output of the Kinematic analysis performed using the Biomech software. For joint angles, which were common to both the digitized data and the data collected on the KinCom machine, the predicted muscle lengths were compared to the actual (observed) muscle



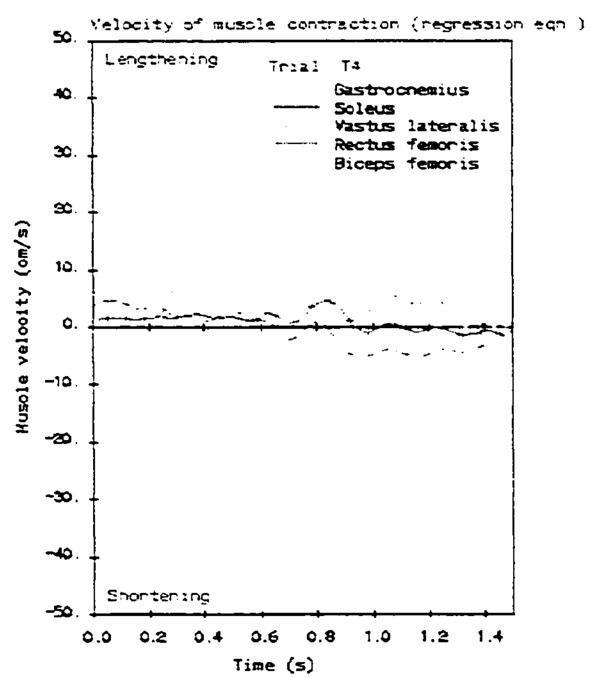


Figure 4.8a: Muscle curves showing the lengthening and shortening of the five muscles of study for the male subject during squatting. Curves calculated using Frigo and Pedotti's (1978) model are displayed at top, while regression model curves are located in the bottom figure. Note the 2 spikes at time 0.3 seconds in the vastus lateralis and biceps femoris curves in the top graph.

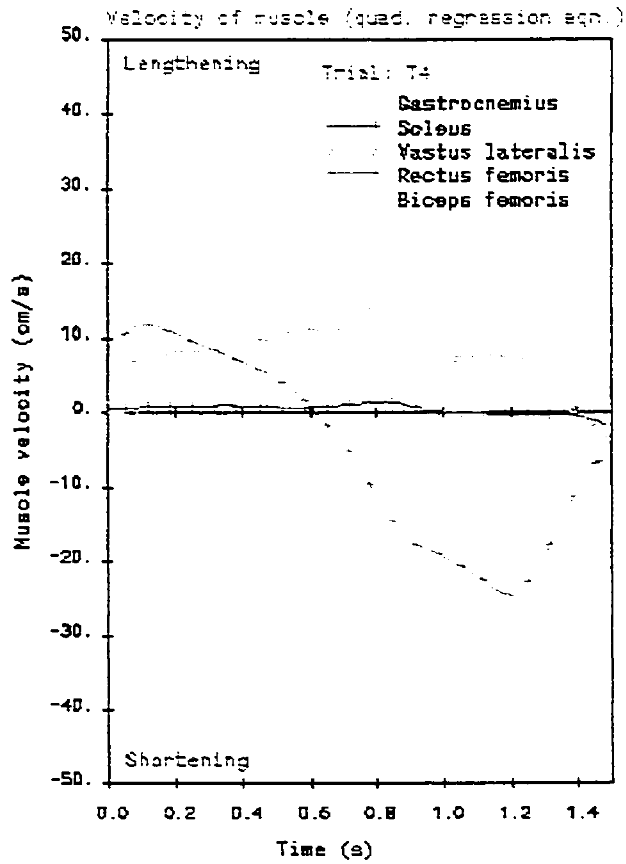


Figure 4.8b: Muscle curves showing the lengthening and shortening of the five muscles of study for the male subject during squatting. Muscle curves were calculated using the general regression equations. Note that no spikes are seen in the curves.

lengths measured externally while the subject was seated on the KinCom. The RMSE between the predicted and observed values was then calculated.

It is important to point out that for biarticular muscles the joint angles obtained from the digitized data seldom corresponded to those used when measuring actual muscle length on the KinCom. For example, a muscle length may be predicted using the general regression model while the knee joint is at 110 degrees and the hip joint is at 100 degree, but the muscle length measurements taken while the subject was on the KinCom may not have happened with the knee and hip joint both at these exact angles. It was decided that if there were 5 or fewer comparisons between predicted and observed muscle lengths than the RMSE would not be calculated, as the results would not be reflective of the sample studied. Table 4.2 lists the results for the RMSEs that were calculated.

Table 4.2: The RMSE calculated between the muscle lengths predicted by the general regression model and the actual observed length measured while the subject was on the KinCom machine. Note that for cases where the predicted and observed muscle lengths do not have at least five corresponding joint angles a question mark is listed in the RMSE column.

Gender	Muscle	Calculated RMSE	Acceptable RMSE
Female	Soleus	3.54	20
	Vastus Lateralis	25.45	25
	Gastrocnemius	?	30
	Rectus Femoris	315.05	30
	Biceps Femoris	30.85	30
Male	Soleus	26.58	20
	Vastus Lateralis	361.39	25
	Gastrocnemius	?	30
	Rectus Femoris	?	30
	Biceps Femoris	?	30

Discussion

It is important to remember, when reading this discussion, that the results in this section were based on the data of only two subjects. Therefore, all generalizations made, and conclusions reached, do not have much support behind them. However, similar trends were observed between the two subjects and the resulting muscle functions were as predicted based on anatomical design (Table 1.1), so it was possible that these two subjects were representative of the larger population. Unfortunately, this cannot be stated with certainty, as it was possible, but unlikely, that these two subjects were both at the same extreme of the population.

Quantitative Analysis – First Part

The comparison of the muscles lengths predicted by the general regression model, the individual regression equations and Frigo and Pedotti's (1978) triangle based model all fell within the allotted range with two exception. For the males, the vastus lateralis lengths predicted by the triangle based model (Frigo & Pedotti, 1978) and the biceps femoris length predicted by the general regression model fell outside the accepted range. This would indicate that these models were unable to accurately predict the lengths of these two muscles. The predicted muscle lengths from the individual regression equations all fell within the accepted range. As the individual equations were built on the individual subject's data it is not surprising that they gave more accurate predictions than the other two models which were built on data collected from a sample group.

Single Joint Motion – Qualitative Analysis

Few differences were observed between the muscle curves produced using the general regression model, the individual regression equations and Frigo and Pedotti's (1978) triangle based model. Both showed the muscles performing their proper functions during single joint, sagittal plane motions. As well, there was a mirroring of the lengthening and shortening patterns of the muscle curves produced by the two models. For example, when one model showed a muscle to be lengthening, the other models also showed lengthening of the same muscle. This was also the observed pattern for muscles that were shortening, or experiencing no change in length, and held true for all five muscles of study.

Even though two models showed the five muscles of interest undergoing the same pattern of length changes, the extent of the changes in muscle length (i.e., velocity) varied. The general regression model and the individual equation showed similar velocities, but these differed greatly from the velocities predicted by the triangle based model (Frigo & Pedotti, 1978). The two types (regression and triangle) of models predicted very different contraction velocities for the same motions and no consistent pattern was observed for four of the five muscles of study. It was possible for one type of model to have higher contraction velocities for all the muscles in one instance and then, in another case, to show contraction velocities much lower than those of the other model type. In addition, it was not uncommon for one model type to calculate velocities lower than the other type of model for some muscles and higher than the other type of model for other muscles. As pointed out in the introduction of this chapter, the differences in velocities most likely arose from the different ways in which the attachment points of the muscles were defined.

The biceps femoris was the exception as it was the only muscle that showed a consistent trend upon examination of contraction velocities. The predicted velocities for the biceps femoris, using the general regression model and the individual regression equations, were always much lower than the velocities for the same muscle obtained using the triangle based model (Frigo & Pedotti, 1978). In addition, the velocities of the biceps femoris and rectus femoris, predicted using the general regression model and the individual regression equations, were quite different. The muscle curves of the biceps femoris always showed absolute muscle velocities that were much lower than the velocities of the rectus femoris. As these two muscles are similar in length and cross the same joints, it is anatomically impossible that the rectus femoris was changing length that much more quickly than the biceps femoris.

In Chapter 2, possible sources of error in the measuring of the biceps femoris muscle were outlined and it was suspected that regression equations for this muscle were not a true reflection of the mathematical relationship that actually exists. The data from this current chapter provided additional support for the conclusion that the biceps femoris data were flawed due to an inability to reach the point of origin of this muscle.

There were two important differences between the models. First, the curves representing the velocities of the vastus lateralis and biceps femoris muscles during knee flexion were discontinuous in Frigo and Pedotti's (1978) model. These discontinuities presented as spikes that interrupted otherwise smooth curves and occurred when there was a changeover in the triangles used to calculate muscle lengths. This was the major downfall of Frigo and Pedotti's (1978) model and was avoided with the use of either regression models, both of which showed no discontinuities.

In addition, the two regression models both appeared to be slightly more sensitive to small changes in muscle lengths than the triangle based model (Frigo & Pedotti, 1978). The female subject performed compensatory motions at the end of both ankle dorsiflexion and hip extension. The male subject also displayed compensatory motion at the end of hip extension. These motions could clearly be seen when the digitized data were animated. The compensatory motions were easy to detect in the muscle curves of the general regression model and the individual regression equations as activity, in the form of peaks and troughs, was observed at the end of the range-of-motion. In comparison, Frigo and Pedotti's (1978) model showed little, or no, activity during these periods when compensatory motions were being performed.

Multi-Joint Motion – Qualitative Analysis

It was quite simple to define the role, concentric or eccentric, a single joint muscle performed during motion using knowledge of the relative position of the muscle at the point where it crosses the joint (Table 1.1). In contrast, the two-joint muscles performed different functions at each of the joints they crossed and this created unique situations where the direction of the resultant movement was somewhat unpredictable (Visser et al., 1990). As such, it was not correct to assume that the net moment of the body segments acted upon by excited muscles during multiarticular motor tasks was the sum of the motions that would occur if each muscle acted in isolation on a joint (Zajac & Winter, 1990).

An example of the biarticular muscles acting in a unpredictable manner is Lombard's (1903) paradox. This paradox occurs when two antagonistic biarticular muscles contract simultaneously to produce motion. For example, when rising from a chair the rectus femoris and the biceps femoris simultaneously contract. Since the rectus femoris is a hip flexor and a knee extensor and the biceps femoris is a hip extensor and knee flexor it would be logical to predict that if these muscles contract at the same time their opposing functions will off set each other and no motion will result. However, this is not the case as extension of both the knee and hip result.

The models examined here showed the biarticular biceps femoris and gastrocnemius muscles to be undergoing similar changes in lengths during the multiarticular squatting motion. However, the models showed the biarticular rectus femoris muscle to be lengthening and shortening at different times. Frigo and Pedotti's (1978) model showed a slow lengthening of the biceps femoris and a slightly faster shortening of the gastrocnemius. The rectus femoris showed an initial, brief lengthening followed by a shortening that continued until the motion stopped. These results indicated that the length of both the biceps femoris and rectus femoris were more affected by motion at the hip joint than they were by motion at the knee joint. In comparison, the length of the gastrocnemius was more affected by knee joint motion than motion at the ankle joint.

Past research (Hawkins & Hull, 1990; Visser et al., 1990) has shown that the length of the biceps femoris and gastrocnemius were most affected by the angle of the hip joint and knee joint, respectively, and this provided support for the results obtained using Frigo and Pedotti's (1978) model. However, the finding that the length of the rectus femoris was most affected by the hip joint received no support in the literature as researchers (Hawkins & Hull, 1990; Visser et al., 1990) have observed that the length of this biarticular muscle is more affected by the knee joint than the hip joint. This means that changes in knee joint angle leads to larger changes in rectus femoris length, than do changes in hip joint angle.

Similar to the triangle based model (Frigo & Pedotti, 1978), the general regression model and the individual regression equations showed a lengthening of the biceps femoris and a shortening of the gastrocnemius, but the absolute values of the contraction velocities of these two muscles differed. On the other hand, a difference between the two regression models and the triangle based model (Frigo & Pedotti, 1978) was observed in the comparison of the muscle curve of the rectus femoris. While the rectus femoris showed only a brief lengthening at the initiation of the squatting motion in Frigo and Pedotti's (1978) model, with the regression models it was shown to be lengthening during the entire first half of the squat. In all three models, the rectus femoris followed its period of lengthening with a period of shortening which lasted until the end of the motion. The extended period of lengthening at the beginning of the motion indicated that the length of the rectus femoris was being dominated by the changes in angle of the knee joint. This observation was in accordance with past research (Hawkins & Hull, 1990; Visser et al., 1990) that observed that the length of the rectus femoris was most affected by changes in the angle of the knee joint.

All models were consistent in the muscle curves of the monoarticular muscles produced during multiarticular motion. During squatting the vastus lateralis and soleus were lengthening and, thus performing their proper role at the single joint which they cross. The vastus lateralis, as well as the biarticular biceps femoris, showed discontinuity spikes in the muscle curves predicted using Frigo and Pedotti's (1978) model. No spikes were observed in the curves produced by either of the regression models.

Quantitative Analysis – Part 2

The RMSEs of the predicted and observed lengths of the soleus and vastus lateralis muscle were calculated for both genders. Only the RMSE of the females' soleus muscle fell within the acceptable range. For the biarticular muscles, many of the RMSEs between predicted and observed muscle lengths could not be calculated due to a lack of correspondence in joint angles. However, for the biarticular muscles where the RMSE could be calculated the resulting values fell outside the acceptable range. Based on the fact that all but one of the calculated RMSEs between predicted and observed muscle lengths fell outside the acceptable range, it is likely that for the muscles for whom no calculations could be performed due to lack of corresponding angles that the RMSEs were also outside the acceptable range.

There were at least three reasons the calculated RMSEs between predicted and observed muscle lengths fall outside the acceptable range. First, the general regression equations were not perfect predictors of muscle length as indicated by the R^2 values that were not equal to one. Second, the assumptions of the model lead to an increased error in the study. Three, the general regression equations did not account for individual differences.

Conclusion

The general regression model developed in this study predicts both muscle lengths that were anatomically possible (with the exception of the male's biceps femoris length) and periods of muscle lengthening and shortening that were reflective of proper muscle functioning. However, the calculated RMSE values were very large. This means that while the general regression model was able to reliably predict muscle function, it was unable to accurately predict muscle length values.

In comparisons to Frigo and Pedotti's (1978) triangle base model the general regression model is just as good at determining muscle function, if not better when considering the action of the rectus femoris during multiarticular motion. It also benefits from not showing any of the discontinuities produced by the triangle-based model (Frigo & Pedotti, 1978).

Chapter 5
Conclusion

General Conclusions

All the muscles in this study were observed to be performing their proper function according to the main actions outlined in Table 1.1, with the exception of the gluteus maximus. During hip flexion, this muscle showed no smooth lengthening, as would be expected, just random fluctuations in length. It was likely that this resulted from poorly defined "effective" origin and insertion points and led to the exclusion of this muscle from the study. It is recommended for future work involving length measurements of the gluteus maximus that either the "effective" attachment points be defined differently, the muscle be divided into functional units which are analyzed separately or the mathematical process of finite elements be applied to the data.

After removal of the gluteus maximus, five long, straight muscles remained for analysis. The first task was to build the model based on height normalized data and test for gender differences. As the height normalized model had low predictability the second task was to improve model fit using different variables for normalization, data transformation and forward selection polynomial regression couple with the addition of height or leg segment length as an independent variable. Finally, the newly built general regression model was compared to the individual regression equations and the triangle based model (Frigo & Pedotti, 1978). The conclusions drawn from this work are outlined below.

1. **An effect of gender was observed.**

   The overall order of the regression equations did not differ between the male and female subjects. However, the values of the constant and the regression coefficients in the equations did show an effect of gender. This difference between the genders appeared to be the result of the male subjects having a larger average height than the females.

2. **Normalization by height and leg segment length was not effective in reducing individual differences, nor was transformation of the data successful in increasing model fit.**

   There was no statistical difference between the R^2 values of the equations based on the height normalized and the leg segment length normalized data. Neither types of normalization were successful in decreasing the scatter in the data (i.e., individual differences) and producing a predictive model. Transformation of the data was also unsuccessful in increasing the R^2 values.

3. **Forward selection polynomial regression with the addition of either height (biarticular muscles) or leg segment length (monoarticular muscles) as an independent variable lead to an increase in model fit.**

   The addition of leg segment length, for monoarticular muscles, and height, for biarticular muscles, accounted for much of the interindividual differences between subjects. This was indicated by the large increases in R^2 values that resulted when either leg segment length or height was added to the independent variable side of the equation. The observed increase in model fit was a result of the high correlation between muscle length and both leg segment length and height.

4. **The type of muscle (monoarticular or biarticular) determines the order of the regression equation.**

   The monoarticular muscles were best described by linear equations, while the biarticular muscles were best described by second-order equations. The only exception was the biceps femoris, but as was pointed out many times in this study it was suspected that the biceps femoris data was flawed. This indicated that the mathematical equations relating muscle length to joint angle(s) became more completed as the number of joints the muscles spanned increased.

5. **The general regression model reliably predicts muscle function, but is not a very accurate predictor of muscle lengths.**

The general regression model predicted muscle lengths that were anatomically possible (with the exception of the male's biceps femoris length) and periods of muscle lengthening and shortening that were reflective of proper muscle functioning as determined by anatomical design. However, the predicted muscle lengths were not very accurate as indicated by the large RMSEs calculated between the predicted and observed values. The low RMSEs were thought to have resulted from measurements errors, assumptions of modelling and individual differences.

6. **The newly developed general regression model was preferred to Frigo and Pedotti's (1978) model.**

The newly developed general regression model produced muscle length curves that were consistent with those produced using Frigo and Pedotti's (1978) model. The only exception was the rectus femoris, which showed different periods of lengthening and shortening during squatting. However, past research (Hawkins & Hull, 1990; Visser et al., 1990) provided support for the results obtained using the regression model. In addition, the regression model did not display the discontinuities, which were a weakness of Frigo and Pedotti's (1978) model.

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Appendix A

1) Grieve et al. (1978)

$$\Delta L_i = A_0 + A_1\theta_i + A_2(\theta_i)^2$$

Where ΔL_i = percent length of segment
A = regression constant
θ = joint angle in degrees

3) Hawkins and Hull (1990)

$$L = C_0 + C_1\theta_i + C_2\theta_2 + C_3\theta_2^2 + C_4\theta_3$$

Where L = normalized muscle length
C = regression coefficients
θ_i = hip angle
θ_2 = knee angle
θ_3 = ankle angle

4) Visser et al. (1990)

$$\Delta l_{oi} = A_o + A_1\theta_i + A_2(\theta_i)^2$$

Where Δl_{oi} = length between origin and insertion
θ_i = joint angle in degrees
A = constant

Appendix B

CONSENT FORM

Name of researchers:	Taunya St. Pierre[1] and Dr. D.G.E. Robertson[2]
Institution, Faculty, Department:	University of Ottawa, Faculty of Science, Department of Biology[1]; University of Ottawa, Faculty of Health Sciences, School of Human Kinetics[2]
Telephone number:	562-5800 ext.4246[1] ; 562-5800 ext.4227[2]
E-mail address:	tstpierr@science.uottawa.ca[1] ; dger@uottawa.ca[2]
Address:	125 University Private Ottawa, Ont K1N 6N5[1,2]

Whenever a research project involves humans, the written consent of the research subjects must be obtained. This does not imply that the project necessarily involves a risk. In view of the respect owed to the research subjects, the University of Ottawa and the research funding agencies have made this type of agreement mandatory.

