# OPTIMIZED ANTHROPOMETRIC MODELLING OF THE FRONT SQUAT

by

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# ABSTRACT

The primary purpose of this thesis was to understand the relationship between the variation in athlete segment lengths (trunk, thigh, shank) and front squat depth as represented by maximum thigh segment rotation angle within the recommended guidelines. A validated segmental anthropometric model was used to simulate the effects of progressively altering thigh and trunk lengths on front squat depth. Both the thigh and trunk lengths were independently progressed through +/- 3 standard deviations, using the anthropometry collected from 41 athletes. This was done for simulated subjects of short (1.65 m for male and 1.55 m for females), average (1.82 m for male and 1.70 m for female), and tall (2.01 m for male and 1.87 m for females) statures. As thigh length increased, the ability to perform a full front squat (to a thigh depth of 180 degrees relative to the right horizontal) decreased. Conversely, as trunk length decreased, the ability to perform a full front squat decreased. The model was modified to progressively alter the thigh-to-trunk ratio from 0.8 to 1.2 for individuals of short, average and tall statures. Effects were similar for all heights for both males and females. Individuals with a thigh-to-trunk ratio above 1 were simulated to not be able to achieve a full front squat. This effect was greater in tall individuals, followed by average and then short. The ankle flexibility measured from the 41 athletes was run in simulations to determine its effects on front squat depth. For 25 of the athletes, the ankle flexibility did not allow their knees to pass the vertical plane of the toes. Flexibility constraints were removed from the model and the knees were moved to the vertical plane of the toes, 5 cm past, and 10 cm past. When the knees were allowed to move to the vertical projection of the toes, 8 athletes could not achieve a full front squat. When the knees were allowed to move 5 cm past the vertical projection of the toes, all athletes were predicted to be able to achieve a full front squat. When ankle flexibility was factored into the model, the results predicted that 16 athletes could not achieve a full front squat. The effects of ankle flexibility on front squat depth appeared to be influenced by the thigh-to-trunk ratio. Of the eight participants predicted not to be able to achieve a full front squat when the knees were allowed to reach the vertical projection of the toes, five had the largest thigh-to-trunk ratios. Athletes with a thigh-to-trunk ratio of 1 or greater may physically not be able to complete a full front squat according to the NSCA guidelines. It is however, more likely that the thigh-to-trunk ratio, which may limit the ability to achieve a full front squat, is significantly less than 1 when a trunk angle greater than 60 degrees is used. Furthermore, anterior knee translation initiated through rotation of the shank appears to be a strategy to maintain equilibrium at the end ranges of the front squat movement. It appears plausible that horizontal knee motion up to 5 cm past the vertical projection of the toes may allow athletes with large thigh-to-trunk ratios to reach full front squat depth and perhaps reduce loading on the low back. Additionally, ankle inflexibility may limit front squat depth.

# LIST OF ABBREVIATIONS USED

**BOS:** Base of Support

**COM :** Center of Mass

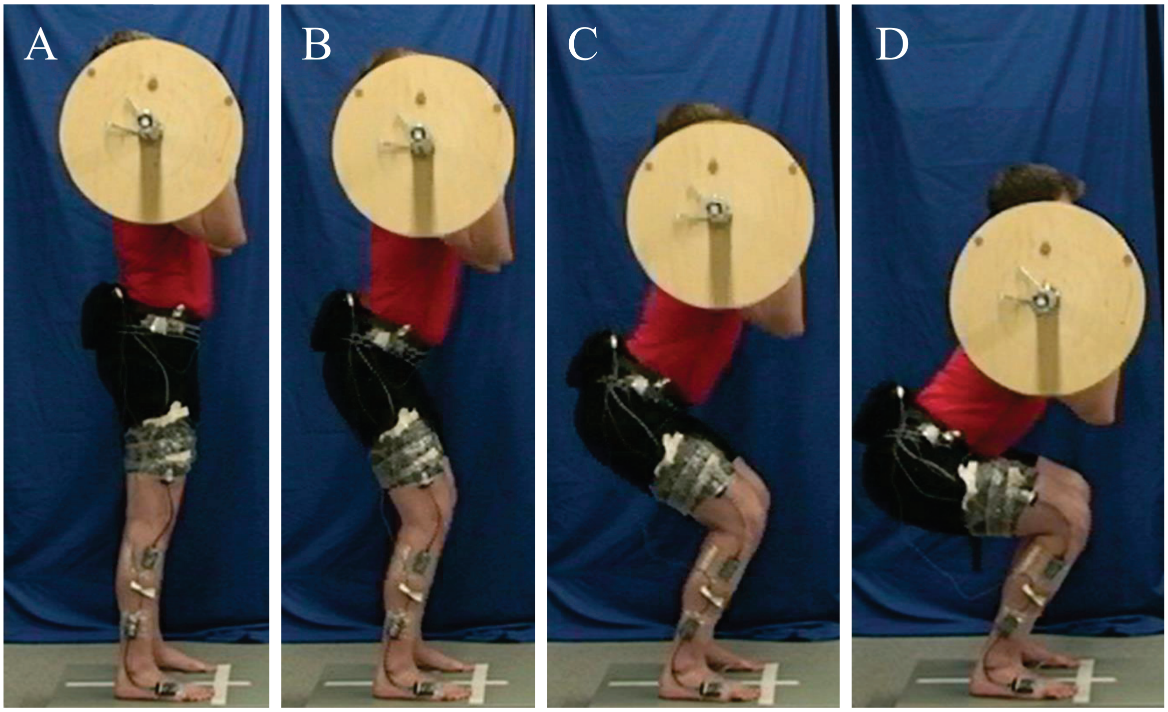
**NSCA:** National Strength and Conditioning Association

# ACKNOWLEDGEMENT

I would like to acknowledge my supervisors Dr. John Kozey and Dr. Sasho McKenzie, as well as my friends and family for their support over these past few years.

## 1. Introduction

The front squat is described by the National Strength and Conditioning Association (NSCA) as a multi-joint lower body exercise. The lift begins by approaching the bar anteriorly at chest level. The bar is grasped with a pronated grip at slightly wider then shoulder width (Graham, 2002). The arms are rotated so that the bar rests on the anterior deltoids and clavicle and the elbows are lifted forward to stabilize the bar (Figure 1).



Front Squat

**Figure 1:** Movement sequence of the front squat lift. (A): Starting position for the front squat. (B): Initiation of the movement. (C): Halfway of the decent phase of the front squat. (D): Bottom position of the front squat.

The weight now rests on the person and they are able to begin the vertical movement of the bar (Graham, 2002). The movement is initiated by a controlled flexion of the hips, knees, and ankles. This controlled motion makes this lift particularly effective when focusing on training the gluteus maximus, quadriceps and hamstring (Graham, 2002). The improvements in the strength of these muscles has been related to a greater resistance to athletic related injuries (Jonhagen, et al. 1994), development of sprinting speed (Blazevich, 2000), and improvements in jumping height (Wisløff, Helgerud, and Hoff, 1998). These outcomes of the front squat training make it a valuable tool for strength and conditioning coaches, but perhaps more relevant; the front squat is commonly used as an ancillary exercise for those athletes that incorporate Olympic lifting into their training.

### 1.2.1 Olympic Lifting

Olympic lifting is an Olympic event, which is comprised of two main lifts, the snatch and the clean and jerk. Training programs incorporating Olympic lifts have been shown to increase sprint speed and vertical jump height. (Canavan, Garrett and Armstrong, 1996, Hoffman, Cooper, Wendell, and Kang, 2004). As such, strength and conditioning coaches from the National Football League (Ebben, 2001), National Basketball League (Ebben, 2003), the National Hockey League (Ebben, 2004), and as much as 85% of collegiate strength and conditioning coaches use the Olympic lifts with their athletes (Durell, 2003). The widespread use of the Olympic lifts in athletic training has subsequently increased the number of athletes from a variety of sports incorporating the front squat into their training programs.

### 1.2.2 The Clean and Jerk and the Front Squat

The most popular of the Olympic lifts is the clean and jerk, which requires the athlete to lift a fixed weight from the floor, thrusting and pulling the bar off the ground vertically and transitioning into a bottom of front squat position (Figure 1D), in order to catch the weight on the front of the body. This is followed by the ascent phase of a front squat in which the lifter rises to a full upright position with the bar still being held on top of the clavicle. The lift is completed with extension of the shoulders and elbows in order to hold the bar overhead. The front squat lift is a key movement pattern within the clean and jerk.

Due to the popularity of the Olympic lifts with strength coaches, the integration of the front squat as a training exercise is common. In its 15-week introductory program to Olympic lifting for collegiate athletes, the NSCA includes the front squat as the predominant exercise for both strength development and technical base for progression in the clean and jerk (Cissik, 1999). The front squat is such an integral component of the clean and jerk that percentage based strength guidelines are widely used when comparing front squat to clean and jerk performance (Cissik, 1999). These guidelines operate on the assumption that progress in the clean and jerk can be limited by performance in the front squat.

The front squat is a versatile lift considering that it can help athletes build a foundation for the Olympic lifts and as well as be used as a standalone strength exercise. According to Durell (2003), the primary goal of strength and conditioning coaches in their application and instruction of training protocols is injury prevention. As a result, in either of the front squat uses, the NSCA recommends adhering to the following guidelines. The knees must not move anterior to the toes so as to avoid excessive shear forces at the knee, the back must remain flat (no relative movement of the vertebrae while the pelvis and trunk move as one unit), the heels must stay in contact with the ground during the entire lift, and the long axis of the thighs should reach parallel with the floor at the midpoint of the movement. If an athlete cannot complete the lift as prescribed, it may lead to undesired specificity in training, loss of transference to more advanced lifts, and an increased likelihood of injury.

These guidelines were probably developed based on the traditional use of the front squat with Olympic lifters, who are known to have specific anthropometrics. Most notably, competitive Olympic lifters have shorter limbs in relation to their torsos (Devi, 2006). Athletes from sports which implement Olympic lifting programs, and therefore, perform a large volume of front squatting, may not have the same anthropometry for which the front squat guidelines where initially developed. Limb segment lengths in relation to torso length may influence factors related to front squatting which are not directly related to the current guidelines set by the NSCA.

### 1.2.3 Considerations Beyond the Guidelines

If only the guidelines were considered there may appear to be no issue with athletes possessing any segment proportions completing the front squat. However, the successful completion of the front squat, according to the guidelines, is also bound by other factors. Muscle strength, flexibility, balance, and coordination of limbs have been shown to influence the ability to achieve an optimal squat position (Comfort and Kasim, 2007, Fry et al., 1988, Kasuyama, Sakamoto, and Nakazawa, 2009). Of the additional factors, perhaps the most relevant when considering an athlete’s ability to execute a front squat according to the guidelines are ankle flexibility, minimum trunk angle, and the overriding consideration that the center of mass (COM) of the athlete and weighted bar must remain inside the base of support (BOS).

### 1.2.4 Base of Support

For a given individual performing a front squat, the anterior-posterior range of the BOS is dictated by foot length, while the anterior-posterior coordinate of the system COM is dictated by the shank, thigh, and trunk segment angles. During the decent phase, the motion of the shank and trunk translate the COM anteriorly, while motion of the thigh translates it posteriorly. Effectively, the shank and trunk rotation must balance the effect of the thigh rotation on the anterior-posterior location of the COM. The coordination of these three limb segments angles, during the front squat, must be such that the vertical projection of the COM remains within the BOS while the athlete also adheres to the aforementioned NSCA guidelines.

Research done by Pai and Patton (1997) showed that anterior-posterior velocity of the COM is important in determining the ability to maintain equilibrium under dynamic conditions by using an inverted pendulum model. They showed that given a static scenario (zero anterior-posterior velocity of the COM), the anterior-posterior limits of the BOS are indeed dictated by foot length, but with increasing COM velocity, these limits begin to shrink. Applying their finding to the front squat, the limits of the BOS during the front squat are likely less than that of the length of the foot. The amount of horizontal velocity of the COM may limit the amount of limb rotation during the descent in order to prevent falling. While the limit of the BOS may be less than the length of the foot, the displacement of the COM, and therefore velocity, is dictated by the simultaneous rotations of the trunk, thigh and shank. Of which, the trunk and shank may be limited due to certain physical considerations.

### 1.2.5 Trunk Rotation

Excessive trunk flexion (negative segment rotation) during the descent phase will result in a large portion of the weight lifted being supported by the hands, and subsequently the relatively weaker muscles of the arms, as opposed to being rested on the clavicle and shoulders (Figure 2).

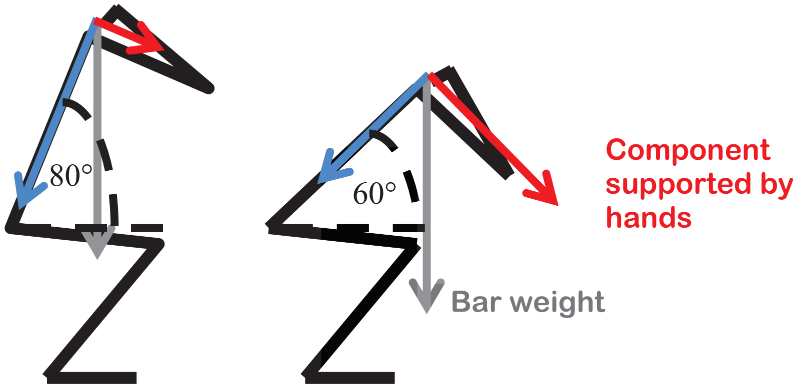


**Figure 2:** Effect of trunk angle on the normal and tangential components of the bar weight relative to the trunk.

As the trunk rotates anteriorly, the hands must support a greater proportion of the bar weight (Figure 2). At a trunk angle of 60 degrees (from the right horizontal), the hand would be supporting a significantly greater proportion of barbell weight than if the trunk was at an angle of 80 degrees. During a front squat, excessive anterior trunk rotation would increase the component of bar weight supported by the hands. This would cause a problem because the magnitude of the load lifted for strength training purposes is typically much larger than the amount of force that can be supported by the arm musculature. Anterior trunk rotation is therefore limited by the ability of the arms to prevent the bar from moving off the clavicle. With this consideration, the trunk is no longer unrestricted in its ability to redistribute the COM in opposition to thigh rotation. The NSCA guidelines recommend that the torso remain as vertical as possible (Graham, 2002). As a counter balance, the trunk must deviate away from the vertical position in order for the vertical projection of the COM to remain inside the BOS. A relatively longer trunk segment would more beneficially offset thigh rotation at an equivalent absolute trunk angle, which would allow for a more vertical torso.

### 1.2.6 Ankle Flexibility

Of further significant importance, the rotation of the shank segment during the descent phase also helps to offset the rotation of the thigh segment during the front squat. Since the heels must remain on the ground at all times, the ankle joint angle is completely dependent upon the absolute angle of the shank. The NSCA guidelines limit the amount of anterior translation of the knee joint, which subsequently limits the amount of shank rotation. As such, the shank is also restricted in its ability to redistribute the COM in opposition to thigh rotation. Due to its balancing effect, ankle joint flexibility has been shown to be predictive of the final deep squat posture (Fry et al., 1988, Kasuyama, Sakamoto, and Nakazawa, 2009).

This guideline comes with the assumption that an athlete possesses sufficient ankle flexibility to allow for the knees to translate to the vertical plane of the toes. It is common practice for an athlete without sufficient ankle flexibility to place plates under the heels, rotating the foot segment without changing the ankle angle, which effectively simulates additional shank rotation (Figure 3) (Larson, Martin, and Weir, 1991). This modification appears to follow the guidelines set by the NSCA as long as the location of the knee joint does not move past the vertical plane of the toes. It is important to consider, that in the development and preparation for the Olympic lifts, a plate placed under the heels is not recommended during a clean and jerk. This may not be an optimal strategy when using the front squat as an ancillary lift for the Olympic lifts.

