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A Study of the Force-Length Muscle Property of the Gastrocnemius in Ice Hockey Players

CAMERON LEONARD
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Reviewed and approved* by the following:

John H Challis
Professor of Kinesiology
Thesis Supervisor

Jonas Rubenson
Associate Professor of Kinesiology
Honors Adviser

* Electronic approvals are on file.

ABSTRACT

Muscle fibers have a force-length property which dictates the force a muscle can produce as a consequence of its length. How much of this curve that is expressed *in vivo* depends on the joint range of motion, the moment arm of the muscle, and the number of sarcomeres in series. The purpose of this study was to determine the expressed section of the force-length curve for the gastrocnemius *in vivo* for a specifically trained population. This study used participants from a Division I Women's Ice Hockey Team. The rationale behind studying ice hockey players is that they perform most of their training at a constrained ankle angle due to the structure of the skate boot, which could affect the *in vivo* expression of the force-length curve of the gastrocnemius muscle.

A muscle model was created of the major plantarflexion muscles and used to estimate plantarflexion moment-angle strength curves (isometric moment versus joint angle) for a variety of model parameters. These simulations predicted that a gastrocnemius with less sarcomeres in series would be more likely *in vivo* to operate on the plateau region of the force-length curve (expressed section). Due to the constraints imposed on the ankle joint of the skate it is hypothesized that the ice hockey players would be more likely to operate on the plateau of the force-length curve than non-specifically trained subjects. The *in vivo* expressed section of the force-length curve of the gastrocnemius was determined for twelve subjects by collecting isometric moment joint angle data and exploiting the fact that the gastrocnemius crosses both the ankle and knee joints. The study found that more of the ice hockey players operated over the plateau region of the force-length curve compared with an untrained group who mostly operated on the ascending limb ($p<0.0001$). These findings suggest that prolonged training with the ankle motion constrained could cause changes in the number of sarcomeres in series producing an adaptive change in the *in vivo* expressed section of the force-length curve.

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Chapter 1

Introduction

1.1 Background

Skeletal muscle has many amazing properties. There are many intrinsic properties in skeletal muscle that contribute to its functionality, one of the most important being the force-length relationship. The force-length relationship is dependent on the main tenants of the Cross-Bridge Theory, which presents the idea that the interaction of myofilaments in the sarcomere contributes directly to force production in muscle (Huxley, 1957). An increase of interactions between the myofilament proteins called actin and myosin forming cross-bridges increases the force a muscle generates.

Classical experiments have given evidence that there is an optimal length of the sarcomeres within muscle when there is optimal overlap of the myofilaments leading to maximum interactions and therefore force production (Gordon et al., 1966). The overall relationship between sarcomere length and force production can be plotted as an approximately parabolic curve. The shape of the static joint-angle moment curve (strength curve) is in-part a function of the force-length curve, but also the relationship between joint angle, muscle length, and moment arm.

There have been a few published studies looking at whether the intrinsic properties in muscle are adaptive across different populations. One study found that immobilizing the hind limb of mice caused changes in muscle architecture, most notably a change in the number of sarcomeres in series when the limb was immobilized in a lengthened position (Williams and Goldspink, 1978). It has previously been shown that athletes who specialized in either cycling or running worked at different ranges of motion *in-vivo* and therefore have different expression of the force-length curve for their rectus femoris muscles (Herzog et al., 1991). The expressed section of the force-length curve of the gastrocnemius muscle in healthy active subjects has been determined (Winter and Challis, 2010), but to date the expressed section of the gastrocnemius has not been investigated for subjects who train under conditions where the range of motion of the ankle is constrained.

1.2 Purpose

The purpose of this study was to determine the expressed section of the force-length curve for the gastrocnemius *in vivo* for a specifically trained population. First, a theoretical muscle model was created for the major plantar flexor muscles. The model presents equations and parameters used to determine muscle moments at specific joint angles, which are then used to construct a joint moment-joint angle curve based on underlying force-length properties. The model was then used to examine the influence of changing the number of sarcomeres in series in the gastrocnemius on the ankle plantar-flexor strength curve. Isometric plantarflexion moment data were collected from twelve college-level ice hockey players. Using equations from the muscle model, gastrocnemius force-length curves were computed for each participant. The data of the twelve participants from this study was compared with extant data from Winter and Challis (2008). This study examined whether the group of ice hockey players showed differences in their expression of the force-length curved compared with existing data taken from a group of people with no specific training.

1.3 Overview of Thesis

Chapter 2 of this thesis presents a review of literature relevant to the intrinsic skeletal muscle properties, the anatomy of the plantar flexor muscles, the properties of the force-length relationship, and the kinematics of the ankle joint during ice skating. Chapter 3 presents the equations and parameters of the muscle model with a subsequent analysis of the influence of number of sarcomeres in series on the plantar flexor strength curve. Chapter 4 details the materials and methods used to determine the expressed section of the force-length curve for 12 ice hockey players. Chapter 5 presents the results of the study. Finally, Chapter 6 summarizes the findings and discusses the potential for future research and the limitations of this study.

Chapter 2

Literature Review

2.1 Overview

In the following sections the pertinent literature related to muscle properties and its plasticity are reviewed. Specifically, the key properties of muscles, the muscles causing ankle plantarflexion, and the documented adaptability of the force-length relationship are reviewed in the following sections and subsections.

2.2 Muscle Properties

There are many important properties of skeletal muscle that contribute to its functionality. To understand these properties, it is important to distinguish between the different classifications of skeletal muscle. The basic units of skeletal muscle permitting it to produce force are its sarcomeres, which are arranged in series to create myofibrils (Gans,1982). An individual muscle fiber is made up of strands of sarcomeres in series. Muscle fibers are grouped together into motor units, which are innervated by a single neuron and work together to create force through their synchronized action. Skeletal muscle is comprised of multiple motor units bound together in parallel to make up a muscle belly, which is then connected to bone at both ends via tendon. Force generated by the muscle is applied to the bone to create body movement, or resist movement. The subsections below will explain some of the major properties of muscle influencing force production.

2.2.1 Force and Cross-Sectional Area

A sarcomere generates force due to the interaction of two proteins within the sarcomere: action and myosin. When a motor unit is stimulated, chemicals are released that changes the position of the filaments within a sarcomere allowing interaction of the thin and thick filaments, actin and myosin respectively. When actin and myosin filaments overlap, a myosin head can bind to actin to create a cross-bridge. The head of this cross-bridge, which attaches to the actin, then rotates to generate force. The Cross-Bridge theory or sliding filament theory presents the idea that the amount of force generated from a muscle is proportional to the number of cross-bridges formed within a sarcomere (Huxley, 1954). When more cross-bridges form in parallel to one another, more muscle force can be produced. This suggests that the cross-sectional area (CSA) of a muscle is proportional to the force a muscle can generate. As the CSA of the muscle belly increases there are more muscle fibers in parallel, indicating an increased number of sarcomeres arranged in parallel to one another. As the number of sarcomeres in parallel increases, more parallel cross-bridges can be formed at one time, which increases the force a muscle can generate (Gans, 1982).

There are a few exceptions that challenge the proportional relationship between muscle force and muscle cross-sectional area including age and amount of connective tissue in a muscle belly. Morse et al. (2005) examined force production of the gastrocnemius in elderly men concluded that other factors besides muscle atrophy contribute to decreased strength in elderly muscle because force production decreased at a faster rate than CSA. The researchers proposed that a reduction in single-fiber specific tension or the decrease of the number of sarcomeres in parallel could be responsible for this decline in strength (Morse et al., 2005).

The Cross-Bridge theory relies on all the parallel fibers within a muscle being arranged in series with the muscle tendon. For these parallel fibers, the force applied to the tendon ($\mathbf{F_T}$) is proportional to its cross-sectional area (CSA).

$$\mathbf{F_T \propto CSA} \qquad \mathbf{[2.1]}$$

However, not all muscles are made up entirely of muscle fibers parallel to the muscle tendon, which complicates the relationship stated in the previous sentence. For example, Fukunaga et al. (1992) used magnetic resonance imaging (MRI) to examine the muscle architecture of the muscles of the lower leg and confirmed that some muscles have an angle between the line of action of the muscle fibers and the line of action of the tendon. Such muscles are referred to as pennate. To accurately determine the force applied by a pennate muscle to the tendon, the angle of pennation (θ) must be accounted for (equation 2.2); (Gans, 1982).

$$\mathbf{F_T \propto PCSA \propto \cos(\theta)\ CSA} \qquad \mathbf{[2.2]}$$

Where PCSA is the physiological cross-sectional area. In 2017, Sopher and his colleagues dissected out muscles that act across the ankle joint from cadavers to better understand the muscle architecture and how variability of that architecture affects muscle forces at the ankle joint (Sopher et al., 2017). Table 2.1 shows the mean measurements of anatomical cross-sectional area (ACSA) and PCSA taken in their study. It was found that PCSA was 3.7-

12.3 times larger than ACSA for muscles that act over the ankle joint and confirmed findings of previous studies that emphasize the importance of the angle of the muscle fibers relative to the tendon (Sopher et al., 2017).

Table 2.1: PCSA and ACSA with Mean ± Standard Deviation of the Plantar-flexor Muscles of the Lower Leg; (Sopher et al., 2017).

Muscle	**ACSA (cm^2)**	**PCSA (cm^2)**
Soleus	7.5 ± 1	98 ± 9
Gastrocnemius	5.8 ± 0.7	36 ± 5
Plantaris	0.3 ± 0.05	0.9 ± 0.1
Tibialis posterior	1.9 ± 0.2	20 ± 1
Flexor longus	1.6 ± 0.2	11 ± 1
Peroneus brevis	0.9 ± 0.1	7 ± 1
Peroneus longus	1.7 ± 0.1	13 ± 2

2.2.2 Force-Length Relationship

The force-length relationship in muscle refers to the force a muscle can produce as the length of the muscle varies. The muscle can be viewed as a single sarcomere, sarcomeres in series, or even a whole muscle. Even at the macroscopic level the force-length properties of muscle are dictated by the properties of the sarcomere. Ramsey and Street (1940) was one of the earliest studies to experimentally describe this relationship between length and force production in muscle. Gordon et al. (1966) drew upon previous considerations of the Cross-Bridge theory, specifically the overlapping of thin and thick filaments that produces force to describe the force-length properties of muscle. They found that there is a range of optimum lengths for a muscle at which it produces peak force (Gordon et al., 1966). When the muscle length is greater than the optimum, there is declining overlap of the thick and thin filaments. In the lengthened state there are less opportunities for cross-bridges to form, which decreases force generation. When the muscle length is shorter than the optimum, there is too much overlap of the filaments so the cross-bridges interfere with one another thus limiting the number of cross-bridges than can be formed (Gordon et al., 1966). The optimum length was described as a plateau of measured muscle tension over a specific range of sarcomere length, indicating that a muscle can generate maximal strength over this length range (Gordon et al., 1966).