I,__________________, am interested in collaborating in the research conducted by Taunya St.Pierre a Masters student in the Department of Biology, Faculty Science at the University of Ottawa, under the supervision of Professor Robertson of the School of Human Kinetics, Faculty of Health Sciences at the University of Ottawa, and their assistants. The title of this project is *Muscular Modelling of the Lower Extremity: The Effect of Varying Joint Angles on Muscle Length.* The purpose of this study is to determine the length of muscles in the lower body based on ankle, knee and hip angles. This information will then be used to determine if two-joint muscles act paradoxically (i.e., in a manner contrary to their normal action). If paradoxical activity is found the secondary objective will be to determine at what joint angles paradoxes occur.

My participation will consist of attending one session held in a physiology/biomechanics laboratory at the University of Ottawa. Each session will last approximately three hours. At the start of the session I will have my anthropometric measurements (height, weight and limb lengths) taken. Then the researcher will palpate and mark the origin and insertion of eight muscles in my lower limbs with a non-toxic marker before the start of testing with the KinCom machine.

Once on the KinCom I will move my ankle joint from full flexion to full extension and this will be considered my normal, comfortable range-of-motion for that joint. Both mechanical and computer KinCom stops will be placed at the ends of the normal the range-of-motion to ensure that neither hyper-flexion nor hyper-extension will occur. This will then be repeated for the knee and hip joints. Following this I will allow the KinCom to passively move my joints within the previously defined normal ranges of motion, stopping at joint angles where the researcher is required to take muscle length measurements. In addition to the mechanical and computer stops, the researcher will provide me with a hand held stop so I can turn off the KinCom at any time if I become uncomfortable.

At each pause in the normal range-of-motion the researcher will electronically digitize the location of the origin and insertion points of the muscles. This involves the researcher gently touching the origin and insertion points of my muscles, as well as my joint centres, with the tip of a Microscribe. These three-dimensional points will be recorded in a computer file.

I understand that the data collected will be used only for research purposes and that my confidentiality will be respected by the experimenter as my name will not be recorded with my data. In fact, I will be assigned an anonymous identification code which will be used throughout the experiment. All results and data pertaining to this study will be kept in a secure area during the thesis process. At no time will my individual regression results be made available to anyone outside the researchers except to myself upon request. The thesis will be written in such a way as to conceal the identity of all participants.

I understand that since this activity deals with the Kin-Com there is a low risk of discomfort as the lever arm moves the joints through its normal range-of-motion. I have received assurances that I can notify the researcher if I feel any discomfort, and that testing will end if I no longer wish to continue. If I feel nervous with any part of the procedure, or have any questions/concerns, I will tell the researcher and the experiment will be stopped. This will provide me with time to decide whether or not I wish to continue on with the session or withdraw.

I am free to withdraw from the project at any time, before or during any testing condition, without fear of reprisal. I have the right to refuse to participate in any one of the testing conditions. I am also free to ask the researcher any questions I wish pertaining to the study.

I wish to proceed with this study as there will be little or no harm done to my own person and the results of this research will be used to create a computer program that will assist future researchers and health care professionals in analysing human movement.

Any information requests or complaints about the ethical conduct of the project may be addressed to the Sciences and Health Sciences Research Ethics Board of the University of Ottawa, or by calling the Protocol Officer for Ethics in Research :

Lise Frigault
Room 302, Tabaret Hall
Phone: 562-5800 ext.1787
E-mail: lfrigaul@uottawa.ca

There are two copies of the consent form, one of which I may keep.

If I have any questions about the conduct of the research project, I may contact the researcher or her supervisor at the numbers provided at the top of the page.

Researcher's signature:______________________ Date:______________

Research Subject=s signature:_________________ Date:_____________

If I wish to receive a summary of the findings of this research which will be available in June 2001 at the following address: 125 University Private (Montpetit Hall Room 319)
Ottawa ON K1N 6N5

Appendix C

Graphs showing the general trends between muscle lengths and joint angles for all muscles of Interest. Biarticular muscle are displayed three times; twice at a single joint and once at both joints. The graphs are organized with the female data displayed on the first page and the male data on the following page.

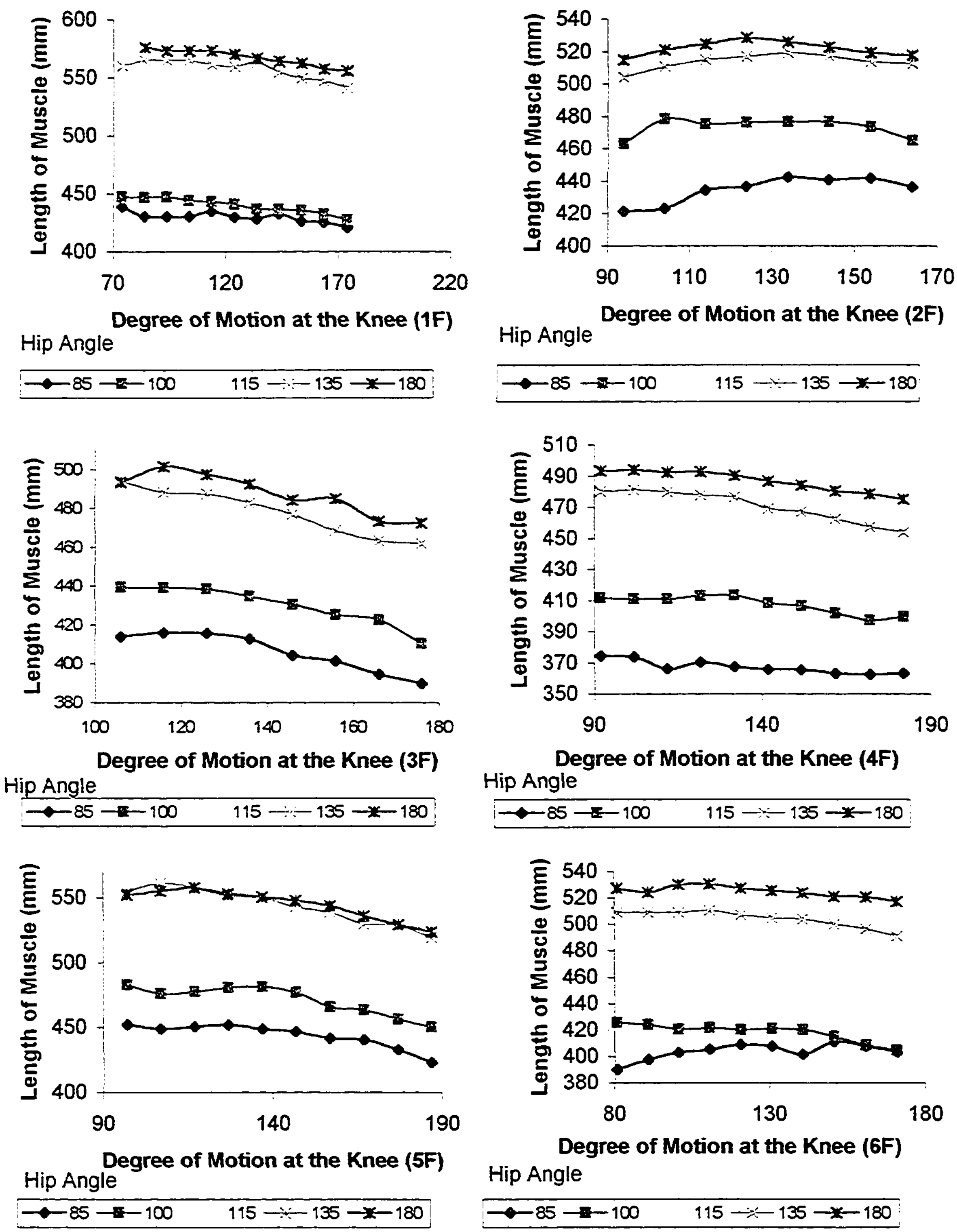


Figure I : Effect of Varying Hip & Knee Joint Angles on Rectus Femoris Length - Females

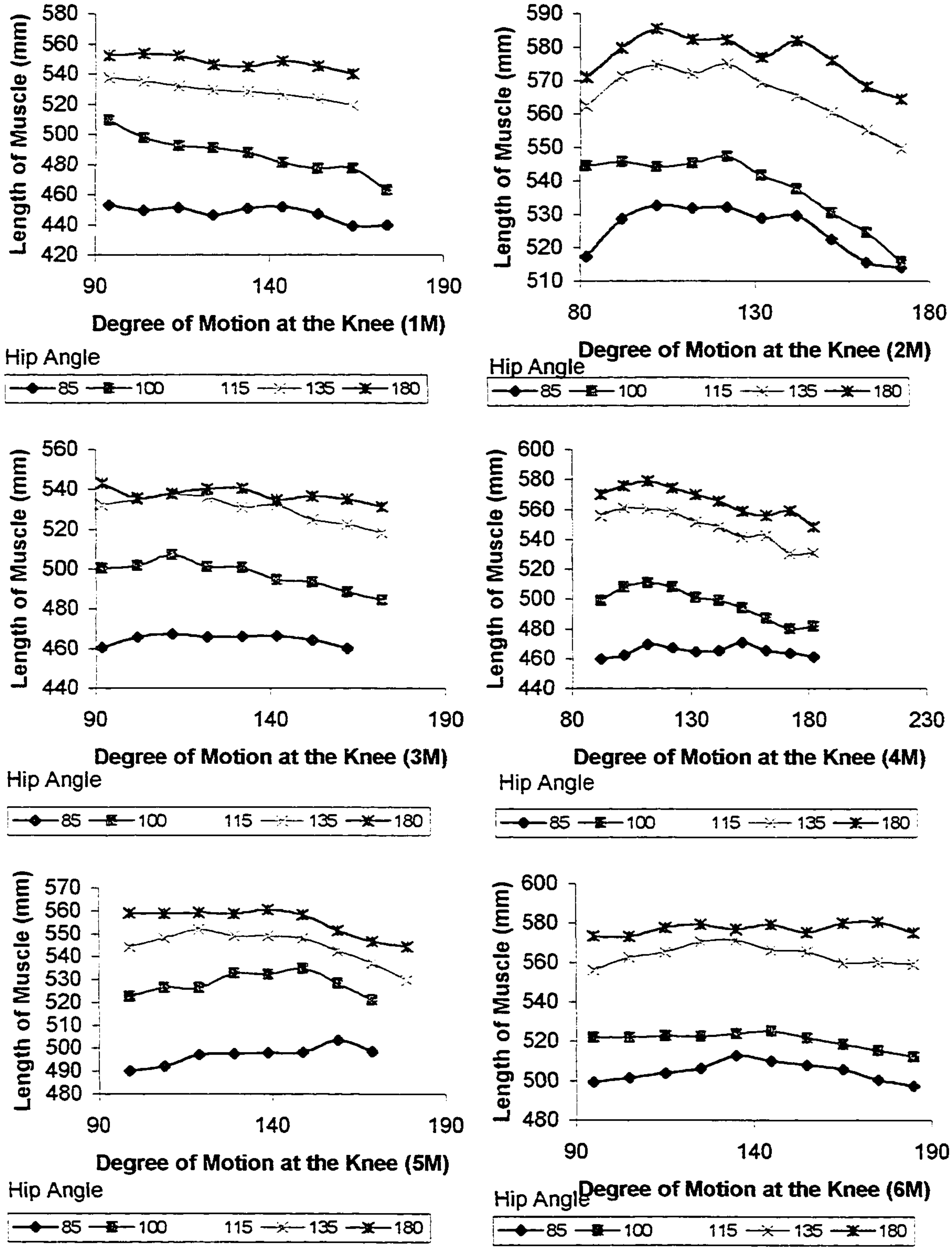


Figure II: Effect of Varying Hip & Knee Joint Angles on Rectus Femoris Length - Males

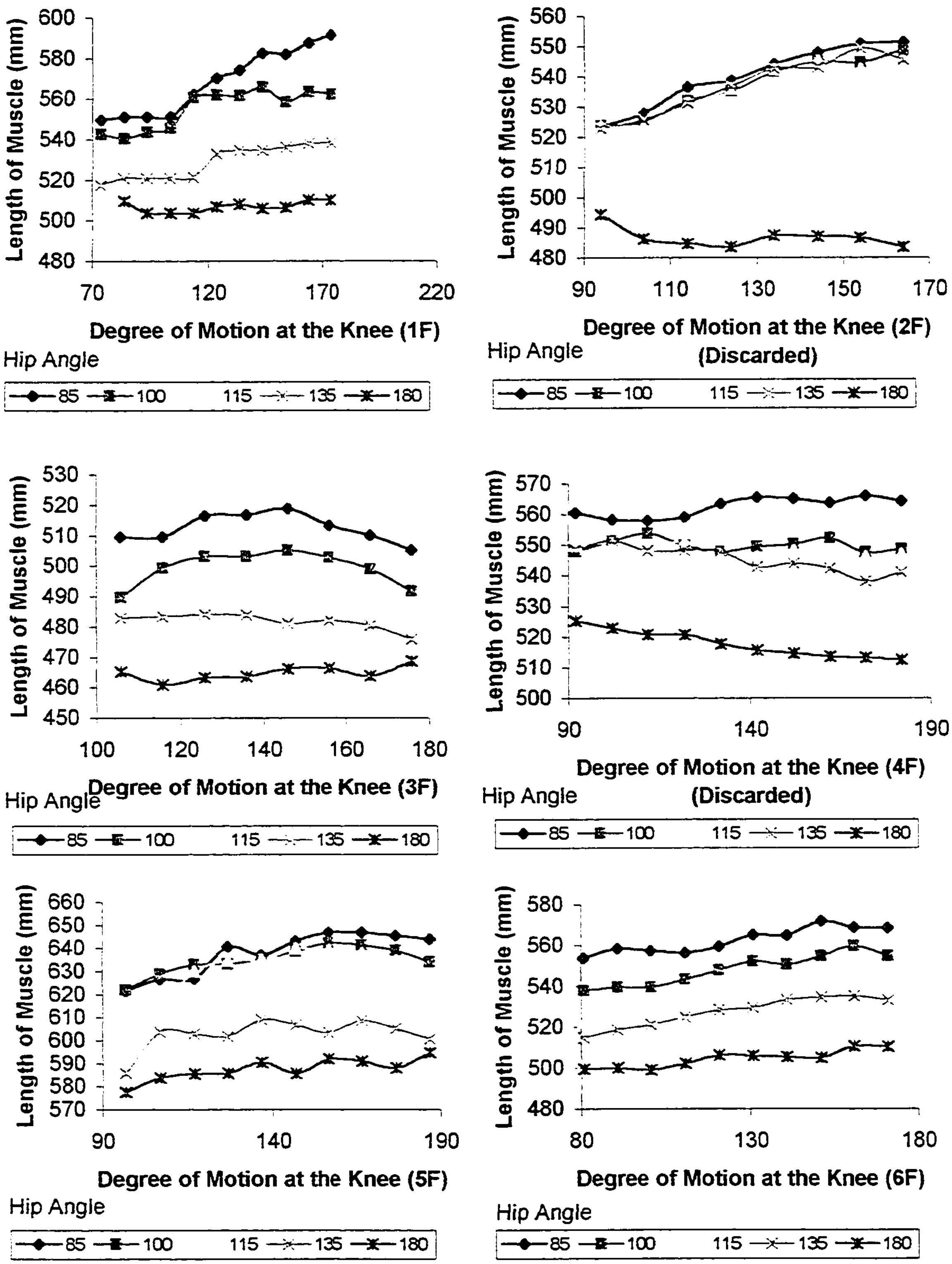


Figure III: Effect of Varying Hip & Knee Joint Angles on Biceps Femoris Length - Females

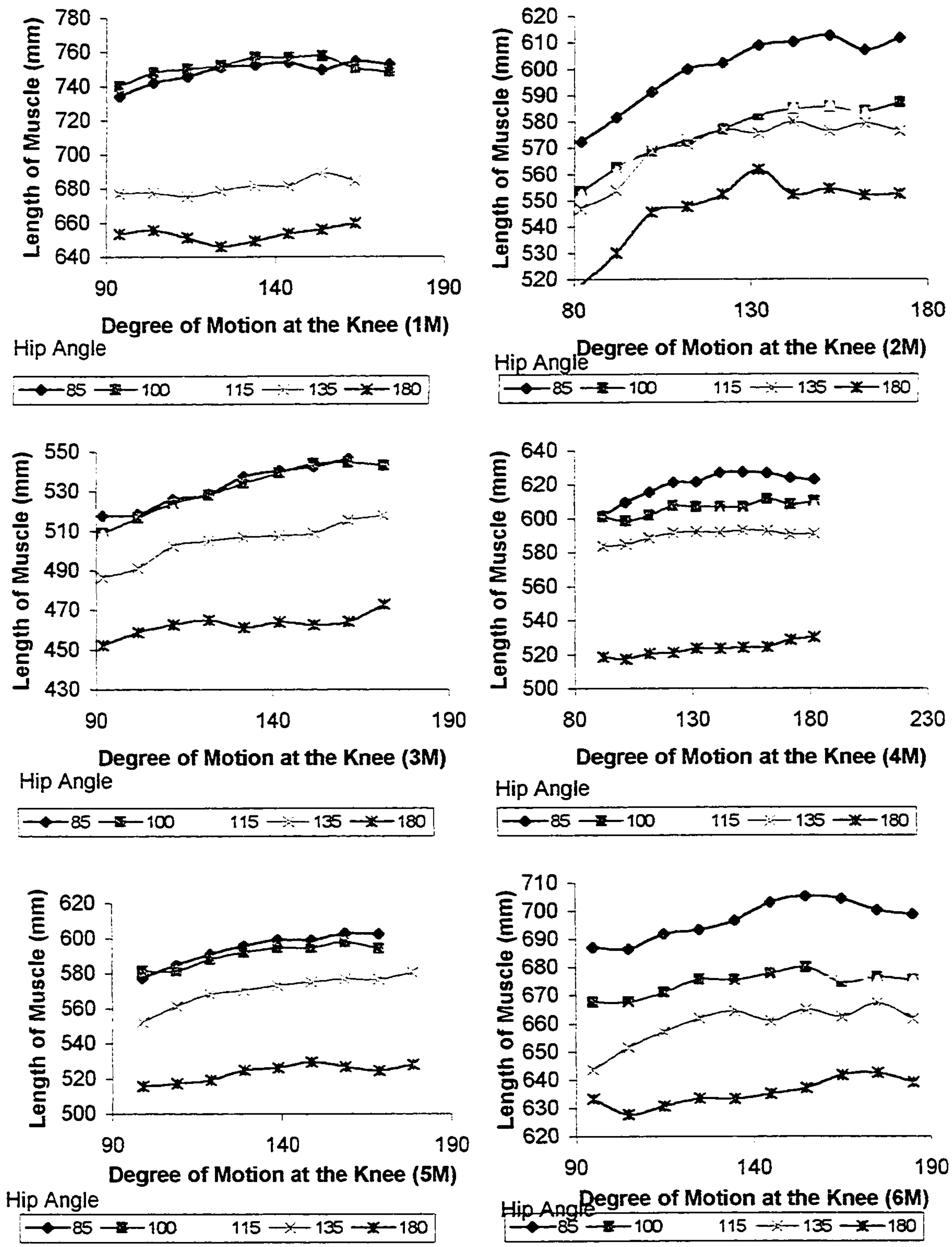


Figure IV: Effect of Varying Hip & Knee Joint Angles on Biceps Femoris Length - Males

