

# High Volume Ergonomic Simulation of Chairs

## Abstract

To understand what makes a chair comfortable or practical we need to test a large number of chairs, both good and bad. Due to the numbers involved we cannot achieve this with physical testing. Instead we use simplified ergonomic simulations. The simulations presented here produce pressure maps within the range given the literature, along with several other measures of comfort and practicality. This was done substantially faster than examples in the literature, permitting collection of thousands of results.

## 1 Introduction

When designing chairs, ergonomics is a vital consideration. That is, we need to determine if the chair is suitable for its purpose. To enable the study of automated chair design we require large data sets measuring the suitability of different chair designs, both good and bad, to use with machine learning.

The quantity of data required makes physical testing impractical, we therefore present simulations that can produce the required data. The simulations need to provide relative values for comfort and practicality so that non-viable chairs could be removed from the design space. Although similar models exist, a modelling program was built for this project for several reasons. First, the user needed to be positioned automatically in any possible chair. Many of the existing models rely on manual positioning and would not be suitable for our high volume data collection. Second, the comfort and practicality measures were required for each chair. Many commercial models are just digital dolls and give no feedback on the suitability of a chair. Those that do were too complex for our needs with a wide range of feedback that was not required such as task simulation and vision zones. Third, most of the more sophisticated models are not available for free and can be very expensive (as they are designed for commercial use). Building a simulation for this work allowed collection of the data required in a lightweight model, suitable for high volume simulation.

The simulations are built using the same parametric structure as the chairs produced by the ChairMaker [20]. This will allow us to directly study the effect of different parameters on the ergonomics of chairs. The parameters include aspects such as seat height or back recline; a full list is given in the supplementary material.

## 2 Ergonomics Background

### 2.1 Ergonomics and Anthropometry

#### 2.1.1 Uses of Ergonomics and Anthropometry

Anthropometry<sup>1</sup> is often used in the field of ergonomics<sup>2</sup> to design tools and furniture that ‘fit’ a wide range of people and allow them to work comfortably and efficiently. Our subject,

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<sup>1</sup>*The comparative study of sizes and proportions of the human body* - <http://www.collinsdictionary.com/dictionary/english/anthropometric>

<sup>2</sup>*The study of the relationship between workers and their environment, esp the equipment they use* - <http://www.collinsdictionary.com/dictionary/english/ergonomics>

the design of chairs, is of particular interest as a significant proportion of people spend their working lives sitting, whether it is in an office or in a vehicle. The design of a chair for these purposes can have a significant impact on both the user's work efficiency, and more importantly, their health [1]. Another motivation for the study of anthropometry for chair design is the comfort of wheelchair users [2], where a well designed chair can have a significant impact on the quality of life of the individual.

In addition to other factors, such as how intuitive a control is to use, ergonomics uses anthropometric data sets of physical measurements (such as size, weight, reach) taken from a sample set of individuals, to allow a designer to predict how a user will interact with a design and whether such an interaction is within a comfortable range of motion of the human body. For example, data on arm length and motion can be used to predict if a user will be able to reach a control (in a car for example) and whether such a reach would take a lot of effort. If the control is difficult to reach but often required, repeated use could cause pain or even be dangerous in the case of an emergency.

### **2.1.2 Sources of Anthropometric Data**

Often the datasets used in ergonomics and anthropometry have been collected for a particular purpose, and this will affect the sample set and the type of measures taken. One motivation for collecting data is public health [3], which contains a large number of samples but limited detail. Another is the efficient or comfortable use of tools, where factors such as limb reach, motion and grip are required. These sets will usually only contain data from possible users (e.g. adults for car interior design). Other data sets are collected for very specific purposes, for example NASA [4] uses anthropometric data in its design standards which includes factors such as foothold flexibility in zero gravity which will not be required in any day to day applications.

The anthropometric data itself comes from a variety of sources, the main one being the simple measurement of volunteers using basic equipment such as tapes and rulers. The same measurements are taken from every volunteer, seated or standing in the same position, then the mean and standard deviation are taken for each measure. More sophisticated 3D measuring tools such as 3D scanners are also being introduced [5].

