Estimating Joint Moments on a Biodex System 3 Dynamometer

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(ABSTRACT)

The purpose of this investigation is to propose a method for determining resultant joint moments from a Biodex System 3 isokinetic dynamometer. Previous investigations using a dynamometers determined that measured moments from a dynamometer do not equate to the moment applied by the joint. Using Biodex System 3 dimensions and equipment, the proposed method corrects for gravity, acceleration and inertia moments, and relative angular movement between the dynamometer and the joint axis of rotation for the knee and ankle. The current method includes gravitations correction using a 3rd order polyfit method to a 4°/s passive trial, and inclusion of inertial moments from the dynamometer arm and limb segment. A method is also proposed to correct for gravitational moments, acceleration and inertia moments, and distal joint moments while testing the hip.

Previously proposed methods are then compared to the proposed method in isometric and isokinetic exertions. The comparison to a known moment concluded that the results for the isometric exertion are accurate for the proposed method. If the torque measurements from the dynamometer are independent of the velocity, as reported by the manufacturer, the validation of the proposed method for isometric testing holds true for isokinetic as well. The results from isokinetic testing show reasonable results for determining the resultant joint moments.

The proposed method can be simplified for clinical or experimental testing. If inertial and acceleration moments are not of concern, than using the proposed gravitational correction will account for the COM (Center of Mass). No additional measurements of the limb segement and dynamometer attachment are needed. The proposed method is recommended for Biodex System 3 isokinetic dynamometer correction in obtaining resultant joint moments at the knee, ankle, and hip.
Acknowledgements

I would like to thank all friends and family members and specifically Mom, Dad, Shorty, and Dave Richter for their constant support.

To Virginia Tech Women’s Rugby Team, their strive for excellence and physical determination to win will always be among my best memories at Virginia Tech.

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Chapter 1: Literature Review

I. Introduction to Dynamometer Testing and Measurement of Muscle Produced Moment

In the study of human mechanics, much research has focused on muscle strength at the joints in clinical and experimental settings [1-4]. Dynamometers are used to describe such muscle strength [5-7]. Muscle strength is described by the moment or torque measured from a dynamometer. In previous studies, the dynamometer torque measurements have been assumed to be an accurate reading of the moment at the resultant joint [2, 8-10]. Through closer observation, the dynamometer measures the moment at the axis of the machine, not exclusively the moment applied by the joint [2, 3, 11]. Table 1.1 lists sources of errors in dynamometer measurement of the resultant joint moment.

Table 1.1: Sources of error in dynamometer measurement.

| 1) Gravity components of dynamometer arm and limb segment |
| 2) Angular acceleration on inertial moment               |
| 3) Misalignment of the dynamometer and joint axis of rotation |
| 4) Relative angular movement between dynamometer and joint axis of rotation |
| 5) Distal joint moments                                  |
| 6) Moments applied in other planes of motion             |
| 7) Mechanical vibrations in the system                   |
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The purpose of this investigation was to develop a method of estimating joint moments from data collected on a Biodex System 3 Isokinetic Dynamometer (Figure 1.1). Others have published methods to correct for one or a combination of dynamometer sources of error to obtain a more accurate measurement of the resultant joint moment [2-4, 7, 11, 12]. The presented method proposes a new method for gravitational correction using a passive dynamic test. It also corrects for moment of inertia and relative angular displacement between the dynamometer and joint axis of rotation. The moments estimated from this method will be compared to other published methods.
This literature review is organized as follows: first, methods published that account for errors between the dynamometer recorded moment and the resultant joint moment. Second, an overview is discussed that describes the proposed method which accounts for errors in measuring the joint moments at the knee, ankle, and hip.

II. Findings of joint moment measurement with a dynamometer

Possible sources of error in determining resultant joint moments measured by a dynamometer include those listed in Table 1.1. Researchers have published many different methods for correcting these errors. Presented are experimental methods for the correction of dynamometer torque reading.

A. Winter gravitational corrections

Winter focused on correcting gravity-associated errors including weight of the dynamometer attachment and leg segment [2, 3, 11]. Knee extensions, while seated,
must overcome the additional gravitational moments of the dynamometer arm and shank-foot. In flexion, the gravitational moments are working with the exertion. Gravitational components can affect the moment recorded by the dynamometer and cause large sources of error when determining resultant joint moments.

Additional equipment and setup procedure was used to apply this method of gravitational correction. Winter used a piezoresistive accelerometer placed on the lever arm of a Cybex dynamometer to identify the gravitational moments while testing the extension and flexion contractions of the knee. To calibrate the system, the subject’s limb rests in the horizontal position while seated in the dynamometer chair. The load recorded by the dynamometer at this position becomes the gravitational correction moment applied to the cosine of the angular position.

Results of Winter’s study found mechanical work error to be 55-510% in flexion and 26-43% in extension recorded by the Cybex Dynamometer and the resultant joint moment. During flexion the error is larger because gravitational moment is working with the motion aiding the subject in a concentric exertion. Conclusions from his study encourage the need for gravitational correction in isokinetic dynamometer readings.

B. Herzog: inertia, gravity, rotational corrections

Herzog published a method that suggest greater source of error in measurement from the moment recorded by a Cybex dynamometer. The additional sources of errors included; moment of inertia, non-rigidity of the system, as wells as gravitational effects [2]. To include the sources of error into the system, Herzog modeled the system as two rigid bodies: the dynamometer arm and the shank-foot segment. Free body diagrams of each rigid body were used to develop the equations of motion which included gravity, inertia, and angular recording of each segment to determine the resultant joint moment from the dynamometer recorded moment. The angular positions of the dynamometer and limb segment were obtained by markers recorded at 50 frames per second from a motion camera perpendicular to the plane of motion of the Cybex dynamometer. Isokinetic knee extensions were performed by the test subject and used for analysis. To determine the required parameters in the equations of motion, many techniques were used. The center of mass position and weight of the attachment arm were found by using a balancing
technique and a scale. A segment model analysis was used to model the dynamometer attachment into measured geometric shapes to determine the mass moment of inertia. The center of mass, weight, and inertia components of the shank-foot segment were determined using anthropometric tables and the parallel axis theorem for rotation about the knee joint.

Results from Herzog’s study express maximum percent errors between the resultant joint moments and those recorded by the Cybex dynamometer to be 17.2%, 11.7%, and 24.3% for 0, 120, 240°/s isokinetic velocity trials. The angle of the Cybex dynamometer arm and angular position of the limb recorded similar angles, with the limb position being slightly smaller than the dynamometer. Herzog recommends that angular error can be reduced with a careful alignment procedure such that the error can account for 2.2% or less and may be neglected. The angular acceleration of the inertial properties of the Cybex attachment and limb segment account for error during the acceleration and deceleration stages of the isokinetic. All recommendations provided by Herzog were from a single subject test; applying percentage errors to other studies should be used with caution. Herzog’s method and procedure for calculating resultant joint moments about the knee reduce much of the error associated with isokinetic dynamometers.

C. Kaufman: Three dimensional analysis of knee exertions recorded by dynamometer

Kaufman et al. applied corrections for gravity, mass moment of inertia, and non-rigidity to a three-dimensional analysis of the system on a Cybex II Isokinetic Dynamometer [11]. The long-axis of the leg is not entirely parallel to the dynamometer arm. No previous published work had examined the motion in alternate planes of motion when using a dynamometer. Equations of motion were developed to include motion in flexion-extension, abduction-adduction, and internal-external rotation. Kaufman explored isokinetic exertions of the knee to determine the true moment applied at the joint in the three planes of motion.

The equations of motion were determined from the inverse dynamic problem solved to obtain three-dimensional intersegmental dynamics at the knee joint. Experimental setup included a tri-axial electrogoniometer that was aligned to the knee and strapped to
the thigh and shank that did not inhibit free movement. Five male subjects with no previous knee surgery or knee disorder participated in the study. A three-orthogonal strain gage was placed on the dynamometer arm to measure the applied force during isokinetic knee exertions. Results showed that rarely does the axis of rotation of the knee remain in alignment with the machine. The angular measurement between the dynamometer and electrogoniometer showed error by 7-9° in flexion and 10-13° in extension. Though the reaction force was not perpendicular to the dynamometer arm, the anterior-posterior motion contributed for 91-93% in flexion and 80-98% during extension. Error between the dynamometer moment and the resultant moment to during extension was 25-29 Nm and 5 Nm during flexion. The use of gravity correction reduced the differences for extension, but increased error in flexion.

D. Kellis alternate gravitational correction methods

Kellis compared different methods for acquiring the gravitational correction to dynamometer moment using a Biodex dynamometer and applied them to isokinetic knee exertions [7]. The first method examined was Winter’s which holds the limb and dynamometer arm horizontal to record maximum moment due to gravity [3]. Westing and Seger used a method, similar Winter’s, in the static position of 30° flexion [13, 14]. The gravitational moment at any angular position is a function of the moment at 30° and the cosine of the recorded angle. Another method, by Nelson & Duncan, presented a dynamic method for recording the gravitational components of the dynamometer arm and limb during a passive 2°/s fall at a specified position [13, 14]. Lastly, anthropometric data was used to determine gravitational affects. As a control, a reaction board measurement was used to determine the gravitational components of the limb [3].

