Supplemental Material

This supplemental material document provides additional detail on the design of compliant buttocks models meant to evaluate wheelchair cushion performance. The buttocks models are parametrically designed to scale to different sizes, reflecting differences in body size of wheelchair users. There are 3 distinct sizes – 40 cm wide, 45 cm wide, and 54 cm wide. They also have two distinct types of shape – trigonometric and elliptical – reflecting differences in buttocks shapes. Each model has an associated substructure of 5 distinct rigid elements that mimic load-bearing aspects of the human skeleton. These protuberances are affixed to a plate that adheres to the top of the buttocks model. The individual element sizes do not change with model size or shape, as these are considered anatomically consistent across persons. The dimensions of these protuberances and their positioning in the model are detailed here. The creation of the two model shapes using equations, constraints, and anthropometric measurements is also described here. The 40cm wide model is used to illustrate dimensions and details in the various figures.

Top Plate Design

The medial-lateral width and the antero-posterior depth of the buttocks are anthropometric measurements used to define the model’s top surface, which in turn defines the dimensions of the top plate. The top plate adheres to the elastomeric shell and contains holes and cutouts to affix the model substructure protuberances to it (Figure 1). The locations of these cutouts are defined by anthropometric measurements of the skeletal load-bearing elements, such as the ischia (medial), the greater trochanters (lateral), and the coccyx.

![Figure 1 Top Plate with cutouts for substructure, as seen from above](image.png)
Substructure Design

The substructure defines load-bearing rigid elements in the buttocks model. Anatomically, these are the aspects of the skeleton that bear the load from cushion to the human through the buttocks. In the model, substructure protuberances project downward from the top plate. The substructure of the model is made of a total of 5 protuberances – 2 ischial, 2 trochanter and 1 coccyx protuberance. 1 ischial and 1 trochanter protuberance are fixed to the top plate, and their symmetric counterparts are removable. The coccyx protuberance is removable. The removable versions have extensions that pass through an opening in the top plate and a mounting cap to secure them. Removable ischial and greater trochanter elements are bored out and designed so pressure sensors can be mounted flush to the respective inferior aspects, as seen in sections below. The coccyx protuberance contains a groove to seat a pressure sensor at its bottom to capture vertical loads. Removable elements permit access to sensors for calibration, whereas the fixed elements are permanently embedded in the elastomer. Mounting sensors on the protuberances allows for measurement of pressure at the interface between ‘tissue’ and ‘bone’ when the model is loaded into a wheelchair cushion.

Shape and cross-sectional dimensions

The shape and dimensions of the fixed protuberances were based upon anthropometric measurements of human skeletal elements. Below the top plate, the dimensions of the fixed and removable version of each protuberance are identical.

Ischial Protuberance

The ischial protuberance is approximated as a cylinder that ends with a hemispherical inferior end. In the removable version, the hemisphere is cut off slightly at the bottom to house a pressure sensor. Figure 2 depicts fixed and removable versions of the ischial protuberance. Figure 3 shows the dimensions of both versions in cm.
Greater Trochanter Protuberance

The greater trochanter protuberance is abstracted as a shelf with a flat inferior square surface, and a larger superior rectangular surface joined by a circular arc. The greater trochanter element sits laterally to the ischial protuberance, and it has a removable version and a fixed version, made in a manner similar to the ischial protuberance.

Figure 4 shows the design of fixed and removable versions of the greater trochanter protuberance. Figure 5 depicts the dimensioned design (in cm).
Sacrum/Coccyx Protuberance
The coccyx protuberance represents the lower sacrum and coccyx. This is a multi-joint structure that is curved in the sagittal plane.
Figure 6 shows the abstracted shape of the sacrum and coccyx with individual elements labeled.
Anthropometric measurements of individual elements and their relative positions were used to define abstracted parameters of the sacral and coccyx vertebrae and overall dimensions, as shown in Table 1. Figure 7 shows a sketch of the bone segments used to create the curve of the coccyx model in the sagittal plane. Slight tweaks of the overall structure were made to insure the model could be defined in a parametric manner and reflect a continuous profile.