Another method of collecting data is from analysis of cadavers. This allows the measurement of factors that may be difficult or impossible while a person is alive, such as the mass of individual limbs [6]. Information about internal structure (such as the skeleton size) can also be found. However there are drawbacks to such a method. For instance, the sample set is likely to be small as there is a limit on the number of bodies donated for scientific research. Another issue is the changes to the body that result from the death of the individual.

A recent addition to data collecting methods is the use of MRI or CT machines. These collect information about the inside of the human body while it is alive. They can also be used to see how different positions can change the measures [7], although there is a limit to the range of movement inside the machine.

Access to the data varies according to the source. Governmental data, such as that from NASA and public health bodies is free to access and use. Likewise academic data, such as the DINED data set from TU Delft [8] is freely accessible. Other data sets, collected by a company for the design of their products or collected using an expensive method (such as the 3D scans [5]) are usually paid for, if they are accessible at all.

## 2.2 Overview of Previous Relevant Ergonomic Research

### 2.2.1 Comfort

Measuring comfort in chairs is done in two ways. The first is subjective and requires the use of questionnaires to get testers to rate statements such as ‘I feel completely relaxed’ to ‘I feel unbearable pain’ [9]. This is often done whilst the tester is doing the sort of tasks expected (such as working at a computer). For practical reasons the test periods may be quite short, Openshaw [10] used periods of 60 minutes per test. However Wachslar and Learner [11] did a study of the comfort of pilot and flight seats that suggested that the overall comfort of a seat can be reasonably predicted within the first 5 minutes of sitting.

The second method is objective and requires the use of sensors to detect potential problems. The most common of these is the use of a flexible grid of pressure sensors [12] to find points of high pressure, mean pressure and overall seat contact area. Openshaw [10] showed that these objective measures are highly correlated to each other and it is possible to predict the subjective comfort from these objective measures using neural networks.

### 2.2.2 Anthropometric Models

There are many existing ergonomic simulation models available, most of which are commercially developed and licensed, such as Tecnomatix Jack from PLM Siemens<sup>3</sup> and 3D Human Model<sup>4</sup>. These are built to be used within a CAD package to enable designers to test potential designs.

These range from set models from a specific data set (e.g. 5th percentile male, 50th percentile female etc) to fully customisable figures where a data set can be chosen and the parameters of the model selected. The use of the models also varies. Some models come in set positions (sit, stand etc) and are just added to a CAD design to enable the designer to get visual feedback about a potential user. Others are fully positionable and can even simulate tasks. These models also give more extensive feedback such as stress on joints and cones of vision. The more advanced models, that can provide useful feedback, are commercially licensed and as such there is little literature available on the techniques used to simulate the interaction of a user with a product.

### 2.2.3 Seat Pressure

As our concern is chair design we will be interested in the pressures at the interface between the seat and the user. One of the reasons that pressure is a concern is that it is an indicator of the comfort of the buttocks. This has been an active area of research due to the importance of good chair design and many simulations have been developed. The most popular method to simulate this pressure is the finite element method, with an early model built by Todd and Thacker [13] and subsequent models built by Wagnac et al [14], Grujicic et al [15] and Zhu et al [16]. Models of this type have been shown to be able to approximate the range and distribution of the interface pressures as well as the pressures inside the body. In particular they are good at showing the effect of the skeletal structure inside the body on the surface pressure if this is modelled. However the drawback to these methods is the length of time taken to simulate a single chair and user. For example the simulations by Grujicic et al took 30 minutes to run, even allowing for the increase in potential computing speed since 2009 this was unacceptably long for our purposes. The model given below has a run time of approximately 3.2 seconds for an equivalent chair and user.

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<sup>3</sup>[http://www.simsol.co.uk/ergonomic\\_analysis\\_jack.php](http://www.simsol.co.uk/ergonomic_analysis_jack.php)

<sup>4</sup><http://www.3dhumanmodel.com>

Existing maps from measurements found in the literature are often related to the study of pressure sores in long term seated positions, such as in the case of wheelchair users. Here they assume a high base level of ergonomic comfort (such as contoured seats and padding) and the concern is the location of higher than average pressures as these are likely to cause pressure sores [17]. An example of a map given in the literature here is shown in figure 1 in a figure from Gutierrez et al [2].