The results suggest that the determination of gravitational moments based on anthropometric data was more accurate than dynamic and static gravity correction methods. Further investigation into the comparison of the dynamic and static methods showed significant differences. This may be due to a greater tension in the hamstring during the static gravitational method. If static or dynamic method is used, it is recommended by Kellis to use the dynamic method for determining the gravitational
correction. Overall, correction for gravitational components in isokinetic dynamometer testing is necessary for accurate resultant joint moments.

**E. Pavol: Inclusion of vibration effects and application to lower extremity joints**

The method proposed by Pavol et al. included correction for moment of inertia, gravitational components, and oscillatory artifacts induced by a Kin-COM isokinetic dynamometer [4]. Oscillatory force artifacts may be introduced by the joint attachment and the limb soft tissues. The equations of motion for the knee and hip included the oscillatory artifacts by modeling the padding on the dynamometer attachment as a Kelvin viscoelastic element. Assuming joint axis of rotation to be the same for the dynamometer and joint, a 90°/s isokinetic exertion was used to determine the stiffness and damping coefficients of the viscoelastic element. Coefficients were confirmed with drop test of a known weight onto the dynamometer attachment padding.

Equations of motion were developed for the knee, hip, and ankle. Using the coefficients of the viscoelastic element adjustments were made to the force recorded by the dynamometer. From the adjusted force, the equations of motion could be used to calculate moment at desired joint. The moments of distal limbs were included in the hip equations of motion by adding the resultant normal force and moment acting on the distal joint to the modeled segment. No viscoelastic parameters were equated with the ankle and simple equations of motion were used for plantar-flexion exertions. All variables besides the moment, velocity, and position gathered on the Kin-Com system were either measured or found using anthropometric tables.

Results for the method of gravitation, inertial, vibration, and distal joint motion correction appeared to effectively remove or reduce the error. The vibrational correction showed observable magnitude and shape of moment-angle or time relationship. Correction for vibrational effects reduces oscillatory artifacts and would preserve the system dynamics than would low-pass filtering alone.
F. Arampatiz: Correction for errors in isometric dynamometer trials on the knee and ankle

Arampatiz corrected for gravity and relative movement between the dynamometer and the joint axis of rotation during isometric exertions [12, 15]. As stated previously, gravitational error is a necessary correction to dynamometer measurement to obtain resultant joint moments. Angular differences at the joint during isometric exertions can also be significant [16, 17]. These errors were corrected for isometric tests on a Biodex System 3 Dynamometer.

Equations of motion were based on Herzog. Kinematics of the knee were recorded using an eight camera Vicon motion analysis system and isometric contractions on a Biodex System 3 dynamometer. Gravitational effects were gathered with a passive 5°/s dynamic method during knee extension phase and ankle plantar flexion phase to determine the gravitational moment for each angular position. Results showed that during isometric knee contractions the resultant moment ranged from 0.33% to 17% difference to the measured Biodex moment. Also, knee angle changed significantly during isometric contraction with an average of 3.5% difference between the dynamometer and joint axis of rotation.

Arampatiz applied gravitational and angular differences between the dynamometer and joint axis of rotation corrections to isometric ankle exertions. Previous studies found that the angular differences between the ankle joint and Biodex recorded angular position during plantar flexion can also be significant [16, 17]. Equations of motion were developed for the ankle attachment and the foot during isometric plantar flexion. Arampatiz determined about a 15° change in ankle position with respect to the dynamometer position during an isometric plantar flexion test. This motion of the foot with respect to the dynamometer significantly influences the resultant moments. Therefore, gravitational and angular position difference should be considered with isometric measurements on a dynamometer for both the knee and ankle.

III. Introduction to Proposed Method

The proposed method attempts to correct gravity moments, angular acceleration and inertia moments, and angular differences between the dynamometer and joint axis of
rotation during movement. In previous studies, gravitational effects play a significant role in measurements made using a dynamometer. Gravitational corrections have been performed in many different ways: static, dynamic, and anthropometric. Moreover, angular position difference between the dynamometer and that of the joint axis of rotation is a source of error which should be included in analysis. Most studies that correct for isokinetic dynamometer errors involve the testing of the knee joint. However, few studies have concentrated on the hip or ankle. The proposed method attempts to correct for the aforementioned errors for the knee, ankle, and hip for use in isometric and isokinetic exertions.

This investigation will also compare Winter’s method of gravitational correction and Herzog’s inverse dynamic correction with anthropometric data, to the proposed method which presents a new method for correcting for gravity. This method will also work for both isometric and isokinetic exertions. To use the above mentioned method, an approach was developed for determining the mass moment of inertia for the dynamometer attachment arms to be used in the present correction method for isometric and isokinetic exertions of the knee, hip, and ankle, applied to the Biodex System 3 dynamometer.
IV. References


Chapter 2: Determination of Mass and Inertial Characteristics of Biodex System 3 Attachments

I. Introduction

The purpose of this study was to identify the mass, center of mass (COM) location, and mass moment of inertia for the knee, hip, and ankle Biodex System 3 dynamometer attachments. These parameters will be used to correct for errors in joint moment measurements associated with gravitational and inertial effects of the dynamometer attachments. The importance of correcting for dynamometer errors has been noted in other publications [1-4].

II. Equation Formulation

Modeling the dynamometer attachment segment accurately requires the determination of distances, masses, and moments of inertia. The dimensions and mass can be measured directly, but special effort is required to estimate the moment of inertia. Two methods of estimating the moment of inertia were performed to compare their results and practicality. These included an experimental approach and model segment analysis of each subassembly element using Pro-Engineering CAD software.

Determining attachment moment of inertia, the experimental approach can be modeled as a swinging pendulum.

$$\sum M_o = \sum I_o \ddot{\theta}$$

where $M_o$ are the moments of forces acting at the point of rotation and $I\ddot{\theta}$ are the inertia and acceleration components. Figure 2.1 shows the experimental set up and the free body diagram for a simple pendulum, respectively.
Figure 2.1: a) Experimental setup with the knee attachment b) Free body diagram of pendulum experiment, $\theta$ measures the angle from where the pendulum is released, approximately 3-4°.

The main force is gravity acting on the system at the COM location, $mg$. The distance from the COM to the axis of rotation, $O$, is $r$, and $\theta$ is the angle from the vertical resting position. The equation of motion for the simple pendulum becomes:

$$-mgr \sin \theta = I_o \ddot{\theta}$$

where $I_o$ is the moment of inertia about axis $O$, and $\ddot{\theta}$ is the angular acceleration. For small angles of $\theta$, it can be assumed that $\sin \theta \approx \theta$. The equation of motion for a linear second order system is:

$$\ddot{\theta} + \frac{mgr}{I_o} \theta = 0$$

Re-writing the equation as a periodic system vibration

$$\ddot{\theta} + \omega^2 \theta = 0$$

where,
\[ \omega_n = \sqrt{\frac{mgr}{I_o}} \]

With \( \omega_n \) representing the natural frequency of the system. To find the natural frequency of the pendulum, the pendulum is pulled back to a position where \( \theta \sim 4^\circ \). The number of oscillations and the time over which they occur can be used to calculate the damping frequency, \( \omega_d \) shown in Figure 2.2.

![Figure 2.2: The oscillation of the system can be used to determine the frequency from the peaks and period of oscillations.](image_url)

\[ nT_d = \frac{n2\pi}{\omega_d} \]

Where \( n \) is the number of oscillations and \( nT_d \) is the damped period of \( n \) oscillations. The natural frequency, \( \omega_n \), is equal to the damped frequency divided by the square root of one subtracted by the decay in the system, where \( \zeta \) is the viscous damping coefficient. The viscous damping coefficient is calculated from the logarithmic decay of the peaks in oscillation.
\[ \omega_n = \frac{\omega_d}{\sqrt{1 - \zeta^2}} \]

\[ I_o = mg \frac{r}{\omega_n^2} \]

The value for \( mg \) can be determined from a scale. The final variable needed to determine the mass moment of inertia from the experiment is \( r \), the distance from the axis of rotation to the COM. To determine the attachment COM location, a segment model analysis using Pro-Engineer software was used to create a 3-dimensional model of each major geometric shape, or subassembly, of the dynamometer attachment arm. Calculating the volume of each subassembly part, and determining the density with respect to the weight measurement, the COM is located at the centroid of each geometric shape. Adding all the 3-dimensional locations of each sub-assembly centroid, the COM location of the final assembly, or dynamometer attachment arm can be found. For many of the attachments, the COM does not correspond to a point on the dynamometer attachment arm, as illustrated in Figures 2.3 of the knee attachment. To simplify, the location of the COM is characterized as the distance from the axis of rotation and the angular offset from the long dynamometer moment arm of the attachment. These are acquired from the global coordinate system of the COM in reference to the axis of rotation of the dynamometer. For purposes of the proposed method, only the COM distances and angular positions with respect to the sagittal plane of motion were used. The moment of inertia was also calculated from Pro-Engineer. The Model Analysis tool in the software uses a mathematical integration process of the volume and location of the COM to calculate the moment of inertia.
Figure 2.3: Free body diagram of COM location from axis of rotation, \( d_{CM} \) and angular offset, \( \phi \), from long axis of knee attachment. \( W_A \) is the weight of the attachment.