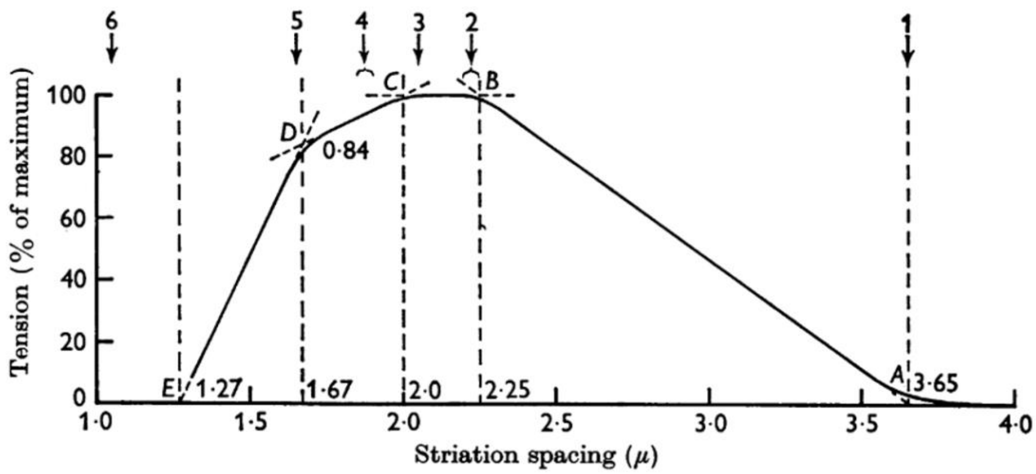


Figure 2.1: The force-length curve representing the length-tension relationship of skeletal muscle from Gordon et al. (1966).

In a study examining the force-length relationship of the rectus femoris *in vivo*, a normalized force-length relationship was plotted against the theorized force-length relationship. The maximal force measured *in vivo* was significantly lower than the theoretical values (Figure 2.2), and the length range that force could be generated was larger *in vivo* compared with predicted values (Herzog and ter Keurs, 1988). These differences were rationalized by the researchers by acknowledging that the PSCA of the rectus femoris might have been overestimated in previous studies, there was possible overestimation of passive forces in this study, and that the rectus femoris might contribute less to knee extension than researchers previously thought (Herzog and ter Keurs, 1988). Passive forces were described as the tension in a muscle when it is stretched past its resting length, but not undergoing active contraction.

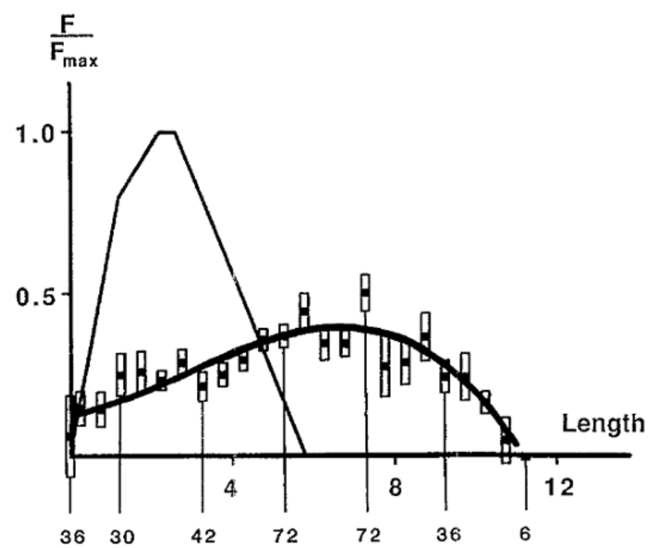


Figure 2.2: Normalized versus theoretical force-length curve in the rectus femoris muscle (Herzog and ter Keurs, 1988).

N.B. - The thick line is the normalized averages from the six participants and the thin line represents the theoretical force-length curve.

A study by MacIntosh in 2017 accepted the fundamental concepts described in the early findings of force-length relationship, (most importantly the concept that muscle can produce the most force from voluntary contraction when sarcomeres are at an optimum length allowing for optimal overlap of thick and thin filaments) and expanded on newer findings relating to length dependence and contractile response (MacIntosh, 2017). Researchers now acknowledge that there is a variation in passive force *in vivo* over the course of contraction due to changes in tendon and fascicle length, which makes it hard to correctly calculate active force (MacIntosh, 2017).

2.2.3 Muscle Moment Arm

Within the context of muscle, the muscular moment at a joint refers to the tendency of the muscle to cause rotation around a joint axis due to the muscle force (Winters, 2000). The moment produced by a muscle is the product of the muscle force and its moment arm at the joint. The moment arm is a measure of the length of the perpendicular line between the muscle force line of action, which is assumed to run straight through the muscle belly parallel to the fibers, to the center of the joint axis. The three methods used to calculate the muscle moment arm are from cadaver dissections, MRI, and ultrasound.

The axis of rotation of the ankle is not in a fixed position, but is instead continuously changing during movement, which has an effect on measurements of the moment arm of muscles that act across the ankle joint (Rugg et al., 1990). A study using MRI to calculate the moment arm of the Achilles tendon and the tibialis anterior *in vivo* found that the average moment arm of the Achilles tendon was not significantly different when measured using a fixed center axis versus a moving axis (Rugg et al., 1990).

Hoy and her colleagues created a musculotendon actuator model to understand the effect of muscle properties, tendon properties, and moment arm on the moment-angle relationship of the hip, knee, and ankle joints (Hoy et al., 1990). They found that each muscle in the model crossing a specific joint produced a peak force at a different joint angle due to differences in their moment arms, and differences in their optimal muscle fiber lengths (Hoy et al., 1990). It is also important to note that this peak moment did not always coincide with the maximum muscle force, maximum moment arm, or maximum voluntary contraction peak in this actuator model (Hoy et al., 1990). For some biarticular muscles, including the gastrocnemius, the angle of one of the spanned joints had a large effect on the peak moment of the other joint. This effectively shifts the moment-angle relationship at the other joint (Hoy et al., 1990).

A recent study used MRI to measure the moment arm of the Achilles tendon *in vivo* in three-dimensions and found that moment arm measured using three-dimensions were significantly smaller than the two-dimensional measurements in previous studies (Hashizume et al., 2012). The researchers attributed these differences to deviations of the ankle joint axis and misalignment of the two-dimensional measurements (Hashizume et al., 2012). Overall, the researchers believe that measuring the Achilles tendon moment arm using three-dimensional methods is more accurate, since the ankle joint rotates in three-dimensions.

2.3 Major Plantar-Flexor Muscles

The term plantarflexion refers to the downward movement of the foot as it rotates about the ankle joint, with the toes moving away from the body. The major plantar-flexor muscles are found in the posterior lower leg, commonly known as the calf muscles. The two-headed gastrocnemius muscle, consisting of a medial and a lateral head together with the soleus muscle comprise the triceps surae. The triceps surae is an important muscle in the walking gait, as the foot pushes against the ground as the ankle joint extends. Plantar flexor muscles are also important in running, jumping, and in the maintenance of upright posture (Bordoni and

Varacallo, 2021). The following subsections will describe the major plantar-flexor muscles followed by a briefer description of the other plantar-flexor muscles.

2.3.1 Soleus

The soleus is a mono-articular muscle located underneath the gastrocnemius in the posterior lower leg. It originates at the posterior fibular head and attaches into the aponeurosis of the gastrocnemius at the Achilles tendon beginning around lower third of the tibia and inserts on to the calcaneus bone in the foot (Bordoni and Varacallo, 2021). The soleus has two main functions, the first is to act as skeletal muscle performing plantarflexion as described above. The second function is as part of the skeletal muscle pump that helps move venous blood back to the heart through muscle contraction.

Experimental evidence shows that the soleus is primarily made up of Type 1 fibers, also referred to as slow-twitch muscle fibers (Johnson et al., 1973). This suggests that the soleus plays a large role in maintaining posture as slow-twitch fibers have a biochemical profile making them able to contract for longer periods of time without fatigue. For example, in the maintenance of an upright stance, the muscle fibers in the soleus can consistently produce force without significant fatigue over a long period of time and thus preventing falling forward.

Bolsterlee and his colleagues used diffusion tensor imaging, a type of MRI technique, to view the 3D muscle architecture of the soleus *in vivo* (Bolsterlee et al., 2018). Their study confirmed the findings of previous studies, which stated that there are four compartments in the soleus muscle: two anterior and two posterior, with differing pennation angles. This study also found that there are intercompartment changes in muscle architecture during passive lengthening (Bolsterlee et al., 2018).

2.3.2 Lateral and Medial Gastrocnemii

The gastrocnemius is a biarticular muscle that crosses both the ankle joint and knee joint. It plays an important role in plantarflexion of the ankle and flexion of the knee. The gastrocnemius has two heads, medial and lateral, that originate from the medial and lateral condyle of the femur respectively. The aponeurosis of the gastrocnemius forms the Achilles tendon as it merges with the soleus tendon at the inferior point of the muscle. Both heads of the gastrocnemius are pennate (Bordoni and Varacallo, 2021). They have similar maximal physiological length ranges, and their architecture are well suited for exertion of a high force over a small range of motion. The biarticular nature helps with transporting power from the knee to the ankle joint (Hujing, 1985).

The medial head is more pennate than the lateral head (Hujing, 1985), meaning that its fibers run further away from parallel to the tendon, forming greater angles. The medial head also has a greater cross-sectional area compared with the lateral head because its volume is larger, and the optimum fiber length is smaller (Hujing, 1985). This allows the medial head fibers to generate more force than the lateral head (Hujing, 1985).

In the lateral head of the gastrocnemius, the muscle fibers have significantly more sarcomeres in series than the medial head (Hujing, 1985). The distal portion of the lateral head has less sarcomeres than the proximal end, meaning that the optimum length of the distal sarcomeres is shorter.

2.3.3 Other Muscles

Other muscles that play a role plantarflexion of the ankle include the plantaris, flexor hallucis longus, flexor digitorum longus, tibialis posterior, peroneus longus, and peroneus brevis. The plantaris muscle is estimated to be absent in 7-20% of the population (Spina, 2007). Table 2.2 shows the percentage of the physiological cross-sectional areas of each muscle contributes to the total cross-sectional area of muscles crossing the ankle joint that can perform plantarflexion (Winter, 2009). This study will ignore these smaller accessory muscles because of their relatively small size and because their tendon paths run close to the bone, thus leading to relatively small moment arms.