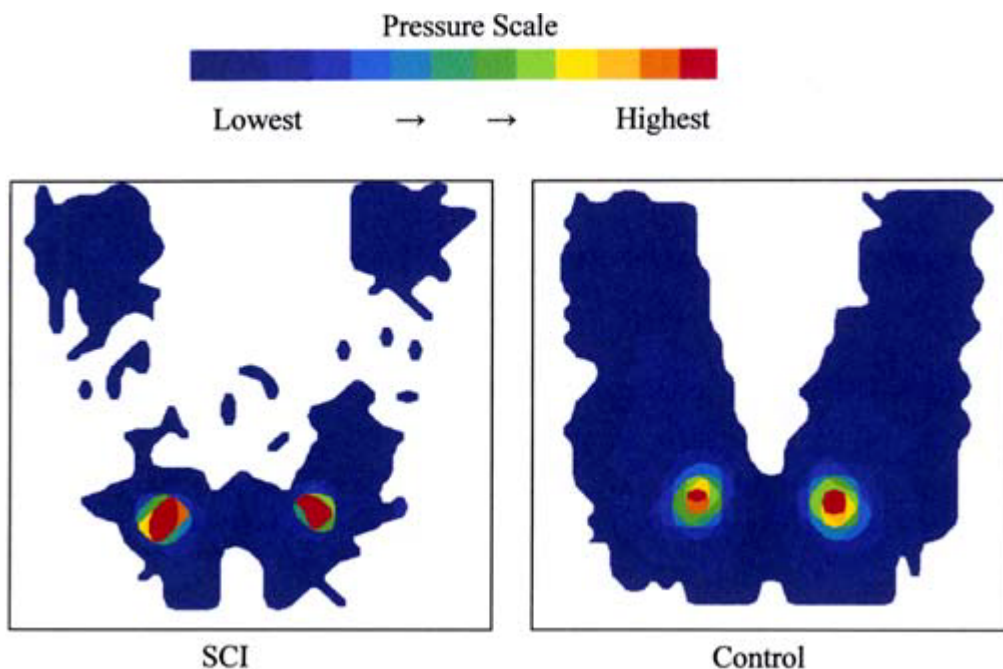


Figure 1: Pressure maps from experiments undertaken by Gutierrez et al[2]. SCI stands for spinal cord injury.

There are also extensive pressure maps relating to the design of office chairs (as in figure 2 which shows a map given on the Herman Miller office chair website<sup>5</sup>). In this case the pressure maps are often displayed alongside alternative products without a scale to demonstrate the advantages of the product to be sold.

Due to the nature of the existing literature it is difficult to find comprehensive comparisons for our model. Even in the cases where we have a scale to the pressure map and information regarding the height and weight of the tester, we do not have detailed information about the shape of the seat. However, to ensure that our model is within a realistic range we use the following cases for comparison: Brienza et al [18] undertook experiments on an 15x15 grid sensor. Their test subjects were a mix of male and female wheelchair users over the age of 65, who weighed between 36.4–106.4 kg. Experiments were done on three foam cushions; flat, contoured and optimised. Peak pressure ranges for the three cushions were 10.8–26.67 kPa, 8.27–16.67 kPa and 3.93–26.67 kPa respectively, although the maximum pressures may have been higher as the sensor mat could not record over 26.67 kPa. In later work Wagnac et al [14] simulated peak pressures of 23.6 kPa for a flat cushion and 16.5 kPa for a contoured cushion. This correlated with their measured pressures as shown in figure 3. Their data was for a healthy male tester aged 24 years, 75 kg and 180 cm. In

<sup>5</sup><http://www.hermanmiller.com/research/solution-essays/the-art-and-science-of-pressure-distribution.html>