III. Procedure

A pendulum apparatus with an ABEC 1 bearing attached to a modified rotating cylinder was used to perform the pendulum experiments on each Biodex attachment. An electrogoniometer, Biometrics Ltd., attached to the pendulum recorded the angular position. The pendulum was released from 3-4º from the vertical and allowed to swing until it came to a complete stop. Three trials were recorded for the hip, knee, and ankle attachments at one inch increments of the variable setting range. Data was sampled at 100 Hz and filtered with a 10 Hz low-pass zero-phase-lag 4th order Butterworth filter.

The dynamometer mass and COM location with respect to the point of rotation was determined using the segment model analysis described previously. A digital vernier caliper (Mitutoyo ten-thousandth precision) was used to measure the dimension of the attachment. An average of five measurements of each geometric dimension was used to create a 3-dimensional model of each major component of the attachment, sub-assembly part. Using the Model Analysis tool in the Pro-Engineering program, the distance from the COM with respect to the axis of rotation, \( r \), and mass moment of inertia was
determined. The global coordinate system was set to the axis of rotation of the
dynamometer. From there the three axis location of the COM was equated. From the
measured geometrical parts, and the density equated from the mass and volume of the
part, the mass moment of inertia was calculated from the inertia tensor at the specified
global coordinate system. Three-dimensional figures of the attachments using Pro-
Engineer can be found in the appendix of this chapter.

All measurements and distances used for inertia and center of mass location are in
the plane parallel to the sagittal plane of the subject’s movement. Other planes of motion
are ignored as 80-99% of knee exertion is in the anterior-posterior direction [5]. All
attachments were analyzed both experimentally and with Pro-Engineering software, over
a range of attachment length settings. Figure 2.4 shows the change in attachment length
setting and the plane of motion analyzed. A linear fit was created from the results of
mass moment of inertia, COM distance from axis of rotation, and angular offset.

Figure 2.4: Shown is the knee attachment hanging freely with a setting of
10 and setting of 15. Photo shows the plane which measurements taken.
This is parallel to sagittal plane of movement when Biodex is in use by
subject.
IV. Results

Knee attachment moment of inertia values from the experiment pendulum swing showed a similar trend in slope and intercept as the segment model analysis, as shown in Figure 2.5. The experimental trend line for the knee was: Inertia=0.2548*Setting_Attachment-1.483. For the segment model analysis the trend line was: Inertia=0.2505*Setting_Attachment-1.4207 based on an average of three trials for each setting.

![Figure 2.5: Moment of Inertia for adjustable settings on the knee attachment.](image)

Figure 2.5: Moment of Inertia for adjustable settings on the knee attachment.

Figure 2.6 shows the hip attachment moment of inertia values from the experiment pendulum swing showed a similar trend in slope and intercept as the Pro-Engineer model analysis. The experimental trend line for the hip attachment was: Inertia=0.2653*Setting_Attachment-1.3957. For the segment model analysis the trend line was: Inertia=0.2808*Setting_Attachment-1.6175.
Figure 2.6: Moment of Inertia for adjustable settings on the hip attachment.

Ankle inertia values from the experiment pendulum swing showed a different trend in slope and intercept from the segment model analysis, Figure 2.7. The experimental trend line for the ankle was: Inertia=0.2001*Setting_Attachment-0.6687. For the segment model analysis the trend line was: Inertia=0.1287*Setting_Attachment-0.1447. The ankle measurements were only taken over a span of two inch attachment setting length because the ankle setting will not change largely between different subjects. The inertia between the two approaches averaged a range of 0.73-0.90 N-m² between the 6.5-8 inch settings lengths.
Figure 2.7: Moment of Inertia for adjustable settings on the ankle attachment.

Figure 2.8: Center of mass distance from axis of rotation of the Biodex dynamometer attachment arm. Trend lines for the COM distance from the axis of rotation: Knee: $y=0.0141x+0.0248$, Hip: $y=0.0162x+0.0018$, Ankle: $y=0.026x-0.0844$
The center of mass and angular offset of the center of mass from the dynamometer arm were determined for each one inch setting using Pro-Engineer. The center of mass and angular offset, \( \phi \), are dependent on attachment length. Figure 2.8 and 2.9 show the results of COM and angular offset, \( \phi \), over the range of attachment settings for the knee, hip, and ankle attachments.

![Graph showing angular offset, \( \phi \), for knee, hip, and ankle attachments.](image)

Figure 2.9: Angular offset, \( \phi \), of center of mass from the Biodex attachment arm. Trend lines for the COM distance from the axis of rotation: Knee: \( y = -0.005x + 0.1364 \), Hip: \( y = -0.0095x + 0.2273 \), Ankle: \( y = -0.0626x + 0.6133 \)

For validation purposes, the experimental and the Pro-Engineer computations of mass moment of inertia of a simple slender rod were compared to textbook mathematical computations. A slender rod of mass (1.01 kg), length (0.3048 m), and diameter (0.013 m) was used. The results, Table 2.1, from the mathematical validation showed the experimental method and Pro-Engineer analysis to have some variance to the mathematical calculation. The Model Analysis used in the Pro-Engineering software uses the integral calculation to determine the mass moment of inertia on any three-dimensional part. The textbook calculation is a simplified formula from the integral for use on a slender rod. Because the textbook calculation and the Pro-Engineer value are based from the same mathematical concept, they yield very similar results.
Table 2.1: Experimental, Pro-Engineer, and text book calculation for slender rod inertia

<table>
<thead>
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<th>Slender Rod</th>
<th>Text Book</th>
<th>Pro-Engineer</th>
<th>Experimental</th>
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<tbody>
<tr>
<td>Heavy (1.01kg)</td>
<td>0.0363 N-m²</td>
<td>0.0364 N-m²</td>
<td>0.032 N-m²</td>
</tr>
</tbody>
</table>

V. Discussion

As a result of this study, methods have been developed to determine the mass moment of inertia, COM location from the dynamometer axis of rotation, and the angular offset of the COM from the long arm of the dynamometer attachment. In addition, regression equations have been developed to predict these values for any attachment length setting.

Both the experimental method and Pro-Engineering analysis produced similar results for the mass moment of inertia. The experimental method could yield different results depending on the number of peaks examined and the zero degree threshold value. The farther away the COM was from the axis of rotation in the pendulum experiment, the more reliable the results. The potential energy of the system is greater when the COM is at a further distance from the axis of rotation creating more oscillations and therefore easier to characterize. The friction coefficient of the bearing can also be a source of error in the pendulum experiment. For the ankle attachment, the COM is close to the axis of rotation yielding few peaks and oscillations to analyze.

The errors are of importance when applying the experimental method are presented. As shown by the results in Table 2.1, the inertia values for a slender rod were influenced by some experimental error. For best results, the larger number of oscillations recorded, the more accurate the natural frequency can be determined. It was observed during the experimental testing of the ankle attachment that few oscillations occurred. This may account for the differences in the moment of inertia values between the experimental and the Pro-Engineer model analysis values.

The center of mass has previously been determined using various balancing techniques [1]. In this work, segment model analysis was used from dimensions of the major geometric components of the dynamometer attachment arm. Dimensions of each sub-assembly part were measured to one-hundredth of a millimeter to determine the
centroid of the each geometric shape. Uniform density was assumed of each geometrical modeled part. As shown in the photos and appendix diagrams of the Pro-Engineer drawings, the center of mass of the attachments does not correspond to a location directly on the dynamometer arm, but rather a floating point. The current method can determine the COM location and distance from the axis of rotation of the dynamometer arm, which is also a floating point inside the connecting end to the Biodex dynamometer. It was felt that measuring the center of mass distance from the axis of rotation using a balancing technique would only be a rough measurement and possible source of error when applied. Therefore, segment model analysis was used for COM location.

Of the present methods, it is recommended to use Pro-Engineer, or other CAD software be to determine the COM location, and moment of inertia values. Taking careful measurements of the geometric shapes, both of COM location and moment of inertia can be calculated and modeled. The parameters calculated in this chapter will be used in the following chapters to correct for errors equated with the dynamometer attachments during isometric and isokinetic exertions.

VII. References
Figure 2.A: Right knee attachment as produced on Pro-Engineer. The center of mass is represented by the three dimensional coordinate marker.
Figure 2.B: Right hip attachment as produced on Pro-Engineer. The center of mass is represented by the three dimensional coordinate marker.
Figure 2.C: Right ankle attachment as produced on Pro-Engineer. The center of mass is represented by the three dimensional coordinate marker.
Chapter 3: Calculating Knee Moment with a Biodex System 3 Isokinetic Dynamometer

I. Introduction

This chapter presents a method for calculating knee torque with a Biodex System 3 Dynamometer. This method uses the Biodex attachment parameters determined in Chapter 2 along with two rigid segment models: one of the Biodex attachment, and one of the lower extremity. The known sources of error that this method attempts to address are: gravity, acceleration and inertia moments, and correction for relative angular movement between the dynamometer and joint axis of rotation during isokinetic and isometric exertions. This method is different from others in that it proposes a new method for gravitational correction. Validation of this method is performed by applying known static loads during isometric testing. This method is also compared to other methods during isometric and isokinetic exertions.