Table 2.2: Percent contributions of six accessory muscles to total the PCSA of plantar flexor muscles (Winter, 2009).

Muscle	**% Contribution**
Soleus	41
Gastrocnemius	22
Tibialis Posterior	10
Flexor Hallucis longus	6
Flexor Digitorum longus	3
Peroneus brevis	9

2.3.4 Plantarflexion Strength Curve

The plantarflexion strength curves can be estimated by measuring the maximal plantarflexion moment with the ankle at multiple angles. As the plantarflexion angle increases (as the toes move further down, away from the body), the maximum strength decreases (Figure 2.3); (Sale et al., 1982).

Previous studies have shown that maximum plantarflexion strength is higher when the knee joint is at full extension at about 180 degrees versus a 90-degree joint angle (Kulig et al., 1984). This occurs because the gastrocnemius-tendon complex is longer when the knee is fully extended since both heads of the gastrocnemius cross the knee joint. The increased length of the gastrocnemius increases the maximum voluntary contraction during plantarflexion (Sale et al., 1982); presumably moving the muscle on its force-length curve so it produces more force.

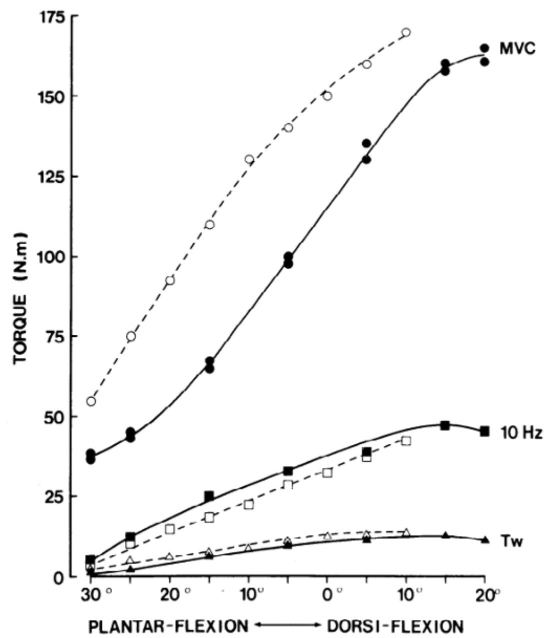


Figure 2.3: Plantarflexion strength curve based on maximal voluntary contraction measurements with knee extended (open circles) and at 90° (closed circle). Reproduced by Sale et al. (1982).

2.4 Intrinsic Muscle Force-Length Properties

While evidence for a relationship between sarcomere length and force was identified in the late 1800s by Blix (Blix, 1874) and later refined in the classical studies by Gordon and his colleagues (Gordon et al., 1966), researchers quickly realized that specific methods would be needed to measure this relationship *in vivo*. In order to better understand the force-length properties of muscle, it is important to recognize situations where this relationship can be manipulated. The following subsections will explain how to quantify the force-length relationship *in vivo*, and the adaptive potential of this relationship.

2.4.1 Measuring the *in vivo* Force-Length Relationship

Hatze was one of the first to propose a model to accurately measure muscle length-tension curves and optimal muscle lengths *in vivo* (Hatze, 1981). Using complex mathematical formulas, Hatze was able to find the peak isometric force and the complete length range over which each head of the triceps muscle could produce force.

Herzog and ter Keurs proposed a method to measure the force-length relationship *in vivo* of biarticular muscles (Herzog and ter Keurs, 1988). Their model made three key assumptions, that the maximum isometric force a muscle can produce is constant at a specific muscle length, they set antagonistic muscle activity as a constant value, and maintained that any joint moments recorded during the study were strictly from muscular forces (Herzog and ter Keurs, 1988). Their proposed method can be used calculate the moment of some multi-joint muscles, which can be compared theoretical values or those obtained in-vitro. The method exploited the manipulation of the length of a biarticular muscle by varying one joint angle (and therefore muscle length) while keeping the other joint the muscle crosses at a fixed angle and measuring the moment at that angle. By doing this in a systematic fashion the force-length properties of a biarticular muscle can be measured.

Winter and Challis acknowledged the assumptions that the Herzog study made and found it to be a useful model to measure the force-length relationship *in vivo* (Winter and Challis, 2008). They analyzed how well the Herzog and ter Keurs (1988) model worked to identify the section of the force-length curve over which an individual muscle worked (Winter and Challis, 2008). Their study focused on identifying which limb of the force-length curve the gastrocnemius operated over in each individual subject. In addition to the experimental data collected, they used a muscle model that generated moment-joint angle profiles. These profiles could then be moderated to help the researchers account for potential sources of noise that could affect experimental data. Winter and Challis concluded that the Herzog and ter Keurs (1988) method is a valid model to reconstruct human force-length curves *in vivo* even in the presence of noise (Winter and Challis, 2008).

2.4.2 Adaptations of the Force-Length Relationship

It is important to understand if the intrinsic muscle properties are adaptive under different loading conditions. An experiment in the 1970's tested if keeping the soleus muscle in mice at a fixed length would influence the number of sarcomeres in the muscle (Williams and Goldspink, 1978). The researchers found that immobilizing the hind limb in a shortened position in young mice caused a significant reduction in the number of sarcomeres in series, while immobilizing the limb in the lengthened position increased the number of sarcomeres in series (Williams and Goldspink, 1978). These results suggest that muscle is plastic in the sense that it can adapt to the habitual length of the muscle by adding or removing sarcomeres in series.

Koh and Herzog performed a similar study with rabbits to determine if the tibialis anterior (TA) muscle would adapt to an altered moment arm and excursion. The TA was released from its retinacular restraint at the ankle joint in the experimental group to increase the moment arm, shown below in Figure 2.4. This release increased the moment arm of the muscle and therefore the range of lengths over which the TA muscle-tendon complex operated. The released muscles adapted by adding more sarcomeres in series. In contrast to the study of Williams and Goldspink (1978), in the study of Koh and Herzog (1998) the muscle was not immobilized but the joints were permitted to go through a normal range of motion post-surgical intervention. The group with the released TA was found to have decreased force production compared to the control group, most likely to maintain a similar level of torque on the joint seen in both groups. The muscle architecture was also altered by the TA release, as the PCSA of the experimental release group was decreased compared to the control and there was an indication of a smaller specific tension. These anatomical changes could have been a result of the smaller forces produced by the released muscle.

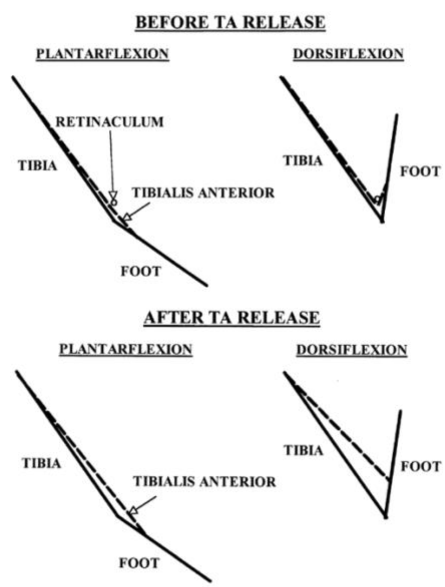


Figure 2.4: Diagram of TA muscle before and after TA release (Koh and Herzog, 1998).

N.B. - The position of the TA muscle (dotted line) in relation to the tibia and the foot (solid lines) before and after being released. These diagrams show how the moment arm of the released

TA muscle is larger when performing plantarflexion and dorsiflexion compared with the normal control.

A study compared the interlimb differences between stroke patients and non-stroke participants to determine if muscle architecture was affected by the disuse and interrupted neural connection caused by a stroke (Adkins et al., 2021). Serial sarcomere number (SSN) and PCSA were measured at three anatomical levels using combined ultrasound and MRI methods. The researchers found that the interlimb differences in SSN and PCSA were significantly larger in the stroke group compared with the non-stroke group, indicating that architectural changes will occur in muscles that are kept at a chronically shortened position due to disuse because of a neural impairment (Adkins et al., 2021). The adaptation seen in this study could contribute to functional impairment of the muscle already affected by the disrupted neural connection.

2.5 Kinematics of the Ankle Joint During Skating Stride

This study is examining over what portion of the force-length curve the gastrocnemius muscle operates in female ice hockey players operates on the force-length curve. The scientific rationale behind using ice hockey players as participants is due to the restrictive nature of the modern skate boot. The boot mostly fixes the ankle joint to prevent against injury, but in doing so constrains the range over which the muscles of the triceps surae can operate. The kinematics of skating differ greatly from natural running or walking gait due a number of factors, most notably because skating requires using two thin blades to move over a frictionless surface while the ankle joint is immobilized.

For a long time, the kinematics of ice skating were not well understood because of the challenge of trying to measure skating kinematics whilst on the ice surface. One of the first modern studies used bilateral twin axis goniometers attached to the ankle and the back of the foot to measure plantarflexion and dorsiflexion of the foot during skating (Pearsall et al., 2001). The researchers found that the skate boot held the ankle joint primarily in a position of dorsiflexion for the entire skating stride cycle.

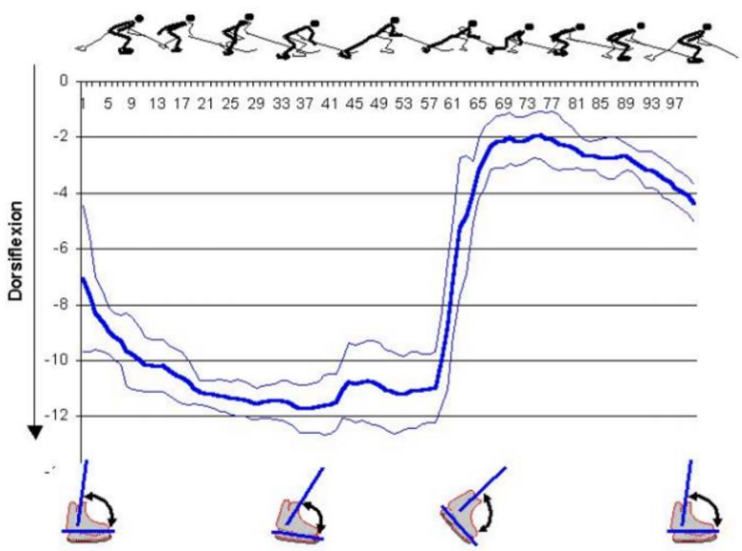


Figure 2.5: Average dorsi- and plantarflexion ankle joint angles during forward skating stride (Pearsall et al., 2001).