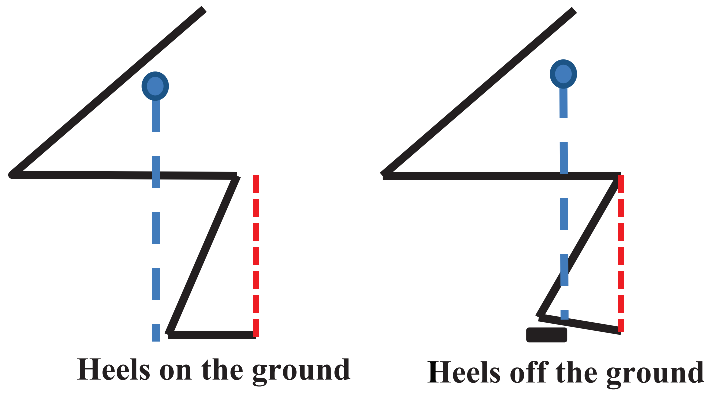


**Figure 3:** Example of the effect of having a plate under the heels on the location of the knee and total body COM.

### 1.2.7 Interaction of the Guidelines, Limitations, Degrees of Freedom, and Segment Lengths

The front squat motion can be defined by three degrees of freedom: rotation of the trunk, thigh and shank. These segment rotations sequentially move the athlete from position A to position D as shown in Figure 1. The sequencing of these rotations dictates the movement of the COM relative to the BOS. The sequence and magnitude of segment rotations is bound by the necessity that the COM remains within the BOS. As such, as the COM approaches the edge of the BOS, the lifter must alter the rotation of these three limbs as to allow for the preservation of total body equilibrium. The rotation of these segments have known effects, positive thigh rotation translates the COM posteriorly, while both anterior trunk and shank rotation translate the COM anteriorly. As a result, the ability to coordinate the limbs to preserve the total body equilibrium is finite and limited. As previously discussed, anterior rotation of the trunk is limited by the ability of the upper body musculature to support the normal component of the weight of the bar in a tangential plane to the trunk, while anterior shank rotation is limited by the NSCA knee translation guideline or, depending on the athlete, maybe even more so by ankle flexibility. The ability to anteriorly shift the COM appears to be an important consideration in the front squat movement. As such, it is possible that the posterior translation of the system COM, due to posterior thigh rotation, may bring the COM to the posterior edge of the BOS before the thighs rotate enough to be considered parallel to the ground. In the case where the COM would translate past the posterior edge of the BOS when the thigh is rotated to parallel, and the trunk and shank have reached their maximal boundaries, the athlete would be forced to limit the amount of posterior thigh rotation in order to prevent falling or taking a step backward.

For a given athlete, the ability to rotate the thighs to parallel with the ground is also influenced by the lengths of the trunk and thigh segments. Consider an athlete in the bottom of the squat position in which the thighs are parallel to the ground and the system COM is at the posterior edge of the BOS (heels). If the athlete’s thigh segment “grew” longer, the athlete would need to increase anterior trunk and/or shank rotation in order to counter-balance the posterior shift in the COM. If the trunk and shank segments had already reached their limit of anterior rotation, then the athlete would need to decrease the thigh angle to maintain the vertical projection of the COM within the BOS. Similar adjustments would need to be made if the trunk segment was reduced in length.

The guidelines for performing the front squat were probably developed based on observations of experts (such as Olympic weightlifters) performing the movement. Given the role that trunk, thigh, and shank rotations play in the distribution of the system COM during the front squat, these experts may have been selected based on their limb segment biases. Specifically, these experts may have different trunk and thigh segment length proportion relative to the various athletic populations (e.g. basketball) now incorporating the front squat into their training programs. It has been shown that tall subjects with short trunks have a more difficult time maintaining heel contact during a front squat (Fry et al., 1988), which suggests that there is a relationship between segmental lengths and the ability to perform a front squat according to the NSCA guidelines. Therefore, the primary purpose of this thesis was to understand the relationship between the variation in athlete segment lengths (trunk, thigh, shank) and front squat depth as represented by the maximum thigh angle (see Figure 1D) within the recommended guidelines. A secondary objective was to investigate the influence of ankle flexibility on the above relationship.

### 1.3 Hypothesis

It was hypothesized that a shorter thigh length relative to the trunk length will facilitate the ability to rotate the thigh to parallel with the ground while maintaining the vertical projection of the system COM within the BOS. It was further hypothesized that ankle flexibility would limit some athletes from achieving a full front squat depth.

## 2. Methods

### 2.1.1 Experimental Approach

The study was designed to help identify the effects of varying limb lengths on the rotation of the thigh and maintenance of bodily equilibrium. Kinematic data from participants performing front squats was used to validate a computer simulation of the front squat motion using the unique anthropometry of each participant. A second computer model was then developed to test the depth of the front squat achievable when using varying limb length combinations from a sample of previously collected anthropometric characteristics of 41 athletes.

### 2.1.2 Participants

Four varsity athletes (two male, two female) volunteered for the validation portion of the study. The participant's body weight, shank, thigh and trunk lengths were measured and are shown in Table 1. All participants had experience with free weight training, and specifically with Olympic lifting. Before data collection, participants were informed of the procedures and requirements of the study and provided informed written consent. Upon arrival, participants were asked to change into athletic clothing. A pair of spandex shorts was provided if they did not bring appropriate clothing. The study was approved by the Dalhousie University Research Ethics Board.

**Table 1:** Anthropometric characteristics of study participants.

| Participant | Gender | Mass (kg) | Height (m) | Shank (m) | Thigh (m) | Trunk (m) |
|---|---|---|---|---|---|---|
| **1** | F | 56.9 | 1.46 | 0.39 | 0.37 | 0.47 |
| **2** | F | 72.4 | 1.52 | 0.43 | 0.43 | 0.48 |
| **Mean** | | 64.6 | 1.49 | 0.41 | 0.4 | 0.47 |
| **3** | M | 72.1 | 1.58 | 0.4 | 0.41 | 0.5 |
| **4** | M | 93 | 1.68 | 0.43 | 0.41 | 0.56 |
| **Mean** | | 82.6 | 1.63 | 0.42 | 0.41 | 0.53 |

### 2.1.3 Data Collection

Each participant's relevent anthropometric characteristic were measured following Deleva's (1996) inertial segment parameter calculations (Appendix A). Anatomical landmarks were identified, palpated, and marked with a pen prior to measurement (Figure 4). A representation of the biomechanical model and the measured anthropometry is shown in Figure 4. A Harpenden anthropometer (Holtan Ltd., UK) was used to measure the limb lengths from the described segment endpoints to the nearest millimeter. Each segment was measured twice and a third time if measurements deviated by more than 4 mm. The average value of each measurement was used as the limb length. A sample of previously collected student athlete anthropometry (Appendix B) was also used in this experiment (Wallace, 2010). The data was collected using the same procedures as described in this study using the same instruments.

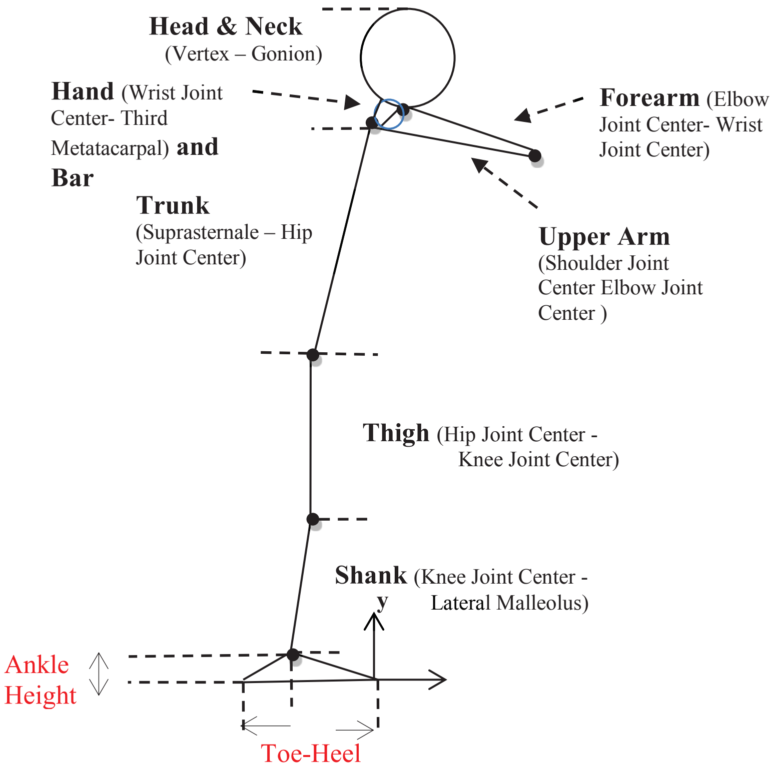


**Figure 4:** Segmental model of a front squat and associated limb length measures.

## 2.2 Squat Trials

### 2.2.1 Testing Protocol

Three uni-axis electrogoniometers (S700 Joint Angle ShapeSensor, Delsys Inc, Boston, MA) were fixed to the participants at the ankle, knee, and hip joints and secured using double sided tape and plastic wrap. The estimated sagittal plane joint center of rotation was aligned with the center marking of the goniometers to measure flexion/extension at each of the joints. Participants performed a warm up exercise by executing a front squat for 12 repetitions with an unloaded Olympic bar. The bar was a standard Olympic bar with a mass of 20 kg. Squat trials started with the bar only and progressed by 22.7 kg (11.4 kg per side) if the participants felt comfortable doing so.

Participants were asked to align their toes directly behind a line perpendicular to their feet marked on the ground. Participants then approached the bar, which rested on the ground and raised it to their shoulders using a clean style lift and rested the bar on their clavicles with a clean style grip. Trial recordings began when the participants indicated they were ready. The participants were asked to execute the squat without a pause at the bottom of the squat and follow miometric (muscle shortening) and pliometric (muscle lengthening) phases each lasting 2 s. The goal of which was to provide a stable and repeatable squatting motion. Participants were also instructed to squat as deep as they could while maintaining a straight low back (no relative motion between pelvis and spine). A 3 minute rest interval was given between each trial in order to allow for full recovery (Willardson, 2006). The squatting motion was videotaped using a digital camera (Sony HDV HDR-HC7 Handycam, Japan). Each video trial was reviewed to ensure that proper form (tempo, straight low back, etc.) was used. The camera was centered in the plane perpendicular to the front squat motion (sagittal). A plumb bob was used to align the center of the camera with the floor marking the participants used to align their toes. The camera recorded at 60 Hz and video was encoded using Dartfish™ (Dartfish 5.0, Fribourg, Switzerland). At the completion of a squat trial, participants gave verbal feedback on whether they believed they had achieved the lowest squat possible within the allotted guidelines. This feedback was weighed against video review of their execution. If the participant's confirmation of their deepest squat matched the necessary technical parameters, the squat trial was deemed appropriate and additional weight was added to the bar. Participants repeated the collection procedure until a second appropriately executed squat was recorded for a total of two well executed squats.

### 2.2.2 Data Collection

Each goniometer was manually calibrated using a mechanical goniometer and a 60 s trial pausing every 10 degrees over a range of 50-100 degrees for the hip, 50-140 degrees for the ankle and 50-180 degrees for the knee. These ranges were chosen to produce the greatest accuracy within the possible ranges achieved at each joint during the front squat. The calibration trials were performed twice for each goniometer and both sets of data were used in performing the calibration of the device. A 2nd degree polynomial was derived using the calibration information for each goniometer (see section 2.2.3). Each goniometer was connected into a Myomonitor® (IV Wireless Transmission and Datalogging System, Delsys Inc., Boston MA, USA) device worn by the participant with a waist belt, which sent the data to a wireless terminal connected to a computer. EMGAcquisition™ software (Delsys Inc., Boston MA, USA) was used to record the goniometer data at a sampling frequency of 1000 Hz.

### 2.2.3 Data Conditioning

The raw voltages recorded from the goniometers were converted to angles using the calibration curve developed for each goniometer. The generic form of the calibration equation is

$$\Theta_x = \mathbf{B_0 + B_1{*}volts + B_2{*}volts^2}, \qquad \mathbf{(1)}$$

where x represents the joint and $B_0$, $B_1$, and $B_2$ are the polynomial coefficients. The specific coefficients for each goniometer are presented in Table 2. The recorded angle-time data was filtered using a 4th order, zero-lag, low-pass Butterworth filter with a cut-off frequency of 10 Hz. In order to isolate the front squat motion, the raw angle information was “trimmed” in Matlab™ from the first detectable sign of movement until the angles had returned to starting values. In order to determine the initial starting joint angles the trial videos were analyzed in Dartfish™. Immediately prior to motion, the joint angles for the ankle, knee, and hip were measured using the angle tool. The raw angle data for each joint was set to the initial joint angle recorded from Dartfish™ and the goniometer data provided the changes from that point. Starting from the ground and moving proximally, joint angles were converted to segment angles for the shank, thigh, and trunk.

**Table 2:** Equation coefficients for the goniometer calibrations.

| | $B_0$ | $B_1$ | $B_2$ |
|---|---|---|---|
| **Ankle** | 156.34 | 44.25 | -1.33 |
| **Knee** | 163.88 | 34.26 | -1.08 |
| **Hip** | 186.59 | 28.35 | -1.87 |

### 2.2.4 Participant Squat Characteristics

The squat characteristics from the four participants are shown in Table 3. The average trunk, thigh, and shank angles at the lowest point in the front squat were 78 +/- 6.7, 156 +/- 8.2, and 59 +/- 5.4 degrees respectively. The average thigh-to-trunk ratio for the participants was 0.82.

**Table 3:** Minimum trunk and shank and maximum thigh angles achieved during the front squat movement and the thigh-to-trunk ratios for the four participants.

| Participant | Thigh:Trunk | Trial | Trunk (deg) | Thigh (deg) | Shank (deg) |
|---|---|---|---|---|---|
| 1 | 0.8 | 1 | 68 | 164 | 61 |
| | | 2 | 69 | 162 | 60 |
| 2 | 0.9 | 1 | 83 | 146 | 51 |
| | | 2 | 87 | 144 | 50 |
| 3 | 0.81 | 1 | 81 | 161 | 63 |
| | | 2 | 78 | 166 | 64 |
| 4 | 0.74 | 1 | 73 | 158 | 62 |
| | | 2 | 75 | 160 | 60 |
| **Mean** | **0.82** | | **78** | **156** | **59** |
| **STDEV** | **0.07** | | **6.7** | **8.2** | **5.4** |

Participant 1 completed four total squat trials, whereas participants 2, 3, and 4 completed 3. Only two trials were selected based on the guidelines described in Section 2.2.1.

### 2.3 Model Design of the Front Squat

A Matlab™ program was written to simulate the motion of a front squat. The model was designed to mimic the primary kinematic degrees of freedom during a front squat (shank, thigh, and trunk rotation) in a pliometric to miometric pattern. A two-dimensional representation of each participant was created using nine geometric segments (foot, shank, thigh, trunk, neck + head, upper arm, forearms, and bar + hand). Absolute segment angles (Figures 5 and 6), derived from the goniometer data as previously described, were used to build an angle-time representation of the front squat. The angles for the upper body were measured directly from the video using Dartfish at the starting position and assumed to be fixed for the duration of the motion. The computer model had three degrees of freedom represented by the absolute angles of the shank, thigh, and trunk. The line from the suprasternale (mid-point of sternum) straight down to the vertical coordinate of the hip joint center represented the trunk, which was modeled to move as a rigid unit. During the proper execution of a front squat, there should be very little relative motion between the pelvis and thorax to reduce the risk of back injury (Rippetoe and Kilgore, 2005). The position of the upper arm, forearm, and hand were constrained to maintain the position of the barbell, which rested across the clavicle. They were angled in such a way that the barbell was always 5 cm above the acromion process. The bar and associated weight was positioned at one-half the hand distance from the wrist joint to the third metacarpal.