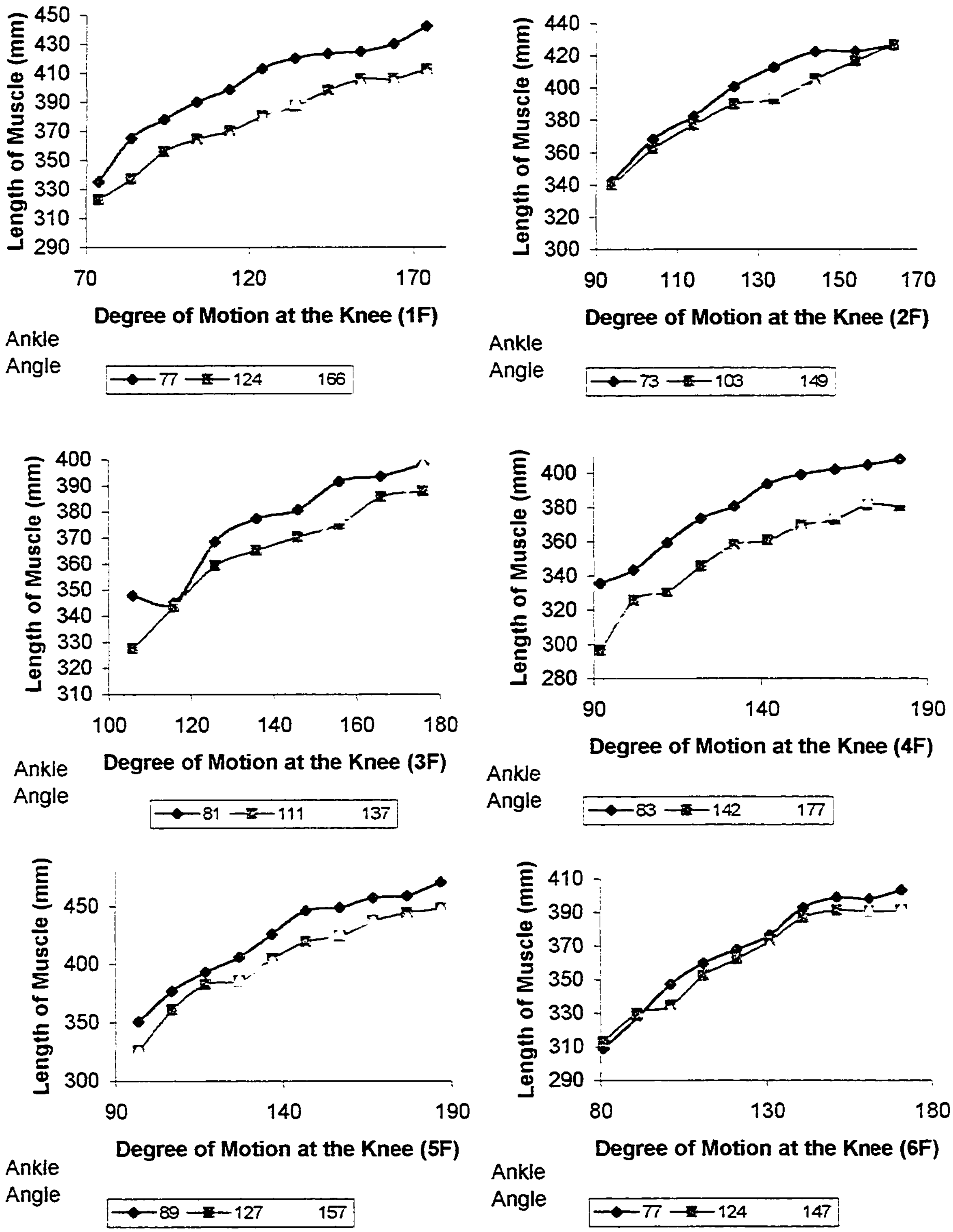


Figure V: Effect of Varying Knee & Ankle Joint Angles on Gastrocnemius Length - Females

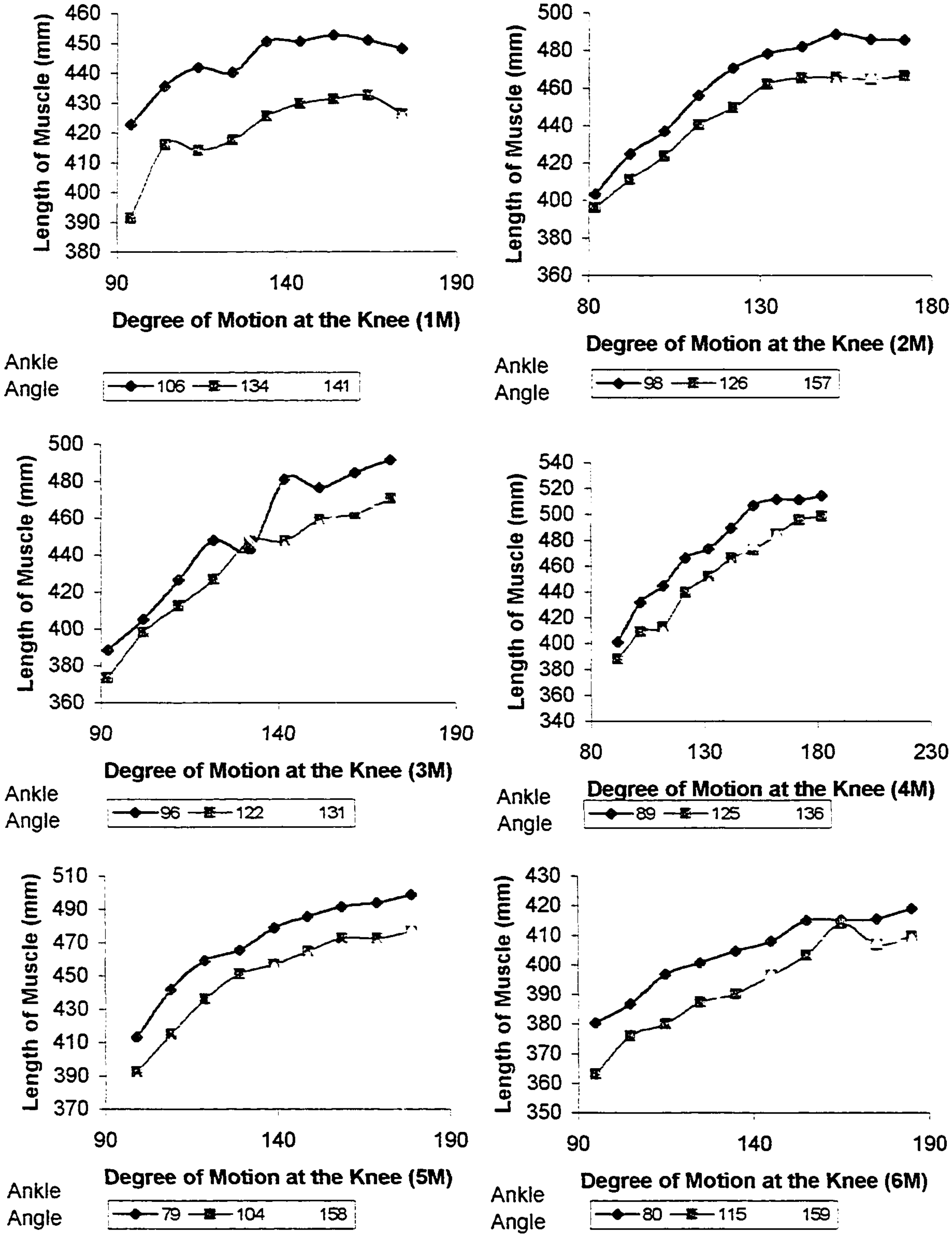
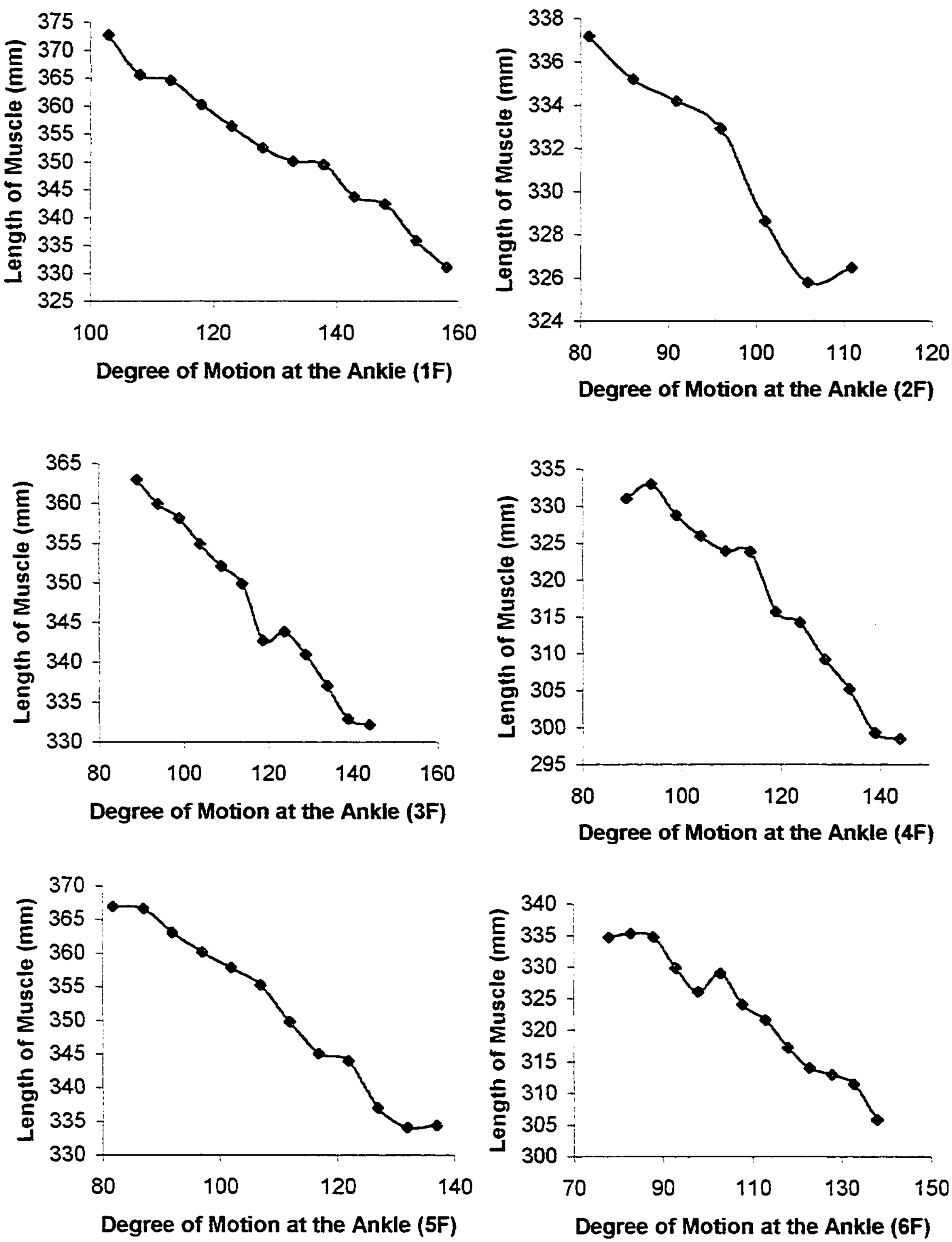


Figure VI: Effect of Varying Knee & Ankle Joint Angles on Gastrocnemius Length - Males