Buckeridge et al. (2014) used a multi-measurement system including EMG and a pressure measurement system to examine muscle activity in the medial gastrocnemius, gluteus maximus, tibialis anterior, vastus lateralis, and vastus medialis and plantarflexion force. The researchers found that there was a large plantarflexion activity during skating, contributing to body acceleration and forward movement. This finding is interesting since plantar flexors behave largely isometrically since the foot is held in a position of dorsiflexion by the skate boot while skating.

One team of researchers compared skating kinematics between a standard skate (SS) and a modified skate (MS). The skate boot was modified by removing the tendon guard in the posterior portion of the skate, raising the eyelet holes, and inserting a lighter, more flexible tongue (Robert-Lachaine et al., 2012). These changes were designed to increase the plantarflexion range of motion during skating. The researchers did not find any quantifiable difference in performance between the SS and the MS, although they acknowledged that skaters would most likely need an adjustment period that was not included in the study (Robert-Lachaine et al., 2012).

2.6 Summary

This chapter has introduced and reviewed literature relevant to this study. The papers highlighted in this chapter provide background information to justify the motivation for this study.

Chapter 3

Muscle Model Analysis

3.1 Introduction

The following sections present a model of the major ankle plantar-flexor muscles. The equations and parameters used to generate this model are presented first, followed by a validation of the model. Then there is an analysis of the influence of changing in the number of sarcomeres in series on the expressed section of the force-length curve.

3.2 Muscle Model

Two muscles were modeled, the soleus and the gastrocnemius. Both heads of the gastrocnemius, medial and lateral, were combined in the model into one functional unit. The force exerted by each muscle and its tendon (F_T), was a function of the muscle active state (q), the maximum isometric force (F_{max}), and the fraction of the maximum isometric force the muscle can produce ($F_L(L_F)$) at its current length (L_F). The relevant equation is,

$$\boldsymbol{F_T = q \cdot F_{max} . F_L(L_F)} \qquad \textbf{[3.1]}$$

The model comprises of fibers which can produce force, and an elastic tendon in series with the fibers (Figure 3.1).

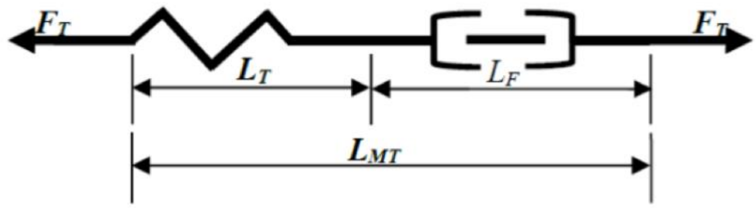


Figure 3.1: Schematic representation of the Musculo-Tendon complex.

N.B. - F_T stands for force applied to the tendon, L_T represents tendon length, L_F represents muscle fiber length, and L_{MT} is the length of the muscle-tendon complex.

The intrinsic relationship between muscle-tendon complex length, tendon length, and muscle fiber length is,

$$\boldsymbol{L_{MT} = L_T + L_F} \quad \textbf{[3.2]}$$

The force-length properties of the muscle fibers were modeled using,

$$\boldsymbol{F_L(L_F) = 1 - \left(\frac{(L_F - L_{F,OPT})}{w.L_{F,OPT}}\right)^2} \quad \textbf{[3.3]}$$

Where, $L_{F,OPT}$ is optimum length of muscle fiber, and w is the parameter indicating width of force-length curve. The width of the force-length curve is dependent on the optimum length of the fibers, and the model width parameter (Figure 3.2).

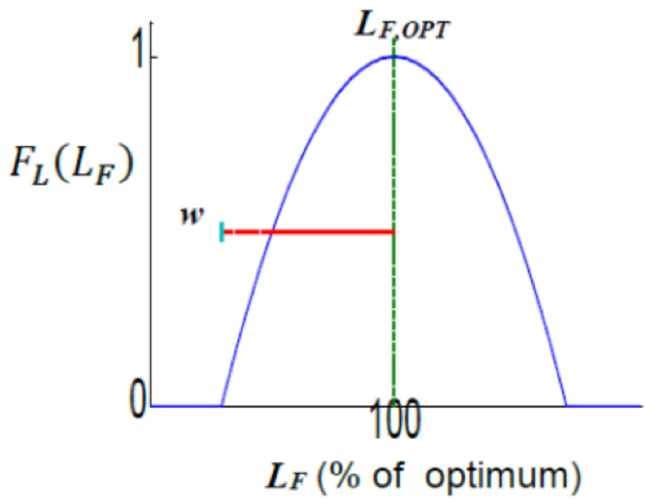


Figure 3.2: Diagram of theoretical force-length curve where optimum length is set to 100.

N.B. - $F_L(L_F)$ is fraction of the maximum isometric force the muscle can produce at its current length (L_F).

In series with the muscle fibers is an elastic tendon, it was assumed there was a linear relationship between the force applied to the tendon, and its length, shown in Equation 3.4.

$$\boldsymbol{L_T = L_{TR} + \frac{c}{F_{max}}.L_{TR}.F_T} \qquad \textbf{[3.4]}$$

Where L_T represents the current length of the tendon, L_{TR} represents resting length of the tendon, and c represents the strain in tendon under maximum isometric force. The model parameter c dictates how much the tendon stretches above its resting length due to the force applied to it (Figure 3.3).

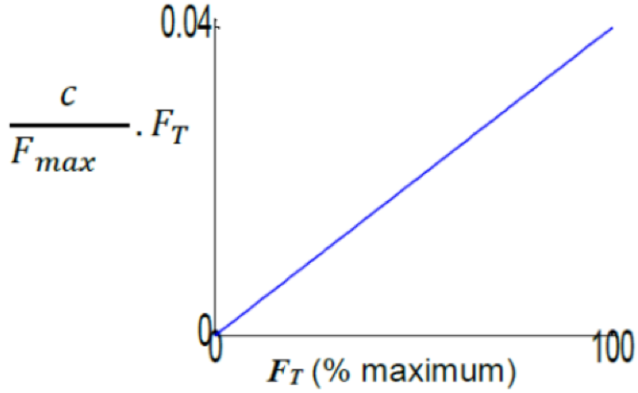


Figure 3.3: Linear relationship of force applied to the tendon, $\boldsymbol{F_T}$, and tendon extension expressed as a percentage of the resting length of the tendon, $\frac{c}{F_{max}}.\boldsymbol{F_T}$.

3.3 Muscle Kinematics

For each of the modeled muscles for every joint angle the length of the muscle-tendon complex, and the moment arm of the muscle at the ankle joint was determined. In Grieve et al. (1978) the change in length of the gastrocnemius (ΔL_{MT}) expressed as a percentage of segment length, was presented as a function of ankle and knee joint angles,

$$\boldsymbol{\Delta L_{MT} = A_0 + A_1\theta_{Ankle} + A_2\theta^2_{Ankle} + A_3 + A_4\theta_{Knee} + A_5\theta^2_{Knee}} \qquad \textbf{[3.5]}$$

For the soleus the same equation applies except terms A_3, A_4 and A_5 are ignored as this muscle does not cross the knee joint.

The moment arm of the gastrocnemius and soleus muscles at the ankle joint can be determined by differentiating equation 3.5 with respect to ankle joint angle,

$$r = A_1 + 2.A_2\theta_{Ankle} \quad \textbf{[3.6]}$$

The equations were reformulated so that they used the definitions of joint angles in Figure 3.4, as the soleus and gastrocnemius have a common tendon crossing the ankle joint, their moments arms are the same. The resulting equations are,

$$\Delta L_{MT,Gastroc.} = a_0 + a_1\theta_{Ankle} + a_2\theta_{Ankle}^2 + a_3 + a_4\theta_{Knee} + a_5\theta_{Knee}^2 \quad \textbf{[3.7]}$$

$$\Delta L_{MT,Soleus} = a_5 + a_1\theta_{Ankle} + a_2\theta_{Ankle}^2 \quad \textbf{[3.8]}$$

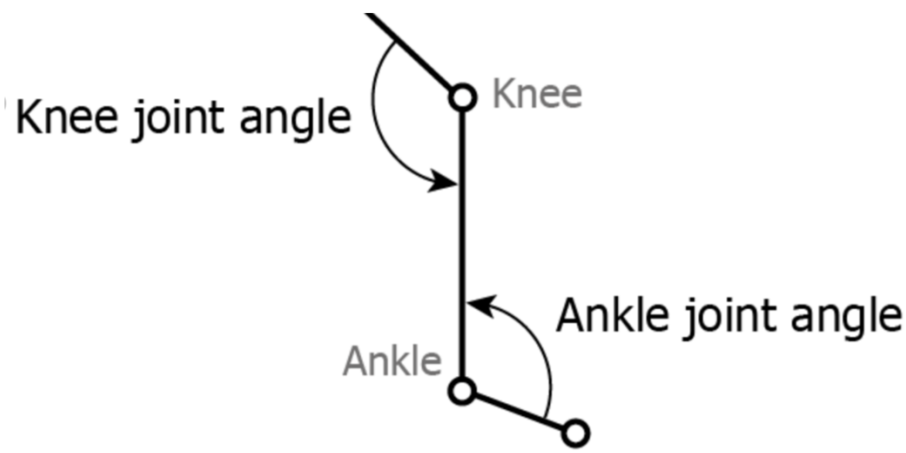


Figure 3.4: Diagram defining the knee and ankle joint angles.

The moment arm of the muscle at the ankle joint can be determined by differentiating the equation with respect to ankle joint angle,

$$r_{Gastroc.} = r_{Soleus} = a_1 + 2.a_2\theta_{Ankle} \quad \textbf{[3.9]}$$

The muscle change in length and moment arm are scaled relative to shank length (SL), and change in muscle length expressed with reference to shank length and overall muscle-tendon length can be determined using a reference length ($L_{MT,Ref}$) for the muscle-tendon complex, therefore,

$$\boldsymbol{L_{MT} = L_{MT,Ref} + \frac{SL.\Delta L_{MT}}{100}} \quad \textbf{[3.10]}$$

$$\boldsymbol{r_{Ankle} = \frac{SL.r_{Soleus}}{100} = \frac{SL.r_{Gastroc.}}{100}} \quad \textbf{[3.11]}$$

3.4 Computation of Ankle Joint Moments

Moments at the ankle joint were computed for a range of ankle and knee joint angles under isometric conditions. The net muscle moment (T_{Ankle}) was computed from,

$$\boldsymbol{T_{Ankle} = r_{Ankle}.F_{Soleus} + r_{Ankle}.F_{Gastroc.}} \quad \textbf{[3.12]}$$

Where, F_{Soleus} represents the isometric force produced by the soleus at the current ankle joint angle, and $F_{Gastroc.}$ represents the isometric force produced by the gastrocnemius at the current ankle joint and knee joint angles.