II. Equation Formulation

To calculate the resultant knee joint moment ($M_j$) from the recorded Biodex dynamometer moment ($M_B$), the system is modeled as two rigid body segments: the dynamometer arm and the shank-foot segment. Shown in Figure 3.1 are the free body diagrams of both segments. All terms are defined in Table 3.1.
Figure 3.1: a) Free body diagram of the Biodex attachment arm. b) free-body diagram of the shank-foot segment.

Table 3.1: Identified variables in the free body diagram.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_B$</td>
<td>moment recorded by the Biodex dynamometer</td>
</tr>
<tr>
<td>$F_S$</td>
<td>force the subject applies on the Biodex attachment</td>
</tr>
<tr>
<td>$W_A$</td>
<td>weight of the Biodex attachment</td>
</tr>
<tr>
<td>$I_B$</td>
<td>moment of inertia of the Biodex attachment about the axis of rotation</td>
</tr>
<tr>
<td>$L_B$</td>
<td>distance from axis of rotation of the Biodex attachment to $F_S$</td>
</tr>
<tr>
<td>$l_1$</td>
<td>distance of attachment connector</td>
</tr>
<tr>
<td>$l_2$</td>
<td>distance of adjustable Biodex arm</td>
</tr>
<tr>
<td>$L_{WA}$</td>
<td>distance between COM of the and the axis of rotation Biodex arm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle of Biodex arm to the horizontal</td>
</tr>
<tr>
<td>$\phi$</td>
<td>offset angle from Biodex attachment to COM</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>angle of force application on the Biodex arm</td>
</tr>
<tr>
<td>$M_j$</td>
<td>resultant joint moment at the knee joint</td>
</tr>
<tr>
<td>$F_B$</td>
<td>the force of the Biodex on the subject</td>
</tr>
<tr>
<td>$W_{sf}$</td>
<td>weight of the human shank-foot</td>
</tr>
<tr>
<td>$I_{SF}$</td>
<td>moment of inertia of the shank-foot about the axis of the knee joint</td>
</tr>
<tr>
<td>$L_F$</td>
<td>distance from joint axis of rotation to $F_B$</td>
</tr>
<tr>
<td>$L_g$</td>
<td>distance between COM of the human shank-foot segment and axis of rotation at the knee joint</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>angle of knee joint with respect to the shank and thigh relative to the horizontal or anatomical position</td>
</tr>
</tbody>
</table>
The first step of the analysis involves using the free body diagram in Figure 3.1a to calculate the force the subject applies to the Biodex attachment arm (\(F_s\)) from the moment recorded by the Biodex (\(M_B\)). The moment applied by the shank is the perpendicular force applied at a distance from the axis of rotation to the point of force, \(L_F\). To find the distance from the force to the axis of rotation, the law of cosines is used because \(\gamma\) is not a right angle.

\[
c^2 = a^2 + b^2 - 2ab \cos(\gamma)
\]

Figure 3.2: Law of cosines is used to determine the normal force of the force applied by the shank on the Biodex attachment.

Using this on our model attachment, the equation for the distance from the \(F_s\) to the center of rotation becomes:

\[
d_{SF}^2 = a^2 + L_B^2 - 2a(L_B)\cos(\gamma)
\]

where

\[
L_B = l_1 + l_2
\]

the variable attachment length as shown in Figure 3.1.

Now that the distance to the force from the center of rotation is found, adjustments are made to find the normal force from the force applied by the shank. Use law of cosines again to find the angle, \(\beta\).

\[
\cos\beta = \frac{a^2 - b^2 + c^2}{2ac} = \frac{a^2 - L_B^2 + d_{SF}^2}{2ad_{SF}}
\]

The moment from the force, \(F_s\), applied to the Biodex arm from the shank is:
The moments acting on the Biodex arm are the moment applied by the force from the shank, and the moment from the gravity/COM of the attachment by its perpendicular distance to the axis of rotation. The COM location will change as the adjustable length of the Biodex arm changes \( l_2 \). The Biodex attachment COM is located by \( \varphi \), the angle between the COM and the attachment arm and the distance from axis of rotation to COM, \( L_{WA} \). These were previously determined in Chapter 2.

The gravitational moment of the dynamometer attachment is:

\[
M_s = W_A L_{WA} \cos(\theta + \varphi)
\]

Summing the moments about the axis of rotation of the Biodex, \( M_B \), the equation of motion becomes:

\[
\sum M_B = I_B \ddot{\theta} - M_B - M_g + M_F = I_B \ddot{\theta} - M_B - W_A L_{WA} \sin(\theta + \varphi) + F_S d_{FS} \sin(\beta) = I_B \ddot{\theta}
\]

From this equation we can find the unknown, \( F_S \).

\[
F_S = \left( M_B + W_A L_{WA} \sin(\theta - \varphi) + I_B \dot{\theta} \right) / d_{FS} \sin(\beta)
\]

The next step of the analysis involves using the free body diagram in Figure 3.1b to calculate the joint moment \( (M_j) \) from the force \( F_B \). To begin, Newton’s second law is applied; the force applied by the shank \( (F_S) \) is equal to the force applied by the Biodex, \( (F_B) \). Using an anthropometric table [1], the COM location for the combined shank-foot segment and the moment of inertia of the shank-foot segment is determined. Applying the parallel axis theorem, inertia about the knee joint \( (I_{SF}) \) is then calculated.

\[
I_{CG} = M_{body} m(l_{segment} r)^2
\]

\[
I_{SF} = I_{CG} + (M_{body} m_{segment}) L_g
\]

where \( r \) is the percent radius of gyration of the segment length, \( m \) is the percent body mass of the shank-foot segment from the body mass \( M_{body} \), and \( L_g \) is the distance from the COM location to the axis of rotation at the knee joint. Finally summing the moments about the axis of rotation of the knee, the equation of motion becomes:
\[
\sum M_j = I_{sf} \ddot{\alpha} \\
M_j - F_B L_f - W_{sl} L_g \cos(\alpha) = I \ddot{\alpha} \\
M_j = I \ddot{\alpha} + F_B L_f + W_{sl} L_g \cos(\alpha)
\]

III. Procedure

To determine the moment about the joint \( (M_j) \), one male (25yrs, 74.8 kg, 1.78m) performed a series of isometric and isokinetic exertions on a Biodex System 3 dynamometer. While standing, a one degree of freedom custom-made electrogoniometer was placed on the lateral epicondyle and aligned with the greater trochanter and lateral malleolus. Electrogoniometer position was recorded and adjusted to zero degrees flexion in the anatomical position. The subject was seated in the dynamometer chair at 85º hip angle from the horizontal, Figure 3.3. The thigh and pelvis were strapped securely to the chair and the shank was strapped to the Biodex attachment arm. Care was taken to align the rotation of the dynamometer with the rotation of the knee joint, which was defined as the point at the lateral epicondyle. Setting length of the Biodex arm was recorded as 13.5 setting. Range of motion was from full extension to 90º flexion.

Figure 3.3: Biodex setup for knee exertions.
Moments due to gravity were recorded from an isometric rest at full extension of subject’s limb. Passive 4º/s trial was recorded from 3 repetitions in the range of motion of 10-90º knee flexion. The final repetition in the passive trial was used in further analysis. Both flexion and extension isometric tests performed at 10, 30, 60 and 90º knee flexion. Both flexion and extension isokinetic concentric tests were performed at 30, 90, and 180º/s. After subject testing, additional tests were performed without the subject using the same range of motion and attachment settings, the isometric rest, and passive 4º/s trials to calibrate the gravitational effect of the Biodex arm.

Biodex attachment position, velocity, torque, and electrogoniometer output were sampled at 200 Hz throughout all testing exertions. All tests were on the body segments on the right side of the body. All raw data was filtered at 4th order 1Hz zero-phase shift Butterworth filter.

First, the gravitational correction moment for the Biodex arm was taken from the non-subject passive 4º/s trial, gathered post experiment, to determine gravitational moments at any angular position within the set range of motion. Acceleration to the passive trial occurs at the ends of the range of motion. With little acceleration and no external forces applied, the major influencing moment during the passive trial is from gravitation components on the Biodex attachment arm. The Biodex attachment gravitational moment can then be characterized as a function of the dynamometer angular position. The gravitational moment of the Biodex attachment, $M_g$, was simplified to the passive moment/angular position data as a 3rd order polynomial, Figure 3.4. This method accounts for the mass, gravity, distance to COM ($L_{WA}$), and the angular offset of the COM ($\phi$).
Figure 3.4: Sample data of the moment of gravity of the Biodex attachment arm and angular position recorded by the dynamometer arm during a passive 4°/s trial. The data is then fit to a 3rd order polyfit line.