FigureVII: Effect of Varying Ankle Joint Angle on Soleus Length -Females

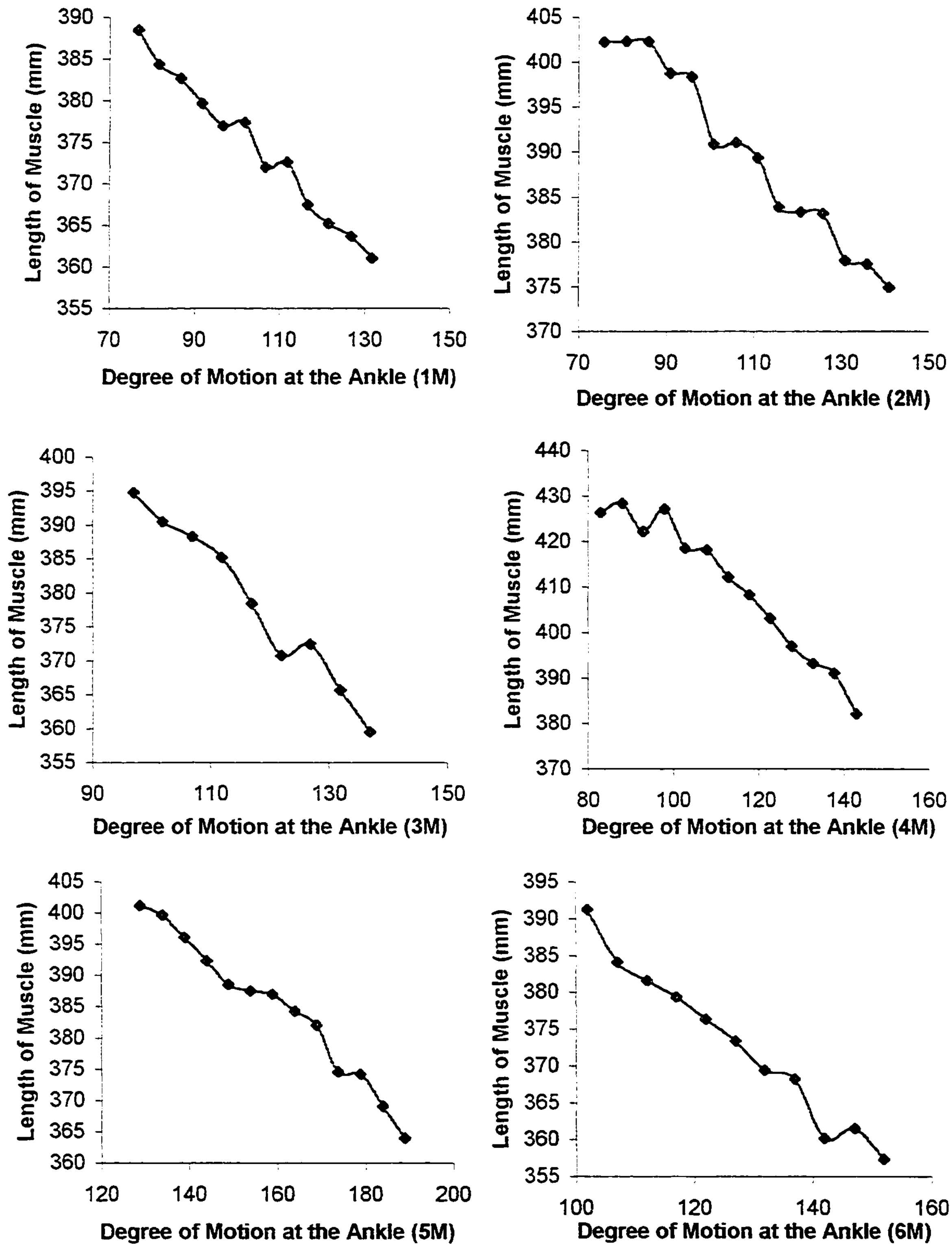


Figure VIII: Effect of Varying Ankle Joint Angle on Soleus Length - Males

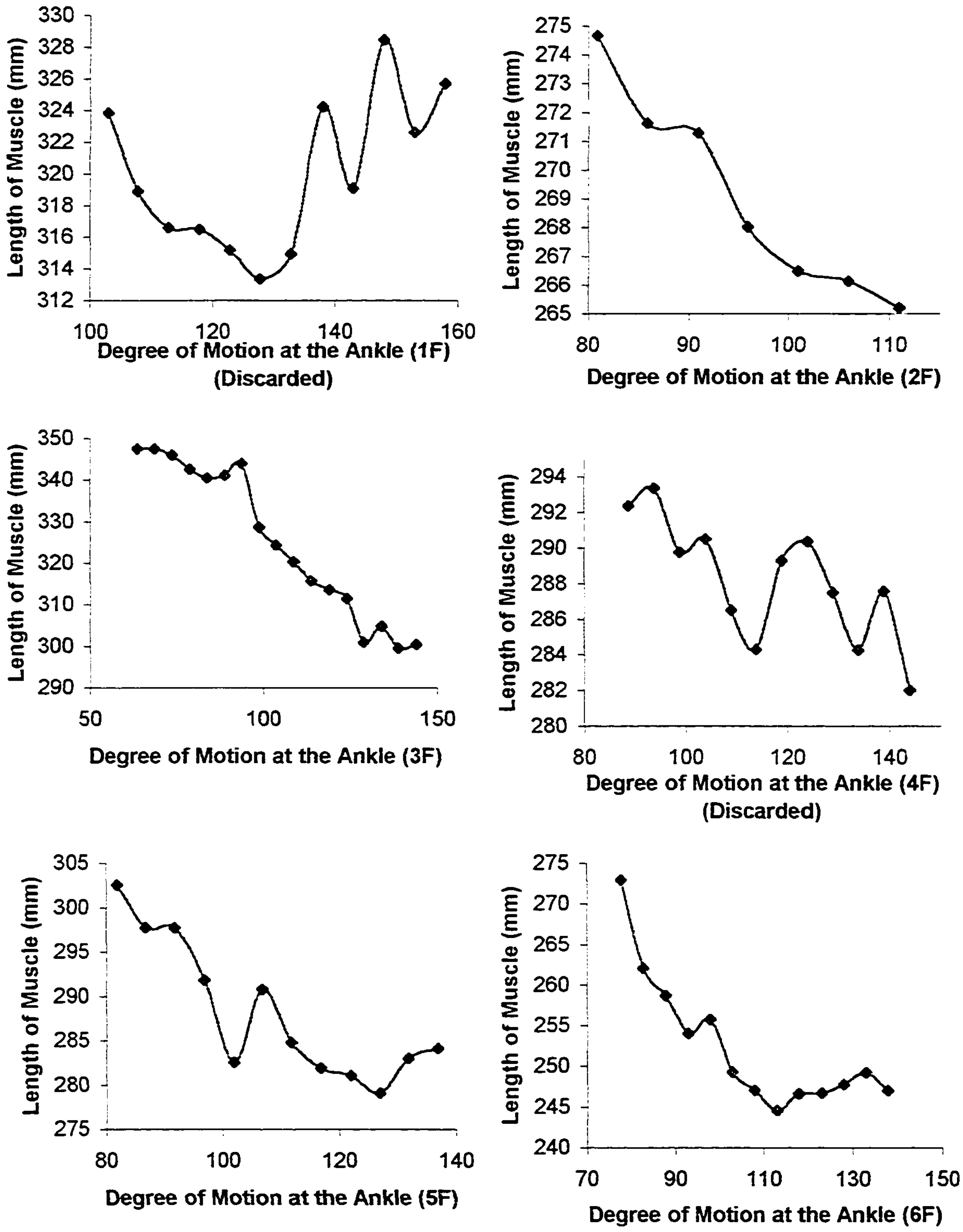


Figure IX: Effect of Varying Ankle Joint Angle on Gastrocnemius Length - Females

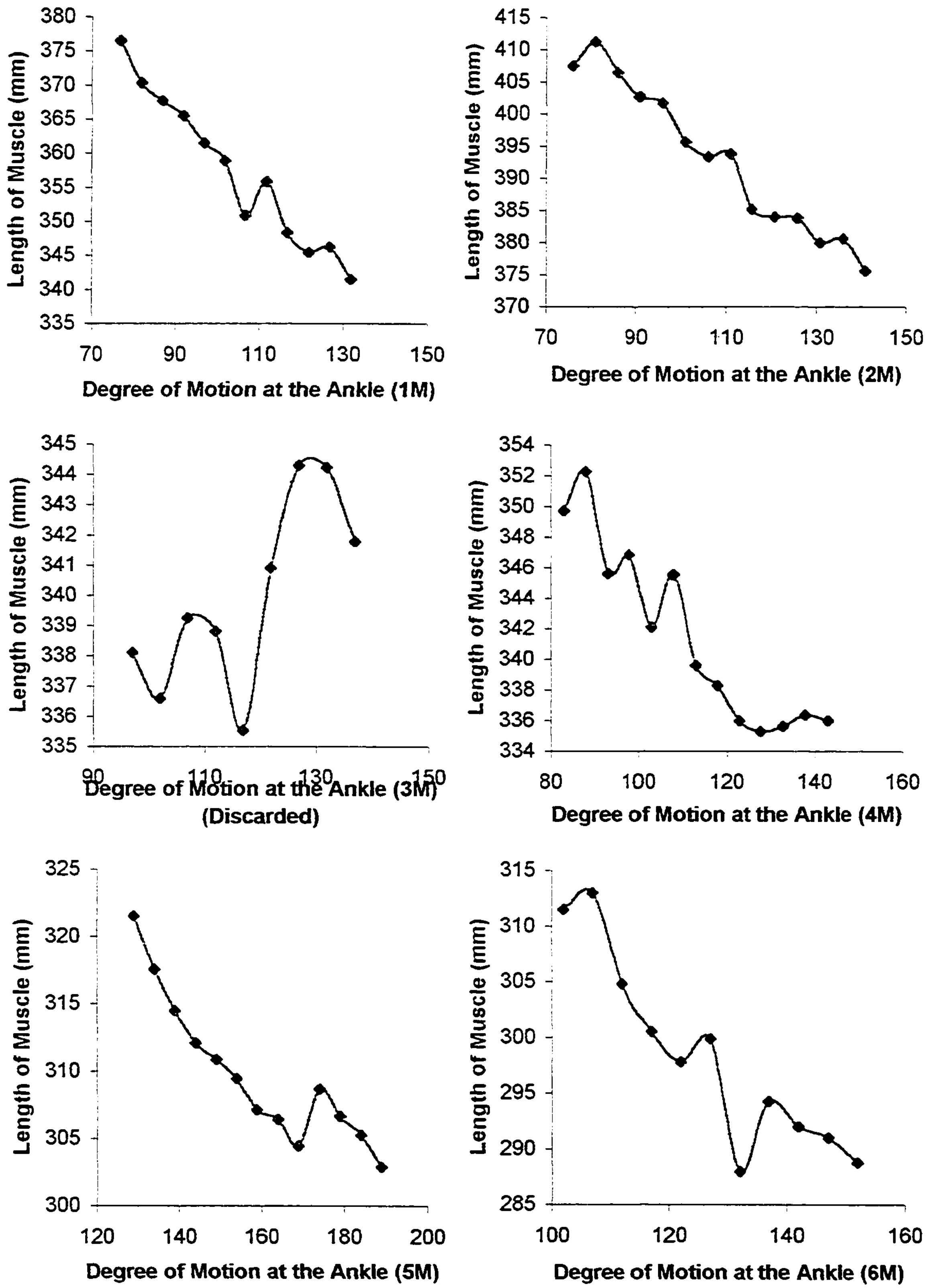


Figure X: Effect of Varying Ankle Joint Angle on Gastrocnemius Length - Males

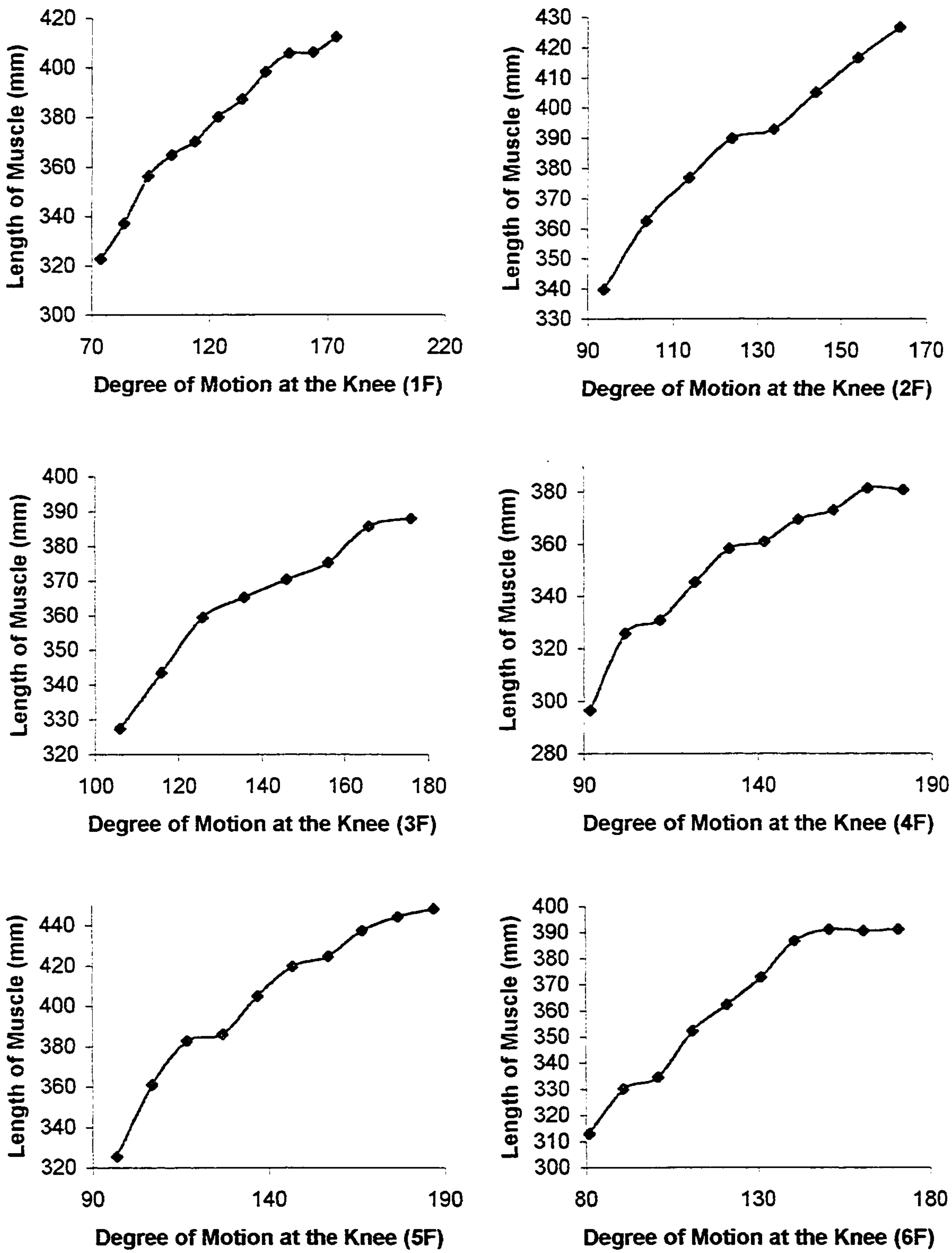


Figure XI: Effect of Varying Knee Joint Angle on Gastrocnemius Length - Females

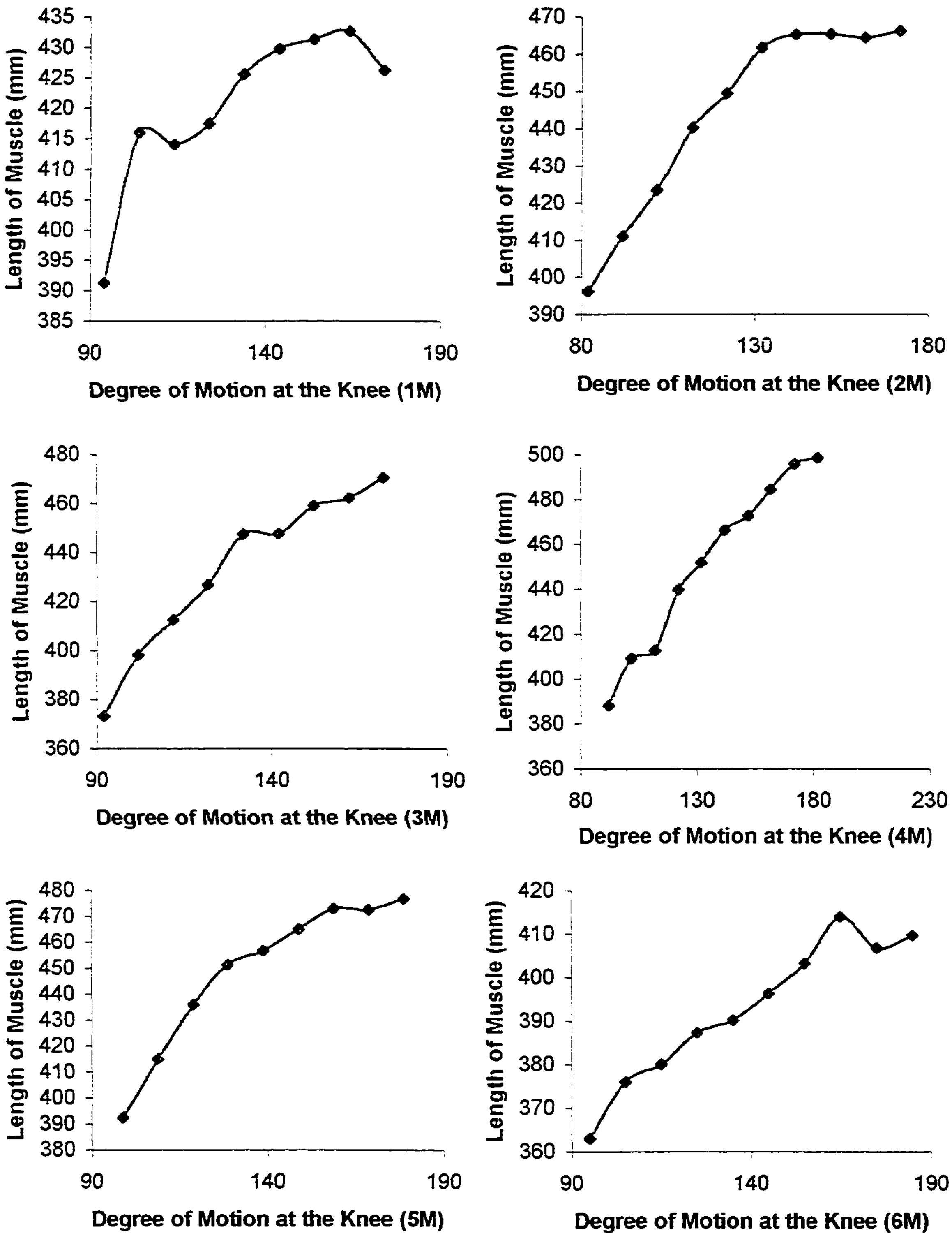


Figure XII: Effect of Varying Knee Joint Angle on Gastrocnemius Length - Males

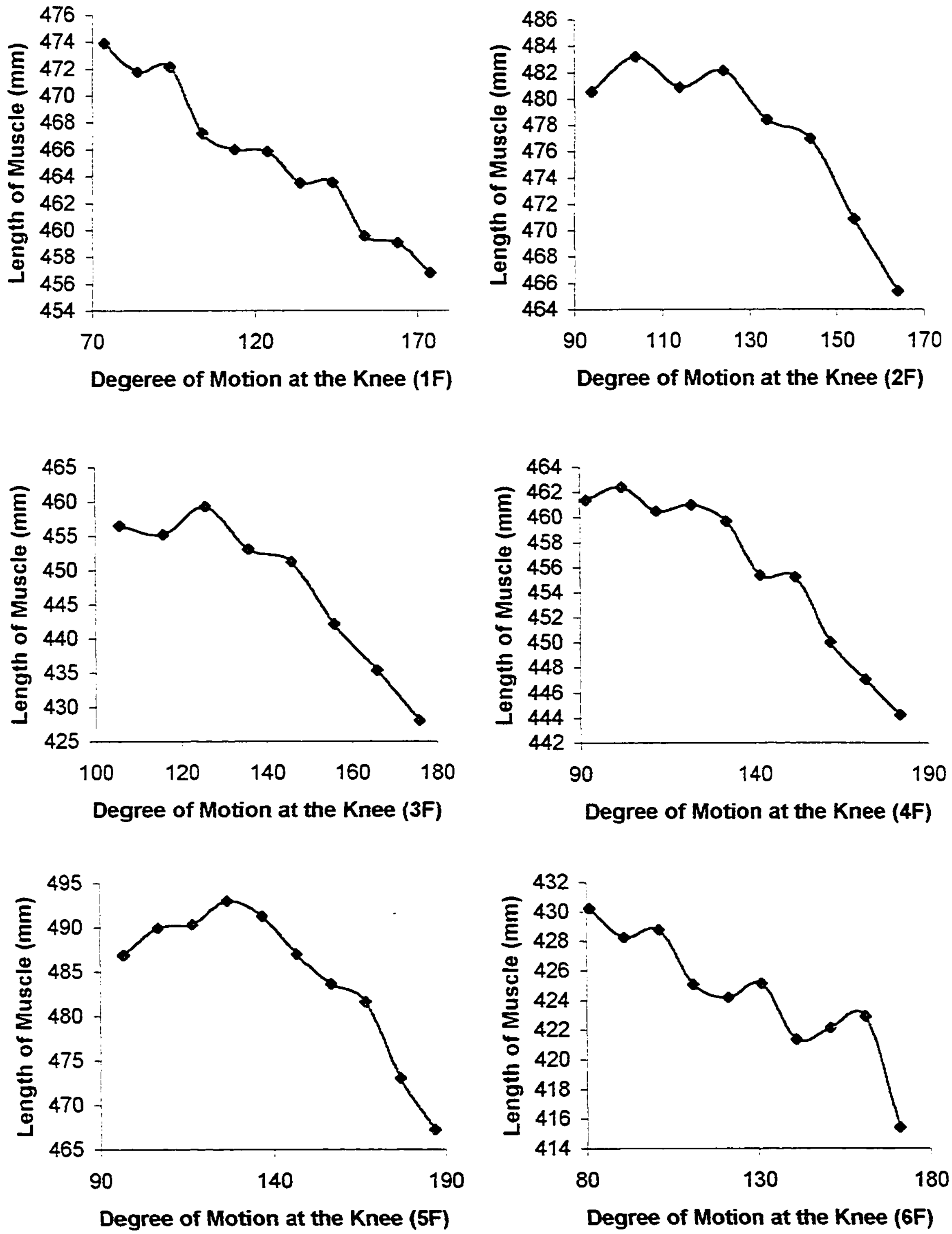


Figure XIII: Effect of Varying Knee Joint Angle on Vastus Lateralis Length - Females

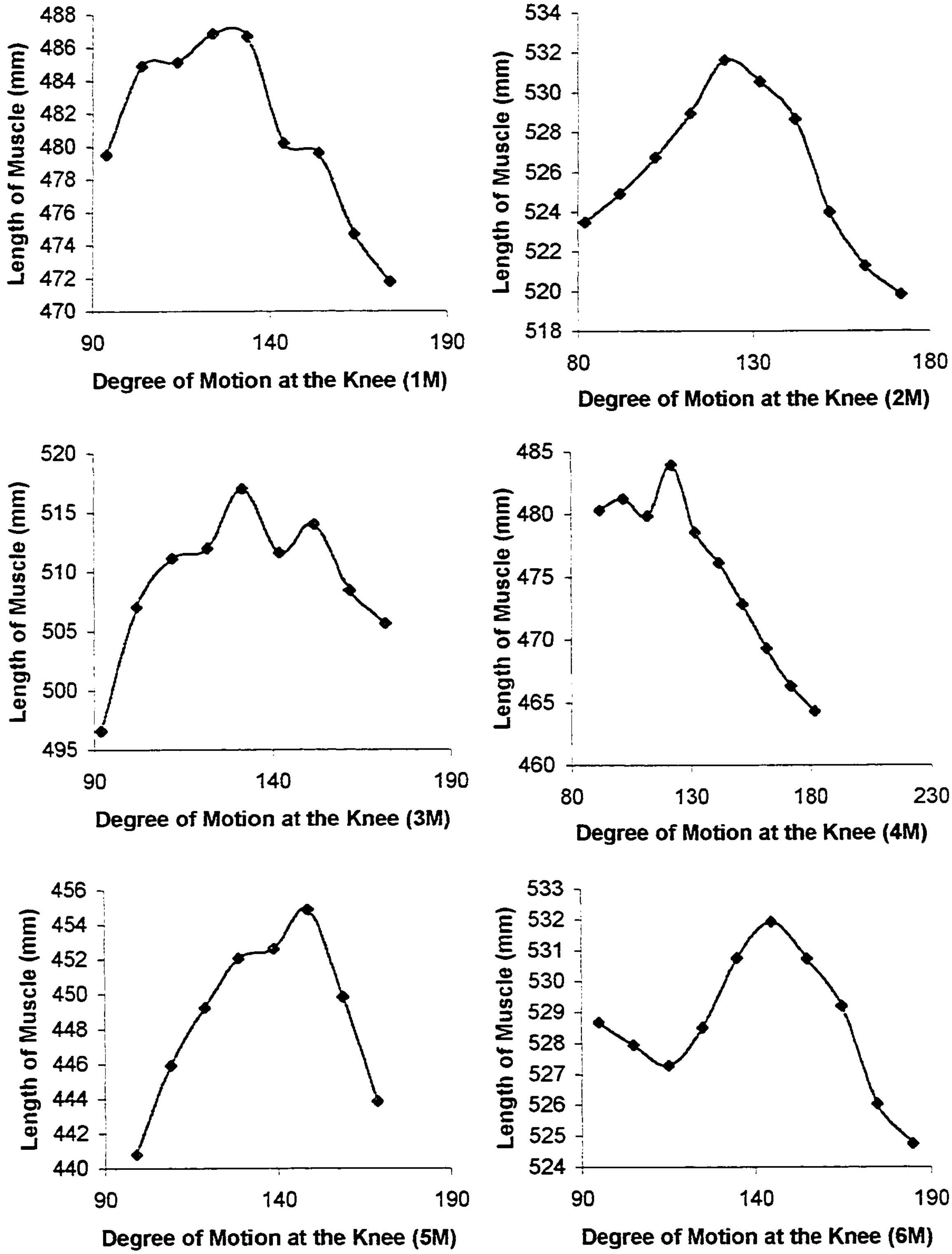


Figure XIV: Effect of Varying Knee Joint Angle on Vastus Lateralis Length - Males