For given ankle and knee joint angles, the moment arms and muscle-tendon lengths were computed using equations 3.7 to 3.10. Then for each muscle-tendon length for each muscle, the maximum isometric force the muscles could produce was computed. The analysis was under assumption that both muscles were maximally activated ($q = 1$). The length of the fibers and the tendon were determined by an iterative procedure. Initially fiber length was estimated by subtracting resting tendon length from the muscle-tendon length. Given this fiber length muscle force was computed using equation 3.3. For this muscle force the tendon length was computed using equation 3.4. Given this estimate of tendon length muscle fiber length was recomputed, and the computation repeated. This sequence was repeated until a consistent value for maximum isometric force was produced.

This approach assumes that the gastrocnemius and soleus haven independent tendons at the ankle joint, which they do not as they have a common tendon - the Achilles tendon. Despite this common tendon the muscles likely function relatively independently relative to the Achilles tendon due to differential sliding between the deep and superficial fibers of the Achilles tendon (Arndt et al., 2012; Franz et al., 2015).

3.5 Model Parameters

The parameters determined required to compute the gastrocnemius and soleus length and moment arm are based on Grieve et al. (1978) (see Table 3.1).

Table 3.1: Model parameters used to determine muscle length and moment arm on data joint angles.

Muscle	**Parameters**							
	a_0	a_1	a_2	a_3	a_4	a_5	$SL\ (m)$	$L_{MT,Ref}\ (m)$
Gastrocnemius	12.31	-4.69	-2.00	-4.35	2.31	0.36	0.368 m	0.4335 m
Soleus	12.31	-4.69	-2.00				0.368 m	0.286 m

N.B. - The base equation is $\Delta L_{MT} = a_0 + a_1\theta_{Ankle} + a_2\theta^2_{Ankle} + a_3 + a_4\theta_{Knee} + a_5\theta^2_{Knee}$, where the input angles are in radians.

The muscle model parameters are based on Winter and Challis (2008), with a few minor adjustments (see Table 3.2).

Table 3.2: The parameters required for the muscle models of the soleus and gastrocnemius.

Muscle	**Parameter**				
	ω	$L_{F,OPT}$	F_{max}	L_{TR}	c
Gastrocnemius	0.55	0.095 m	1419 N	0.372 m	0.04
Soleus	0.55	0.056 m	2867 N	0.236 m	0.04

N.B. - ω is the parameter indicating width of force-length curve, $L_{F,OPT}$ represents optimum length of muscle fiber, F_{max} stands for maximum isometric force, L_{TR} is the resting length of the tendon, and c is the strain in tendon under maximum isometric force.

3.6 Model Validation

To evaluate the model simulations were performed for a range of ankle angles with the knee joint either fully extended or flexed to 90 degrees. As the gastrocnemius is biarticular its contribution to the net moment at the ankle joint will change as knee angle changes (even for an invariant ankle angle). The soleus muscle as it is mono-articular is only influenced by the ankle joint angle. Therefore, there should be a different moment-ankle joint angle profile with the knee extended compared with the knee flexed. The model estimates of the ankle joint isometric muscle moment due to the actions of the gastrocnemius and soleus we computed for a range of ankle angles, and with the knee either fully extended or flexed to 90 degrees. To evaluate the model, model output the resultant ankle muscle moment was compared with the data collected by Sale et al. (1982) (see Figure 3.5).

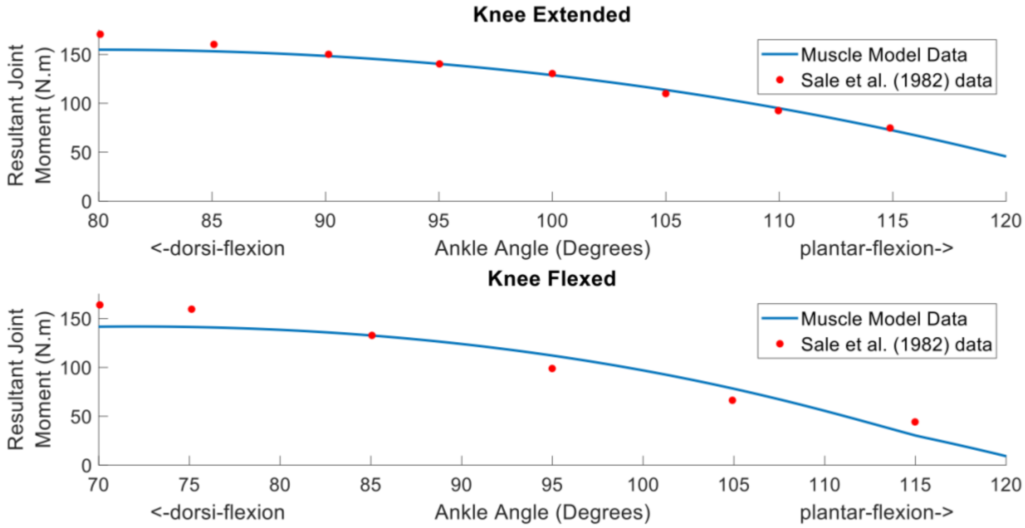


Figure 3.5: The resultant joint moments at the ankle joint produced by a model of the soleus and gastrocnemius muscles, compared with the experimental data from Sale et al. (1982).

While a complete validation of a model is never feasible (Panjabi, 1979), the model captures some of the essential properties of muscle and produces an output which compares favorably with the experimental data of Sale et al. (1982).

3.7 Model Analysis

If hockey players habitually have a reduced range of ankle motion due to the constraint of the skate (See Appendix B), compared with its range of motion in everyday activities it is feasible that their gastrocnemius will adapt by reducing the number of sarcomeres in series. The muscle model was run under two conditions, 1) with the original parameter set, and 2) with the optimum length of the gastrocnemius reduced to 80% of its original value. A reduction of the number of sarcomeres in series in the gastrocnemius would reduce its optimum length. These simulations indicate that the gastrocnemius has a change in the expressed section of the force-length curve because of reducing the optimum length (see Figure 3.6). Notice that with the knee extended that the gastrocnemius shifted from working on the ascending region of the force-length curve to the incorporating the plateau region.

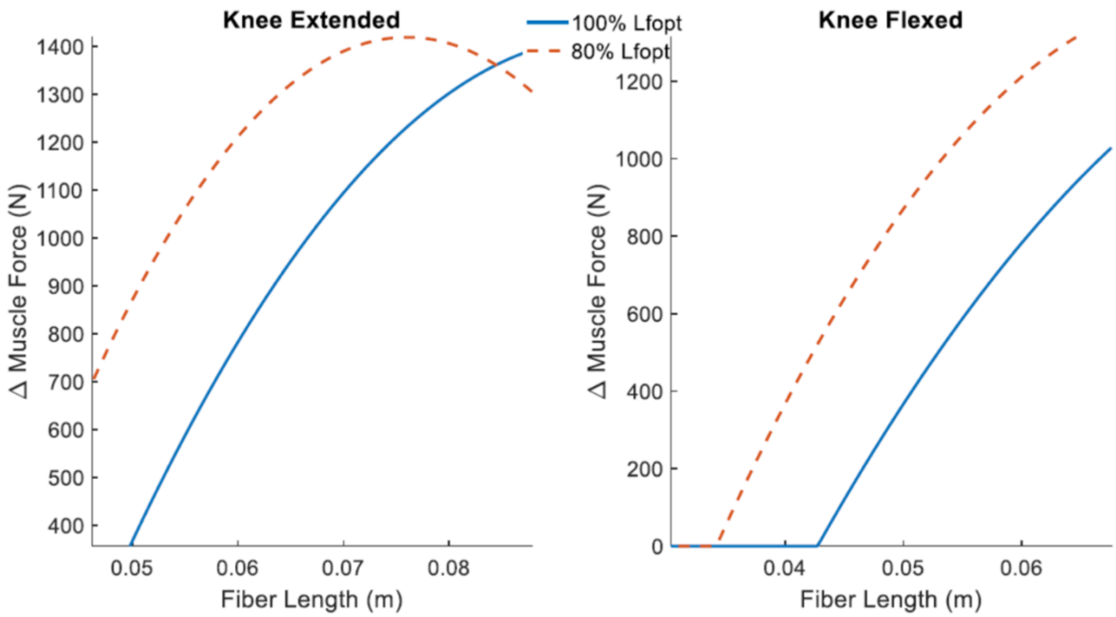


Figure 3.6: Change in muscle force with different optimum fiber lengths from 70 to 120° of plantarflexion.

3.8 Summary

This chapter presented a model of the plantar flexor muscles and then a subsequent validation of the model. Then the model was run once under original parameters and then run again with the optimum length shortened to 80% of the original value. The model analysis showed a shift towards expression of the plateau of the force-length curve.

Chapter 4

Materials and Methods

4.1 Overview

This chapter will describe the study participants, the testing equipment, testing protocol, and how the data was processed and analyzed. The aim of this study was to re-construct the force-length diagram of the gastrocnemius for each subject, and then compare these data to extant data.

4.2 Subjects

Potential participants were recruited by word of mouth from the Penn State Women's Ice Hockey Team. The criteria that were required to be a participant in this study are listed below.

- 18–26-year-old women
- Play Division I level ice hockey
- No previous lower limb surgery
- No pain or injury of the lower limb in the last six weeks

Participants self-selected which leg was to be tested. All participants chose to test their right leg. A total of 12 subjects were recruited. The characteristics of the subject pool were mass 69.7 kg ± 7.20, height 1.67 m ± 0.044, age 19.3 years ± 1.20, and shank length 35.0 cm ± 1.50. All participants provided written informed consent (see appendix A for form). All procedures were approved by the Institutional Review Board (Study number 00018762)

4.3 Testing Equipment

The primary measure of interest in this study was maximum voluntary isometric plantarflexion moment. The maximum isometric plantarflexion moment was measured using the Biodex System 3 isokinetic dynamometer in the Biomechanics Lab at Penn State. The Biodex is a computerized robotic measurement system which can measure a participant's isometric plantarflexion moment. A specialized protocol was created using the Biodex software for this experiment. Two versions of this protocol were created, one with ascending ankle angles and one with descending ankle angles; subjects were randomly assigned to either protocol.