**Table 1 Sacrum-coccyx anthropometric measurements used to abstract the model element**

<table>
<thead>
<tr>
<th>Anthropometric component</th>
<th>Measured value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lumbo-sacral angle</td>
<td>30°</td>
<td>Angle along top of S1 vertebral body to the horizontal</td>
</tr>
<tr>
<td>sacral length(cm)</td>
<td>10</td>
<td>Length between the superior aspect of S1 and inferior aspect of S5</td>
</tr>
<tr>
<td>sacral curvature</td>
<td>70°</td>
<td>Angle between line connecting the superior and inferior borders of S1 and the line connecting the same borders of S5</td>
</tr>
<tr>
<td>Coccyx length(cm)</td>
<td>Total: 3.5</td>
<td>Total: Length between the superior aspect of C1 and the inferior aspect of S5 C1,C2,C3: Individual Coccyx segment lengths</td>
</tr>
<tr>
<td></td>
<td>C1: 1.4</td>
<td>C1,C2,C3: Individual Coccyx segment lengths</td>
</tr>
<tr>
<td></td>
<td>C2: 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3: 0.9</td>
<td></td>
</tr>
<tr>
<td>Coccyx widths (cm)</td>
<td>C1: 3.5</td>
<td>Width of coccygeal segments</td>
</tr>
<tr>
<td></td>
<td>C2: 1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3: 1.5</td>
<td></td>
</tr>
<tr>
<td>Intercoccygeal angles</td>
<td>20° S5-C1</td>
<td>Angles between the bodies of adjacent vertebrae</td>
</tr>
<tr>
<td></td>
<td>25° C1-C2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5° C2-C3</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 7 sketch of sacrum and coccyx segments based on anthropometric data*
Note that, unlike the abstracted shape shown in Figure 6, the sketch shown in Figure 7 shows only the vertebral segments between S5 and C3. In the protuberance’s full design, a vertical extrusion covers the distance between the superior end of S5 and the plate holding the substructure (Figure 8).

The full coccyx protuberance is removable. Figure 9 shows the coccyx CAD model, highlighting the S5C1 joint location and the vertical aspect above S5. It also includes a part that goes through the top plate and can be fastened to it from above (Figure 10).
The finished CAD part has a groove to mount and align a pressure sensor. The inferior aspect of this protuberance is a horizontal face that orients the pressure sensor to measure vertical loading (Figure 11). Figure 12 shows the dimensions of the protuberance. Note the tapering at the bottom to match coccyx segment widths noted in Table 1.
Substructure Spatial Dimensions

Positioning of the substructure’s individual elements is based on the relative distances between elements. The ischial (medial) spacing, trochanter (lateral) spacing and the relative coccyx position are based on anthropometric measurements shown in Figure 13.

![Figure 13 Anthropometric measurements for hip width = 40 cm](image)

(a) Ischial spacing, trochanter spacing, vertical distance between ischial and trochanter elements (b) coccyx position relative to ischial tuberosity (lowest point of ischium)

As mentioned above, the removable medial, lateral and coccyx protuberances are also capable of holding pressure sensors. Figure 14 (a) shows the full substructure, and Figure 14 (b) and (c) show the substructure with removable protuberances mounted to the top plate, and positioned using anthropometric measurements.
Figure 14 Substructure (a) the medial, lateral and coccyx protuberances (b) medial and lateral protuberances positioned based on anthropometry (c) coccyx protuberance positioned based on anthropometry
Shape of compliant shell
This section describes the details of model shapes and their construction in CAD. Two model shapes are defined to represent different types of buttocks shapes, designed such that they accept the same substructure for the same hip width. Thus, the overall width, breadth, depth as well as the separation of inferior aspects of each model are the same regardless of model shape (Figure 15).

![Figure 15 Frontal view of models illustrating equal width, and equal distance between inferior aspects](image)

Equations and creation of model shape
This section describes the process of creating the shape of the two buttocks models based on anthropometric data applied to the substructure elements, constraints to ensure smooth contours, and overall model dimensions to match the top plate’s edges.

Elliptical model
To build the elliptical model in CAD, a partial ellipsoid is created by truncating a full ellipsoid at a given height from its bottom most point (Figure 16 (a)). This height (= 6.3 cm), along with a vertical extrusion above the truncated partial ellipsoid, helps accommodate the substructure and allows for a defined amount of thickness of model material under the protuberances.

The partial ellipsoid is further truncated to form one half of the model (bold contours in Figure 16 (b)), This truncation is based on the known distance of the ischial protuberance from the center of the model. For the 40 cm wide model, the inferior aspects are spaced at 11 cm. Thus, a truncation of 5.5 cm from its inferior aspect defines the midline.

The shape is then mirrored to achieve a symmetrical structure (Figure 16 (c)).
Figure 16 Construction of elliptical model, shown with 40cm wide model
The major diameter \( (D_{\text{major}} = 36 \text{ cm for 40cm wide model}) \) and minor diameter \( (D_{\text{minor}} = 31 \text{ cm for 40cm wide model}) \) of the ellipsoid can be used in an ellipsoid equation to define the overall shape. The same aspect ratio of major diameter to minor diameter is used for all sizes.

\[
\left( \frac{x}{D_{\text{major/2}}} \right)^2 + \left( \frac{y}{D_{\text{minor/2}}} \right)^2 + \left( \frac{z}{D_{\text{minor/2}}} \right)^2 = 1
\]

**Trigonometric model**

For the trigonometric model, both the medial-lateral direction (Curve A) and the antero-posterior direction (Curve B) shown in Figure 17 are divided into a trigonometric segment and an elliptical segment.

![Image](image_url)

*Figure 17 (a) Trigonometric Model with 2 curves defining its shape (b) Curve A as seen in front view (c) Curve B as seen in side view*

In the medial-lateral direction, a trigonometric equation defines the model’s inferior curve between the midpoints of the substructure’s lateral protuberances (Figure 18 (a) – Equation 1). It is then joined to the lateral edge of the model by an ellipse which transitions the profile to be coincident to the vertical projection (Figure 18 (a) – Equation 2). Together, these two curves define Curve A of the model.