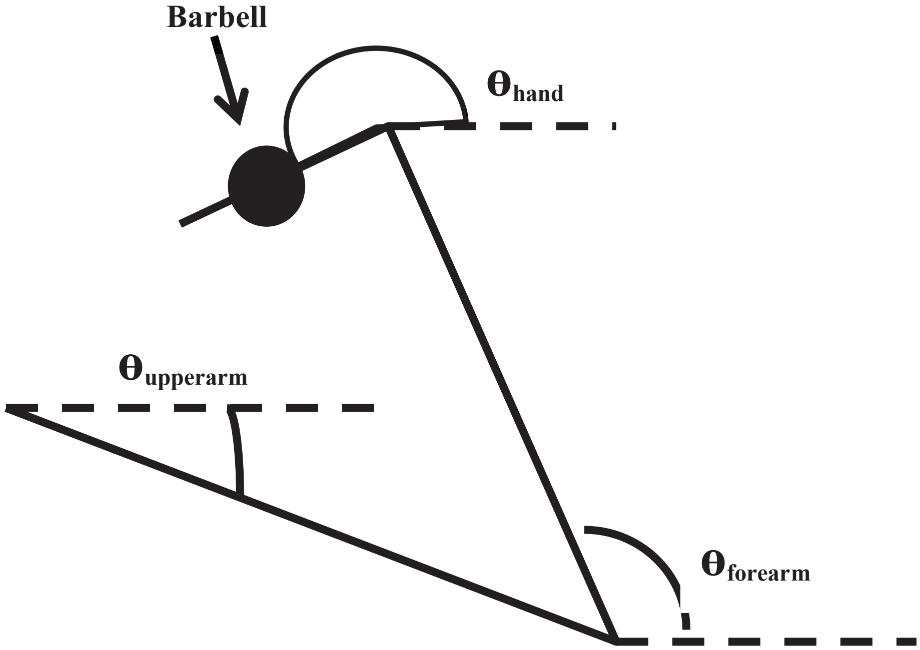


**Figure 5:** Absolute angle measurements of the upper extremities.

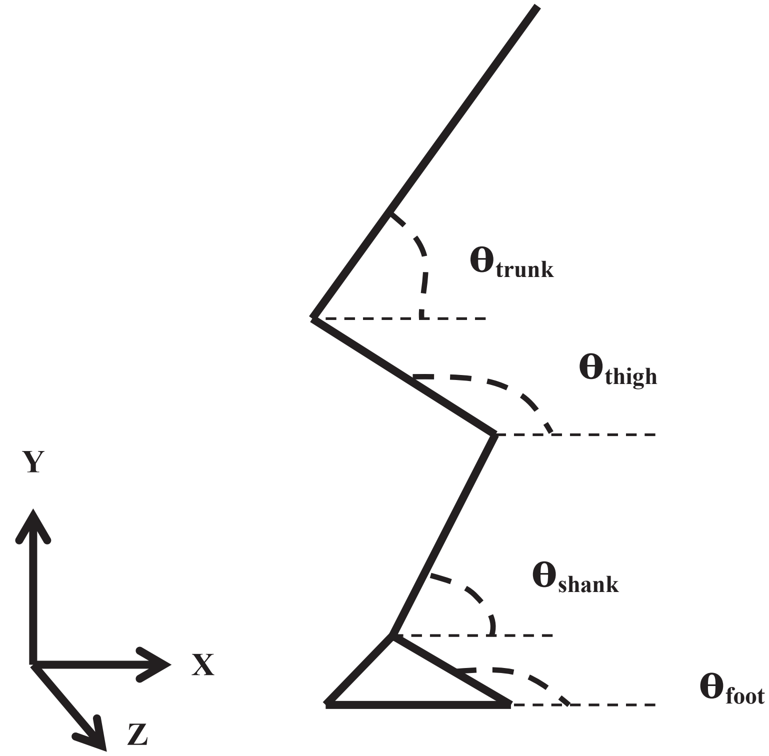


**Figure 6:** Absolute segment angle calculation for lower extremities and trunk.

### 2.3.1 Model Kinematics

Using the model described in the previous section, the front squat motion was described by the angular time series of the shank, thigh and trunk segments which when performed without stopping, can be described as a cyclical pattern. The angular displacement of each segment can be considered to follow a sinusoidal pattern recreated as a simple sine or cosine wave. Using the actual maximum and minimum joint angle recorded for a segment, a Fourier series was used to model the angular displacement of the segment over the time required to complete the front squat motion. Separate Fourier series were derived from the squat motions of each participant, creating individually matched sinusoidal patterns to closely match the actual squatting motion. In the first Fourier series, the value B is obtained using the following equation,

$$\mathbf{B}_x = (\Theta\_\mathbf{max}_x - \Theta\_\mathbf{min}_x)/2, \qquad \mathbf{(2)}$$

where x, $\Theta\_max_x$, and $\Theta\_min_x$ represent the joint, and the maximum and minimum joint angles for a given front squat. This formula determines half the magnitude of the range of motion for segment *x*. In order to create an angle-time series this range was then entered into a second series

$$\Theta(x,i) = (\Theta\_\mathbf{max}_x - \mathbf{B}_x) + \mathbf{B}_x * \mathbf{cos}(2 * \mathbf{pi} * (1/\mathbf{f}_x) * t_i), \qquad \mathbf{(3)}$$

where *i* is the index of the time value *t* at a given interval within the matching angle-time series for a joint during the front squatting motion; *f* is the frequency in hertz at which the overall front squatting motion is occurring determined by

$$f_x = 1/\mathbf{T}\ , \qquad \mathbf{(4)}$$

where T is the total time for the motion. When the variables shown in Figure 7 were entered into Equations 2 and 3, it was then possible to model a series of values on a cosine wave matching the amplitude, length and frequency of the original angular-time series as captured through the goniometers. By further manipulating Equation 3, we then calculated a matching angle for the entire squat time interval for the shank, thigh, and trunk (Figure 8).

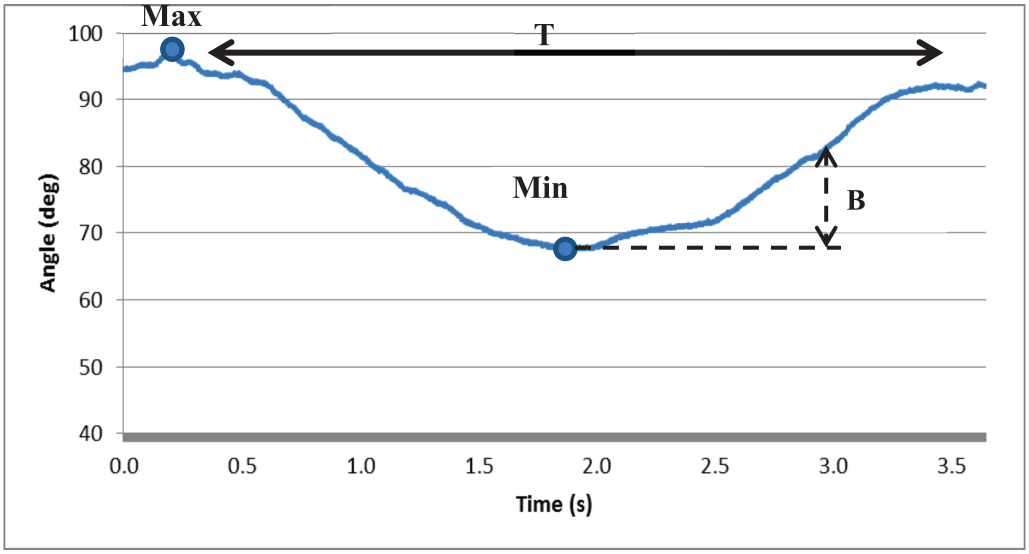


**Figure 7:** Time and amplitude variables recorded from actual front squatting motion used in the Fourier series.

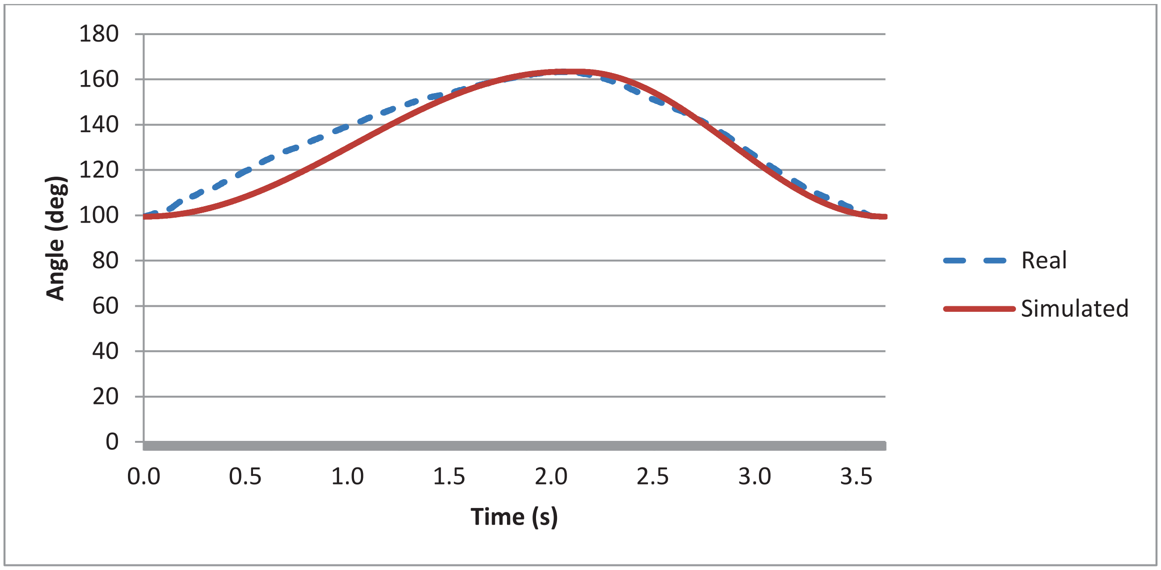


**Figure 8:** Fourier series matched to max and min for the thigh angle.

One of the main boundaries of the models prediction of whether the modelled motion was feasible was the issue of body equilibrium. Equilibrium was defined to have been maintained if the horizontal position of the COM remained between 0 and 90% of the distance from the toe to the heel. In order to isolate the relationship between anthropometry and the effects of body equilibrium on thigh rotation during the front squat, there must be minimal horizontal velocity of the COM, but not insignificantly so as to not represent a well-controlled lift. Pai and Patton (1997) showed that a backwards fall (loss of equilibrium) could be initiated before the horizontal position of the COM reaches the end (heel) of the BOS with very low horizontal velocities. Based on lab tests performed at St Francis Xavier University, 90% of the BOS was the most extreme squat position that participants could maintain without falling backwards while moving at minimal movement velocities (similar to a 2 s tempo squat). Therefore the 90% limit is in accordance with findings by Pai and Patton (1997).

### 2.3.2 Model Parameters

Subject specific anthropometric dimensions served as input into the model to determine segment lengths and mass centers. The inertial properties outlined by Zatsiorsky and Seluyanov with the adjustments suggested by De Leva (De Leva, 1996; Zatsiorsky, 2002) were used to define these properties for each segment. The specific segmental endpoints followed standard biomechanical definitions and are described in Appendix A and shown in Figure 4.

### 2.3.3 Model Optimization

Despite matching the amplitude, frequency and length of the original squat characteristics, the validity of the model, specifically the COM x coordinate, did not meet the requirements set out in the initial development of the model (further discussed in the next section). Due to the nature of the squat motion, the trunk, thigh, and shank segments may achieve their maximum position before the COM arrives at the ’bottom of squat’. For example, the shank may stop rotating about the ankle before the thigh and trunk angles reach their respective final positions (Figure 9). These differences created minor problems for the model in its initial form. To correct for this, a method was developed to simulate the limb coordination such that they reach their end positions at the proper time.

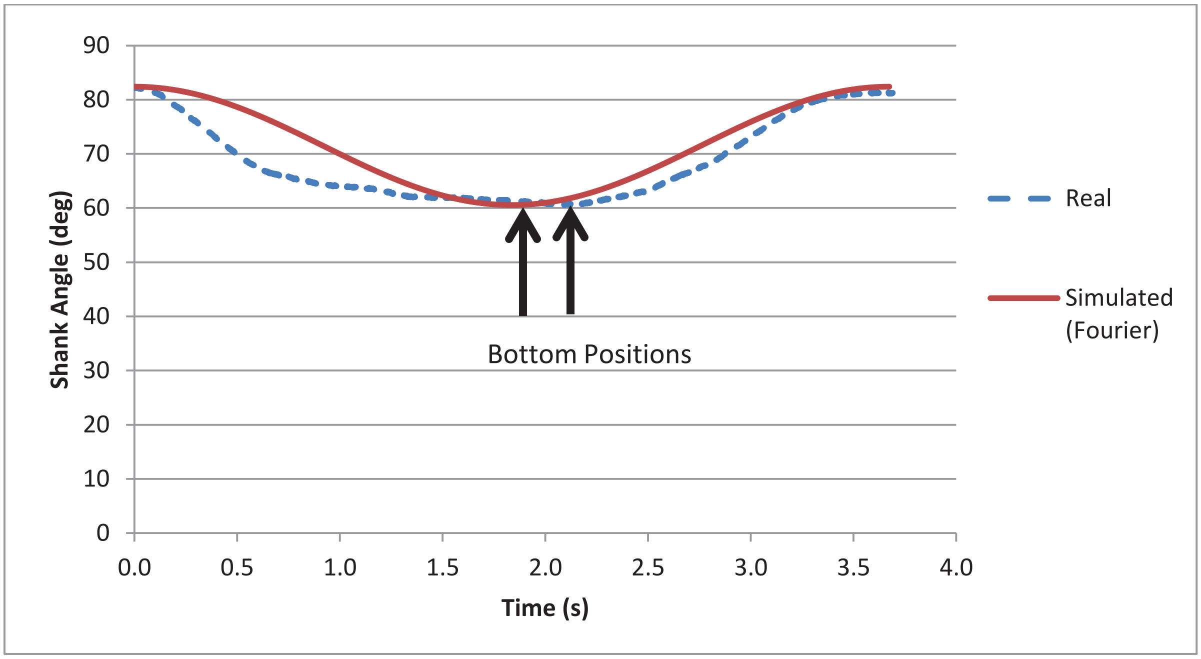


**Figure 9:** Difference in “bottom of squat” position with the actual shank motion and a simulated Fourier series.

In order to account for the phases of motion, the sinusoidal patterns were adjusted in the time domain so that the time to the maximum position of each joint (bottom position of each segment) matched the actual lowest point in the squatting motion. In order for this to be accomplished two new Fourier series needed to be created and their angle-time series precisely combined. The first Fourier series was designed to match the length of time required to reach the minimum angle. Using the parameters set in Equations 2 and 3, $f$ was changed such that

$$f_x = 1/(2 * t_{\min\Theta}), \tag{5}$$

where $t_{\min\Theta}$ is the time at the minimum angle for joint $x$. With the modified frequency this resulted in an angle-time series with the same amplitude as the actual squatting motion but with perfectly symmetrical pliometric and miometric phases, each of which matching the original time of the pliometric phase. The second Fourier series was designed to create a miometric phase which more closely mimicked the real motion. The frequency variable was once again changed,

$$f_x = 1/((2 * t_{\min\Theta} - T) * 2), \tag{6}$$

by subtracting the total time of the first series (Eq. 5) by the time of the original series (Eq.4) and doubling its length. When used in combination with Equations 2 and 3, this resulted in an angle-time series which created perfectly symmetrical pliometric and miometric phases; however, the length of time of each phase now corresponded to the miometric phase of the original motion. The angle-time series created using the new frequencies in Equations 5 and 6 were combined ($F_{new}$) in the following way,

$$F_{new} = [F_p(1:\min) : F_m(\min:\text{end})], \tag{7}$$

where the time series from the pliometric Fourier ($F_p$ calculated using Equations 2, 3, and 5), was taken from the first value until the minimum and then proceeded by the values from the miometric Fourier ($F_m$, calculated using Equations 2,3, and 6) which were taken from its minimum to the last value. This process created a new angle-time series which matched the real squatting motion in amplitude, length and frequency but now also in its pliometric and miometric phase timing. The net result of putting these two curves together is shown in Figure 10.