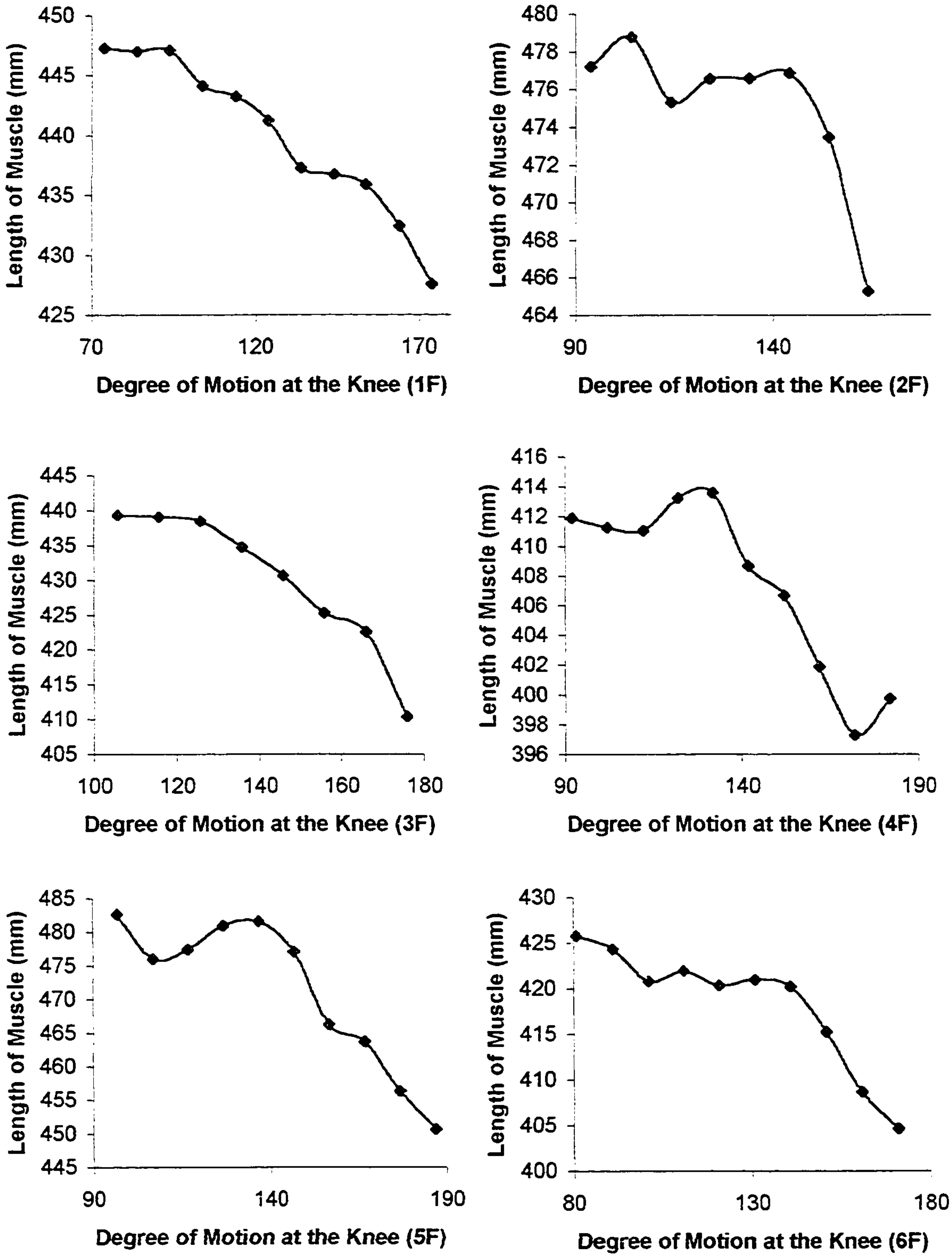


Figure XV: Effect of Varying Knee Joint Angle on Rectus Femoris Length - Females

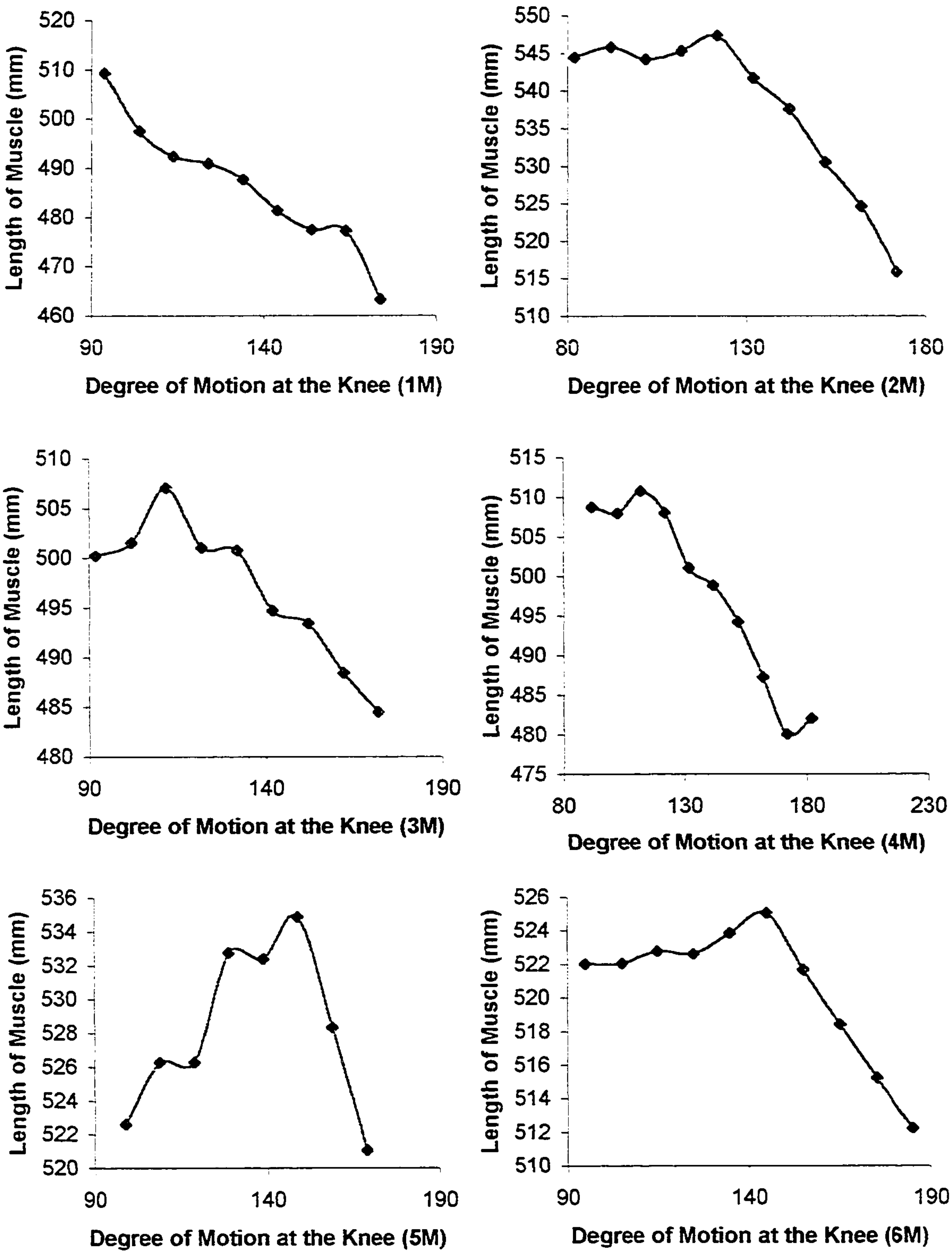


Figure XVI: Effect of Varying Knee Joint Angle on Rectus Femoris Length - Males

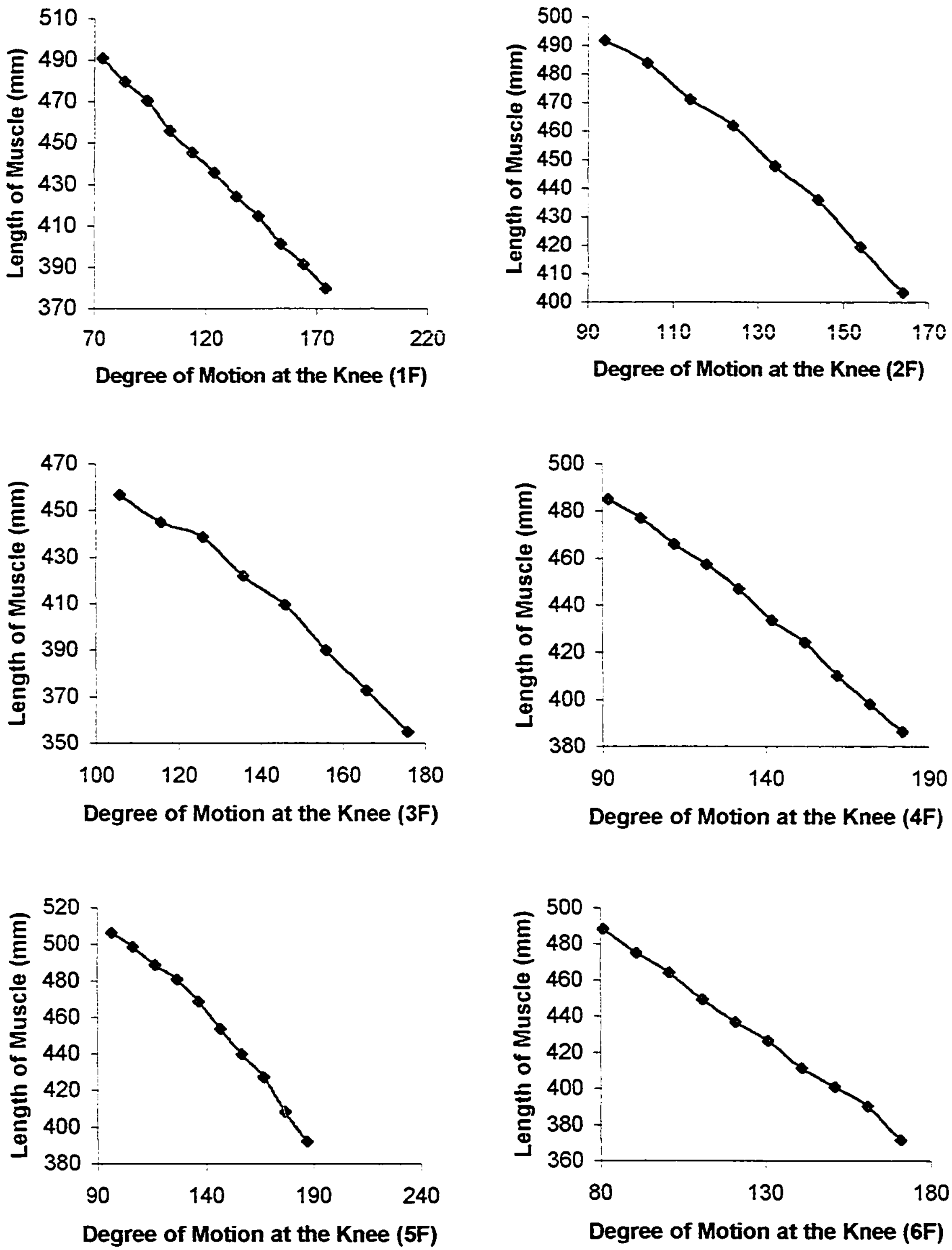


Figure XVII: Effect of Varying Knee Joint Angle on Vastus Lateralis Length (arc) - Females

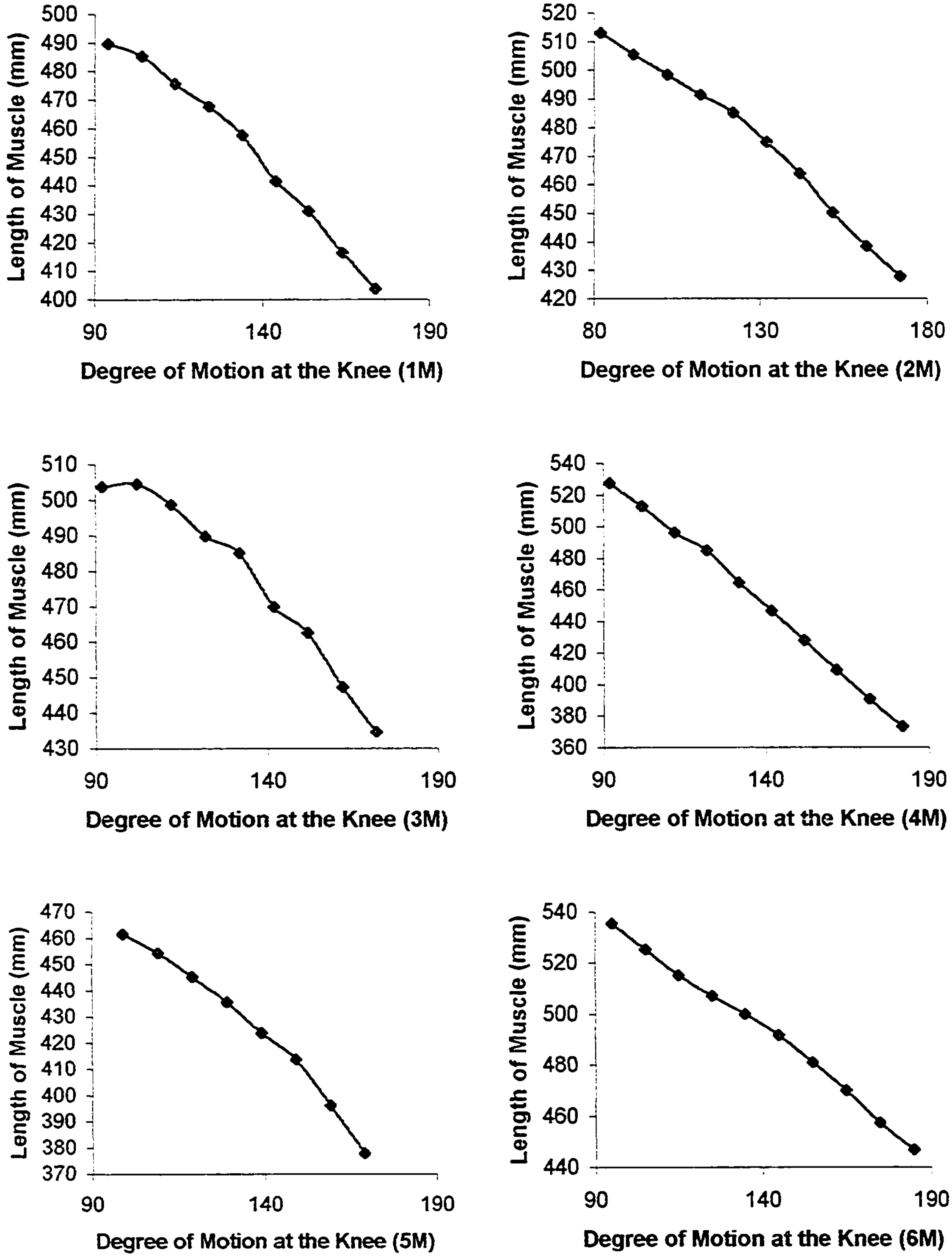


Figure XVIII: Effect of Varying Knee Joint Angle on Vastus Lateralis Length (arc) - Males

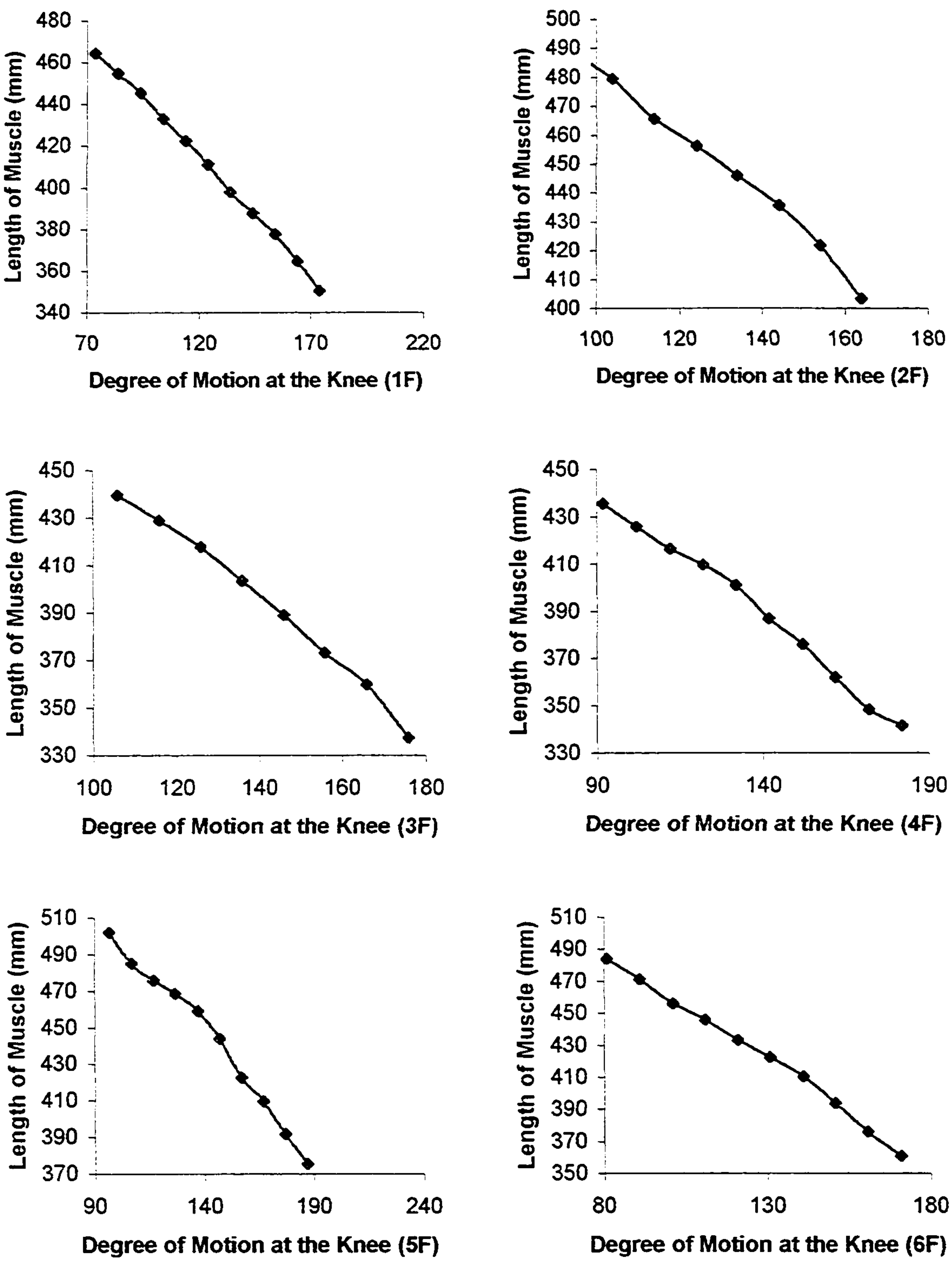


Figure XXIX: Effect of Varying Knee Joint Angle on Rectus Femoris Length (arc) - Females