4.4 Testing Protocol

The following subsections describe the entire testing protocol carried out in this study. The subjects were familiarized with the protocol before coming into the Biomechanics Lab. Once in the lab, each participant underwent a warm-up period followed by the maximum voluntary isometric plantarflexion moment efforts in the Biodex. Other supplemental measurements were also taken.

4.4.1 Preparation Prior to Testing

Subjects were first familiarized with the study during the recruiting process. Prior to participation, potential subjects were read a screening script that outlined the criteria and protocol of this study. Potential participants that met the criteria and expressed interest in participating were scheduled to come into the lab for data collection. In the lab, each participant was refamiliarized with the protocol and asked to provide written informed consent prior to participation. Each subject was encouraged to perform a five-minute warm-up period prior to testing on the Biodex machine. The participants were encouraged to warm-up by their method of choice. They were provided with a treadmill, stationary bike, and a space to perform dynamic exercises.

4.4.2 Biodex Testing

Each participant was seated in the Biodex machine, and the equipment was adjusted to the individual to ensure comfort and stability. The participant was secured in the Biodex machine with a seatbelt and chest straps. The foot of the limb being tested was positioned on a plate and secured with Velcro straps, and there was a strap across the upper shin to provide stability. It was important to make sure that the participants shin of the leg being tested was parallel to the floor when seated in the Biodex (see Figure 4.1).

Figure 4.1: Mock photo demonstrating the set-up of the participant in the Biodex machine. Shown here at a knee angle of approximately 120° of flexion and an ankle angle of approximately 30° of plantarflexion.

Each subject's full range of ankle joint motion was calculated using the Biodex. The protocol was then initiated. The protocol automatically took participants through a series of isometric maximum voluntary contraction efforts of plantar flexion. Participants performed maximum effort at six different ankle joint angles: 0°, 15°, 25° of dorsiflexion and 15°, 30°, 40° of plantar flexion. Two trials were conducted at each ankle joint angle, with each effort lasting 5 seconds with 30 seconds of rest between. This protocol was repeated three times at knee angles of 90°, 120°, and 180°.

Two versions of the protocol were created to mitigate fatigue as a confounding factor across subjects. The first protocol started with the ankle placed at 25° dorsiflexion and then moved sequentially to 40° plantar flexion. The second protocol was the opposite, starting at 40° plantarflexion and then moved sequentially to 25° dorsiflexion. The protocol used along with the order of knee angles were randomized for each participant.

4.4.3 Other Measurements

In addition to the strength data collected using the Biodex machine, supplemental anatomical data was collected from each subject. Other measurements taken were knee circumference, maximum calf circumference, ankle circumference, shank length, and calcaneus thickness. Knee circumference, maximum calf circumference, and ankle circumference were all measured using a tailor's tape measure (see Figure 4.2). Shank length was measured from the lateral condyle to the lateral malleolus using a ruler (see Figure 4.3d). Calcaneus thickness was measured using calipers (see Figure 4.3e).

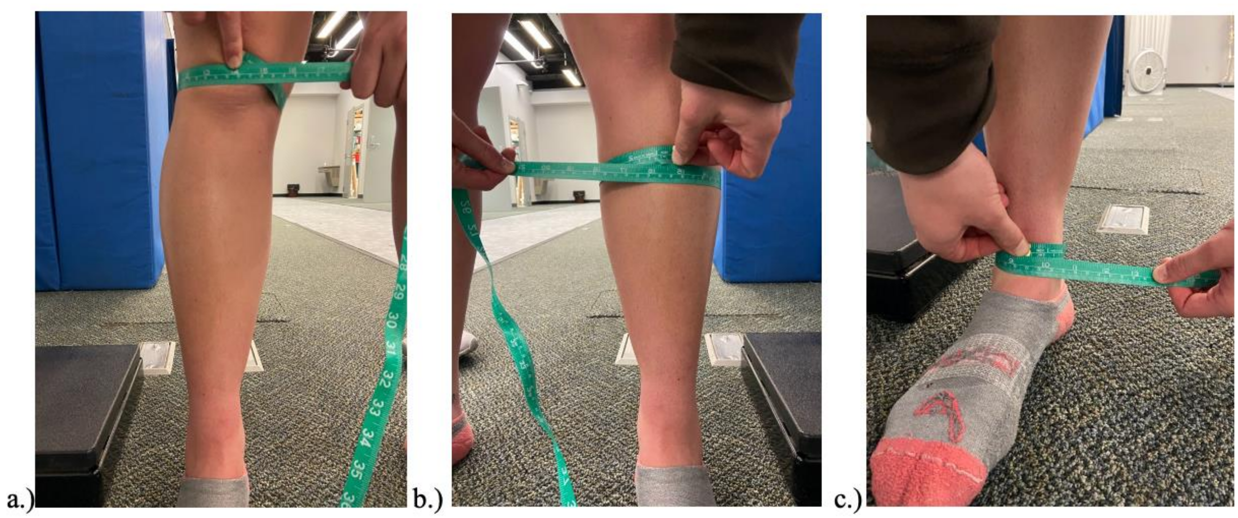
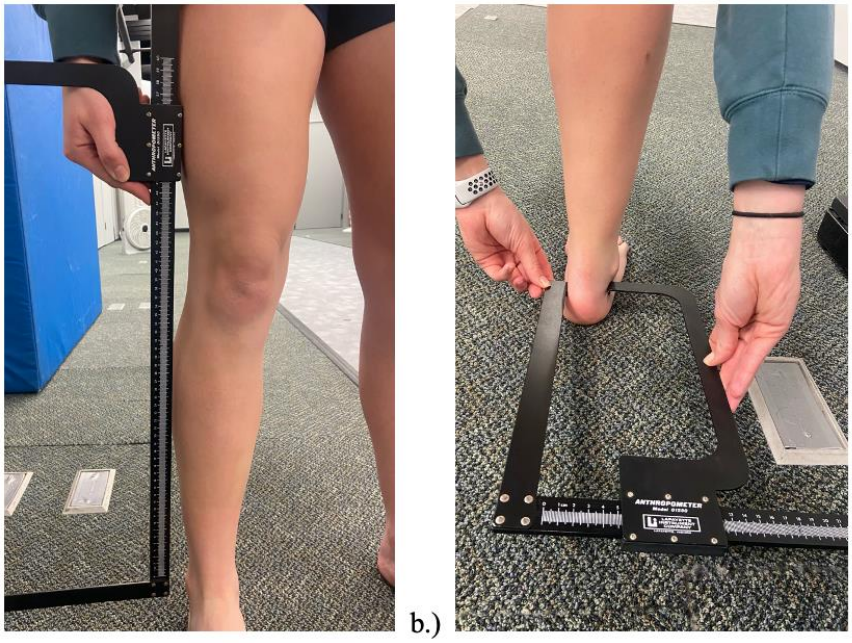


Figure 4.2: Collection of knee circumference (a), maximum calf circumference (b), and ankle circumference (c) were measured using a tailor's tape measure, seen here in green.



a.) b.)

Figure 4.3: Collection of shank length (a) and calcaneus thickness (b) using a ruler and calipers.

4.5 Data Processing

The maximum isometric plantarflexion moment data for each subject were exported to an Excel document along with their anthropometric data. The three moments generated at a given ankle angle across the three different knee angles will be referred to as a set. Each set shows the change in force produced as the length of the gastrocnemius changes. The level of flexion in the knee changes the lengths of the muscle fibers of the gastrocnemius due to its biarticular nature, while the soleus length remains constant for each set as it is monoarticular. Therefore, for a given set the contribution of the soleus to the ankle joint remains constant due to its fixed length, and the contribution of the gastrocnemius changes due to its length changes caused by variations in the knee joint angle.

For each data set, the ankle muscle moment arm and the muscle-tendon lengths were computed using equations 3.11 and 3.10 respectively. For each set the lowest moment recorded was treated a reference and subtracted from the other moments, these moments were then divided by the muscle moment arm to give the change in gastrocnemius force. Repeating this for each set gave six pairs of data points representing the length of the gastrocnemius and the change in its muscle force. The data sets were ordered relative to the muscle-tendon length, then a line fitted to the first two data points and used to predict the force value of the first data point in the next set, and the force difference was then subtracted from all the data points in this second set, this was repeated for all subsequent sets. This resulted in 12 data points which described the length of the muscle-tendon complex and the corresponding change in force of the gastrocnemius. Then a second order polynomial was fitted to these data points given that it produced a curve with downward concavity. If this was not the case, a straight-line was fitted to the data instead.

The expressed section of the gastrocnemius of each subject was found by locating where the peak force value fell on the range of muscle-tendon lengths. If the force peaked in the shortest 40% of muscle fiber lengths, then it was identified as operating on the descending limb. If the force peaked at more than 60% of the fiber lengths, then it was identified as operating on the ascending limb. If the force peaked within the range of 40-60% of the fiber lengths, then it was identified as operating on the plateau region.

4.6 Statistics

For all collected data descriptive statistics, mean and standard deviation, were computed. Resultant joint moments were normalized with respect to subject mass. For the experimental subjects the numbers of subjects expressing either the ascending, plateau, or descending limb of the force-length curves was determined. The frequencies of expressed sections were compared using the chi-square test with the results from an earlier study, Winter and Challis (2008) performed in the same lab using the same equipment and analysis methods.

4.7 Summary

This chapter presented the criteria and characteristics of the twelve subjects. Then the study equipment, protocol, and data processing were described, followed by an overview of the statistical methods used.

Chapter 5

Results

5.1 Overview

The following sections present the results of the study. The sections describe the anthropometric measurements, the expression of the force-length curve, and the analysis of active insufficiency.

5.2 Subject Anthropometry and Strength

The twelve subjects in this study had a mean height of 1.67 m ± 0.044, mass of 69.7 kg ± 7.20, and age of 19.3 years ± 1.20. The subjects had a mean shank length of 35.0 cm ± 1.50 and calcaneus thickness of 4.7 cm ± 0.49. The mean range of angle joint motion was 78.8° ± 7.90 from full plantarflexion to full dorsiflexion.

The mean peak moment produced by the subjects was 94.3 N·m ± 35.7. The peak moment values were normalized to account for the association between strength and mass. The normalized mean peak moment was 1.35 $N{\cdot}m{\cdot}kg^{-1}$ ± 0.48. The mean minimum moment produced was 4.00 N·m ± 4.65, although some subjects were unable to produce a moment for certain joint configurations (see Section 5.4). The normalized mean minimum moment was 0.06 $N{\cdot}m{\cdot}kg^{-1}$ ± 0.06.

5.3 Expression of the Force-Length Curve

Polynomials were fitted to muscle-length and change in force data for the gastrocnemius to characterize the shape of the expressed section of the force-length curve (see Figure 5.1). For each subject the shape of the curve determined the *in vivo* expressed section of the force-length curve. Figure 5.1 represents a subject who operated on the plateau of the force-length curve.