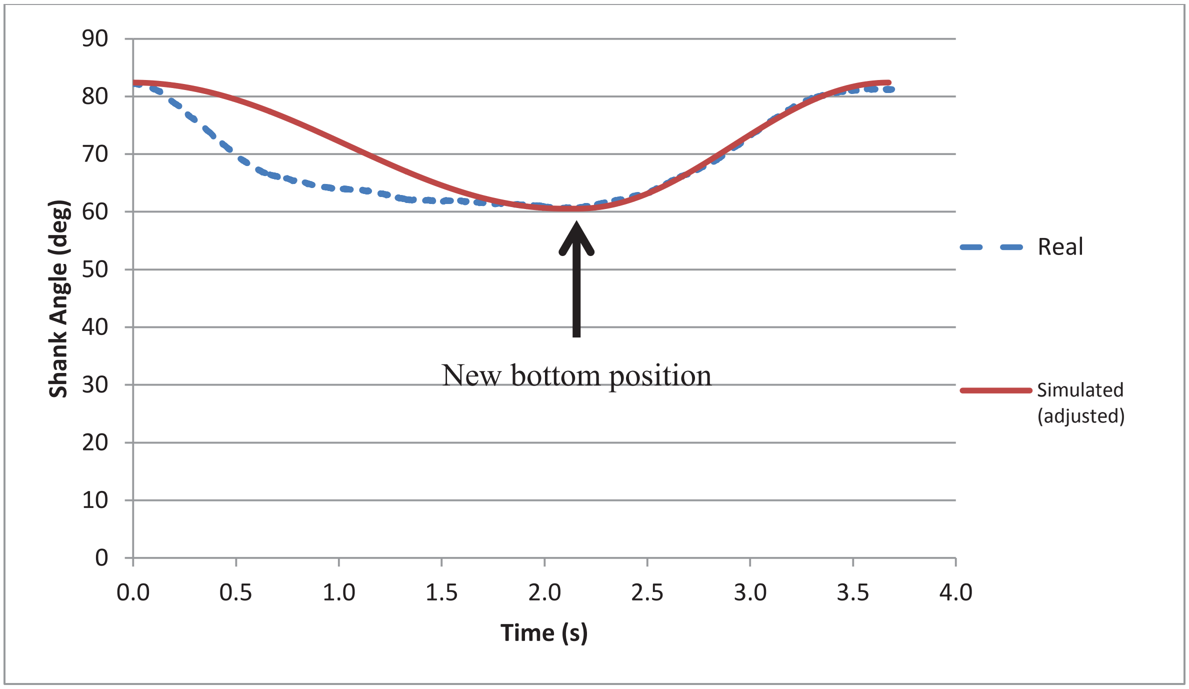


**Figure 10:** New bottom position with adjusted curves.

### 2.3.4 Bottom of Squat

The revised kinematic data and motion model was set to use the Powell optimization algorithm which yields a minimal root mean square (RMS) difference between the actual segment angle time series and the predicted Fourier series. In order to achieve the highest possible agreement between the Fourier series and actual squatting motion (minimal RMS difference) a pause value was added to the endpoint of the predicted segment motion to more accurately match the real motion. Adding a pause value to existing angle-time series required alterations to the Fourier series outlined in the previous section. When a pause value was added to the angle time series at the defined bottom position of the squat, this lengthened the angle time series to a value larger than the original squatting time. Naturally, the second half of the Fourier curve must be time adjusted in order to fit based on the pause duration (Figure 11).

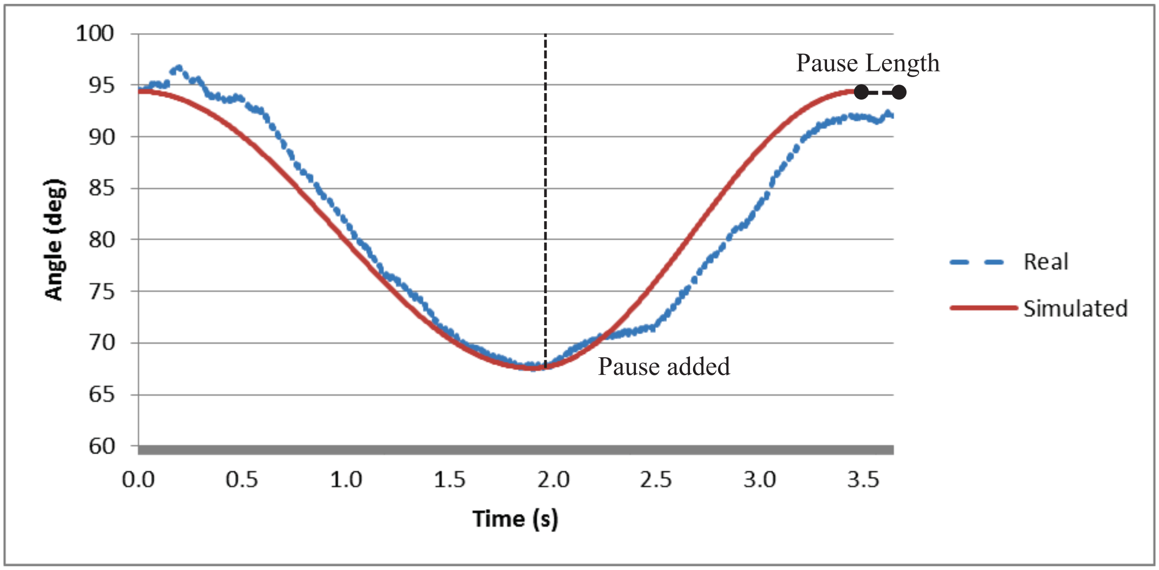


**Figure 11:** Time adjusted Fourier series cut in half and a pause value is added of optimized length.

This was accomplished by altering the frequency of the second half of the curve by the time length of the pause added. Equation 6 was modified to adjust for a pause value in the following way,

$$f_x = 1/((2*t_{\min\Theta} - \mathrm{T})*2 - \mathrm{P}_x), \tag{8}$$

where $P_x$ is the length of the pause value. When Equation 8 was used in place of Equation 6 this shortened the breadth of the miometric phase of the motion by the length of the pause which was added using the following modification to Equation 7,

$$\mathbf{F}_{\mathbf{new}} = [\mathbf{F}_{\mathbf{p}}(1:\min) : \Theta_{\min}(0:\mathrm{P}_x) : \mathbf{F}_{\mathbf{m}}(\min:\mathrm{end})], \tag{9}$$

where, $\Theta_{\min}$ is the minimum angle of the segment time series at which the pause will occur for a length of time that has been optimized to yield the lowest RMS between real and simulated motion. This allowed for the sequencing of the three segments to more accurately reflect the variation in how participants coordinated their limbs into the bottom of squat position. Figure 12 shows the pause adjusted Fourier series which has been optimized to yield the smallest RMS value.

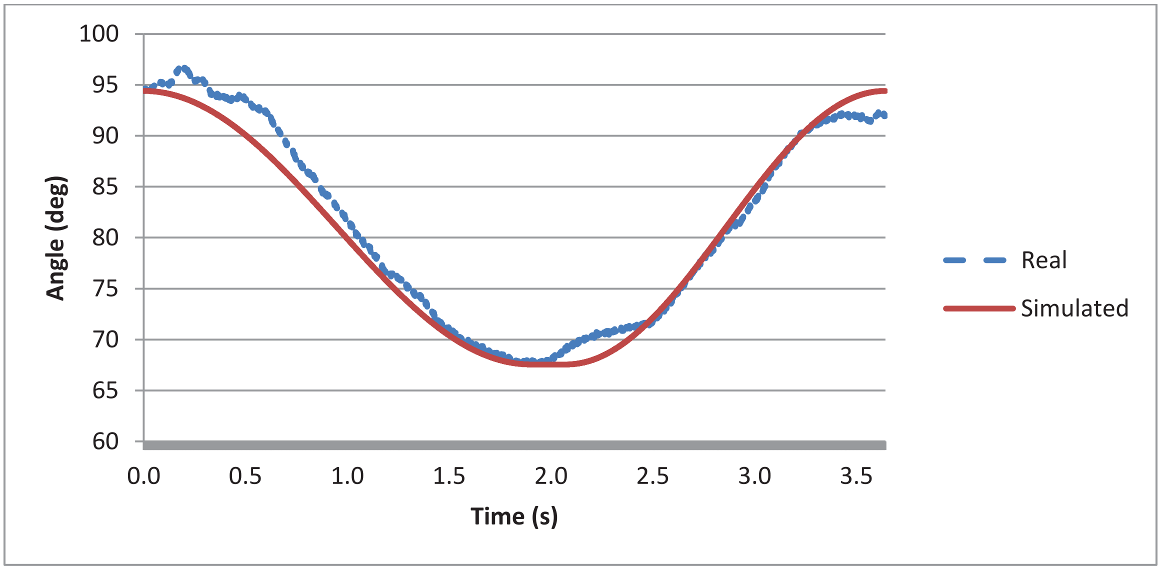


**Figure 12:** Pause adjusted Fourier series optimized for a minimum RMS.

The extent to which the pause values were added to angle-time series is shown in Table 4. Pause values appeared to have improved the validity of the shank time-series the most with a mean pause length of 505 which is equates to 0.5 s in time. It can be noted that in trial two for participant one, that a pause length of 74 (0.074s) is found to be optimal for the trunk. This value, although much larger than the mean trunk pause length, is still significantly small when compared to the four second squatting tempo.

**Table 4:** Pause lengths (pause units 1 = 0.001s) added for each segment angle-time series for each participant and trial.

| **Participant** | **Trial** | **Pause Length** | | |
|---|---|---|---|---|
| | | **Shank** | **Thigh** | **Trunk** |
| 1 | 1 | 974 | 2 | 2 |
| 1 | 2 | 756 | 2 | 74 |
| 2 | 1 | 738 | 1 | 1 |
| 2 | 2 | 661 | 2 | 2 |
| 3 | 1 | 208 | 1 | 1 |
| 3 | 2 | 251 | 1 | 2 |
| 4 | 1 | 418 | 2 | 2 |
| 4 | 2 | 617 | 1 | 1 |
| | **Mean** | **505** | **1.5** | **13.7** |

### 2.3.3 Statistical Validation

For each participant trial the RMS differences between the real and modelled motions were calculated for the trunk, thigh, and shank angular displacement curves as well as the linear displacement curves for the x and y coordinates of the system's COM. The RMS values for all curves were calculated to represent the level of agreement between the model and actual squatting motion. The generic formula,

$$\mathbf{RMS_{(x)} = \Sigma \, ( \, ( \, 1/n^{*} \, ( \, (\Theta_{realx(1)} - \Theta_{simx(1)})^{2} + (\Theta_{realx(2)} - \Theta_{simx(2)})^{2} + \ldots + (\Theta_{realx(n)} - \Theta_{simx(n)})^{2} \, ))^{\wedge}\tfrac{1}{2}} \qquad \textbf{(10)}$$

where $x$ is the segment being analyzed, $\Theta_{real}$ is the measured angle from the actual motion, $\Theta_{sim}$ is the simulated angle from the outcome of Equation 9 and $n$ is the total number of time points in the angle-time series, was used to calculate the RMS for a given segment or COM variable.

Optimization of the pause value increased the RMS for the shank, thigh, and y coordinate of the COM by 2.1 degrees, 1.7 degrees and 1.2 cm respectively, and decreased the RMS for the trunk and x coordinate of the COM by 3.9 degrees and 3.3 cm, respectively (Table 5).

**Table 5:** Comparing the average RMS values for eight squat trials between initial Fourier series equations and with an optimized pause value added.

| Trial | Shank (deg) | Thigh (deg) | Trunk (deg) | COGx (m) | COGy (m) |
|---|---|---|---|---|---|
| **Before** | 1.8 | 4.8 | 6.0 | 0.050 | 0.020 |
| **Optimized** | 4.0 | 6.4 | 2.1 | 0.017 | 0.032 |
| **Difference** | 2.1 | 1.7 | -3.9 | -0.033 | 0.012 |

Although an increase in RMS value is generally undesired, the optimization allowed for greater agreement between the actual squatting motion and the x coordinate of the COM. This is justifiable given that the ability to maintain balance is dependent on this variable.

## 2.4 Theoretical Experiments

### 2.4.1 Experiment A: Effect of Segment Length on Squat Depth

Segment lengths of the trunk, thigh, and shank were systematically altered within a range of possible values to determine the effect of segment length on thigh rotation bounded by body equilibrium. Considering the NSCA guidelines, the most extreme posture for front squat technique was programmed as a stationary position throughout the motion. This consisted of a shank angle that fixed the knee joint at the edge of the toes and fixed the trunk to 60 degrees from the horizontal (Figure 13). Given these fixed segment angles the model now had a single degree of freedom: thigh angle. The thigh segment was progressed, in 1 degree increments, through a full range from 90 (vertical standing) to 180 degrees (full squat) from the right horizontal to simulate a complete front squat. An iterative loop was programmed which allowed the model to progressively alter a selected segment’s length in increments proportional to the standard deviation of the participant sample. Specifically, the range of segment lengths investigated was based on the anthropometry of a sample of 41 student athletes (21 males, 20 females) recorded in a previous study (Wallace, 2010). All segment lengths, within ± 3 standard deviations (SD) of that segment’s mean length in the sample, were simulated in increments of 0.1 SD. This was systematically performed for the foot, shank, thigh, and trunk. All other segment lengths were held constant while one segment was being investigated. This was also done separately with the thigh-to-trunk ratio, starting with a ratio of 0.8, and progressing by 0.01, to 1.2. The trunk length was kept constant and the thigh length was manipulated to achieve the necessary ratio. To account for variation in sex and stature, the entire process was repeated six times, once each for a simulated male participant of 1.65 m (5’5”), 1.82 m (6’) and 2.01 m (6’7”) and a simulated female of 1.55 m (5’1”), 1.70 m (5’7”) and 1.87 m (6’1.5”). The thigh angle where the COM x coordinate passed outside the limit of balance described in section 2.3.1 was used as a measure of squat depth performance.

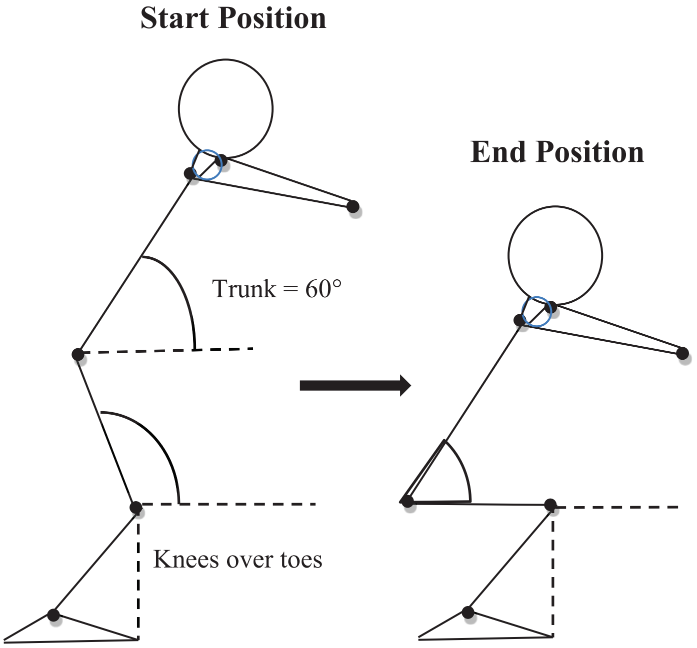
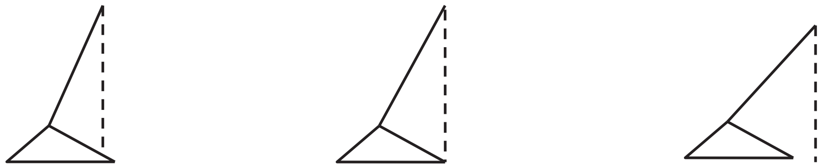


**Figure 13:** Most extreme front squat posture allowing the knees to be in line with the vertical projection of the toes and the trunk to be at 60 degrees.

### 2.4.2 Experiment B: Ankle Flexibility and Knee Translation

While the notion that the horizontal position of the knees should not pass anterior to the toes during a squatting motion is a generally accepted guideline, it is neither universally agreed upon, nor is it adhered to by the World's best Olympic weightlifters. Further, it is possible that an athlete's limited ankle flexibility may prevent their knees from translating anteriorly to the toes, let alone past. As such, it is worthwhile to investigate the front squat without fixing the horizontal coordinate of the knees to be the same as the toes. The preliminary model was altered to use ankle flexibility measures in conjunction with anthropometric data collected on a sample of athletes from a previous study (Wallace, 2010). Segment length and ankle flexibility data from each of the 41 participants from this sample were systematically entered into the program and the maximum squatting depth predicted through simulation was recorded. The program was then altered so that the horizontal coordinate of the knees was set equal to the toes for all participants. The model was executed again and the results were recorded. The model was altered further to progressively allow the knees to move past the toes 1 cm at a time. This was repeated until the knee joint was a maximum of 10 cm past the toes. The effects of knee motion past the toes on the location of the COM at the end range of the front squat were recorded. The three different simulation conditions are shown in Figure 14.