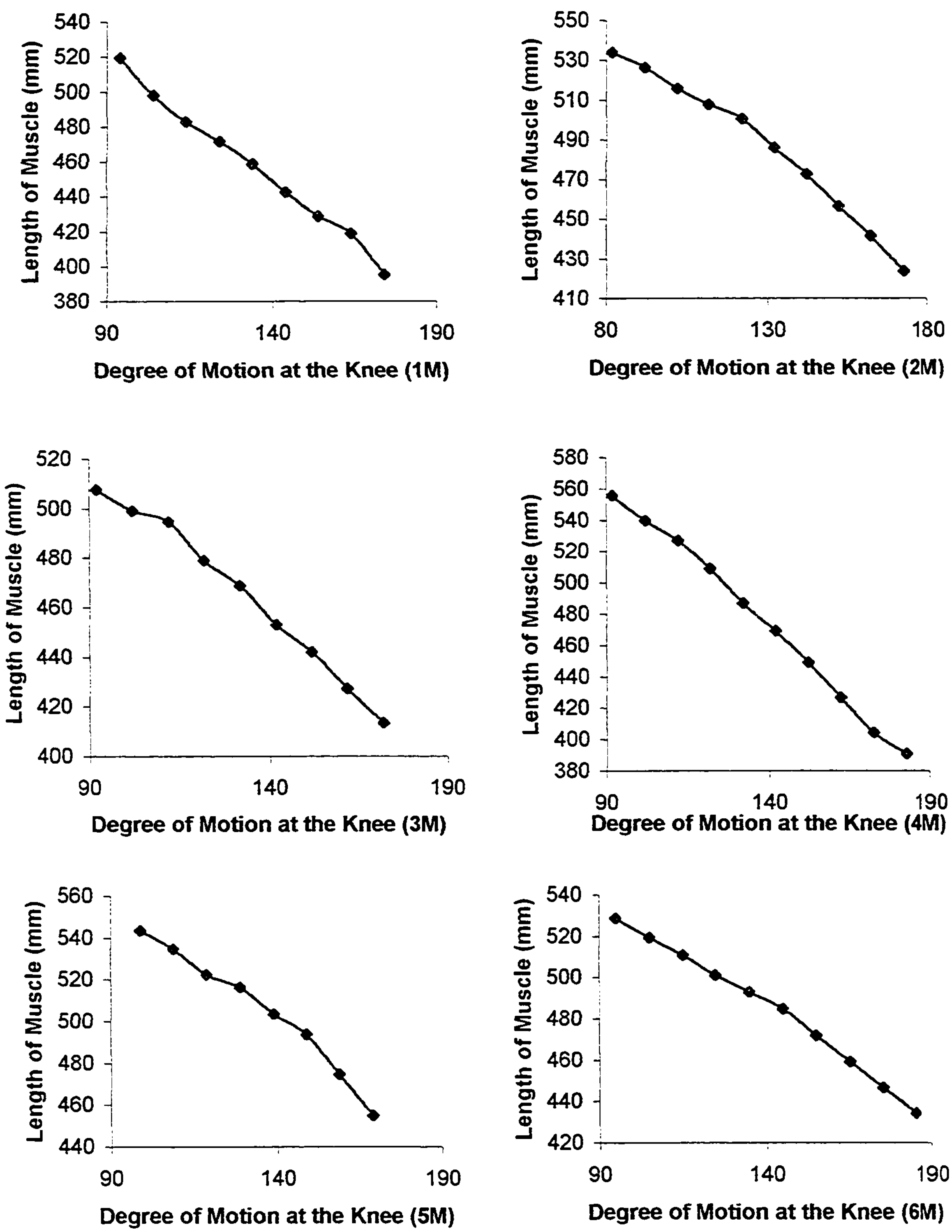


Figure XX: Effect of Varying Knee Joint Angle on Rectus Femoris Length (arc) - Males

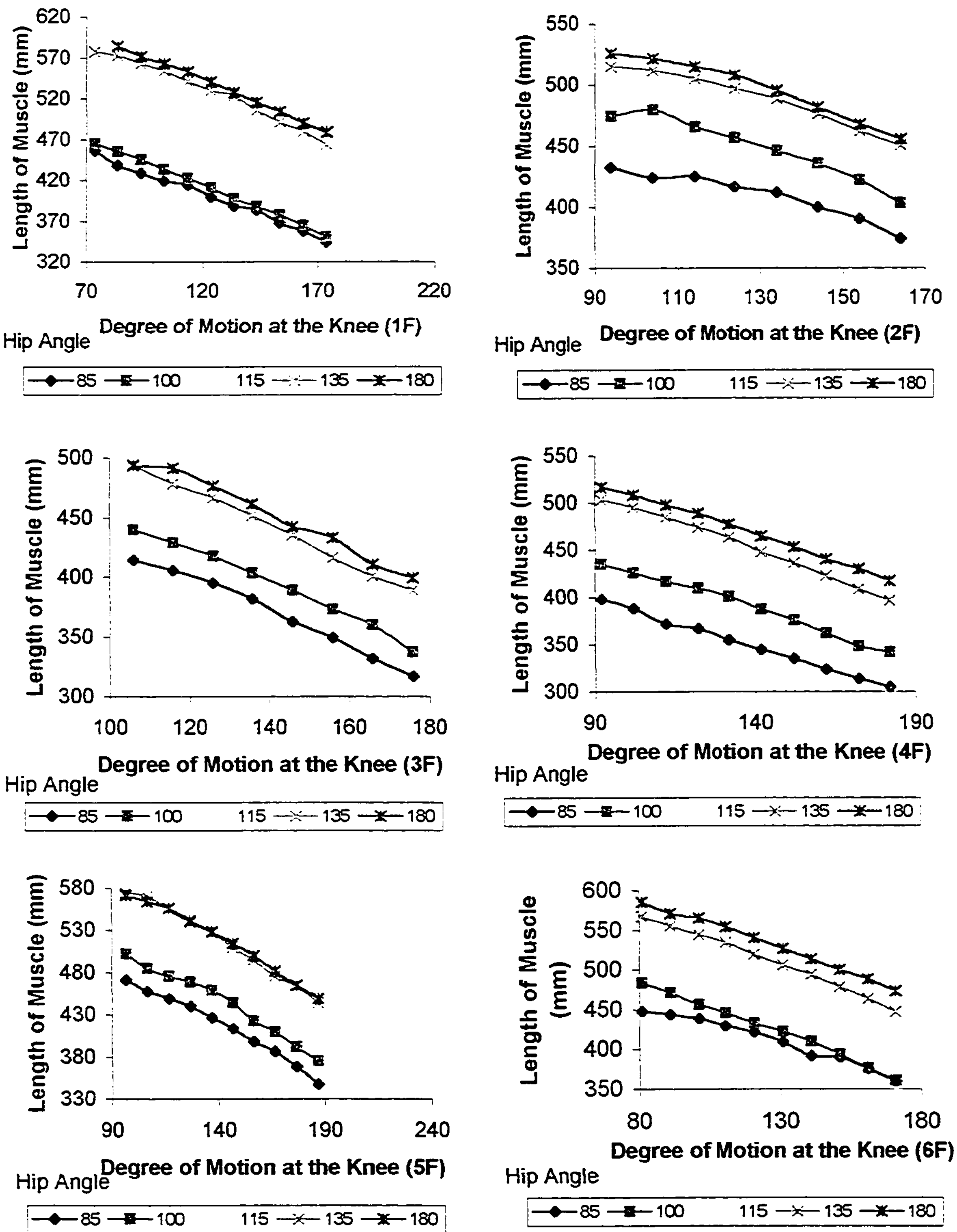


Figure XXI: Effect of Varying Hip & Knee Joint Angles on Rectus Femoris Length (arc) - Females

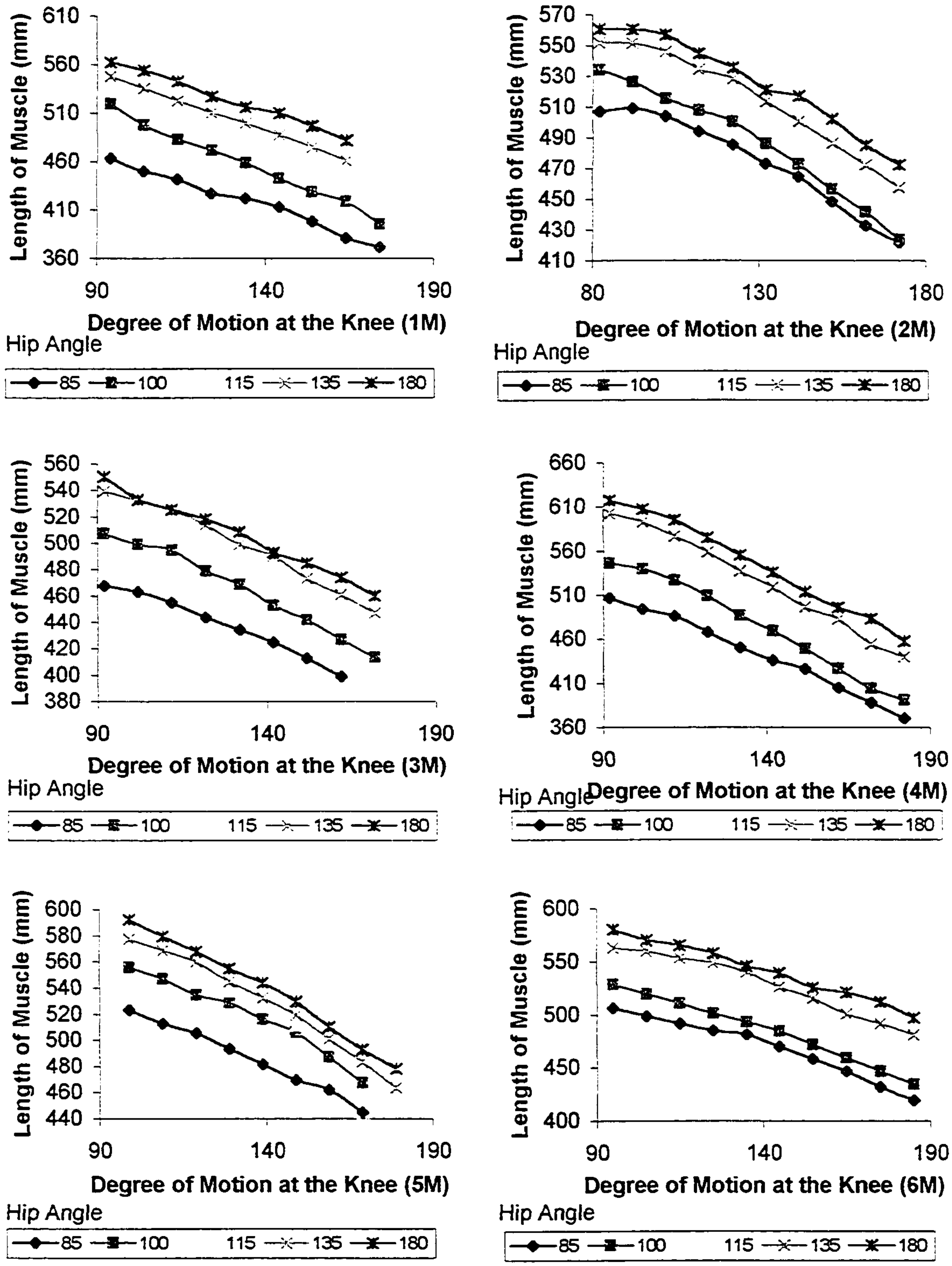


Figure XXII: Effect of Varying Hip & Knee Joint Angles on Rectus Femoris Length (arc) - Males

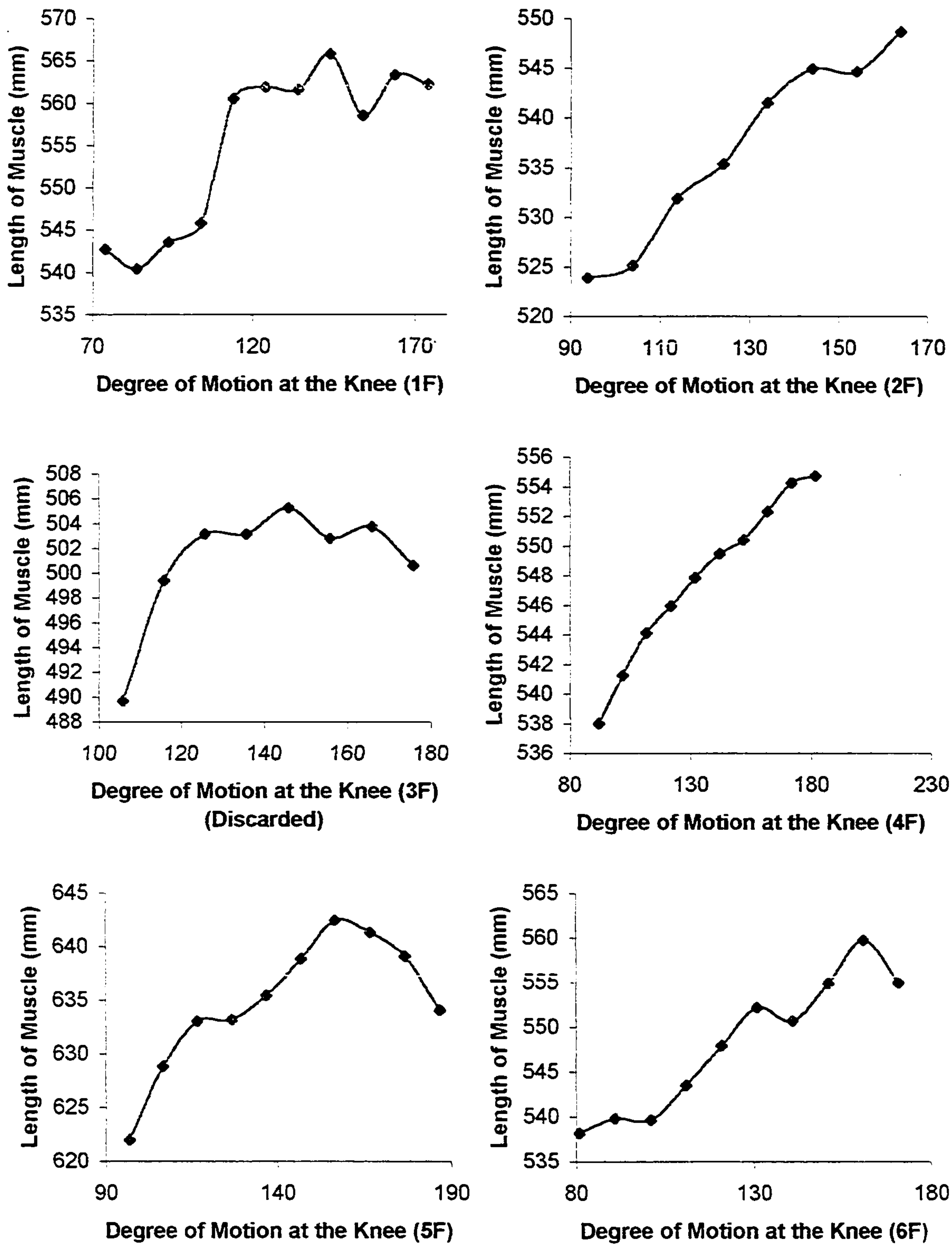


Figure XXIII: Effect of Varying Knee Joint Angle on Biceps Femoris Length - Females