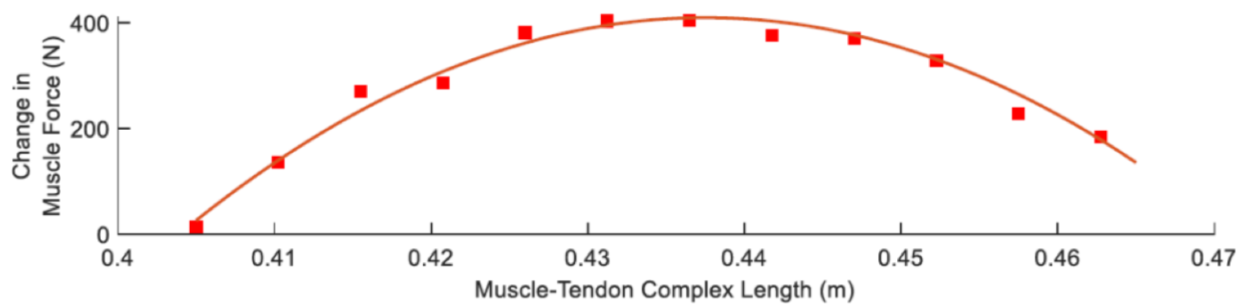


Figure 5.1: Force-length curve for exemplar participant. For thus subject their data would be characterized as operating on the plateau of the force-length curve.

It was determined that six of the subjects operated on the ascending limb of the gastrocnemius force-length curve, five operated on the plateau, and one operated on the descending limb (see Figure 5.2). This distribution of the expressed section for participants in this study was compared with the data of Winter and Challis (2008). In Winter and Challis (2008), the force-length curve of the gastrocnemius of 28 subjects was measured *in vivo*, and the portion of the curve over which they operated was determined. The data from the 12 ice hockey players in this study was compared to the data from the 28 average participants from Winter and Challis (2008) (see Table 5.1).

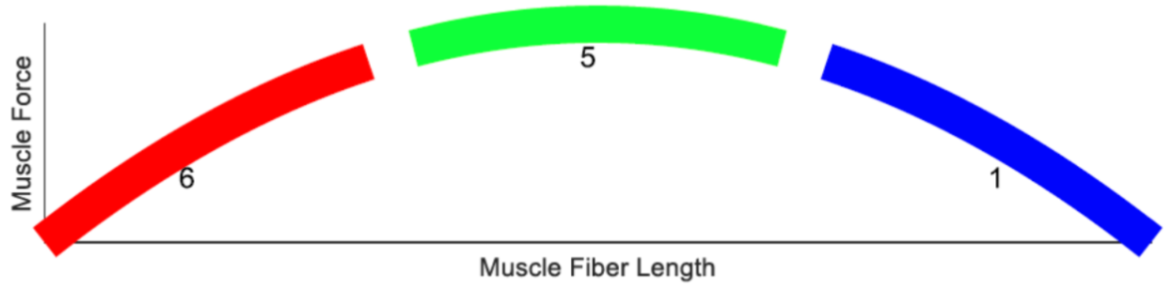


Figure 5.2: Distribution of participants based on expression of force-length curve.

Table 5.1: The portion of the force-length curve expressed *in vivo* for the gastrocnemius for subjects in this study and the distribution predicted by Winter and Challis (2008).

	Expressed Section		
	Ascending	**Plateau**	**Descending**
Experimental Data	6	5	1
Predicted	10.3	0.4	1.3

A chi-squared test was performed to compare the distribution of the expressed section of the force-length curve for the subjects in this study with the distribution predicted by the results from Winter and Challis (2008). There was a statistically significant difference in the frequency of the expressed section of the force-length curve for ice hockey players compared to a group of non-specifically trained people ($p<0.0001$).

5.4 Active Insufficiency

Active insufficiency can occur when a biarticular muscle, like the gastrocnemius, operates at extreme joint orientations. This shortens or extends the muscle over both joints simultaneously, causing almost all muscle tension to be lost and making it difficult to produce a muscle moment at that position because the muscle fibers are either too long or too short to actively produce force. At the extreme ankle joint angles some participants were not able to produce an active moment. Four of the subjects could not produce a muscle moment when their knee was at 180° flexion and their ankle was at 130° plantarflexion. For these joint orientations, the plantarflexion muscles of these four subjects had active insufficiency, meaning the muscles were too short to produce force. Of the participants who were found to operate on the ascending limb, two were unable to produce a muscle moment at 130° plantarflexion at any of the three knee angles (see Subject Number 2 and 5 in Table 5.2).

Table 5.2: Active insufficiency among participants at three knee angles at maximum plantarflexion.

			Knee Angle	
Subject Number	**Expressed section**	**180°**	**120°**	**90°**
1	ascending	Y	Y	Y
2	plateau	N	N	N
3	ascending	Y	Y	Y
4	plateau	N	Y	Y
5	plateau	N	N	N
6	plateau	Y	N	N
7	ascending	N	N	N
8	plateau	N	N	N
9	ascending	N	N	N
10	descending	Y	N	N
11	ascending	N	N	N
12	ascending	N	N	N

N.B. – if a subject was able to produce a moment at the given knee angle, at maximum plantarflexion, the table indicates Y (yes), otherwise N (no).

5.5 Summary

This chapter has described the subject anthropometry, their expressed section of the force-length curve *in vivo*, and presents when active insufficiency occurs for the subjects.

Chapter 6

Discussion

6.1 Overview

This study presented a theoretical model of the ankle plantar flexor muscles. The model equations and parameters were used to predict the expression of the force-length curve in a theoretical subject with fewer sarcomeres in series in the gastrocnemius. This study then collected isometric plantarflexion moment data for twelve subjects who are highly trained ice hockey players. The data collected was compared with extant data from Winter and Challis (2008).

The following sections present the muscle model analysis (Chapter 3) and the experimental analysis (Chapters 4 and 5). This chapter also discusses the limitations of this study and the proposed direction for future studies.

6.2 Muscle Model Analysis

For the analysis, the model was run under the original parameters, which produced typical *in vivo* strength curves, and then run again with the gastrocnemius optimum muscle fiber length reduced to 80% of the original value. The analysis was done to examine if a person with gastrocnemii muscles with less sarcomeres in series would have a different expression of the force-length curve compared with someone with more sarcomeres in series. The model analysis showed that the expressed section of the force-length curve shifted to the left when run with an optimum length reduced by 80%, meaning that the plateau region was more expressed rather than the ascending limb (see Figure 3.6).

Ice hockey players complete much of their training in a skate boot that greatly reduces the range of motion of the ankle joint (see Appendix B). It seems possible that high-level ice hockey players who have played the sport for many years, and engaged in extensive sport-specific training, could show changes in architecture of their plantar flexor muscles, specifically a reduced number of sarcomeres in series. This idea is supported by the study of Williams and Goldspink (1978), who found that mice whose hind legs were immobilized in a shorted position had a reduced number of sarcomeres in series in their soleus muscle. In addition, a study conducted by Herzog and his colleagues (1991) found differences in expressed section of the force-length curve of the rectus femoris when comparing cyclists with runners due to differences in the range of motion of the knee and hip joint of those two activities.

The results of the model analysis were consistent with the theory that ice hockey players show differences in expression of the force-length curve. Ice hockey players are assumed to have a reduced number of sarcomeres in series due to the reduced range of motion of their ankle joint when they are training and competing in skates. Fewer sarcomeres in series would decrease the optimum length of their gastrocnemius muscle, changing the *in vivo* expression of the force-length curve compared with a population with a greater optimum length. This is exactly what the model analysis demonstrated, and when the optimum length was shortened, there was a shift towards expression of the plateau portion of the force-length curve instead of the ascending limb.

6.3 Experimental Analysis

The following paragraphs describe the outcomes of the experimental analysis. The study found that the population of highly trained subjects showed differences in the expression of the force-length curve of the gastrocnemius muscle compared to data from an untrained population. Ice hockey players had higher frequency of expression of the plateau region of the force-length curve compared with a normal population. The mean peak moment for the ice hockey players occurred at shorter optimum gastrocnemius fiber lengths compared with values from a previous study (Winter and Challis, 2008). Only 50.0% of the subjects in this study expressed the ascending limb of the force length curve while 41.6% expressed the plateau portion and 8.3% expressed the descending limb. This differs from values in literature that found that 85.8% of an untrained population operated on the ascending limb, 3.3% operated on the plateau of the curve, and 10.8% operated on the descending limb (Winter and Challis, 2008).

Some of the ice hockey players demonstrated active insufficiency at extreme joint positions. It is common that a person operating on the ascending limb of the curve would be unable to produce a plantarflexion moment when the ankle joint is at an extreme position, since the fibers cannot shorten sufficiently to produce force. A person operating on the plateau of the force length curve should be able to produce a plantarflexion moment at every ankle angle in this study. Subject 4 and Subject 6 both operated on the plateau of the curve but could not generate a plantarflexion moment with their ankle at 130° plantarflexion at some knee angles. This anomaly could have occurred because those subjects could have produced force in those joint configuration but were unable to voluntarily activate their muscles at those extreme positions.

6.4 Synthesis

The outcome of the model analysis matches the major findings of the experimental analysis. Both found that a population with a shorter optimum gastrocnemius muscle length (likely attributed to having fewer sarcomeres in series) expressed more of the plateau region of the force-length curve. These findings indicate that a population of highly trained subjects who perform their training with constrained ankle mobility show a shift in the force-length curve towards expression of the plateau of the curve. This suggests that there is an adaptive potential manifested in a change in the force-length properties of skeletal muscle. When discussing adaptive potential, it is important to realize that this study could not determine how or when the subjects possessed fewer sarcomeres in series compared with an average population. It is still unknown if ice hockey players adapt to have fewer sarcomeres in series in their gastrocnemius because of performing at a constrained ankle angle or if a population with a lower number of sarcomeres in series than average is at an advantage to become better ice skaters. Animal studies do indicate that the number of sarcomeres in series in a muscle fiber alter due to changes in muscle *in vivo* excursions (e.g., Williams and Goldspink, 1978; Koh and Herzog, 1998).

6.5 Study Limitations

The limitations will be presented for the model and then the experimental portions of this study.