A different trigonometric equation defines the model’s inferior curve in the anterior-posterior direction (Figure 18 (b) – Equation 3). It is then joined to the anterior and posterior edges of the model by an ellipse in a manner similar to the medial-lateral direction (Figure 18 (b) – Equation 4). Together, these curves define Curve B of the model.
The defining equations are a function of the model’s width, the elastomer thickness under the ischial and trochanter protuberances, the spatial relationship between these protuberances, and the vertical aspect above the models. Figure 19 shows a labelled sketch of the parameters used in the equations and their values for the 40 cm wide model. As with the elliptical model, one half of the shape is defined and mirrored to create the complete profile. Table 2 shows the parameters for the different trigonometric model sizes.
Table 2 Equation parameters for different model sizes

<table>
<thead>
<tr>
<th>Model Width</th>
<th>Model Depth</th>
<th>Thickness under ischial protuberance (T1)</th>
<th>Thickness under trochanter protuberance (T2)</th>
<th>Spacing between Midline and ischial protuberance (L1)</th>
<th>Spacing between medial and trochanter protuberances (L2)</th>
<th>Cutoff Height (H1)</th>
<th>Spacing between trochanter center and model lateral aspect (D2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>25</td>
<td>2.0</td>
<td>2.0</td>
<td>5.5</td>
<td>12.0</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>45</td>
<td>29</td>
<td>2.5</td>
<td>2.5</td>
<td>6.0</td>
<td>13</td>
<td>2.0</td>
<td>3.5</td>
</tr>
<tr>
<td>54</td>
<td>36</td>
<td>3.0</td>
<td>3.0</td>
<td>6.75</td>
<td>14.75</td>
<td>2.0</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Equations governing each of the distinct curves in the M/L direction and A/P direction are described below. For all 4 equations, note that

\[ x = \text{Medial-Lateral direction} \]

\[ y = \text{up/down (loading) direction} \]

\[ z = \text{Antero-Posterior direction} \]

**Equation 1- Frontal view, inferior curve**

Equation 1 defines the shape of the trig model from the midline to the center of the lateral protuberance. The curve is in the x-y plane, highlighted in Figure 20.

![Figure 20 Highlighted shape of trig model from midline to center of lateral protuberance](image)

The sinusoidal curve (Trig Model Equation 1) is guided by dimensions of the model and constrained to (1) reach its inferior-most point under the ischial protuberance, and (2) flatten out under the trochanter protuberance. The equation is thus defined as

\[
y = -\left(\frac{40 + T_1 - T_2}{2}\right) \cos \left(\frac{\pi (x - L_1)}{L_2}\right) - (45 - H_1 + T_1)
\]

*(Trig Model Equation 1)*

**Equation 2- Frontal view, end curvature**

Equation 2 defines the elliptical curves connecting the point under the center of the lateral protuberance to the lateral edge of the model. This curve is in the x-y plane, and highlighted in Figure 21.
The ellipse is constrained to create a continuous curve by (1) starting horizontally flat underneath the center of the trochanter, and (2) ending vertical at the lateral edge of the model. Its equation (Trig Model Equation 2) is thus based upon 2 parameters: 1) height from trochanter to the inferior aspect of the model underneath it (which equals T2), and 2) the distance from center of the trochanter to lateral aspect of the model (which equals D2).

\[
\left( \frac{x}{T_2} \right)^2 + \left( \frac{y}{D_2} \right)^2 = 1
\]

(Trig Model Equation 2)

Equation 3 - Sagittal view, inferior curve

Equation 3 defines the shape of the trig model’s inferior curve in the sagittal (z-y) plane (Figure 22).

This curve is constrained to (1) share the same trigonometric curve characteristics as Trig Model equation 1, and (2) end at a horizontal distance of L2 from the inferior aspect of the model, like equation 1 does. Its equation is thus given by

\[
z = - \left( \frac{40+T_1-T_2}{2} \right) \cos \left( \frac{\pi y}{L_2} \right) \text{ for } -L_2 \leq y \leq L_2
\]

(Trig Model Equation 3)

Equation 4 - Sagittal view, end curvature

Equation 4 defines the elliptical curves connecting the end of the sagittal inferior curve with the model’s anterior / posterior edge in the sagittal (z-y) plane.
Figure 23 Highlighted shape of trig model’s end curvature in the sagittal plane

The ellipse is constrained to create a smooth curve by (1) starting at the same slope as the end of the Equation 3 curve, and (2) ending vertically at the anterior/posterior ends of the model.

The curve’s equation (Trig Model Equation 4) relies upon 4 parameters 1) the model depth in the A/P direction 2) Spacing between medial and lateral protuberances (L2), 3) Thickness under lateral protuberance (T2), and 4) Cutoff Height (H1).

The equation guiding the ellipse is given by

$$\left(\frac{y}{\text{model depth}} - L_2\right)^2 + \left(\frac{z}{20 + T_2 - H_1}\right)^2 = 1$$  \hspace{1cm} (Trig Model Equation 4)