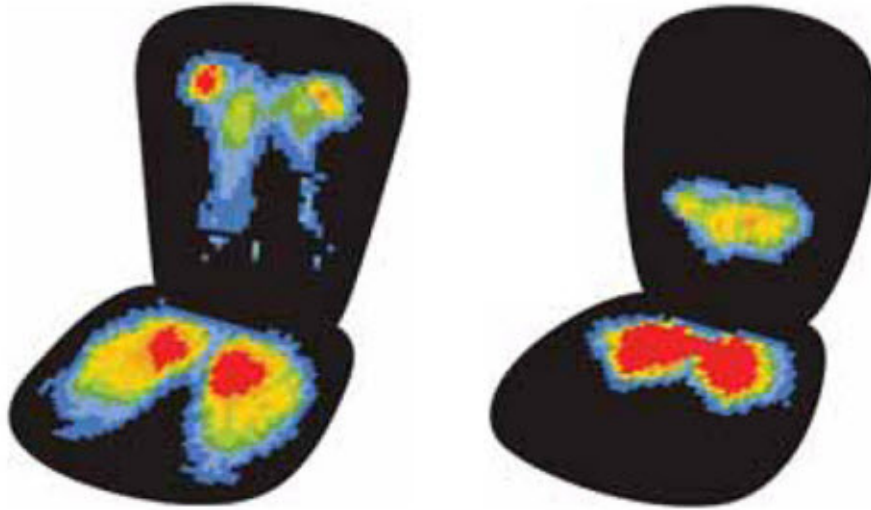


Figure 2: Examples of good (left) and bad (right) pressure maps given by Herman Miller

Zhu [16] a finite element method is used to simulate the pressure on a  $540 \times 540$  mm flat seat cushion of thickness 60 mm. The peak pressure of the figure in a vertical position was 38.72 kPa.

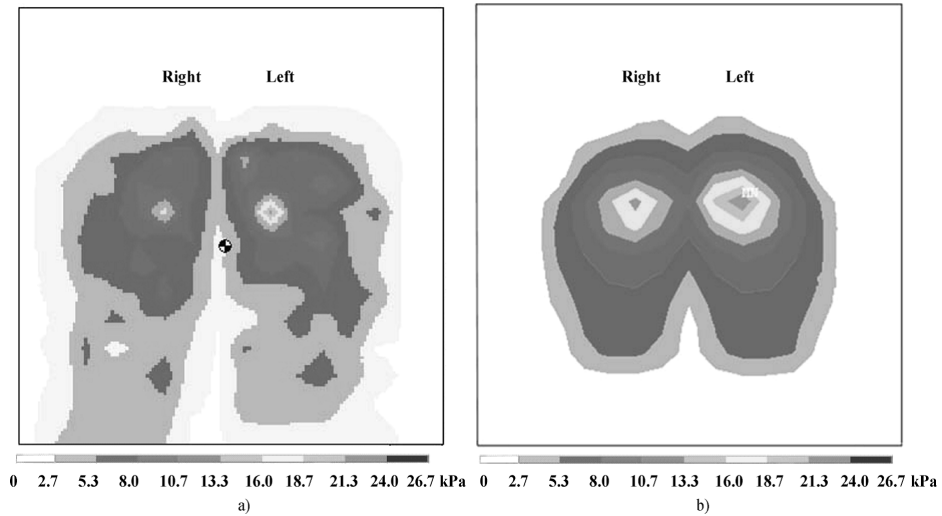


Figure 3: Pressure map from experimental data (left) and finite element method (right) from Wagnac et al [14]

### 3 Ergonomic Simulations

Simulations of objective measures of comfort are used. The first measures are the maximum pressure values between body and chair. As described in the previous section this is widely used as a measure of comfort and can be simulated. In addition we find a value of the

curvature of the spine as poor posture is bad for the spine [1].

However, on their own the comfort measures are not sufficient. As our chairs can be reclined and both the back and seat extended, the program is capable of producing a bed. This would score highly on our comfort measures. To counteract this we introduce practicality measures. To be practical, a chair must be easy to get in and out of, and it should allow the user to perform tasks while seated. To measure how easy a chair is to get into we find the distance from the feet to the floor. Performing tasks has two requirements; forward facing eyes to view the task, and hands at desk height in a comfortable position to work (upper arms vertical and lower arms horizontal, level with the desk is recommended in [1]). We therefore measure the difference of these angles from the optimum. There are also size considerations for the chair, a dining chair will not want any excess width or depth as they are designed to be used in close proximity to each other.