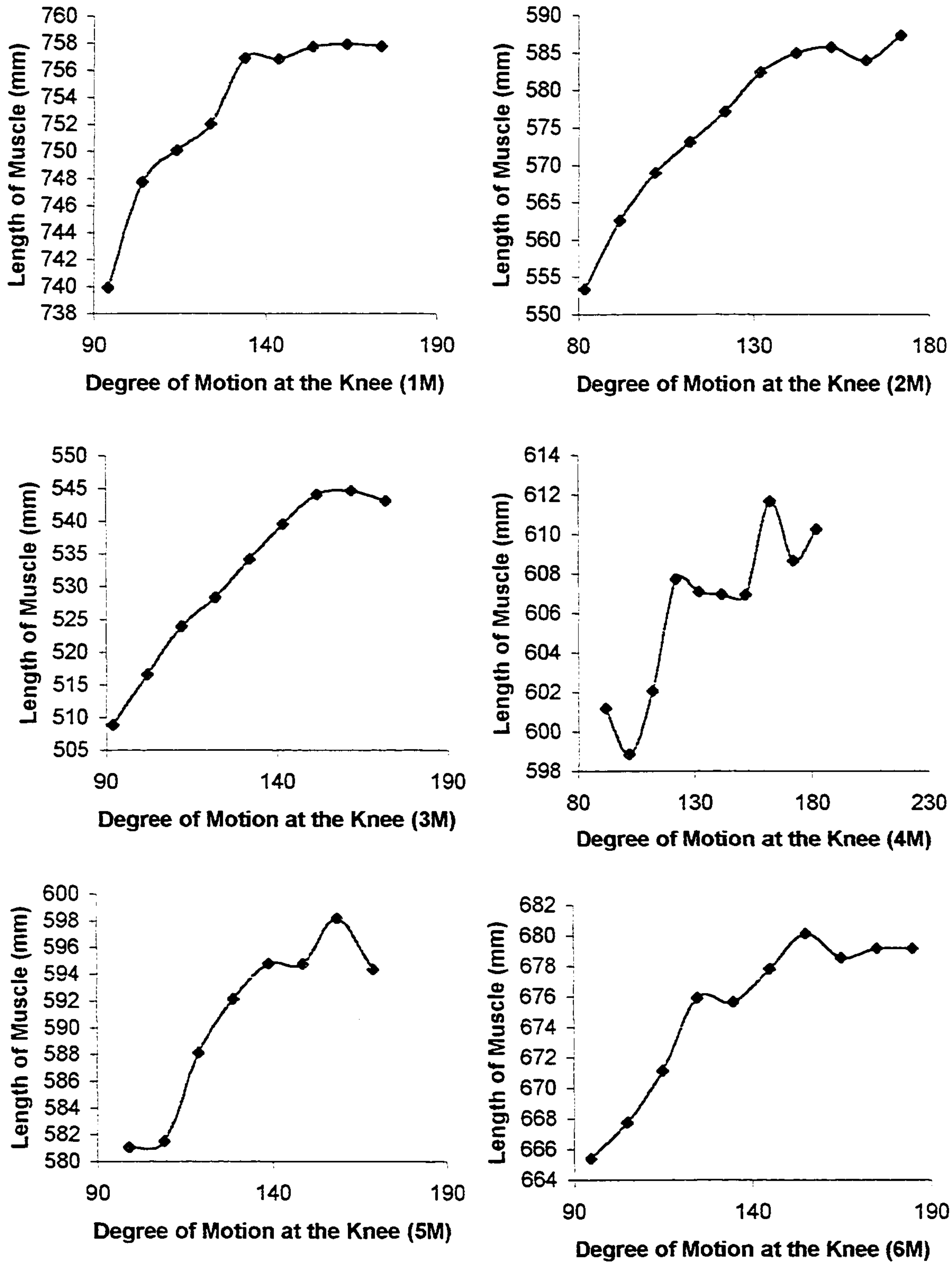


Figure XXIV: Effect of Varying Knee Joint Angle on Biceps Femoris Length - Males

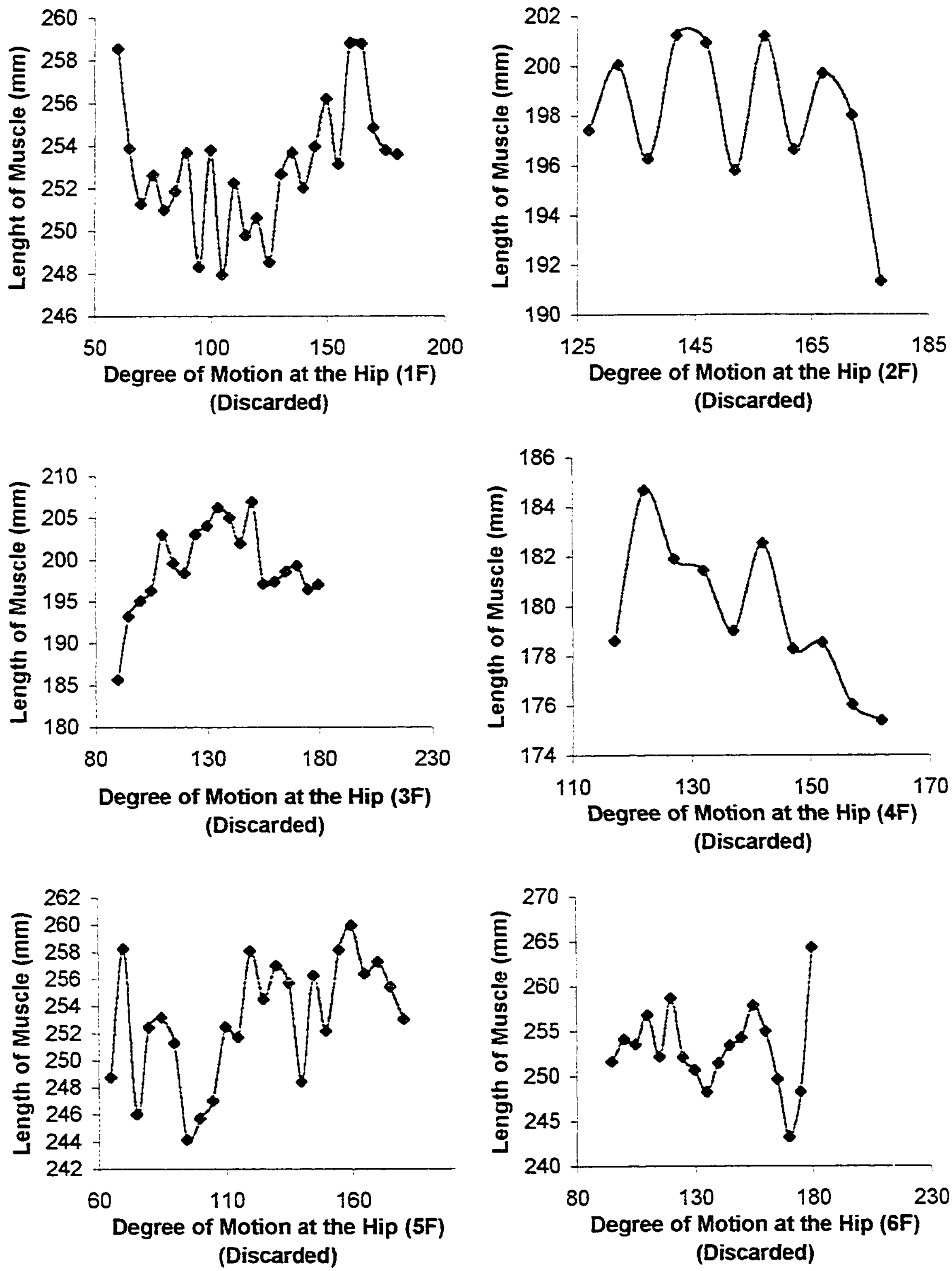


Figure XXV: Effect of Varying Hip Joint Angle on Gluteus Maximus Length - Females

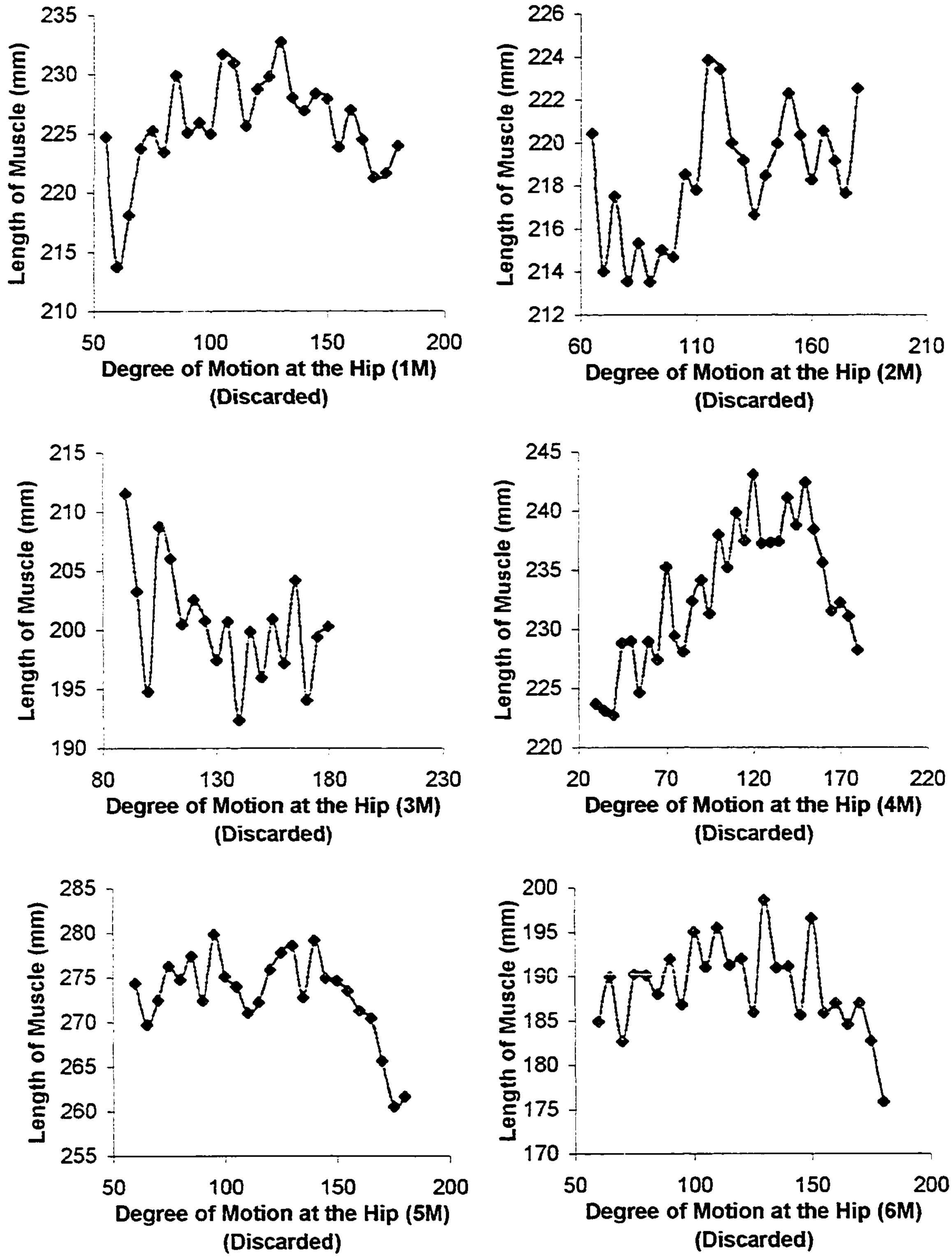


Figure XXVI: Effect of Varying Hip Joint Angle on Gluteus Maximus Length - Males

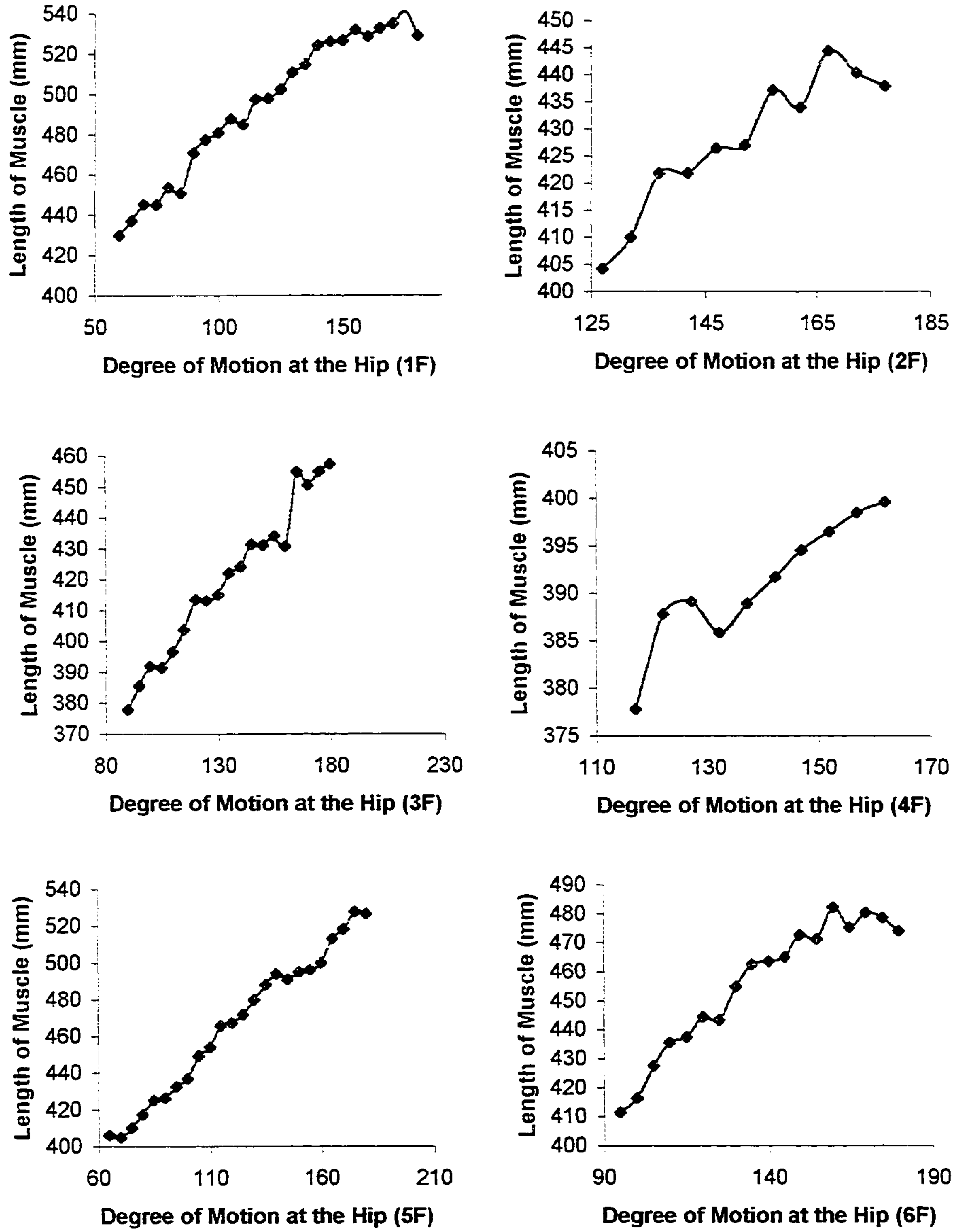


Figure XXVII: Effect of Varying Hip Joint Angle on Rectus Femoris Length - Females

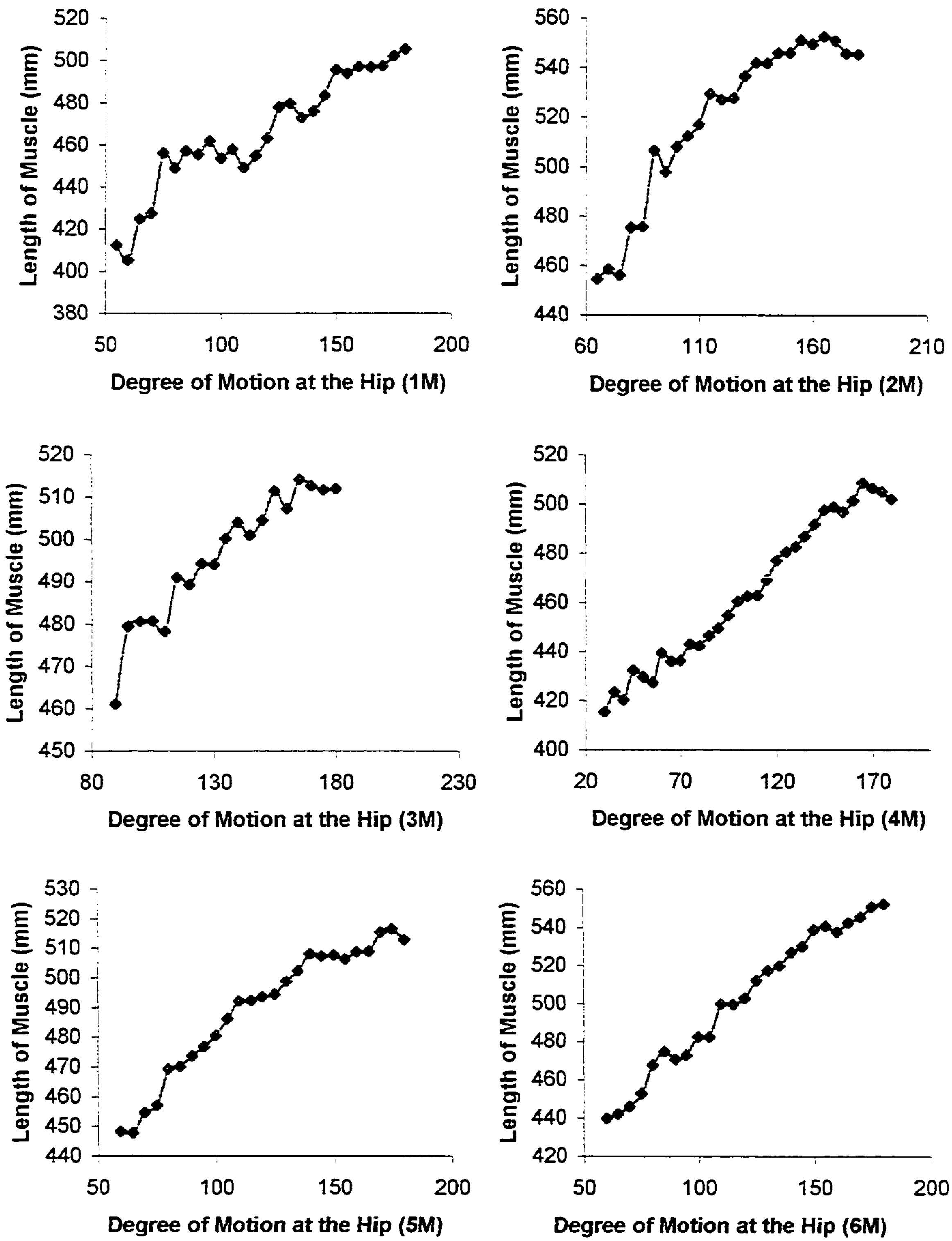


Figure XXVIII: Effect of Varying Hip Joint Angle on Rectus Femoris Length - Males

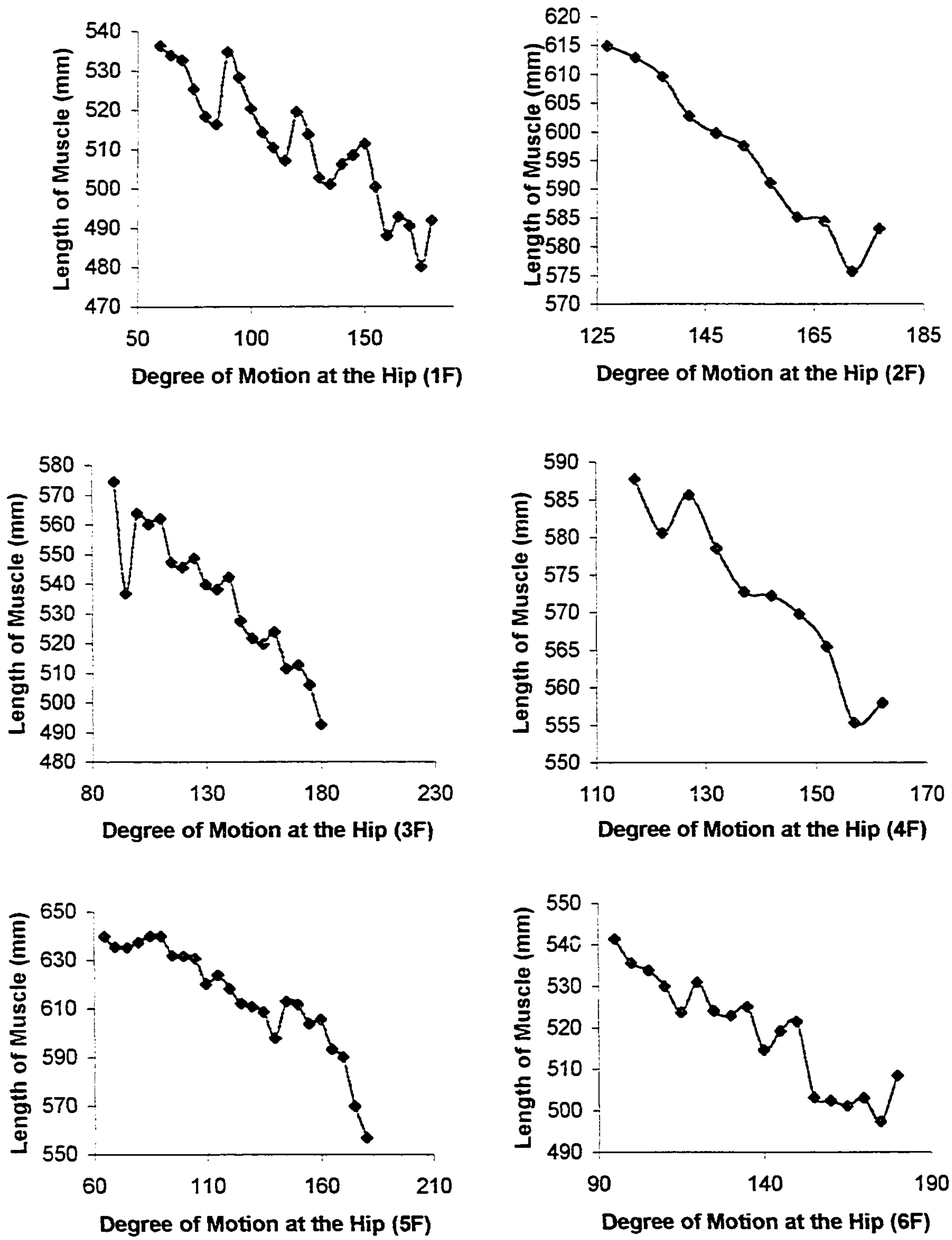


Figure XXIX: Effect of Varying Hip Joint Angle on Biceps Femoris Length - Females