Lack of ankle flexibility

Knee to toes

Knees progressively past toes

**Figure 14:** The three different squat simulations: Lack of ankle flexibility, knees to toes, and knees progressively moved past toes.

# 3. Results

## 3.1 Validation Trials

RMS results from validation trials between actual squatting and simulated squatting are shown in Table 6. Mean RMS values of 3.99 +/- 0.05, 6.42 +/- 0.1 and 2.11 +/- 0.1 degrees for the shank, thigh and trunk angles were calculated from the eight trials (two trials for each of the four participants). The mean RMS value for the linear displacement of the COM was 1.7 +/- 0.03 cm in the x direction and 3.2 +/- 0.2 cm in the y. An example of the data recorded from the goniometer for Participant 2 during Trial 2, compared with the simulated values for the shank, thigh, and trunk, is shown in Figure 15. The path of the COM calculated from the goniometer angles compared with those calculated with the simulated angles can be found in Figure 16 for the x and y directions respectively.

**Table 6:** RMS values for all squatting trials comparing optimized simulated motions to actual squatting angles as well as a comparison of COM movement.

| Participant | Trial | Shank (deg) | Thigh (deg) | Trunk (deg) | COGx (m) | COGy (m) |
|---|---|---|---|---|---|---|
| 1 | 1 | 3.95 | 6.42 | 2.30 | 0.017 | 0.029 |
| | 2 | 3.99 | 6.37 | 2.21 | 0.016 | 0.029 |
| 2 | 1 | 3.95 | 6.30 | 2.08 | 0.017 | 0.033 |
| | 2 | 4.01 | 6.51 | 2.04 | 0.017 | 0.034 |
| 3 | 1 | 4.01 | 6.47 | 2.01 | 0.017 | 0.032 |
| | 2 | 4.00 | 6.38 | 2.12 | 0.017 | 0.031 |
| 4 | 1 | 4.02 | 6.49 | 2.00 | 0.017 | 0.033 |
| | 2 | 3.88 | 6.27 | 1.89 | 0.017 | 0.032 |
| | **Mean** | **3.99** | **6.42** | **2.11** | **0.017** | **0.032** |
| | **STDEV** | **0.05** | **0.1** | **0.1** | **0.0003** | **0.002** |

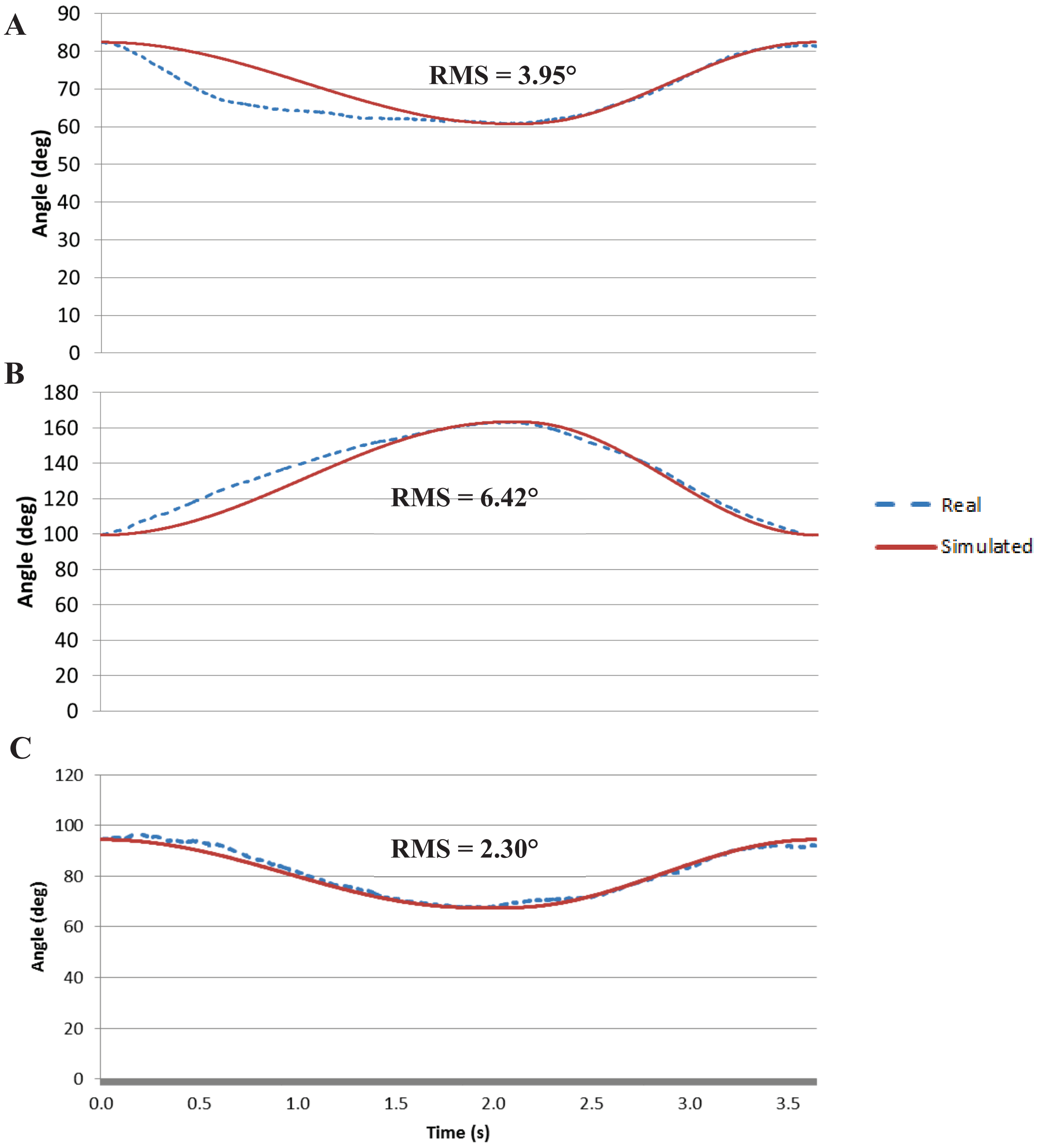


**Figure 15:** (A) Trunk angles from an actual front squat compared with the simulated motion from the model (Participant 1, Trial 1). (B) Thigh angles from an actual front squat compared with the simulated motion from the model (Participant 1, Trial 1). (C) Shank angles from an actual front squat compared with the simulated motion from the model (Participant 1, Trial 1).

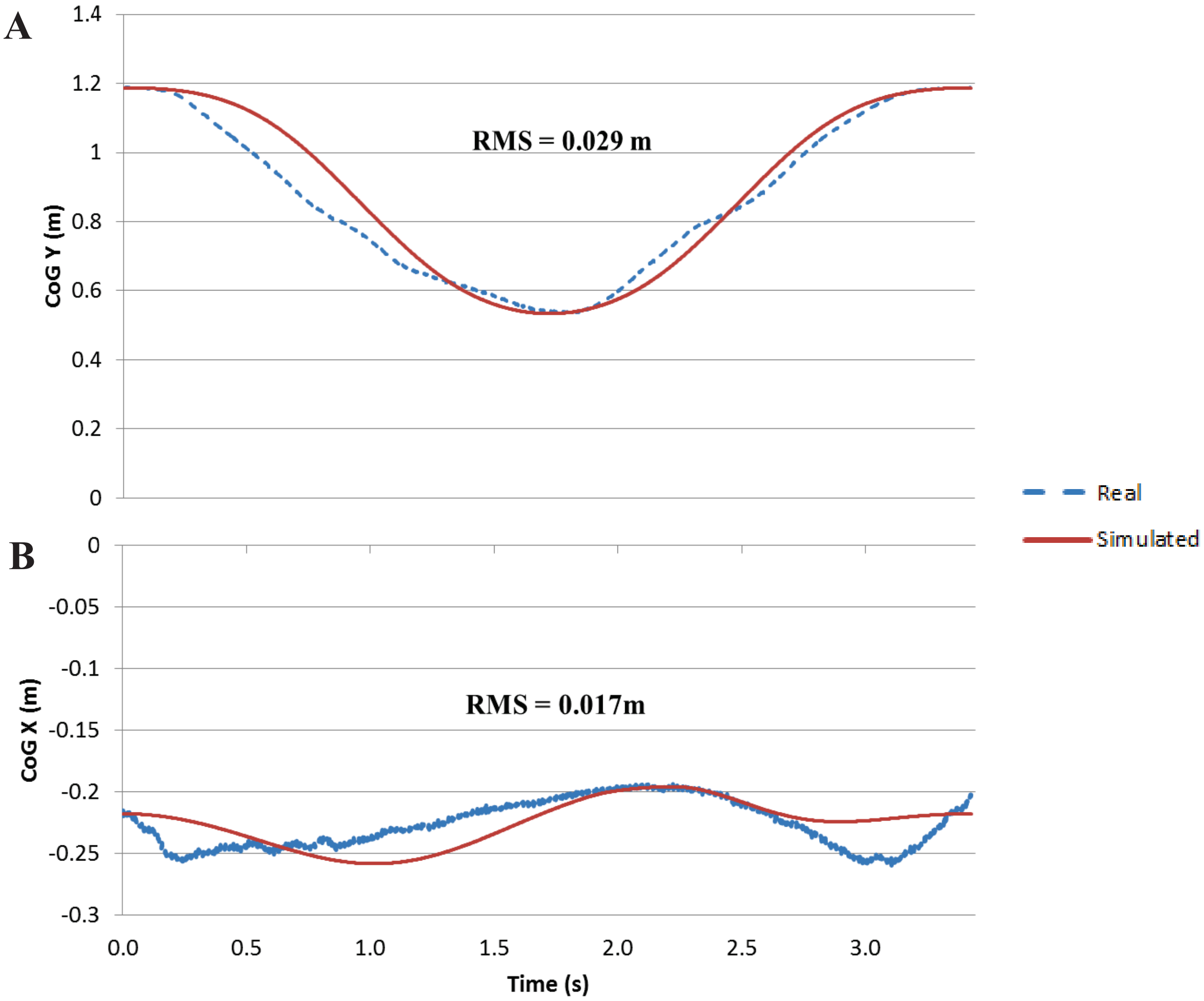


**Figure 16:** (A) COM y coordinates from an actual front squat compared to the simulated motion from the model (Participant 1, Trial 1). (B) COM x coordianates from an actual front squat compared with the simulated motion from the model (Participant 1, Trial 1).

## 3.2 Experimental Trial Results

### 3.2.1 Experiment A

The average anthropometric values collected from Wallace (2010) from a sample of 21 male and 20 female varsity athletes are listed in Tables 7 and 8. On average, males and females had similar thigh-to-trunk ratios (0.98); however, males were proportionally taller and heavier.

**Table 7:** Average mass, height and, lower body anthropometric data with standard deviations for males and females. Mass recorded in kilograms and length in meters.

| | Gender | Mass (kg) | Height (m) | Toe-heel (m) | Toe-ankle (m) | Ankle height (m) | Shank (m) | Thigh (m) |
|---|---|---|---|---|---|---|---|---|
| Average | Male | 88.8 | 1.83 | 0.27 | 0.22 | 0.06 | 0.43 | 0.48 |
| SD | | 10.6 | 0.06 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 |
| Average | Female | 69.0 | 1.71 | 0.24 | 0.19 | 0.05 | 0.4 | 0.45 |
| SD | | 9.7 | 0.09 | 0.01 | 0.01 | 0.004 | 0.03 | 0.03 |

**Table 8:** Average upper body anthropometric data with standard deviations for males and females. Mass recorded in kilograms and length in meters.

| | Gender | Trunk (m) | Upperarm (m) | Forearm (m) | Hand (m) | Head (m) |
|---|---|---|---|---|---|---|
| Average | Male | 0.49 | 0.31 | 0.27 | 0.12 | 0.19 |
| SD | | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 |
| Average | Female | 0.46 | 0.28 | 0.24 | 0.11 | 0.18 |
| SD | | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 |

The result of simulating variations in trunk length for participants of short (1.65 m for male and 1.55 m for females), average (1.82 m for male and 1.70 m for female), and tall (2.01 m for male and 1.87 m for females) statures showed that longer trunks affected squatting depth for average and tall males and females of all heights (Figure 17). Trunk anthropometry affected squatting depth at differing lengths, with taller individuals being affected to a greater extent than shorter individuals on an absolute level. This effect was similar for both men and women. Simulations of thigh length variations showed that thigh length affected males and females of all heights (Figure 18). Thigh length changes had an opposite effect on squatting depth performance compared to trunk length. Absolute increases in thigh length affected shorter individuals to a greater extent. This effect was also similar for both men and women.

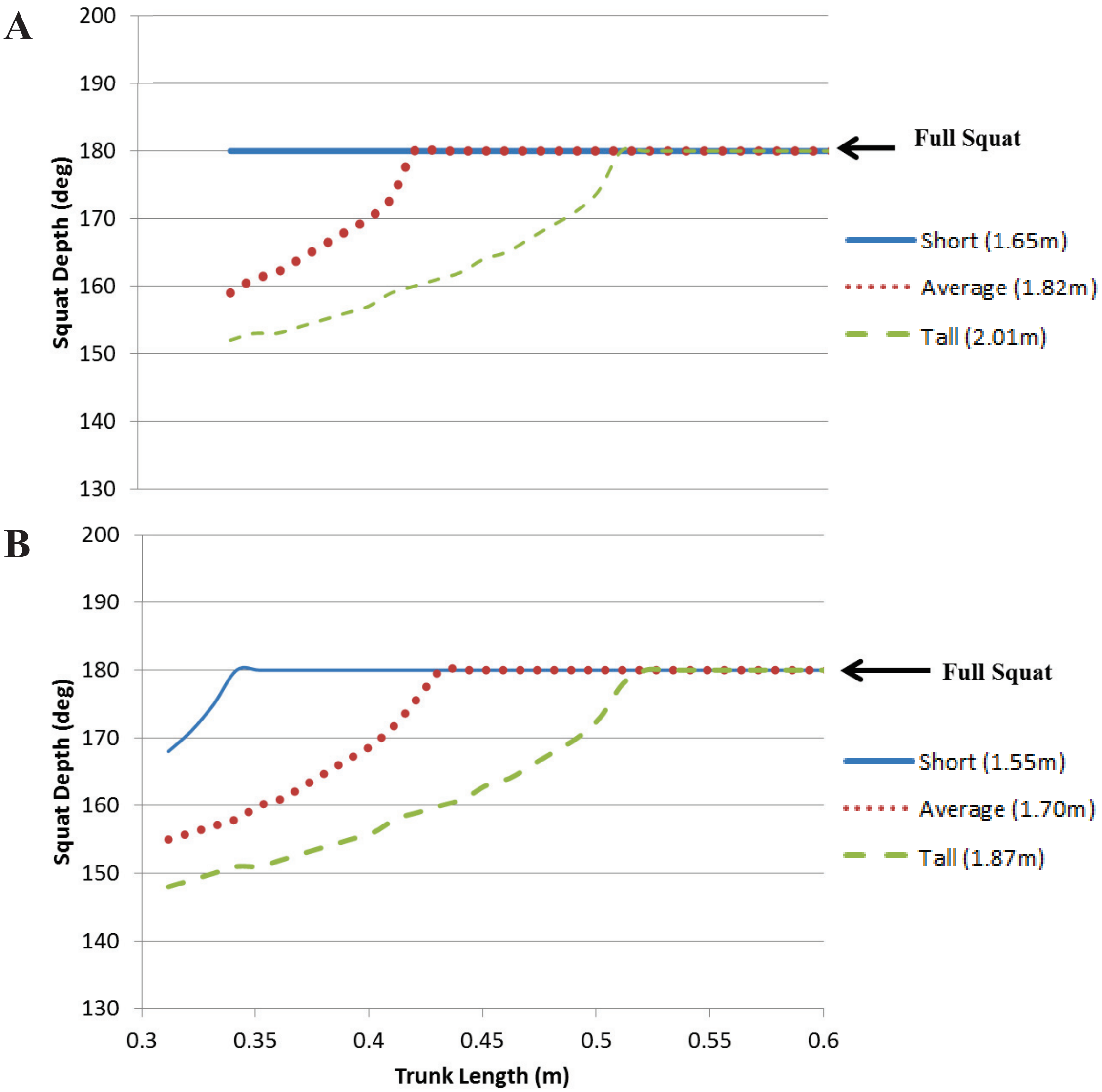


**Figure 17:** (A) Effect of trunk length on squat depth in three simulated male participants (B) Effect of trunk length on squat depth in three simulated female participants.

