INTRODUCTION
There are an estimated 623,000 lower-limb amputees in the United States [1]. Kinematic and kinetic gait analyses are widely used to analyze gait patterns of amputees and determine how safe prosthetic devices are. In this project, we focused on older adults with unilateral transfemoral amputations. Kinetic gait analyses require knowledge of each body segment’s inertial parameters, such as mass, Center of Mass (CoM), and mass moment of inertia. Directly measuring inertial parameters [2] requires time and disassembly of all prosthetic components, and typical regression models only work for healthy individuals. Geometric models have been used to provide estimates of segment parameters in both healthy individuals [3] and amputees [4]. Geometric models require only a series of anthropometric measurements, and therefore have the potential to be much less time-consuming and easier to implement than direct measurement. Additionally, a geometric model provides estimates of residual limb parameters, which is not possible via direct measurement. The goal of this research is to develop a simple geometric model to determine the inertial parameters of the prosthetic limb in a transfemoral amputee.

METHODS
This model was developed for one unilateral transfemoral amputee. Measurements were taken at the thigh (comprising the prosthetic socket, the residual limb, and any socket adapters), the shank (comprising the prosthetic knee, the pylon, and any associated pylon adapters) and the foot (comprising the prosthetic foot inside the shoe).
A certified prosthetist disassembled the prosthesis and direct measurements of mass and CoM were taken for all three segments on a laboratory force plate and balance board, respectively.

Figure 1 summarizes the measurements taken at the thigh socket. Diameters were taken in the Medial/Lateral (M/L) and Anterior/Posterior (A/P) direction every 3 cm. Straight distance from the first and last diameter locations to the proximal and distal edges of the socket were recorded along with the dimensions of any adapters and the socket’s thickness.

For the shank, M/L, A/P, and overall length measurements of the knee were recorded at the proximal and distal edges of the prosthesis housing. The pylon’s overall length and the dimensions of any adapters were recorded.

![Diagram of Socket Measurements](image-url)

**Figure 1:** Socket measurements: Red solid lines are diameters taken every 3 cm. The blue double line is the straight distance from the most proximal diameter to the proximal edge of the socket. The green dashed line is the straight distance from the distal diameter measurement to the distal end of the socket.
The prosthetic foot remained in the shoe during all measurements. M/L and Superior/Inferior (S/I) measurements were recorded every 3 cm from the back of the shoe moving distally to the toe tip.

Five geometries were used in constructing the geometric model of the lower leg: (1) cylinder, (2) elliptical solid, (3) semi-ellipsoid of revolution, (4) rectangular prism, and (5) stadium solid. Mass, CoM, and mass moment of inertia were calculated for each geometry according to Kwon [5]. Tissue density was assumed to be 1.1 g cm$^{-3}$ [6] and known densities were used for prosthetic components.

RESULTS AND DISCUSSION
The thigh is a series of elliptical solids capped by a semi-ellipsoid of revolution. The socket is a homogeneous shell whose major and minor radii are determined by the M/L and A/P diameters, and the residual limb is assumed to fill the inner volume. Adapters are modeled as rectangular prisms or cylinders. The shank contains three components. The prosthetic knee is an elliptical solid whose major and minor radii are determined by the A/P and M/L measurements. Knee mass is readily available in most manufacturers’ specification sheets. The pylon was modeled as a hollow cylinder with standard dimensions of an inner diameter of 2.5 cm and an outer diameter of 3 cm. The foot consists of a series of stadium solids. The recorded foot mass is used to determine foot density.

Table 1 provides selected comparisons between the directly measured values and model estimates of inertial parameters. Due to the prosthetic knee’s complexity the shank model assumes a homogeneous elliptical solid. The elliptical solid requires only four measurements and accurately predicts shank CoM within 1 cm. Likewise; the foot model predicts foot CoM within 2 cm.

The model overestimates socket mass. A socket is molded specifically to an amputee’s residual limb, so socket thickness may vary over the length of the socket. Measuring socket thickness at multiple locations on the socket will likely increase the model’s accuracy.

Further work will include a generalization of foot mass to eliminate the requirement to measure foot mass directly, and therefore eliminate the need to disassemble any part of the prosthesis. Additionally, application of the model to a larger pool of participants will further validate the model.

REFERENCES

ACKNOWLEDGEMENTS
Funding was provided by a grant from the American Orthotic and Prosthetic Association.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model Estimate</th>
<th>Measured Value</th>
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<tbody>
<tr>
<td>Shank CoM*</td>
<td>15.7</td>
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<tr>
<td>Foot CoM*</td>
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<tr>
<td>Socket Mass</td>
<td>1.65</td>
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* Distance from proximal end of segment