6.5.1 Model Limitations

Any theoretical model has inherent limitations because it is an idealization of the system it is designed to represent. The predictions that the model makes are not always indicative of how experimental subjects will perform in real-life circumstances, or of individual human variance of muscle properties. This model worked under the assumption that the plantar flexor muscles were maximally activated for all joint configurations. It might not be possible for all experimental subjects to reach maximal activation of plantar flexor muscles at all joint configurations. This muscle model was validated; however, it is still feasible that the model had inappropriate parameters. This could be explained as one error affecting a parameter was compensated for by another error in a different parameter to still produce the expected, validated model output.

6.5.2 Experimental Limitations

The experimental protocol assumed that every subject was making maximum efforts for every joint configuration tested. Subjects were instructed to push as hard as they could for every effort, although fatigue potentially affected a subject's ability to produce maximum effort. This was accounted for by randomizing what order knee angle each subject tested in while also randomizing the order of ankle joint angles. This study also used the ankle-joint angle movement arm relationship from Grieve et al. (1978) and generalized it to the subjects of the study. This may not be an entirely accurate description of the ankle joint for every subject, but if the ankle-joint angle moment arm relationship captures the general pattern then the expressed section of the force-length curve can be accurately determined (Winter and Challis, 2008).

6.6 Future Studies

The findings in this study provide a good starting place for future research examining the adaptive potential of the force-length properties in skeletal muscle. The experimental analysis in this study could be replicated with a larger population that contains male and female players at the college level. It would also be useful to conduct a study comparing frequency of expression of the plateau region of the force-length curve of the gastrocnemius between high-level players versus younger players in high school or below. A longitudinal study could be appropriate to understand how muscle architecture changes over a lifetime, and whether sport-specific training would cause the number of sarcomeres in series to change to become advantageous for that sport.

6.7 Conclusion

The analysis, both the model based and experimental, assumed that the expressed section occurred due to in the number of sarcomeres in series, but other changes in muscle and joint architecture could have caused these changes. For example, an unusual ankle-joint angle moment arm relationship or ratio of fiber optimum length to tendon slack length could change the expressed section of the force-length curve. Analysis by Winter and Challis (2010) indicate that a change in the number of sarcomeres in series is the most likely candidate. Therefore, this study indicates that trained female Division I ice hockey players demonstrated different properties of their gastrocnemius force-length curve *in vivo*, likely reflecting a change in the number of sarcomeres in series in that muscle compared with non-specifically trained subjects.

Appendix A

Consent Form

CONSENT FOR RESEARCH
The Pennsylvania State University

Title of Project: A Study of the Intrinsic Force-Length Muscle Properties of the Gastrocnemius in Ice Hockey Players

Principal Investigator: Cameron Leonard

Address: 29G Rec Hall, University Park, PA 16802

Telephone Number: (919) 609-1489

Faculty Advisor: John Challis, PhD

Faculty Advisor Telephone Number: 814-863-3675

We are asking you to be in a research study. This form gives you information about the research.

Whether or not you take part is up to you. You can choose not to take part. You can agree to take part and later change your mind. Your decision will not be held against you and there will be no penalty or loss of benefits to which you are entitled.

Please ask questions about anything that is unclear to you and take your time to make your choice.

1. Why is this research study being done?

This research is being done to gain a greater understanding of the adaptive potential of the force-length properties of muscle in different situations.

2. What will happen in this research study?

We will ask you to come to the Biomechanics Lab located in Rec Hall for data collection. You will be asked to warm up in any preferred method and you will be given access to a treadmill, stationary bike, or an area to perform dynamic stretches. During this warm-up period you will be reminded of the study protocol and potential risks and then you will be asked if you still want to participate in the study. If you still wish to continue in the study you will provide written consent at this time.

We will then ask that you be seated and strapped in to the Biodex machine. The Biodex will be set at specific joint angles for the knee and ankle. The test will consist of maximum effort plantarflexion force at six different ankle joint angles over three positions of the knee, so eighteen total trials. Each trial will consist of two efforts, and the effort generating the highest force will be taken as the maximum for that trial. Between every effort you will have about a minute to rest, look at your phone, or talk with the investigator. Secondary measurements will be taken during some of these rest periods. The secondary measurements include shank length, ankle circumference, knee circumference, maximum calf circumference, and calcaneus thickness.

3. What are the risks and possible discomforts from being in this research study?

There is a risk of slight discomfort while performing maximum isometric contraction in the Biodex. Additionally, there is a risk of slight muscle fatigue or soreness the next day. Performing physical activity involves some risk of injury, however the tasks you complete here will not be more dangerous than typical activities you are already completing, and injuries are therefore not expected. There is a risk of loss of confidentiality if your information or your identity is obtained by someone other than the investigators, but precautions will be taken to prevent this from happening. The confidentiality of your electronic data created by you or by the researchers will be maintained as required by applicable law and to the degree permitted by the technology used. Absolute confidentiality cannot be guaranteed.

4. What are the possible benefits from being in this research study?
4a. What are the possible benefits to others?

By participating in this study, you will help us to understand if the force-length relationship of the gastrocnemius can be adaptive or present differently from the normalized relationship due to immobilization of the ankle joint during high-level sport activity.

5. How long will you take part in this research study?

If you agree to continue in this research, it will take you between one to two (1-2) hours to complete during one (1) study visit.

6. How will your privacy and confidentiality be protected if you decide to take part in this research study?
6a. What happens to the information collected for the research?

Efforts will be made to limit the use and sharing of your personal research information to people who have a need to review this information. Reasonable efforts will be made to keep the personal information in your research record private. However, absolute confidentiality cannot be guaranteed.

- Your research records will be labeled with code number and will be kept in a password protected file.

In the event of any publication or presentation resulting from the research, no personally identifiable information will be shared.

We will do our best to keep your participation in this research study confidential to the extent permitted by law. However, it is possible that other people may find out about your participation in this research study. For example, the following people/groups may check and copy records about this research.

- The Office for Human Research Protections in the U. S. Department of Health and Human Services
- The Institutional Review Board (a committee that reviews and approves research studies) and Penn State's Office for Research Protections.

6b. What will happen to my research information and/or samples after the study is completed?

We may use your research information for future research studies and your research information may be published in a scientific journal. Future research may be similar to this study or completely different. Before we use or share your information or samples we will remove any information that shows your identity.

7. What are the costs of taking part in this research study?

7a. What happens if you are injured as a result of taking part in this research study?

It is possible that you could experience complications or injuries as a result of being in this research study. If you experience a side effect or injury and emergency medical treatment is required, seek treatment immediately at any medical facility. If you experience a side effect or injury and you believe that emergency treatment is not necessary, you should contact the principal investigator listed on the first page of this consent form as soon as possible. You should also let any health care provider who treats you know that you are in a research study.

In the unlikely event you become injured as a result of your participation in this study, medical care is available. It is the policy of this institution to provide neither financial compensation nor free medical treatment for research-related injury. By agreeing to participate in this study, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

8. Will you be paid or receive credit to take part in this research study?

You will not receive any payment or compensation for being in this research study.

9. What are your rights if you take part in this research study?

Taking part in this research study is voluntary.

- You do not have to be in this research.
- If you choose to be in this research, you have the right to stop at any time.
- If you decide not to be in this research or if you decide to stop later, there will be no penalty or loss of benefits to which you are entitled.

If you decide to withdraw for any reason, you will have the option to request your data be destroyed. If you do not request your data is destroyed, it may be used in future analyses.

The person in charge of the research study or the sponsor can remove you from the research study without your approval. Possible reasons for removal include having pain the lower limb in the past six weeks.

10. If you have questions or concerns about this research study, whom should you call?

Please call the head of the research study (principal investigator), Cameron Leonard (919) 609-1489 if you:

- Have questions, complaints, or concerns about the research, including questions about compensation.
- Believe you may have been harmed by being in the research study.

You may also contact the Office for Research Protections at (814) 865-1775, IRB-ORP@psu.edu if you:

- Have questions regarding your rights as a person in a research study.
- Have concerns, complaints, or general questions about the research.
- You may also call this number if you cannot reach the research team or wish to offer input or to talk to someone else about any concerns related to the research.

INFORMED CONSENT TO TAKE PART IN RESEARCH

If you choose to participate in this research study, please sign your legal name on the line below.

____

Print name

____ Date: ________________

Signature of participant

____ Date: ________________

Signature of PI

Appendix B

Ankle Range of Motion with No Shoes, in Sneakers, and in Ice Skates

Condition	Maximum Dorsiflexion	Maximum Plantarflexion	Range of Motion
No Shoes			77°
Sneakers			70°
In Skate Boot			15°

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ACADEMIC VITA

Cameron Leonard

Education

The Pennsylvania State University, University Park, PA — *Fall 2017 – Spring 2022*

Bachelor of Science in Biology and Neuropsychology with Honors in Kinesiology

Cumulative GPA [redacted] | Major related GPA [redacted]

Academic Experience

EmergeOrtho in North Carolina — *May 2019 – August 2019*

Shadowing Intern

- Attended 100+ surgeries at an outpatient facility as a student observer
- Shadowed Dr. Wilson, MD, joseph.wilson@emergeortho.com in patient meetings three days a week at the clinic
- Improved interpersonal skills with patients, created rapport with Dr. Wilson and staff, and widened understanding of the demands of a career in medicine

Penn State Schreyer's Honors College — *Fall 2017 – Spring 2022*

Honors Scholar

- Fulfilled 35 credits of honors-level courses
- Engaged with the community and alumni through events led by Schreyer's Honors College
- Completed an individual thesis in the discipline of kinesiology

Independent Research Study — *Fall 2021 – Spring 2022*

Principal Investigator

- Designed a scientific study to examine adaptive potential of the force-length property of skeletal muscle
- Completed CITI certification to be qualified to work with human subjects and gained approval of study design from the Office of Research Protection
- Worked closely with a faculty advisor, John Challis jhc10@psu.edu, throughout entire thesis
- Conducted in-person data collection with twelve subjects in the Biomechanics Lab at Penn State University
- Submitted a 70+ page thesis with study findings to the Schreyer's Honors College committee.

Work Experience

State Athletics — *Summer 2017 – Spring 2022*

nt Athlete

- Attended practices, workouts, meetings, and games 40+ hours per week for five years
- Built leadership skills and improved communication by being in a team setting with teammates and staff members
- Represented Penn State while traveling to away competitions during the season
- Interacted with fans at multiple post-game skates and autograph signings

Moe's Southwest Grill — *June 2020 – September 2020*

Crew Member

- Served customers on the line, helped with food prep, ensured our restaurant location was always clean
- Completed mobile orders and responded to customer service concerns

Penn State University Hockey Camp — *Summers of 2017, 2018, 2021*

Camp Counselor

- Responsible for the safety and well-being of 30 children between the ages of 14-16
- Led multiple activities throughout the day both on the ice and off the ice
- Provided 24-hour supervision