The process was then repeated with the passive trial with the test subject to create a 3rd order polyfit that includes gravitational moment of the shank-foot segment. The gravitational correction polyfit from the Biodex arm was subtracted from the dynamometer moment to obtain the gravitational moments of the shank-foot segment. This was fit to a 3rd order polynomial at each angular position according to the electrogoniometer recorded position. Sample data from a single range of motion passive 4°/s trial is shown in Figure 3.5.
Figure 3.5: Sample data of moment of the shank-foot versus angular position recorded by the electrogoniometer during a passive 4°/s trial. The data is then fit to a 3rd order polyfit line.

The equations of motion are then used for the isometric and isokinetic tests. Using gravitational polyfit for the Biodex attachment, $M_g$, inertia and acceleration moments, and the recorded dynamometer readings, the force applied by the shank, $F_S$ can be determined. The equation of motion for the shank-foot can be used to calculate the resultant joint moment from the calculated value of $F_S$, the gravitational polyfit for the shank foot, and the remaining parameters obtained from anthropometric table [1].

The approach for a polyfit function to describe the gravitational effects was supported from findings by Helwig [2]. While testing the reliability of dynamometers, it was noted that there was a small difference in gravitational values existing at different angles. A test conducted previously on the Biodex attachment arm found that the gravitation correction was only correct when the offset angle, $\varphi$, was included in the cosine of the angular position of the gravitational moment calculation: $M_g = mg\cos(\theta + \varphi)$. To simplify the calculations, a polyfit line of 3rd order was fit to the passive data. For similar reasons it was also employed to determine the gravitational
moments of the shank-foot for reasons that the angular offset of the COM in the human limb segment can not be accurately determined, and differs between subjects.

Results from the method proposed here were compared to Winter’s and Herzog’s published methods [3, 4]. Winter’s method corrected for gravitational components from the isometric test. The obtained moment at the recorded angle (10º flexion) is the gravitational correction moment. This gravitational moment became a function of the resultant moment multiplied by the cosine of angular position. The gravitational moment was subtracted from the moment of the Biodex to obtain the gravity corrected values.

In Herzog’s method, the variables in the equation of motion were used for the Biodex attachment arm previously determined in Chapter 2. The length of the shank was measured with a measuring tape and the subject’s body weight was found from a scale. With the gathered subject data, the location of the COM and the moment of inertia of the shank were obtained from anthropometric percentage tables [1]. Angular position of the knee was obtained from the electrogoniometer. The equations of motion were used to determine the resultant moment about the knee.

IV. Results

Prior to using the proposed method with isokinetic and isometric testing, validation of the described method was necessary. Sample results are shown for a validation test in which a moment of 29N-m was applied while the subject was at 30° flexion. The subject was instructed to rest and avoid applying any muscle contractions at the knee joint. A 11.4 kg weight applied a force on the dynamometer attachment arm at a distance parallel to the connection point of the shank-foot to the attachment. Since the subject was at rest assuming no additional moments was applied from the muscles at the joint. The known applied moment simulates a moment applied at the knee joint. Figure 3.6 shows the moment recorded by the Biodex and the moment as calculated from the proposed method. Testing at 30, 45, 60º knee flexion in both flexion and extension yield reasonable results as further validation.

Representative samples of the results from applying the proposed method are shown for isometric and isokinetic tests in Figures 3.7-3.9. The isometric extension test at 30º knee flexion, shown in Figure 3.7 are the moment recorded by the Biodex, Winter’s
attachment and limb gravitational correction, Herzog’s anthropometric correction, and the current method proposed. For the first portion of the test the subject is not exerting any moment at the knee joint. The correct moment at the knee joint should then be zero when all gravitational components are corrected. Differences between the compared methods are observable at the resting state and also during the isometric exertion. Moment recorded by the Biodex includes gravitational effects to the recorded data and does not accurately determine the moment applied at the knee joint. Winter’s gravitational correction overestimates in the resting state, while Herzog’s anthropometric method underestimated during the resting state. From this plot, it appears as if both Winter and Herzog methods will not accurately determine the isometric contraction if normalized at rest.

Figure 3.6: An applied moment of 29 N-m is applied to the Biodex arm while the subject is at rest at a 30° flexion. Shown are the Biodex moment reading, the calculated moment from the proposed method, and comparison methods from Winter and Herzog.
Figure 3.7: Isometric concentric knee extension test at 30° knee flexion. Prior to exertion the subject is at rest.

Figure 3.8 is an isokinetic test at 30°/s extension, and Figure 3.9 is 30°/s flexion. In each case the proposed method (Herrmann) appears to have more accurate results for the unloaded condition. Prior to the knee extension exertion, the subject was at rest, so the resultant moment produced by the knee should approximately be zero. The Biodex moment and Winter’s gravitational correction do not estimate the initial moment of the trial to be zero. The anthropometric method, Herzog, showed similar characteristics to the proposed method during the entire exertion.
Figure 3.8: Isokinetic concentric knee extension test at 30°/s. Biodex recorded moment underestimates throughout the trial. Winter method overestimates. Herzog and proposed method (Herrmann) have consistent similar moments.

During the isokinetic knee flexion at 30°/s, there were noticeable differences between the multiple methods, Figure 3.9. An isokinetic test in flexion cannot begin with a zero moment produced by the knee, the gravitational moments of the shank and attachment arm must be exceeded to reach full extension prior to the flexion exertion. The moment shown by Winter’s method, Herzog’s method, and the proposed method prior to the exertion support this. As the trial ends, Herzog’s and the proposed method observe the approach zero moment applied by the knee joint.
Figure 3.9: Isokinetic concentric knee flexion exertion at 30°/s. Prior to exertion, the knee joint must apply enough force to hold the attachment arm and shank-foot segment at near horizontal position before flexing, as shown in this plot.

Large differences were observed in the angular position between the Biodex recorded position and the electrogoniometer. Figure 3.10 contains samples of the position data from an isometric and isokinetic test. For the isometric test, there was a large difference in angular position between the Biodex and the electrogoniometer. During the isokinetic test the electrogoniometer range of motion was smaller than that of the Biodex dynamometer.
Figure 3.10: The angular positions as recorded by the Biodex and the electrogoniometer attached at the lateral epicondyle of the knee. a) the angular values of the Biodex and the electrogoniometer during an isometric knee exertion at 30° knee flexion. b) the angular position of the Biodex arm and the electrogoniometer reading during an isokinetic concentric knee extension 30°/s exertion.

V. Discussion

The method proposed appears to reduce the effects of gravity, angular acceleration and inertia moments, and relative angular position movement between dynamometer and the joint axis at the knee and is unique in determining the gravitational moment correction. Validation test of a known applied moment showed results of the
The proposed method shows a better estimate of the resultant joint moment than the other methods.

Gravity, angular acceleration and inertia moment, and relative angular position between the Biodex dynamometer and joint axis of rotation were corrected for in the proposed method. The need for gravitational correction is noted and methods of correction have been published in literature [3-6]. Winter’s method only took gravitational components from an isometric resting position. Herzog took gravitational components from measured or anthropometric tables. The proposed method uses a 3rd order polynomial fit equation to depict the gravitational correction for both the Biodex arm and shank-foot segment. This method includes the mass, gravity, perpendicular distance to the COM, and angular offset of the COM to dynamometer arm into the equation of motion. This method simplifies the necessary measurements to fill the equations of motion by gathering them in a passive test over the pre-determined range of motion.

However, corrections developed by Winter and Herzog, did not accurately predict the isometric exertion. Prior to an isometric exertion, the moment applied by the joint should be small, approximately zero. Winter and Herzog’s methods showed moment at the resting point prior to and after the exertion. This was also not consistent over the different angles of isometric testing. The proposed method was reasonably consistent at zero moment prior to exertion and over all isometric angles tested.

During the isokinetic testing it was observed that the Biodex moment underestimates the resultant knee joint during extension and overestimates during flexion. This is in compliance with other published results [4]. Prior to knee extension exertion, the leg was at rest at approximately 90° flexion. In this state, little to no gravitational effects should be occurring. Winter’s gravitational correction overestimated the isokinetic trial prior to exertion. Herzog’s anthropometric correction approximately matched the proposed method. Kellis noted that anthropometric method is more accurate during an isokinetic test than gravitational correction as validated here [6].
The observed differences between the Biodex angular position and the electrogoniometer can significantly influence the resultant moment [7]. The motion of the knee may be due to deformation of soft tissues of the leg, or alignment issues with the dynamometer [4, 6, 7]. Care to obtain proper alignment was taken when positioning the subject with the dynamometer and little difference in the angular position was found during the gravitational testing, though the electrogoniometer range of motion was always less than that of the Biodex, also noted by Herzog [4]. It is most likely that the soft tissue causes a significant deformation and therefore an angular difference between the Biodex and electrogoniometer. This problem is difficult to prevent or control because the properties of soft tissues can vary among subjects and be influenced by length or change in shape during activation [7]. Kaufman et al. reported about a 10-13° difference between angular motion during isokinetic knee extensions [8]. Arampatzis found error of 10-15° during isometric exertions [7]. These values are in agreement with the present study.