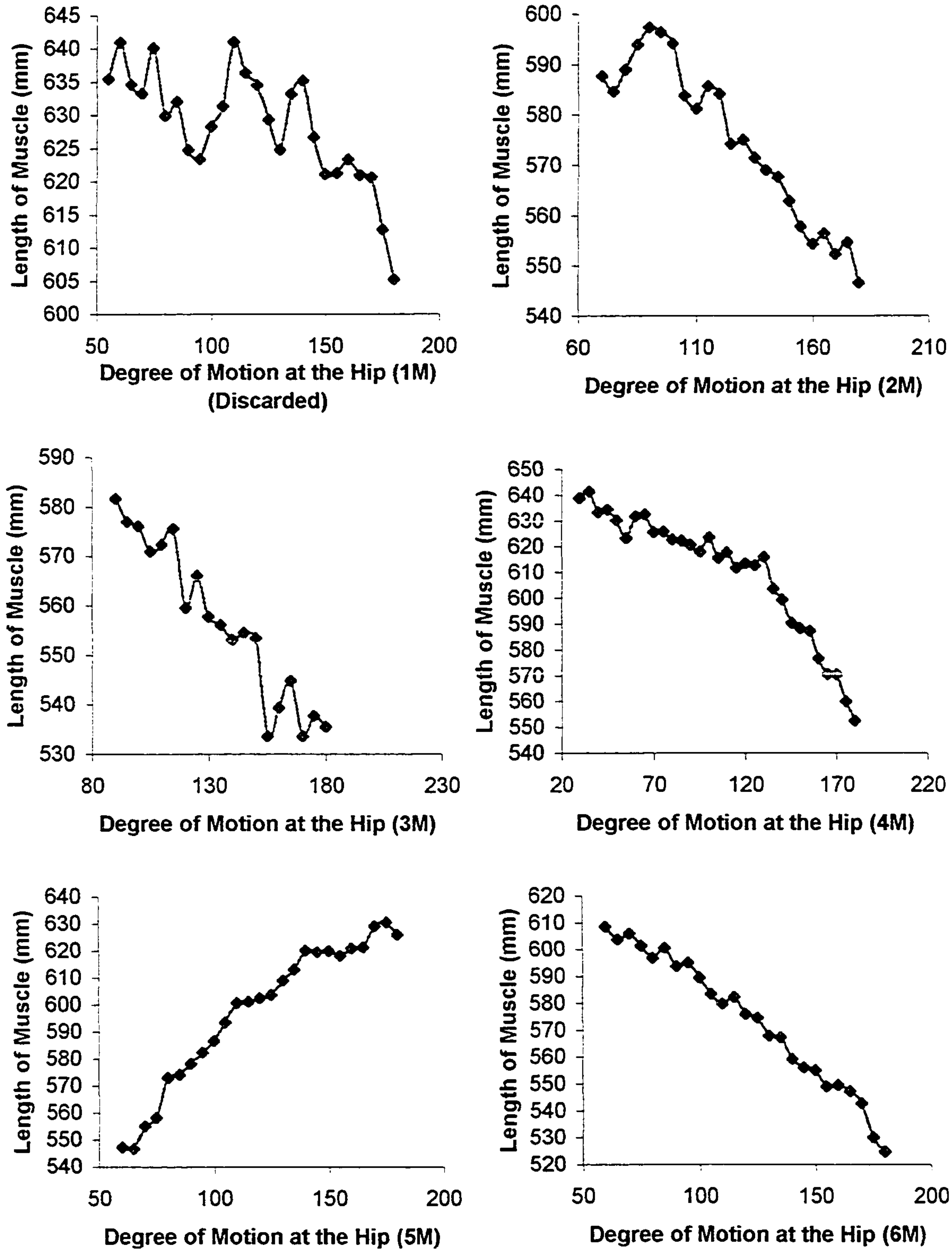


Figure XXX: Effect of Varying Hip Joint Angle on Biceps Femoris Length - Males

Appendix D

Calculating the Length of Muscles Inserting Through the Patella

Muscle Length = (total muscle length - length from midpatella to tibial tuberosity) + (arc length)

Arc Length = $(\theta/360) * 2\pi$radius

θ = maximum angle - current angle

Radius = length from centre of rotation of the knee joint to midpatella

<u>Example</u>

Total Muscle Length = 473.9072 mm
Length from Midpatella to the Tibial Tuberosity = 77 mm
Maximum Angle = 174°
Current Angle = 74°
Radius = 54 mm

Muscle Length = $(473.9072 - 77) + (((174-74)/360) * 2\pi(54))$
$= 491.15$ mm

Appendix E

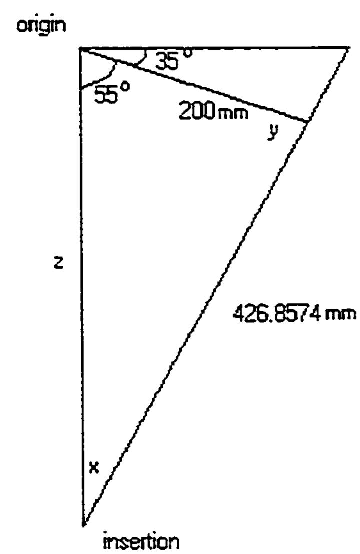
Determining the Length of the Biceps Femoris Muscle

<u>Sine Law</u>

(sin55/426.8574) = (sinx/200)
x = 22°

y = 180-55-22
y = 103°

(sin55/426.8574) = (sin103/z)
z = 507.7741mm



Appendix F

Comparison of Mathematical Equations

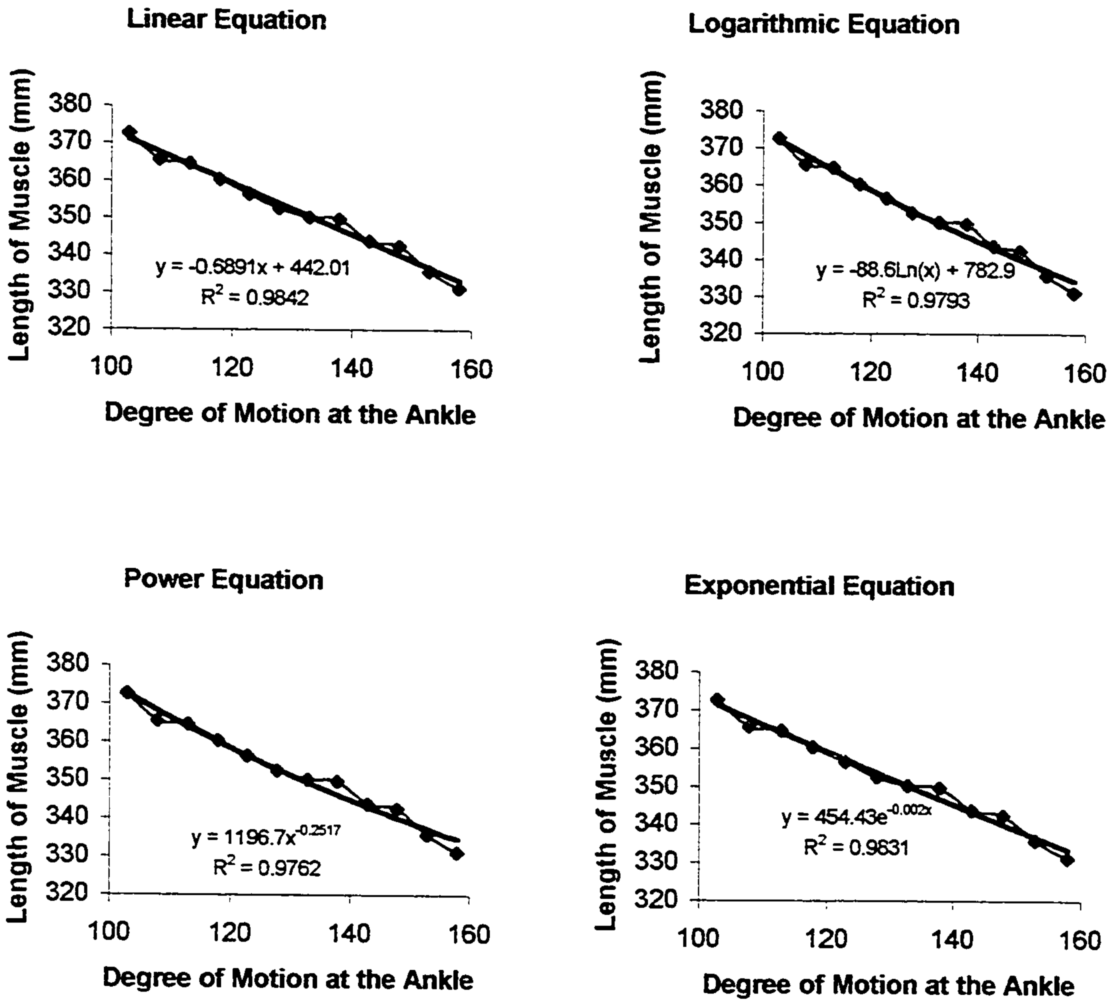


Figure XXXI: Graphs showing the effect of varying ankle joint angle on soleus muscle length with 4 different types of mathematical equations fit to the data of a single female subject.

Appendix G

Comparison of Mathematical Equations

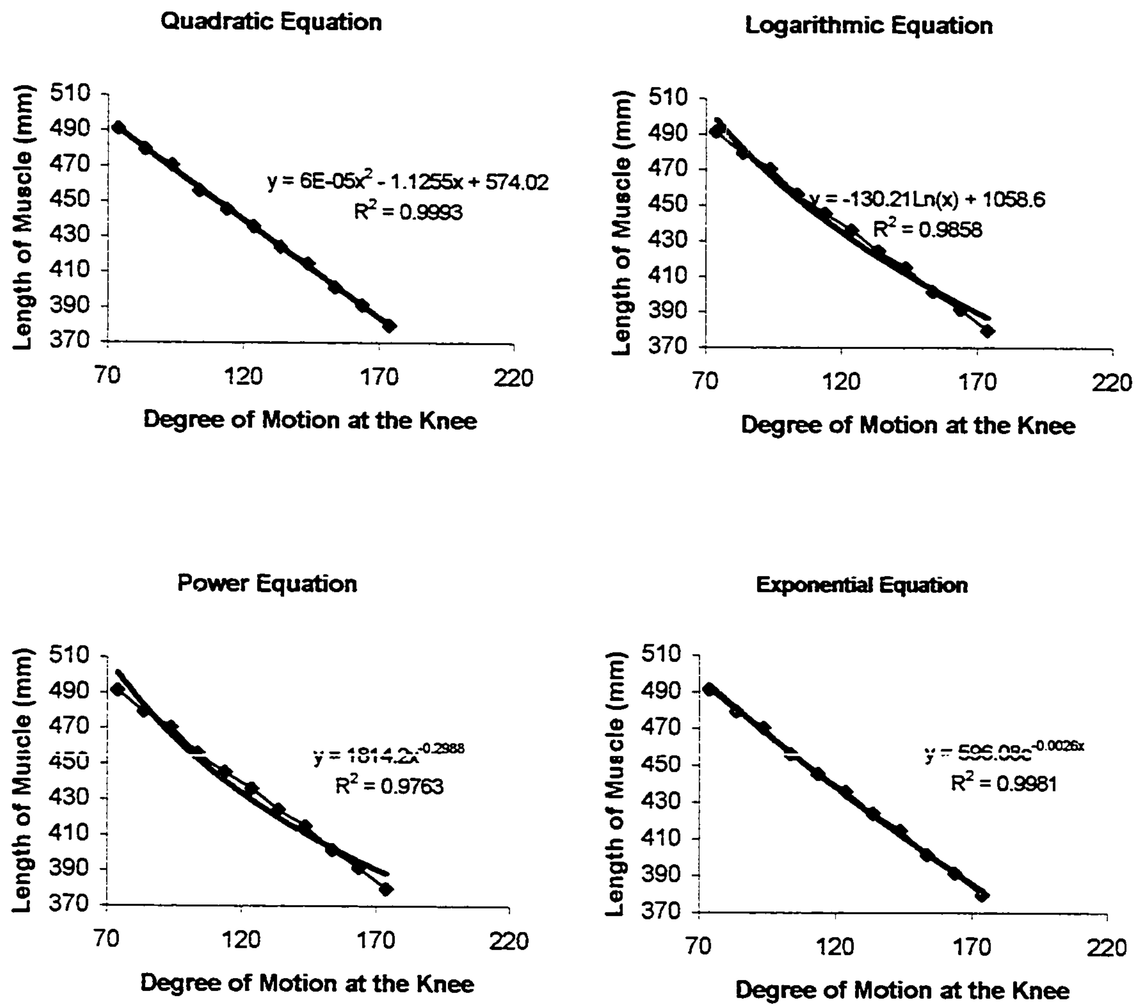


Figure XXXII: Graphs showing the effect of varying knee joint angle on vastus lateralis muscle length with 4 different types of mathematical equations fit to the data of a single female subject.

Appendix H

Individual regression Equations

Su	Muscle	Joint 1	Joint 2	Equations	R^2 Value
1F	Soleus	Ankle		y = -0.6891x + 442.01	0.9842
	Vastus Lateralis	Knee		y = 6E-05x2 - 1.1255x + 574.02	0.9993
	Rectus Femoris	Knee	Hip	$y = -0.00155x^2 - 0.74379x + 1.58212z + 396.72367$	0.8327
	Biceps Femoris	Knee	Hip	y = 0.27835x – 0.65324z + 585..40585	0.9279
	Gastrocnemius	Knee	Ankle	$y = -0.0079x^2 + 2.90066x - 0.37084z + 197.86762$	0.9727
2F	Soleus	Ankle		y = -0.4028x + 370.14	0.9399
	Vastus Lateralis	Knee		y = -0.006x2 + 0.2806x + 518.61	0.9991
	Rectus Femoris	Knee	Hip	$y = -0.00889x^2 + 1.34352x + 0.83130z + 340.34642$	0.8282
	Biceps Femoris	Knee	Hip	y = 0.28592x - 0.54766z + 557.91457	0.7640
	Gastrocnemius	Knee	Ankle	$y = -0.01545x^2 + 5.23830x - 0.2557z + 5.08051$	0.9736
3F	Soleus	Ankle		y = -0.5805x + 414.96	0.9867
	Vastus Lateralis	Knee		y = -0.0085x2 + 0.9379x + 452.95	0.9978
	Rectus Femoris	Knee	Hip	$y = -0.00489x^2 - 0.08942x + 0.82442z + 428.21131$	0.8996
	Biceps Femoris	Knee	Hip	y = -0.03654x - 0.46819z + 550.89043	0.8483
	Gastrocnemius	Knee	Ankle	$y = -0.00601x^2 + 2.56846x - 0.30571z + 160.04479$	0.9490
4F	Soleus	Ankle		y = -0.6626x + 394.59	0.9629
	Vastus Lateralis	Knee		y = -0.0025x2 - 0.4193x + 545.44	0.9993
	Rectus Femoris	Knee	Hip	$y = -0.0018x^2 - 0.63122x + 1.1975z + 393.06008$	0.8861
	Biceps Femoris	Knee	Hip	y = -0.05096x – 0.43328z + 604.99323	0.9090
	Gastrocnemius	Knee	Ankle	$y = -0.00873x^2 + 3.24209x - 0.27813z + 127.09608$	0.9394
5F	Soleus	Ankle		y = -0.6696x + 424.51	0.9809
	Vastus Lateralis	Knee		y = -0.0062x2 + 0.4952x + 516.82	0.9992
	Rectus Femoris	Knee	Hip	$y = -0.00547x^2 + 0.15549x + 1.05665z + 439.47128$	0.8687
	Biceps Femoris	Knee	Hip	y = 0.17276x – 0.58395 z + 666.17456	0.8735
	Gastrocnemius	Knee	Ankle	$y = -0.01131x^2 + 4.50975x - 0.37420z + 52.23291$	0.9858
6F	Soleus	Ankle		y = -0.4963x + 376.42	0.9645
	Vastus Lateralis	Knee		y = -0.0004x2 - 1.156x + 584.23	0.998
	Rectus Femoris	Knee	Hip	$y = -0.00329x^2 - 0.41595x + 1.31377z + 419.79478$	0.8818
	Biceps Femoris	Knee	Hip	y = 0.21751x –0.58494z + 580.03868	0.9555
	Gastrocnemius	Knee	Ankle	$y = -0.00835x^2 + 3.09887x - 0.17019z + 130.86368$	0.9856
1M	Soleus	Ankle		y = -0.4811x + 424.6	0.9851
	Vastus Lateralis	Knee		y = -0.0058x2 + 0.4496x + 500.2	0.9975
	Rectus Femoris	Knee	Hip	$y = -0.00143x^2 - 0.87828x + 0.96752z + 499.79216$	0.9186
	Biceps Femoris	Knee	Hip	y = 0.16581x – 1.08542z + 817.62776	0.8418
	Gastrocnemius	Knee	Ankle	$y = -0.00755x^2 + 2.39883x - 0.86901z + 355.13965$	0.9609
2M	Soleus	Ankle		y = -0.4638x + 440.06	0.9711

	Vastus Lateralis	Knee		y = -0.0045x2 + 0.2006x + 526.33	0.9981
	Rectus Femoris	Knee	Hip	$y = -0.00724x^2 + 0.75017x + 0.52726z + 464.34115$	0.9571
	Biceps Femoris	Knee	Hip	$y = 0.33512x - 0.48563z + 591.07396$	0.8301
	Gastrocnemius	Knee	Ankle	$y = -0.01283x^2 + 4.12949x - 0.45138z + 196.90441$	0.9846
3M	Soleus	Ankle		$y = -0.8736x + 480.65$	0.9744
	Vastus Lateralis	Knee		y = -0.0084x2 + 1.3062x + 456.21	0.9944
	Rectus Femoris	Knee	Hip	$y = -0.0035x^2 - 0.18546x + 0.68991z + 464.34115$	0.8855
	Biceps Femoris	Knee	Hip	$y = 0.33128x - 0.78704z + 591.94189$	0.9514
	Gastrocnemius	Knee	Ankle	$y = -0.00956x^2 + 3.82004x - 0.65346z + 181.55135$ 0.	0.9705
4M	Soleus	Ankle		$y = -0.7695x + 496.82$	0.9495
	Vastus Lateralis	Knee		y = -0.0029x2 - 0.9565x + 640.53	0.9991
	Rectus Femoris	Knee	Hip	$y = -0.00415x^2 - 0.67354x + 0.99756z + 552.42308$	0.9277
	Biceps Femoris	Knee	Hip	$y = 0.15512x - 0.98843z + 687.6139$	0.9347
	Gastrocnemius	Knee	Ankle	$y = -0.01143x^2 + 4.43471x - 0.66641z + 151.10267$	0.9867
5M	Soleus	Ankle		$y = -0.5853x + 477.73$	0.9728
	Vastus Lateralis	Knee		y = -0.0088x2 + 1.1853x + 429.56	0.9982
	Rectus Femoris	Knee	Hip	$y = -0.00611x^2 + 0.37504x + 0.52613z + 521.35586$	0.9996
	Biceps Femoris	Knee	Hip	$y = 0.2462x - 0.77603z + 633.95368$	0.9445
	Gastrocnemius	Knee	Ankle	$y = -0.01429x^2 + 4.98048x - 0.2927z + 80.80158$	0.9501
6M					
	Soleus	Ankle		$y = -0.6426x + 454.58$	0.9794
	Vastus Lateralis	Knee		y = -0.0021x2 - 0.3627x + 587.44	0.9978
	Rectus Femoris	Knee	Hip	$y = -0.00429x^2 + 0.22569x + 0.76739z + 467.92819$	0.9468
	Biceps Femoris	Knee	Hip	$y = 0.15711x - 0.59286z + 718.36895$	0.9298
	Gastrocnemius	Knee	Ankle	$y = -0.00495x^2 + 1.89564x - 0.16595z + 251.04386$	0.9362