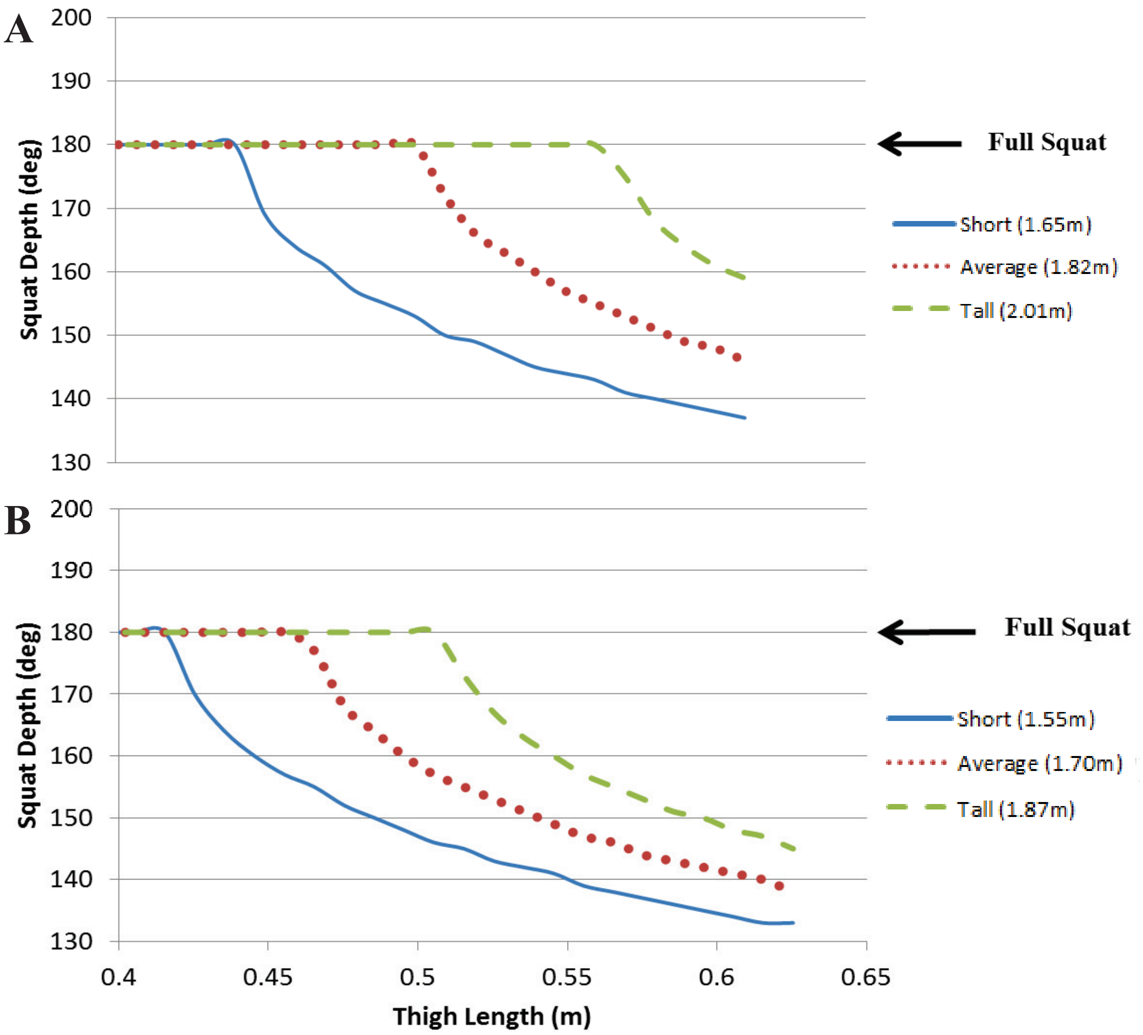


**Figure 18:** (A) Effect of thigh length on squat depth in three simulated male participants (B) Effect of thigh length on squat depth in three simulated female participants.

The kinematics of the COM of the participants during simulations showed that when isolating the bottom of squat position, increases in trunk lengths shifted the COM forward (anteriorly) and increases in thigh lengths moved it backwards (posteriorly) (Figures 19 and 20).

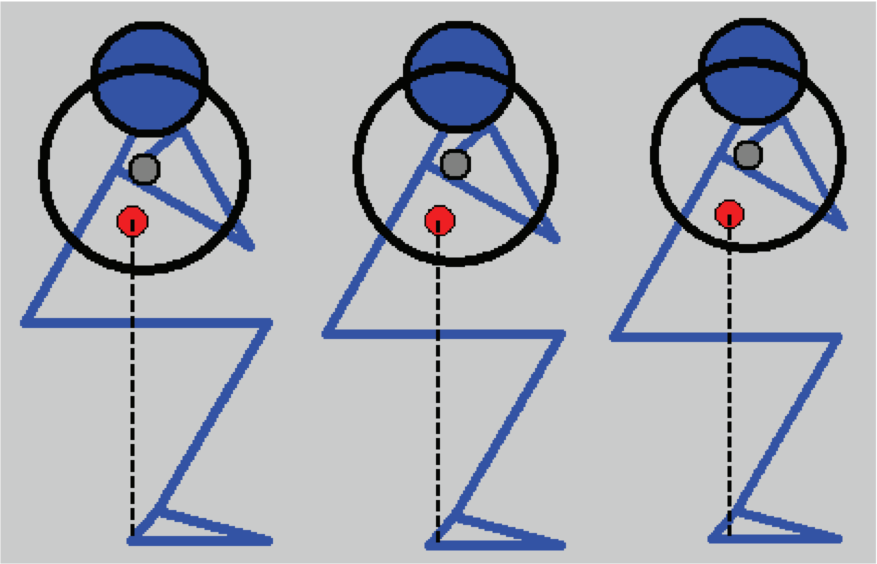


**Figure 19:** The effects of trunk length on the location of the COM using the average male anthropometry. From the left, trunk lengths of 0.35, 0.4, and 0.45 meters.

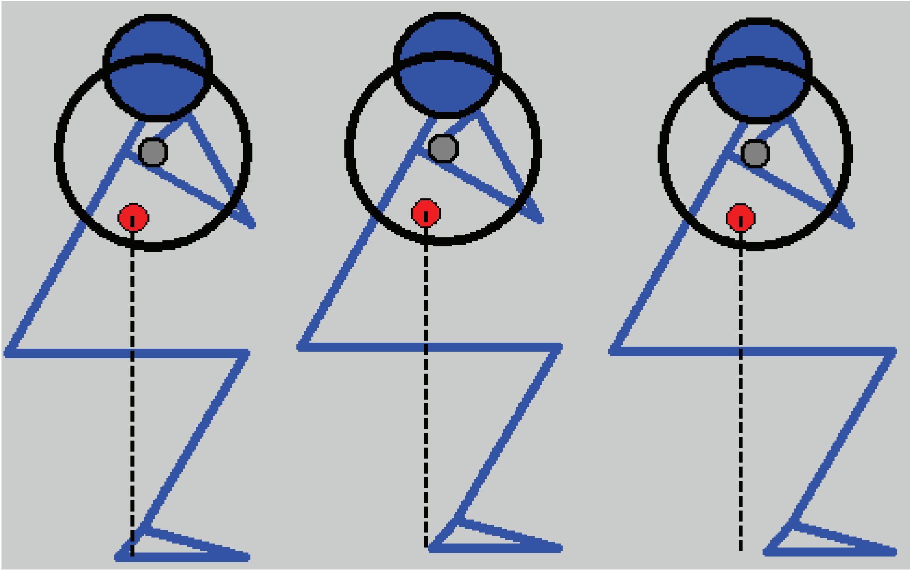


**Figure 20:** The effects of thigh length on the location of the COM using the average male anthropometry. From left, thigh lengths of 0.5, 0.55, and 0.6 meters.

Results from altering the thigh-to-trunk ratio in simulated participants of short (1.65 m male, 1.55 m female), average (1.82 m male, 1.70 m female), and tall (2.01 m male, 1.87 m female) are shown in Figure 21. Thigh-to-trunk ratio had a similar effect on squatting depth across all statures, although there was a slightly greater effect on taller, followed by average, and then shorter individuals. This effect was greater for males than for females; however, the trend was similar.

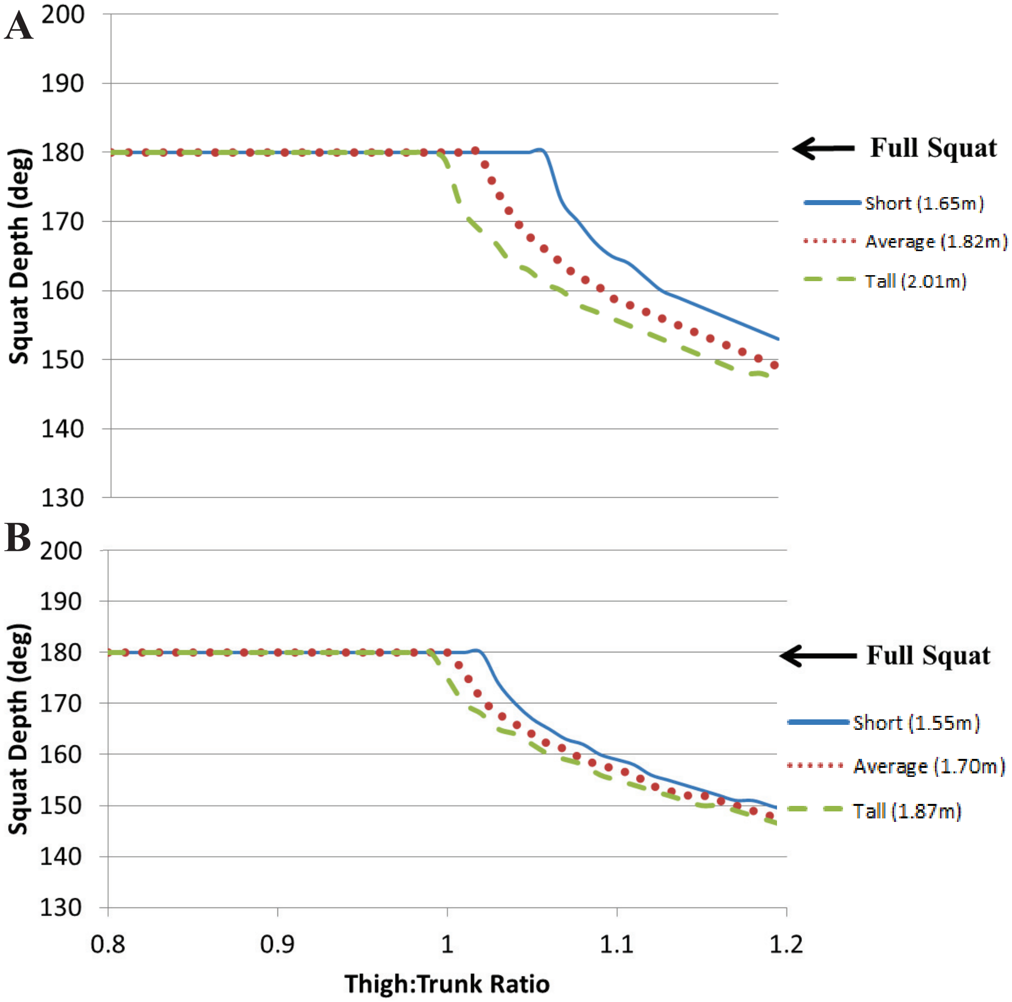


**Figure 21:** (A) Effect of altering the thigh-to-trunk ratio on squat depth in three simulated male participants. (B) Effect of altering the thigh-to-trunk ratio on squat depth in three simulated female participants.

### 3.2.2 Experiment B

Of the 41 athletes sampled, when ankle flexibility was factored in, the model predicted that 16 out of those 41 athletes could not achieve a thigh angle of 180 degrees in the front squat. The distribution of ankle flexibility among sampled athletes is shown in Figure 22. Out of the 41 athletes, 25 did not have sufficient ankle flexibility for the horizontal position of their knees to be anterior of their toes. For 15 out of the 16 athletes that the model predicted could not achieve a full front squat, the ankle flexibility was such that the horizontal position of the knee could not reach that of the toes. However, ankle flexibility could not solely account for the ability/inability to achieve full front squatting depth. It is important to note that some participants whose knees could not reach the horizontal position of the toes also achieved full squatting depth (Figure 23).

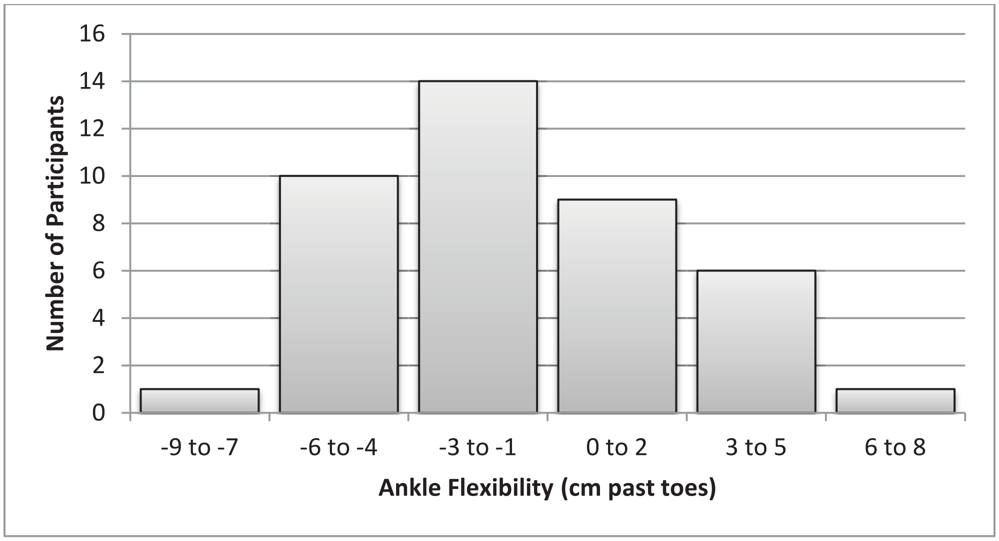


**Figure 22:** Distribution of ankle flexibility with reference to the ability to push the knees past the vertical projection of the toes.