Assumptions made when determining the equations of motion include the force of the shank acting on the Biodex is perpendicular to the pad on the Biodex attachment. Another is the foot and shank is one segment and the foot does not add any additional moment to the free body diagram. Another possible source of error is the influence of tissue movement on the electrogoniometer position.

The proposed method appears to have more improved results than those from a simple gravitational correction and use of anthropometrics in a two rigid body system. Use of the 3rd order polyfit gravitational equation shows reasonable correction for the gravitational components of the system in comparison to the other methods. The proposed method is advantageous because it provides a method that corrects of gravitational, includes acceleration and inertia moment correction, and relative angular position between dynamometer and joint axis of rotation in both the isometric and isokinetic testing. Another advantage of the proposed method is that it provides a method for correcting the above mentioned errors, based on the specific design and geometry of the Biodex System 3 Dynamometer. Use of the proposed method is recommended in estimating the resultant moment of the knee joint.
VII. References


Chapter 4: Calculating Ankle Moment with a Biodex System 3

Isokinetic Dynamometer

I. Introduction

This chapter presents a method for calculating ankle moment from a Biodex System 3 Dynamometer. This method uses the Biodex attachment parameters determined in Chapter 2 along with a rigid segment model of the foot. The known sources of error this method attempts to address are: gravity, angular acceleration and inertia moment, and correction for relative angular movement between the dynamometer and joint axis of rotation during isokinetic and isometric exertions. This method is also compared to other methods during isometric and isokinetic exertions.

II. Equation Formulation

To calculate the resultant knee joint moment ($M_j$) from the recorded Biodex dynamometer moment ($M_B$), the system is modeled as two rigid body segments: the dynamometer attachment and the foot segment. Shown in Figure 4.1 are the free-body diagram of the ankle attachment and the foot. All terms are defined in Table 4.1.

![Figure 4.1](image)

Figure 4.1: a) Free body diagram of the Biodex ankle attachment arm. b) Free body diagram of the foot segment. The two rigid body segments are used to calculate the resultant moment at the ankle joint.
The first step of the analysis involves using the free body diagram in Figure 4.1a to calculate the force the subject applies to the Biodex attachment arm ($F_S$) from the moment recorded by the Biodex ($M_B$). The moment applied by the foot occurs at the 5th metatarsal head, perpendicular to the ankle platform at a distance, $L_B$:

$$M_F = F_S L_B$$

where $L_B$ distance is dependent on the anthropometric measurements of the subjects foot and placement on the ankle attachment platform. The location of the head of the 5th metatarsal, the point of application of $F_S$, on the ankle platform is determined from the location of the heel:

$$\text{Heel} = 0.0254(0.35(S_{pf}) - 2.65)$$

$$L_B = \text{Heel} + A_{\text{meta}} + H_{\text{ankle}}$$

$S_{pf}$ is the platform setting of the heel cup situated to hold the subjects foot in place during testing. $A_{\text{meta}}$ is the distance from the malleolus to the head of the 5th metatarsal; $H_{\text{ankle}}$ is the distance from the heel to the malleolus as gathered from anthropometric tables [1].

The gravitational moment of the Biodex attachment is characterized by the distance from the axis of rotation to the attachment COM, $L_{gB}$, and angular offset, $\varphi$. These were determined from methods discussed in Chapter 2. The equation for the gravitational moment becomes

$$M_g = W_A L_{gB} \sin(\theta - \varphi)$$

Summing the moments about the axis of rotation of the Biodex, the equation of motion becomes:
\[ \sum M_B = I_B \ddot{\theta} \]
\[ M_B + M_g + M_F = I_B \ddot{\theta} \]
\[ M_B + W_A L_g B \cos(\theta + \phi) + F_s L_B = I_B \ddot{\theta} \]

From this equation we can find the unknown force applied by the subject, \( F_s \).

\[ F_s = -I_B \ddot{\theta} + W_A L_g B \cos(\theta + \phi) + M_g / L_B \]

The next step of the analysis involves using the free body diagram in Figure 4.1b to calculate the joint moment \( (M_j) \) from the force \( F_B \). To begin, Newton’s second law is applied; the force applied by the shank \( (F_S) \) is equal to the force applied by the Biodex, \( (F_B) \). Using an anthropometric table, the COM location and the moment of inertia of the foot segment is determined. Applying the parallel axis theorem, inertia about the ankle joint \( (I_{SF}) \) is then calculated.

\[
I_{CG} = M_{body} m (I_{segment})^2
\]
\[
I_{SF} = I_{CG} + (M_{body} m_{segment}) L_g
\]

where \( r \) is the percent radius of gyration of the segment length, \( m \) is the percent body mass of the foot segment from the body mass \( M_{body} \), and \( L_g \) is the distance from the COM location to the axis of rotation at the ankle joint. Finally summing the moments about the axis of rotation of the ankle, the equation of motion becomes:

\[
\sum M_j = I_{A} \ddot{\theta}
\]
\[
-M_j + W_F L_g \cos(\alpha - \gamma) - F_B L_F = I_A \ddot{\theta}
\]
\[
M_j = I_{A} \ddot{\theta} + F_B L_F + W_F L_g \cos(\alpha - \gamma)
\]

where \( \gamma \) is the angular position of the COM of the foot from the perpendicular to the plantar surface of the foot.
III. Procedure

One subject (25yrs, 74.8 kg, 1.78m), performed a series of isometric and isokinetic exertions on a Biodex System 3 Dynamometer. The subject was seated in the dynamometer chair with 85° hip flexion and the shank resting in a horizontal position, Figure 4.2. The subject was strapped at the pelvis and thigh to restrict any leg or torso movement. The lateral malleolus was carefully aligned with the axis of rotation of the dynamometer arm. An electrogoniometer was placed on the medial malleolus and secured to the subject’s foot and shank prior to experimentation. Straps were used to secure the foot to the ankle attachment platform. Range of motion was set for 25° plantar flexion and 20° dorsiflexion. A passive 4°/s trial was also used to determine the gravitational components. To compare the proposed method with others, moments due to gravity were recorded from an isometric rest and 20° plantar flexion. Isometric tests were exerted at 0, 10, and 20° plantar flexion, and 15° dorsiflexion from the anatomical position. Isokinetic tests were exerted at 30, 90, and 180°/s in plantar flexion and dorsiflexion. After subject testing, with the same range of motion and attachment settings, the isometric rest, and passive 4°/s trials without the subject were recorded to calibrate the gravitational effect of the Biodex arm.

Biodex attachment position, velocity, torque, and electrogoniometer output were sampled at 200 Hz throughout all testing exertions. All tests were on the body segments on the right side of the body. All raw data was filtered at 4th order 1Hz zero-phase shift Butterworth filter.
First, for the proposed method, the gravitational correction moment for the Biodex arm was taken from the non-subject passive 4°/s trial, gathered post experiment, to determine gravitational moments at any angular position within the set range of motion. The gravitational moment of the Biodex attachment, $M_g$, was simplified to the passive moment/angle data as a 3rd order polynomial. This method accounts for the mass, gravity, distance to the COM, $L_{gb}$, and the angular offset of the COM, $\phi$.

The process was then repeated with the passive trial with the test subject to create a 3rd order polyfit that includes gravitational moment of both the Biodex arm and the foot segment. The gravitational correction polyfit from the Biodex arm was subtracted from the combined gravitational moment recorded from the Biodex. The remaining moment was associated with the gravitational component of the foot. This was then polyfit to obtain the gravitational moments of the foot segment at each angular position with respect to the electrogoniometer angular position. The equations of motion are then used to determine the force applied by the shank, $F_s$, using the gravitational polyfit correction equation and the dynamometer reading, $M_g$, the inertia of the dynamometer attachment from Chapter 2, and moment recorded by the Biodex. The remaining variables used to
determine the resultant joint moment of the ankle are obtained from an anthropometric table [1], and polyfit gravitational correction to the electrogoniometer angular position reading.

Results from the method proposed here were compared to Winter’s and Herzog’s published methods [2, 3]. Winter’s method corrected for gravitational components from the moment recorded at 20° plantar flexion. This gravitational moment became a function of the 20° plantar flexion moment multiplied by the cosine of angular position to obtain the resultant moment of the ankle joint. The gravitational moment was subtracted from the moment of the Biodex to obtain the gravity corrected values.

Implementing Herzog’s method, the variables in the equation of motion were used for the Biodex attachment arm previously determined in Chapter 2. The length of the foot was determined with a measuring tape, and the subject’s body weight was found from a scale. With the gathered subject data, the location of the COM and the moment of inertia of the foot were obtained from anthropometric percentage tables [1]. Angular position of the ankle was obtained from the electrogoniometer. The equations of motion were used to determine the resultant moment about the ankle.