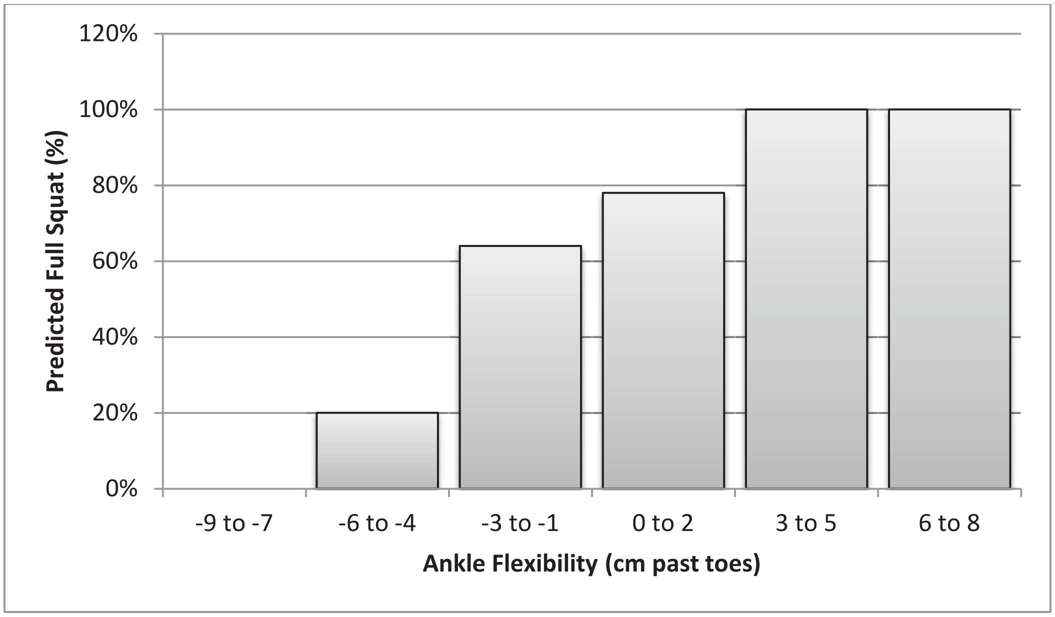


**Figure 23:** Percentage of participants predicted to be able to achieve full front squatting depth based on ankle flexibility.

When the model allowed the knees to move to the toes, 8 out of 41 athletes (2 male, 6 female) could not achieve the proper depth in the front squat. Of those 8 athletes, 5 had the largest thigh-to-trunk ratios and all 8 were in the top 10. The model predicted that no athlete with a thigh-to-trunk ratio of over 1.1 could complete a full front squat and only 53.5 percent of those with a thigh-to-trunk ratio between 1 and 1.09 (Figure 24). The percentage of predicted successful squats diminished with increasing thigh-to-trunk ratios (Figure 24). The distribution of thigh-to-trunk ratios is presented in Figure 25. The majority of athletes had thigh-to-trunk ratios under 1.

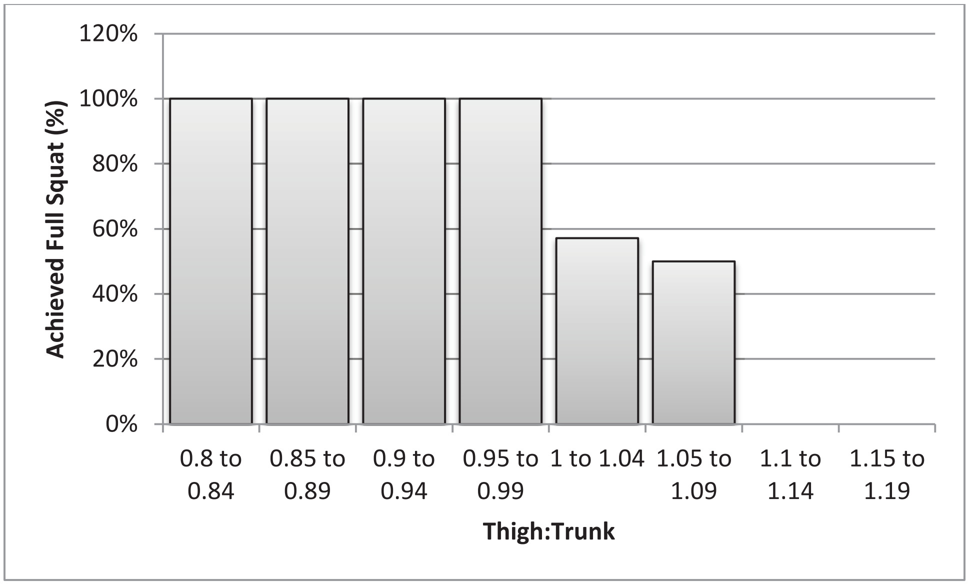


**Figure 24:** Percentage of participants predicted to be able to achieve full front squatting depth based on thigh-to-trunk ratio.

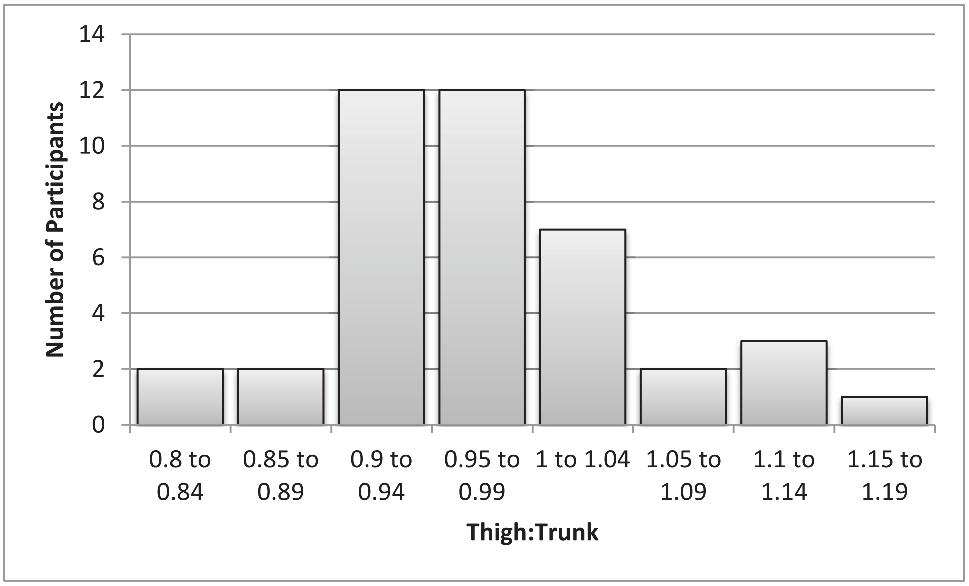


**Figure 25:** Distribution of thigh-to-trunk ratios among 41 measured athletes.

When the knees were allowed to move past the toes all athletes achieved sufficient depth at 5cm past the toes. Progressively allowing the knee to move from -5 cm to +5 cm past the toes shifted the COM anteriorly (Figure 26).

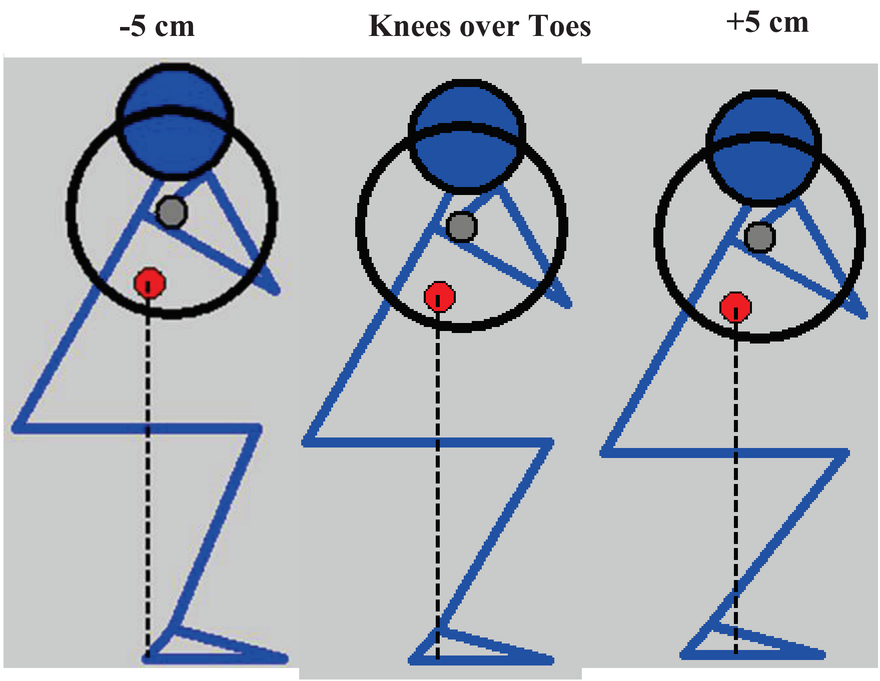


**Figure 26:** Effect of varying degrees of ankle flexibility on the location of the COM.

## 4. Discussion

The front squat is utilized by a large number of athletes from many different sports. The lift is used as a stand-alone strength exercise or as a precursor to the clean and jerk in order to train athletic qualities. In either of these uses, the NSCA recommends that during the execution of this lift the knees must not move anterior to the toes, the back must remain flat (no relative movement of the vertebrae while the pelvis and trunk move as one unit), the heels must stay in contact with the ground during the entire lift, and the long axis of the thighs should reach parallel with the floor at the midpoint of the movement. Due to the guidelines outlined by the NSCA and the unique anthropometry of athletes using this lift, it has been hypothesized that a shorter thigh length relative to the trunk length will facilitate the ability to rotate the thigh to parallel with the ground while maintaining the vertical projection of the system COM within the BOS. This research study used previously collected anthropometry of 41 varsity athletes, in combination with directly measured front squat kinematics and optimization measures to study the effects of limb lengths, limb length ratios, and joint flexibility on the hypothetical squat kinematics. Two-dimensional kinematic data were collected, processed, and conditioned to perform the optimized model performance. The RMS difference between true and modeled front squat kinematics (trunk, thigh, and shank angles along with vertical and horizontal COM coordinates) were measured to ensure the validity of the model kinematics. The optimized squat kinematics were bound by the constraints of the angular motion of the shank and trunk as well as the inherent requirement to maintain total body equilibrium. In Experiment A, using a modified version of the validated kinematic model, segment lengths of the trunk, thigh, and shank were systematically altered within a range of possible values to determine the effect of segment length on front squatting depth. In

Experiment B, using a sample of previously collected anthropometry from an athletic population, the kinematic model was further modified to predict the depth of the front squat movement with altered ankle flexibility. The model simulated front squatting depth for the horizontal knee position initially limited by the flexibility of the athlete, and then progressed starting from a horizontal position over the vertical plane of the toes to 10 cm past in increments of 1 cm, to determine the effect of ankle flexibility and motion on the ability to achieve a full front squat within the defined criteria.

The primary purpose of the thesis was to understand the relationship between the variation in athlete segment lengths (trunk, thigh, shank) and front squat depth as represented by the maximum thigh angle. The idealized kinematics of the squat has the participant achieving a horizontal thigh position while maintaining the overall COM within the BOS (10-100%) in the sagittal plane. Using the validated model, a relationship between anthropometry and the amount of possible front squat depth was quantified. Findings from Experiment A and B help support the hypothesis that a shorter thigh length relative to the trunk length will facilitate the ability to rotate the thigh to parallel with the ground while maintaining the vertical projection of the overall system COM within the BOS. As trunk length decreased (Figure 15) and as thigh length increased (Figure 16), front squat depth was reduced. More specifically, a large (>1) thigh-to-trunk ratio appears to disadvantage an individual attempting to perform a front squat to full depth. Furthermore, by modifying the model, the secondary objective, which was to quantify the effects of ankle flexibility on achieving a horizontal thigh position while maintaining the overall COM within the BOS (10-100%) in the sagittal plane, was addressed. Findings from Experiment B show that ankle flexibility limits the maximum ankle dorsi-flexion and therefore hinders the anterior translation of the COM, further limiting the ability to achieve a full front squat while adhering to the recommended criteria. This supports the secondary hypothesis that ankle flexibility may limit front squat depth in some athletes.

## 4.1 Counterbalancing Effect of the Trunk

The results from this thesis indicate that a large thigh-to-trunk ratio (>1) appears to be a limiting factor in achieving a horizontal thigh position while maintaining the overall COM within the BOS (10-100%) in the sagittal plane, in the front squat movement. According to the sample of athlete anthropometry, 32% of athletes had a thigh-to-trunk ratio of 1 or above. However, it is important to note that the predictions of our model were based on the assumption that an extreme trunk angle of 60 degrees relative to the right horizontal was maintained. During the validation process, the lowest trunk angle observed was 68 degrees (Table 3). It stands to reason that a trunk angle of 60 degrees may be too excessive, especially if trying to adhere to the NSCA guideline of attempting to maintain a near vertical trunk. As a result, the actual thigh-to-trunk ratio, which may be detrimental to the location of the COM between the BOS (0-90%) in the sagittal plane of a front squat, may be less than 1; therefore, the athletic population potentially affected could be greater than 32%.

The results from this thesis corroborate the findings on the influence of trunk length on front squat performance from Caruso et al. (2009). Caruso et al. showed that trunk length was a predictor of the maximum amount of weight lifted during a front squat, with longer trunks being associated with more weight lifted. While Caruso et al. did investigate the lengths of various body segments relative to standing height; they did not investigate the ratio of thigh-to-trunk length on front squat performance. The findings on trunk length by Caruso et al. may be explained by the ratio of thigh-to-trunk length and its subsequent influence on the position of the COM in a deep squat position. More specifically, relatively longer thighs and shorter trunks favor a more posterior total body COM than would relatively shorter thighs and longer trunks (Figure 27). The trunk can be envisioned as a counterbalance during the front squat motion, helping to redistribute the COM anteriorly with increased trunk rotation (Figure 19). Athletes who have proportionally shorter trunks are therefore more limited in their ability to use the trunk as a counterbalance. The extent to which the trunk can serve as a counterbalance during the front squat is limited by the fact that the athlete must support proportionately more bar weight with the arm musculature as the trunk rotates anteriorly.

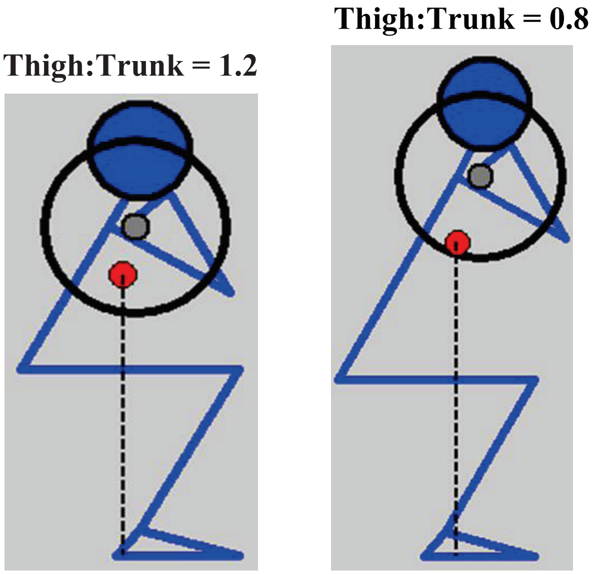


**Figure 27:** Effect of thigh-to-trunk length ratio on the vertical projection of the COM relative to the BOS at the mid-way point of a front squat.

### 4.2 Effects of Anterior Translation of the Knees on Front Squatting Depth

According to the NSCA, while performing a front squat, an athlete should not have their knees move anterior to their toes. In this investigation, using previously collected athlete anthropometry, it was found that over half of the athletes did not possess sufficient ankle flexibility to allow their knees to reach the horizontal coordinate of the anterior edge of the BOS (toes), as such, the ability of the athlete to compensate for posterior translation of the COM during the pliometric phase is limited (Figure 22). Moreover, results from Experiment B showed that when ankle flexibility limitations and anterior knee motion constraints are removed, the ability to achieve a horizontal thigh position while maintaining the overall COM between the BOS (10-100%) in the sagittal plane is improved. To the extent that when model constraints were changed to allow the knees to translate 5 cm anterior to the toes, all athletes were then capable of achieving full depth (thigh angle of 180 degrees) in the front squat. Effectively, the trunk motion is bound by the strength of the supporting arm musculature; shank rotation is bound by both flexibility and by the assumption that any horizontal knee motion past the vertical projection of the toes is dangerous to the ligamentous structure of the knee. There is therefore an inherent assumption that the apparent injury risks of excessive anterior knee motion is of a greater risk to the athlete than excessive anterior trunk rotation during the front squat. While Russell and Phillips (1989) concluded that trunk inclination is associated with the greatest risk to the lower back, the notion of recommending knee motion past the toes during the squat has received mixed support in the literature. Fry, Smith, and Schilling (2003) reported that unrestricted knee motion past the toes during a squat increased shear forces but within tolerable capacity of healthy posterior and anterior cruciate ligaments. The shear forces on the knee are also dependent on the velocity of the squat, of which, the front squat component within the clean and jerk would likely involve significantly greater shear forces than the more controlled isolated lift. Observations from elite Olympic lifters show the use of excessive knee motion past the toes. While seemingly paradoxically, knee strains in Olympic weightlifters only accounted for 1.25% of all reported injuries and of particular interest, lower back muscle strains account for 48.3% of injuries in Olympic weightlifters (Calhoon and Fry, 1999). Furthermore, anterior translation of the knees over the edge of the BOS has been shown to reduce loading at the hip and low back while significantly increasing it at the knee joint (Escamilla, 2001). These findings may suggest that an appropriate amount (up to 5cm) of anterior knee motion past the vertical projection of the toes may be warranted. In particular, with the athletes who are predisposed to a more posterior location of the COM at the bottom position of the front squat. It is therefore plausible that additional shank rotation may be in fact beneficial when attempting to reduce loading the lower back (Figure 28).