IV. Results

Representative samples of the results from applying the proposed method are shown for isometric and isokinetic tests in Figures 4.3-4.6. The isometric tests, plantar flexion and dorsiflexion, at 0° ankle plantar flexion, shown in Figure 4.3 and 4.4 have the moment recorded by the Biodex, Winter’s method, Herzog’s method, and the current method proposed. For the first portion of the test the subject is not exerting any moment at the ankle joint. The correct moment at the ankle joint should then be zero when all gravitational components are corrected. Differences between the compared methods are observable at the resting state and also during the isometric exertion. Moment recorded by the Biodex includes gravitational effects to the recorded data and does not accurately determine the moment applied at the ankle joint. Winter’s gravitational correction overestimates in the resting state, Herzog’s anthropometric method underestimates during the resting state. Both Winter and Herzog methods will not accurately determine the isometric contraction if normalized at rest.
Figure 4.3: Isometric ankle plantar flexion at zero degrees ankle plantar flexion.

Figure 4.4: Isometric dorsiflexion at zero degrees ankle plantar flexion.
Figure 4.5 is an isokinetic test at 30°/s plantar flexion across two consecutive exertions. Prior to the exertion, the subject must move the dynamometer platform to the beginning of a plantar flexion range of moment. To do this, the subject applied a dorsiflexion moment as shown by the positive moment prior to the plantar flexion exertion (negative moment).

Figure 4.5: Isokinetic 30°/s concentric ankle plantar flexion

During the isokinetic ankle dorsiflexion at 30°/s, there were noticeable differences between the multiple methods, Figure 4.6. The moment at the COM of the Biodex
attachment creates a large moment such that the resting point of the entire attachment and foot is at the full range of motion of plantar flexion. Prior to a dorsiflexion concentric exertion, the system rests at the plantar flexion position, therefore the resultant moment at the ankle joint should be zero. The Biodex moment, Winter’s, and Herzog’s gravitational corrections did not estimate the initial moment of the trial to be zero.

![Figure 4.6: Isokinetic 30°/s concentric ankle dorsiflexion](image)

Figure 4.6: Isokinetic 30°/s concentric ankle dorsiflexion

Angular position during isokinetic trials showed displacement towards final range of motion in plantar flexion. Figure 4.7 displays the results of the position data gathered
from the electrogoniometer and Biodex axis of rotation. Angular position difference was also found in isometric tests. The difference ranged from 2-5° during the exertion.

![Figure 4.7: Position of the ankle with respect to the dynamometer position during a 30°/s Isokinetic exertion](image)

**V. Discussion**

The method proposed appears to reduce the effects of gravity, acceleration and inertia, and relative angular position movement on the joint moment at the ankle and is unique in determining the gravitational moment correction. Results shown were similar to those found in the knee test. The unique approach to calculating the gravitational correction with a 3rd order polynomial fit to the passive testing allowed for a large correction error compared to Winter’s and Herzog’s methods.

Few studies have been found that correct for gravitation, mass moment of inertia, and misalignment errors during ankle exertions. Pavol and Arampatiz developed inverse dynamic equations to determine the actual moment applied by the ankle joint. Pavol included gravitational and mass moment of inertia of the dynamometer attachment as
well as the foot during isokinetic testing [4, 5]. Arampatiz’s dynamic equations corrected for gravitational and relative motion of the ankle joint to the dynamometer axis of rotation.

Heavy attachment added a large moment for the subject to overcome in isokinetic exertions prior to plantar flexion concentric exertion. A dorsiflexion exertion can start at rest from plantar flexed range of motion without any necessary joint activation to hold the attachment in place because of the gravitational moment of the Biodex attachment and range of motion. This is just the opposite for plantar flexion exertions. To begin the range of motion for a plantar flexion exertion, the test subject must exert a substantial moment against the Biodex gravitational moment to rotate the ankle attachment to the initial range of motion before a plantar-flexion exertion can begin. This has not been established in previous studies and may be a large source of error when determining the maximum exertion applied.

Other sources of error include the angular position between the dynamometer and the ankle joint. Differences have been published during isometric exertion of the ankle [5-7]. Motion between forefoot and rear foot can reach 7-9 ° [5]. These differences were also found in the current study and are a source or error during the isometric tests, and may influence isokinetic trials as well.

Assumptions made when determining the equations of motion include: the force of the foot acting on the Biodex occurs at the position of the 5th metatarsal head perpendicular to the platform at a distance from the axis of dynamometer rotation. A possible cause of error is the heel pad and straps used to secure the ankle to the ankle attachment platform, resulting from the elasticity, which could allow movement of the foot from the ankle platform during exertions. Another possible source of error is the influence of tissue movement on the electrogoniometer position.

The results obtained with the proposed method appear be more accurate than those from a simple gravitational correction (Winter) and use of anthropometrics in a two-rigid-body system (Herzog). The ankle angle changes during an isometric test and has a smaller range of motion than the Biodex. The proposed method has the advantage because it provides a method that corrects the sources of error and works in both the
isometric and isokinetic testing. Use of the proposed method is recommended in estimating the resultant moment of the ankle joint.

VI References


Chapter 5: Calculating Hip Moment with a Biodex System 3 Isokinetic Dynamometer

I. Introduction

This chapter presents a method for calculating resultant hip moment from a Biodex System 3 Dynamometer. This method uses the Biodex attachment parameters determined in Chapter 2 along with a rigid segment model of the thigh and shank-foot segments. The known sources of error it attempts to address are gravity, mass moment of inertia, and additional moments from distal limb segments. This method is different from others reported in literature in that it uses the gravitational correction method for the dynamometer attachment used in Chapter 3 and 4 while modeling the thigh and shank-foot as two rigid segments connected by a frictionless joint.

II. Equation Formulation

The knee movement is important to the calculation of the moment about the hip because it may add error into the calculated moment about the hip joint. The thigh and shank-foot segment are modeled as a two-link planar manipulator design. To begin, the equations of motion for the thigh and shank-foot limb segments are developed by identifying the three types of torque influencing the system: 1) Inertial torques, which are proportional to the acceleration. They are caused by the acceleration of the driven joint itself and by the accelerations of the joints. 2) Coriolis torques which are proportional to the product of two joint velocities. 3) Centripetal torques which are proportional to the square of other joint velocities and are caused by a rotation of a link around a point. Static torques are mainly caused by the gravity force and are proportional to the vertical gravity component. The Euler-Lagrange equation of motion for a two-link planar manipulator is used to identify the torque at the hip and also at the knee. Figure 5.1 illustrates the free body diagram of the Biodex attachment arm and the two rigid segments connected by a frictionless joint of the thigh, shank-foot limb segments [1]. Table 5.1 lists the variables in the free body diagram and equations of motion.
Figure 5.1: Free body diagrams of the Biodex attachment arm, and the thigh and shank-foot, two rigid segments connected by a frictionless joint.

Table 5.1: Identified variables in the free body diagram.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_B$</td>
<td>moment recorded by the Biodex dynamometer</td>
</tr>
<tr>
<td>$F_S$</td>
<td>force the subject applies on the Biodex arm</td>
</tr>
<tr>
<td>$W_A$</td>
<td>weight of the Biodex arm</td>
</tr>
<tr>
<td>$I_B$</td>
<td>moment of inertia of the Biodex arm</td>
</tr>
<tr>
<td>$L_B$</td>
<td>distance from axis of rotation of the Biodex arm to $F_S$</td>
</tr>
<tr>
<td>$L_{gB}$</td>
<td>distance between COM of the Biodex arm and the axis of rotation Biodex arm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle of Biodex arm to the horizontal</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>offset angle from Biodex arm to center of mass</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>angle of force application on the Biodex arm</td>
</tr>
<tr>
<td>$M_j$</td>
<td>resultant joint moment at the hip joint</td>
</tr>
<tr>
<td>$M_{j2}$</td>
<td>resultant joint moment at the knee joint</td>
</tr>
<tr>
<td>$F_B$</td>
<td>the force of the Biodex on the subject</td>
</tr>
<tr>
<td>$m_1$</td>
<td>mass of thigh segment</td>
</tr>
<tr>
<td>$m_2$</td>
<td>mass of shank-foot segment</td>
</tr>
<tr>
<td>$I_1$</td>
<td>inertia of the thigh</td>
</tr>
<tr>
<td>$I_2$</td>
<td>inertia of the shank-foot</td>
</tr>
<tr>
<td>$L_F$</td>
<td>distance from joint axis of rotation to $F_B$</td>
</tr>
<tr>
<td>$L_1$</td>
<td>distance from hip joint to knee joint</td>
</tr>
<tr>
<td>$L_2$</td>
<td>distance from knee joint to ankle joint</td>
</tr>
<tr>
<td>$L_{c1}$</td>
<td>distance between COM of the human thigh segment and hip joint</td>
</tr>
<tr>
<td>$L_{c2}$</td>
<td>distance between COM of the human shank-foot segment and knee joint</td>
</tr>
<tr>
<td>$\theta_1$, $\theta_2$</td>
<td>angle of hip joint, angle of knee joint</td>
</tr>
</tbody>
</table>
The moment recorded from the Biodex ($M_B$) is corrected for gravitational ($M_g$) and inertial components ($I_B$) to determine the force applied at the point of exertion from the thigh onto the dynamometer arm ($F_T$). The moment of inertia of the Biodex attachment was gathered by methods described in Chapter 2. Gravitational moment of the dynamometer attachment arm was found using the passive polyfit method described in Chapter 3.

Using Newton’s second law, the calculated force can be used to determine the moment applied by the hip joint during exertions. To do this, equations of motion are based on Euler-Lagrange method to model of the thigh and shank-foot limbs as a two-rigid segments linked together by a frictionless joint. Summing the moments about the hip joint, the equation for the hip joint becomes:

$$M_{Hip} = H_{11}\ddot{\theta}_1 + H_{12}\ddot{\theta}_2 + h\dot{\theta}_1^2 - 2h\dot{\theta}_1\dot{\theta}_2 + G_1 + F_S(L_B)$$

The moments about the knee joint become:

$$M_{Knee} = H_{22}\ddot{\theta}_2 + H_{12}\dot{\theta}_1 + h\dot{\theta}_1^2 + G_2$$

Where the following terms are described as:

$$H_{11} = m_1L_{c1}^2 + I_1 + m_2(L_{c1}^2 + L_{c2}^2 + 2L_1L_{c2}\cos\theta_2) + I_2$$
$$H_{22} = m_2L_{c2}^2 + I_2$$
$$H_{12} = m_1L_{c1}L_{c2}\cos\theta_2 + m_2L_{c2}^2 + I_2$$
$$h = m_2L_{c2}\sin\theta_2$$
$$G_1 = m_1L_{c1}g\cos\theta_1 + m_2g(L_{c2}\cos(\theta_1 + \theta_2) + L_1\cos\theta_1)$$
$$G_2 = m_2L_{c2}g\cos(\theta_1 - \theta_2)$$

$G$ is the gravitational correction for each segment, $H$ is the inertial, and $h$ is the angular momentum expressed in the inertial form. For this experiment, the angular position of the hip, $\theta_1$, is assumed to be the same as the angular position of the dynamometer arm, $\theta$. The angle for the knee, $\theta_2$, is recorded by the use of a electrogoniometer at the lateral
epicondyle of the knee to measure angular displacement in reference to the axis at the hip. Lengths of the body segments were measured with a tape measure. All distances to the COM and mass moment of inertia were found using anthropometric tables [2].

III. Procedure

One subject (25yrs, 74.8 kg, 1.78m), performed a series of isometric and isokinetic exertions on a Biodex System 3 Dynamometer. The subject was secured to the Biodex System 3 dynamometer in the supine position with straps securing the subject’s torso and pelvis to the dynamometer chair, Figure 5.2. Care was taken in aligning the axis of rotation of the dynamometer arm with the greater trochanter. The thigh is connected to the Biodex arm and strapped in securely and the shank-foot segment is allowed to hang freely. Prior to placement in the Biodex chair, a one degree of freedom custom-made electrogoniometer was placed on the lateral epicondyle and aligned with the greater trochanter and lateral malleolus. The electrogoniometer position was recorded and adjusted to zero degrees flexion in the anatomical position.

Figure 5.2: Biodex setup with subject for hip exertions.
Biodex attachment position, velocity, torque, and electrogoniometer output were sampled at 200 Hz throughout all testing exertions. All tests were on the body segments on the right side of the body. All raw data was filtered at 4th order 1Hz zero-phase shift Butterworth filter.

First, for the proposed method, the gravitational correction moment for the Biodex arm was taken from the non-subject passive 4º/s trial, gathered post experiment, to determine gravitational moments at any angular position within the set range of motion. The gravitational moment of the Biodex attachment, \( M_g \), was simplified to the passive moment/angular position data as a 3rd order polynomial. This method accounts for the mass, gravity, distance to COM, \( L_{gb} \), and the angular offset of the COM, \( \varphi \). Using anthropometric measurements, the equations of motion developed for the two rigid segments of the thigh and shank-foot were used to calculated the moment at the hip and knee during isometric and isokinetic trials. Isometric exertions were taken in both flexion and extension at 10, 30, 45, 60º hip flexion. Isokinetic concentric extension and flexion was recorded for 30, 60, 90º/s exertions.

**IV. Results**

Sample results of the proposed method applied to determine the joint torque at the hip joint are shown in Figures 5.3 and 5.4. Figure 5.3 illustrates the Biodex recorded moment, calculated hip moment, and calculated distal knee joint moment for an isometric hip extension at 20º hip flexion. Recording of the exertion began five seconds prior to the exertion to establish a non-exertion threshold. The Biodex recorded moment was substantially different than the calculated hip moment. During the initial resting period, prior to the exertion, the hip moment was approximately 5 N-m, where as the Biodex recorded moment was 35 N-m. Little to no moment was applied at this time by the hip joint and should therefore approximate to zero. The calculated hip moment works reasonably well for an isometric exertion.
Figure 5.3: Isometric extension at 30° hip flexion

Figure 5.4 illustrates the Biodex recorded moment, the calculated hip moment, and the distal moment of the shank-foot at the knee joint during three consecutive isokinetic concentric 30 °/s hip extension. Recording began at zero degrees hip flexion three seconds prior to hip flexion movement needed to obtain the range of motion starting point before hip extension.
IV. Discussion

The proposed method appears to reduce the gravitational moments, inertia components, and distal joint moments. Unfortunately, the gravitational polyfit correction method proposed in Chapter 3 for the for a two-link system such as the thigh and shank-foot segment cannot be exclusively used. Though, the anthropometric data applied to the hip equation of motion yielded reasonable correction results for the isokinetic and isometric trials. Further investigation and reduction of external sources of error should be applied to make this method more affective.

Few studies have been published that use dynamometers to obtain hip torques. Dean et al. used a Biodex System 2 AP dynamometer to quantify age related decrease in the ability of female participants to generate whole leg movements about the hip [3]. An apparatus was used to confine the test subject to a standing position with the right leg allowed to perform straight-legged hip flexion and extension. The hip was aligned with
the rotation axis of the dynamometer. Restraining the knee reduces the range of motion of the test subject’s hip joint. In an actual fall, the subjects will not keep their leg segment straight through the entire movement. Bending the leg while stepping forward reduces the effect of inertial load and potentially allows for faster movements. Deans’ measurements from a straight-leg experiment cannot easily compare to physiological measurements and no correction for gravity or acceleration for inertia moment was made.

Pavol et al. presented a method that introduced corrections for gravitational moments, dynamometer accelerations, and distal joint motion into the joint moments [4]. His method was based on the specifics of the KIN-COM isokinetic dynamometer. For the current proposed method, the equations of motion were derived from text book Euler-Lagrange method for a two rigid segments connected at a frictionless joint and applied specifically to the Biodex System 3 Dynamometer.

Assumptions made when testing the proposed method included modeling the shank-foot as one segment. It was assumed that the foot has little distal moment to cause large error in the system. The COM of the segment modeled limbs are assumed to be on the two-link model segment. Angular position of the hip was assumed to be the same as the angular position of the dynamometer axis of rotation when aligned carefully.

Obstruction of the distal joint movement while in the supine position, warrant modification to the dynamometer chair for the hip experiment. During isokinetic trials in both extension and flexion, the shank-foot segment would hit, or drag along the end of the dynamometer chair. Careful adjustments to the protocol and encouragement were given to the test subject to avoid the hitting the end of the chair, but this error should be taken into consideration when applying hip testing on the Biodex dynamometer.

The proposed method appears to reduce the gravitational moments, angular acceleration and inertia moments, and distal joint moments. An advantage of the proposed method is that it provides a method for correcting the above mentioned errors, based on the specific design and geometry of the Biodex System 3 Dynamometer. Further investigation and reduction of external sources of error should be applied to make this method more affective.
V. References


Chapter 6: Additional Notes for the Reader

The methods proposed for calculating the resultant joint moment for the knee and ankle joint can be simplified from the complex approach presented. For non-isokinetic testing and trials where inertia is not of concern to the desired results, the methods proposed in Chapter 2 for determining the mass moment of inertia of the dynamometer attachment are unnecessary. This also implies that the inertia properties of the limb segment are also excessive. The sum of all moments in the equation of motion is then equal to zero.

\[ \sum M_j = 0 \]
\[ M_B - M_{gB} - M_{gj} = 0 \]

Where the recorded moment of the Biodex is \( M_B \), and gravitational moments of the dynamometer attachment and limb segment are \( M_{gB} \) and \( M_{gj} \). The gravitational moments can be found using the 3\textsuperscript{rd} polynomial fit described in Chapter 3 for the dynamometer attachment and limb segment. Using this gravitation correction method reduces the need for determining the COM location and simplifying the procedure further. It is advised to continue using a goniometer at the joint to determine the angular difference from the dynamometer angular position.

To summarize, the aforementioned procedure is an adjustment to the proposed method described in the previous chapters. This simplified procedure can be used to determine the resultant joint moment during non-isokinetic testing. It is advised that during isokinetic testing, the proposed method, including the inertia components, described in Chapter 3 be used to calculate the resultant joint moment.