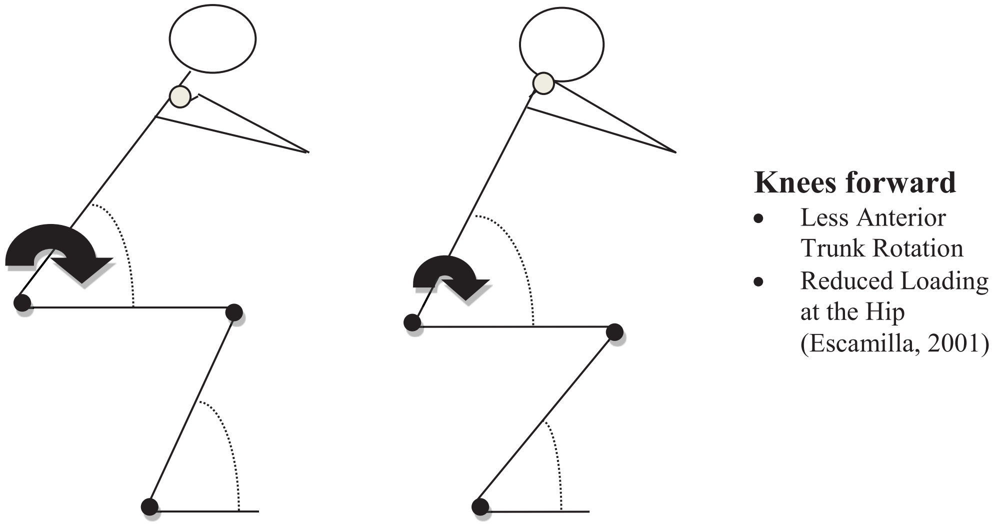


**Figure 28:** Effect of knee position on trunk angle.

### 4.3 Limitations of the model

The model was limited by the criteria of the front squat movement. A minimum trunk angle of 60 degrees was set for experiments A and B. Although no published literature indicates that a properly executed front squat would surpass this trunk angle, it may be possible that an athlete could perform a front squat with a greater amount of trunk flexion. This squatting posture may not be possible due to the limited strength of the upper body musculature (Figure 2) and would; however, most likely represent an unsafe lift (Russell and Phillips, 1989). The model was programmed to be an extreme scenario for front squat posture, in specific regards to trunk flexion. As such, the results of this study may indeed reflect a trend towards an effect of anthropometry on the front squat depth which may in reality, be more pronounced. Given that the average trunk angle recorded for the participants during front squatting trials was 78.5 degrees, and their average thigh-to-trunk ratio was 0.82 (Table 3), yet no participant reached a horizontal thigh position while adhering to the front squat guidelines, may be evidence that the thigh-to-trunk ratio which limits the ability to reach a horizontal thigh while adhering to the front squat criteria, is smaller than 1:1. This would also result in a more meaningful implication for ankle flexibility and anterior knee translation and its relation to bodily equilibrium during the front squat. This would not change the nature of the study findings; neither would it change the recommendations.

## 4.4 Conclusions

Athletes with a thigh-to-trunk ratio of 1 (and potentially less) may physically not be able to complete a full front squat according to the NSCA guidelines. Furthermore, anterior knee translation initiated through rotation of the shank appears to be a compensation mechanism in order to maintain equilibrium at the end ranges of the front squat movement. It appears plausible that horizontal knee motion up to 5 cm to the toes may allow athletes with large thigh-to-trunk ratios to reach full front squat depth and perhaps reduce loading on the low back. Additionally, ankle inflexibility may limit front squat depth and increase the likelihood of injury.

## 4.5 Practical Applications

Strength and conditioning specialists seeking to design a training program using the front squat may benefit from measuring thigh and trunk lengths along with ankle flexibility. This may help to identify key characteristics, which may limit an athlete's ability to safely perform the lift to a full squat depth. Strength and conditioning specialists should incorporate ankle flexibility training as a development exercise as well as slight progressive knee motion past the toes for athletes who have difficulty performing this lift. While developing ankle flexibility, the use of weight plates placed under the heels may be an appropriate interim strategy in order to preserve equilibrium and safe lower back loads. Extra attention should be paid to athletes with longer thighs than trunks as they may be predisposed to exaggerated trunk or knee positions, which could increase the risk of injury. Based on the data collected from Wallace (2010), this could potentially affect one third (Figure 25) of all athletes.

## 4.8 Future Implications

Kinanthropometry appears to be an area of interest which has been minimally researched. The influence of anthropometry on various exercise recommendations need to be explored in greater depth amongst athletic populations. Future research could incorporate the addition of joint forces and an exploration of the anthropometric variations on joint kinetics.

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**Appendix A:** Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters (De Leva, 1996)

| | Endpoints | | Longitudinal length (mm) | |
|---|---|---|---|---|
| **Segment** | **Origin** | **Other** | **F** | **M** |
| Head | VERT | MIDG | 200.2 | 203.3 |
| Trunk | SUPR | MIDH | 529.3 | 531.9 |
| UPT | SUPR | XYPH | 142.5 | 170.7 |
| MPT | XYPH | OMPH | 205.3 | 215.5 |
| LPT | OMPH | MIDH | 181.5 | 145.7 |
| Upper arm | SJC | EJC | 275.1 | 281.7 |
| Forearm | EJC | WJC | 264.3 | 268.9 |
| Hand | WJC | MET3 | 78 | 86.2 |
| Thigh | HJC | KJC | 368.5 | 422.2 |
| Shank | KJC | LMAL | 432.3 | 434 |
| Foot | HEEL | TTIP | 228.3 | 258.1 |

| **Nomenclature and Definition of Terms** | |
|---|---|
| AJC, EJC, HJC, KJC, SJC, WJC | respectively, the joint centers of ankle, elbow, hip, knee, shoulder, and wrist |
| Heel | the posteior point of the heel |
| LMAL | lateral malleolus - the most lateral point on the lateral malleolus |
| MET3 | 3rd metacarpale - a point on the dorsal sulcus between the tip of the third metacarpal (knuckle) and the base of the third finger |
| MIDG, MIDH, MIDS | mid-gonion, mid-hip, and mid-shoulder - the points midway between the gonions, hip joint centers, and shoulder joint centers, respectively |
| OMPH | omphalion - the center of the navel |
| SUPR | suprasternale - the most caudal point on the margin of the jugular notch of the sternum |
| TTIP | the tip of the longest toe |
| VERT | Vertex - the most cranial point of the head, when the head is oriented in the Frankfort plane. |
| XYPH | xyphion - the midpoint of the sulcus between the body of the sternum and the xyphoid process |

# **Appendix B:** Anthropometry (Wallace, 2010)

| Subject # | Mass | Height | Toe-heel | Toe-ankle | Ankle height | Leg | Thigh | Trunk | Upperarm | Forearm | Hand | Head | Ankle Flex | Sex M=1 F=2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (kg) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (deg) | |
| 1 | 89.8 | 1.81 | 0.257 | 0.207 | 0.069 | 0.398 | 0.452 | 0.497 | 0.292 | 0.256 | 0.118 | 0.181 | 60 | 1 |
| 2 | 75.3 | 1.81 | 0.265 | 0.216 | 0.059 | 0.426 | 0.478 | 0.493 | 0.311 | 0.263 | 0.123 | 0.181 | 61 | 1 |
| 3 | 84.3 | 1.76 | 0.264 | 0.213 | 0.060 | 0.419 | 0.438 | 0.484 | 0.296 | 0.254 | 0.112 | 0.176 | 66 | 1 |
| 4 | 59.0 | 1.64 | 0.236 | 0.187 | 0.053 | 0.377 | 0.425 | 0.423 | 0.268 | 0.234 | 0.102 | 0.164 | 58 | 2 |
| 5 | 81.0 | 1.75 | 0.245 | 0.196 | 0.056 | 0.404 | 0.45 | 0.493 | 0.289 | 0.246 | 0.116 | 0.175 | 65 | 2 |
| 6 | 97.8 | 1.87 | 0.278 | 0.227 | 0.070 | 0.427 | 0.501 | 0.495 | 0.317 | 0.27 | 0.126 | 0.187 | 65 | 1 |
| 7 | 94.3 | 1.87 | 0.265 | 0.216 | 0.068 | 0.43 | 0.493 | 0.498 | 0.32 | 0.267 | 0.119 | 0.187 | 62 | 1 |
| 8 | 86.3 | 1.81 | 0.279 | 0.221 | 0.054 | 0.424 | 0.487 | 0.492 | 0.301 | 0.268 | 0.13 | 0.181 | 67 | 1 |
| 9 | 79.0 | 1.82 | 0.262 | 0.213 | 0.066 | 0.419 | 0.483 | 0.482 | 0.294 | 0.256 | 0.117 | 0.182 | 67 | 1 |
| 10 | 75.8 | 1.87 | 0.248 | 0.199 | 0.056 | 0.445 | 0.517 | 0.461 | 0.293 | 0.249 | 0.117 | 0.187 | 70 | 2 |
| 11 | 85.0 | 1.76 | 0.262 | 0.201 | 0.049 | 0.424 | 0.468 | 0.442 | 0.3 | 0.27 | 0.119 | 0.209 | 68 | 1 |
| 12 | 83.0 | 1.75 | 0.263 | 0.205 | 0.050 | 0.412 | 0.442 | 0.472 | 0.269 | 0.262 | 0.124 | 0.211 | 64 | 1 |
| 13 | 81.0 | 1.88 | 0.284 | 0.232 | 0.050 | 0.478 | 0.519 | 0.46 | 0.314 | 0.285 | 0.131 | 0.185 | 61 | 1 |
| 14 | 56.0 | 1.65 | 0.23 | 0.181 | 0.054 | 0.366 | 0.408 | 0.469 | 0.248 | 0.23 | 0.101 | 0.172 | 61 | 2 |
| 15 | 77.5 | 1.78 | 0.243 | 0.186 | 0.049 | 0.412 | 0.469 | 0.452 | 0.281 | 0.25 | 0.107 | 0.19 | 66 | 2 |
| 16 | 75.0 | 1.78 | 0.239 | 0.19 | 0.049 | 0.401 | 0.448 | 0.471 | 0.292 | 0.261 | 0.11 | 0.195 | 58 | 2 |
| 17 | 84.5 | 1.86 | 0.265 | 0.216 | 0.054 | 0.448 | 0.492 | 0.458 | 0.299 | 0.285 | 0.129 | 0.191 | 70 | 2 |
| 18 | 68.3 | 1.74 | 0.25 | 0.201 | 0.060 | 0.408 | 0.457 | 0.462 | 0.267 | 0.246 | 0.113 | 0.184 | 65 | 2 |
| 19 | 85.0 | 1.88 | 0.259 | 0.207 | 0.061 | 0.429 | 0.471 | 0.506 | 0.313 | 0.266 | 0.118 | 0.201 | 68 | 1 |
| 20 | 107.0 | 1.95 | 0.287 | 0.237 | 0.061 | 0.471 | 0.487 | 0.512 | 0.325 | 0.29 | 0.129 | 0.212 | 65 | 1 |
| 21 | 99.0 | 1.94 | 0.284 | 0.235 | 0.057 | 0.474 | 0.497 | 0.522 | 0.324 | 0.29 | 0.129 | 0.188 | 55 | 1 |
| 22 | 82.0 | 1.81 | 0.252 | 0.203 | 0.052 | 0.442 | 0.476 | 0.479 | 0.305 | 0.273 | 0.117 | 0.206 | 63 | 1 |
| 23 | 112.0 | 1.92 | 0.274 | 0.225 | 0.062 | 0.46 | 0.484 | 0.527 | 0.318 | 0.283 | 0.123 | 0.209 | 67 | 1 |
| 24 | 105.0 | 1.84 | 0.271 | 0.222 | 0.066 | 0.442 | 0.437 | 0.517 | 0.324 | 0.276 | 0.123 | 0.188 | 55 | 1 |
| 25 | 99.0 | 1.82 | 0.265 | 0.215 | 0.058 | 0.426 | 0.446 | 0.53 | 0.298 | 0.276 | 0.117 | 0.195 | 61 | 1 |
| 26 | 60.5 | 1.72 | 0.248 | 0.199 | 0.051 | 0.414 | 0.46 | 0.469 | 0.278 | 0.237 | 0.108 | 0.186 | 53 | 2 |
| 27 | 86.0 | 1.78 | 0.268 | 0.218 | 0.061 | 0.426 | 0.511 | 0.451 | 0.297 | 0.265 | 0.124 | 0.208 | 60 | 2 |
| 28 | 77.0 | 1.82 | 0.269 | 0.219 | 0.060 | 0.41 | 0.505 | 0.439 | 0.339 | 0.252 | 0.125 | 0.169 | 63 | 1 |
| 29 | 78.5 | 1.64 | 0.238 | 0.189 | 0.055 | 0.373 | 0.467 | 0.45 | 0.289 | 0.237 | 0.106 | 0.183 | 59 | 2 |
| 30 | 59.0 | 1.60 | 0.218 | 0.169 | 0.049 | 0.37 | 0.419 | 0.437 | 0.264 | 0.224 | 0.096 | 0.187 | 46 | 2 |
| 31 | 82.0 | 1.78 | 0.259 | 0.206 | 0.049 | 0.438 | 0.487 | 0.476 | 0.296 | 0.26 | 0.12 | 0.192 | 54 | 1 |
| 32 | 79.8 | 1.85 | 0.26 | 0.211 | 0.059 | 0.426 | 0.477 | 0.517 | 0.313 | 0.262 | 0.114 | 0.188 | 59 | 1 |
| 33 | 81.0 | 1.76 | 0.252 | 0.199 | 0.052 | 0.398 | 0.47 | 0.485 | 0.273 | 0.259 | 0.115 | 0.202 | 56 | 1 |
| 34 | 55.0 | 1.56 | 0.221 | 0.172 | 0.049 | 0.347 | 0.438 | 0.431 | 0.259 | 0.225 | 0.1 | 0.172 | 63 | 2 |
| 35 | 67.0 | 1.65 | 0.241 | 0.192 | 0.049 | 0.395 | 0.417 | 0.427 | 0.281 | 0.238 | 0.103 | 0.182 | 54 | 2 |
| 36 | 65.0 | 1.57 | 0.239 | 0.19 | 0.049 | 0.376 | 0.402 | 0.427 | 0.249 | 0.237 | 0.101 | 0.183 | 55 | 2 |
| 37 | 74.8 | 1.76 | 0.25 | 0.201 | 0.054 | 0.418 | 0.439 | 0.503 | 0.291 | 0.259 | 0.116 | 0.195 | 57 | 2 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 38 | 60.0 | 1.68 | 0.233 | 0.184 | 0.049 | 0.406 | 0.438 | 0.473 | 0.289 | 0.239 | 0.106 | 0.182 | 61 | 2 |
| 39 | 69.0 | 1.73 | 0.238 | 0.189 | 0.049 | 0.421 | 0.448 | 0.498 | 0.282 | 0.233 | 0.116 | 0.183 | 55 | 2 |
| 40 | 70.0 | 1.76 | 0.258 | 0.209 | 0.049 | 0.415 | 0.454 | 0.491 | 0.286 | 0.256 | 0.111 | 0.19 | 55 | 2 |
| 41 | 59.0 | 1.73 | 0.229 | 0.18 | 0.049 | 0.379 | 0.443 | 0.49 | 0.275 | 0.225 | 0.1 | 0.184 | 63 | 2 |