### 3.1 Generating Test Subjects

It was decided that a range of test models was needed to test the chairs. This was due to work by Reed et al [19], reported by Herman Miller [21] which concluded that seat pressure can depend on height and build as well as just weight. For example, a thin, tall person may be the same weight as a short, stocky person but as they have less fat the pressure at contact will be higher.

The ergonomic data used to build the model was from TU Delft's DINED anthropometric database [8] (unless otherwise stated). This is an online resource that provides easy access to several anthropometric data sets, including the one taken by DINED researchers in the Geron project [22] of Dutch adults. This was the set used in the model. The data was given in 6 groups; ages 20-30, 31-60 and 60+ separated by male and female. Although a mean of all these groups was given it was decided that the groups would be kept separate as males and females have different distributions of body fat and this could affect the pressure maps. For each measurement and group a mean and a standard deviation value was taken from the database.

A new person was generated by randomly selecting an age, gender, height and weight. The height and weight factors were given by two Gaussian random values with mean 0 and standard deviation 1. Then for each measurement a new value was found using the relevant primary factor as a guide. For example, if we were to generate a female in her 20s with height factor ( $F_h$ ) 0.5 and weight factor ( $F_w$ ) 1.0 we would find her seated shoulder height as shown in equation (1). The shoulder height factor ( $F_s$ ) is another Gaussian distributed value with mean 0 and sd 1 used so that individual test subjects have different proportions, for our example we use value -0.8. The weight factor is not used as shoulder height will mostly indicate the overall height of an individual and not their weight.

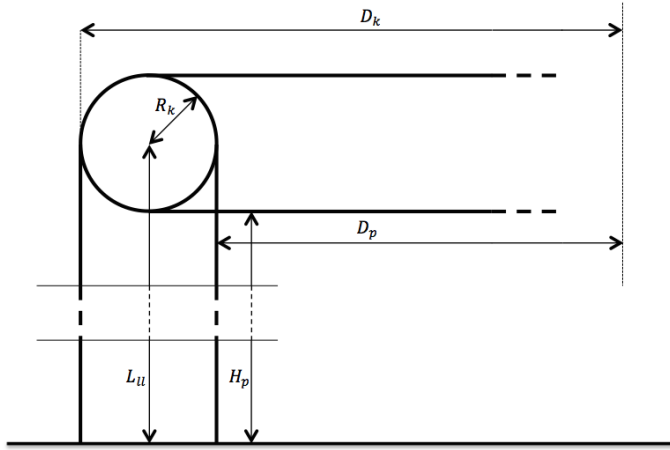


Figure 4: How  $R_k$  and  $L_u$  can be found from anthropometric data.

$$\begin{aligned}
 M_s &= 582\text{mm (mean shoulder height of 20-30 years female)} \\
 S_s &= 29\text{mm (standard deviation of shoulder height of 20-30 years female)} \\
 F_h &= 0.5 \\
 F_w &= 1.0 \\
 F_s &= -0.8
 \end{aligned}$$

$$\begin{aligned}
 \text{Shoulder Height} &= M_s + (0.9 * F_h + 0.1 * F_s) * S_s \\
 &= 582 + (0.9 * 0.5 + 0.1 * (-0.8)) * 29 \\
 &= 582 + 0.37 * 29 \\
 &\approx 593\text{mm}
 \end{aligned}$$

(1)

Some measurements were calculated slightly differently, for example if they contained elements of both height and weight. A full list of DINED measurements used and the method of calculating the equivalent value used in the model is given in the supplementary information. The individual measurements found this way could then be used to find the variables required by the model.

### 3.2 Skeleton Modelling

The ergonomic modeller uses a simple skeleton model with 6 main joints; centre of the skull, neck, central spine, hip, knee and foot. Two additional joints were used in the arms; shoulder and elbow. The distances between these joints were found using the anthropometric measurements found using the DINED data. Since these measurements are taken from the outside of a person, many of the skeleton dimensions had to be inferred from several of the values.

We give as an example, the calculation of the size of the knee joint and the length between the knee and foot. These are calculated from the anthropometric values popliteal (back of the knee) height, buttock-knee depth and popliteal depth. As shown in figure 4, we

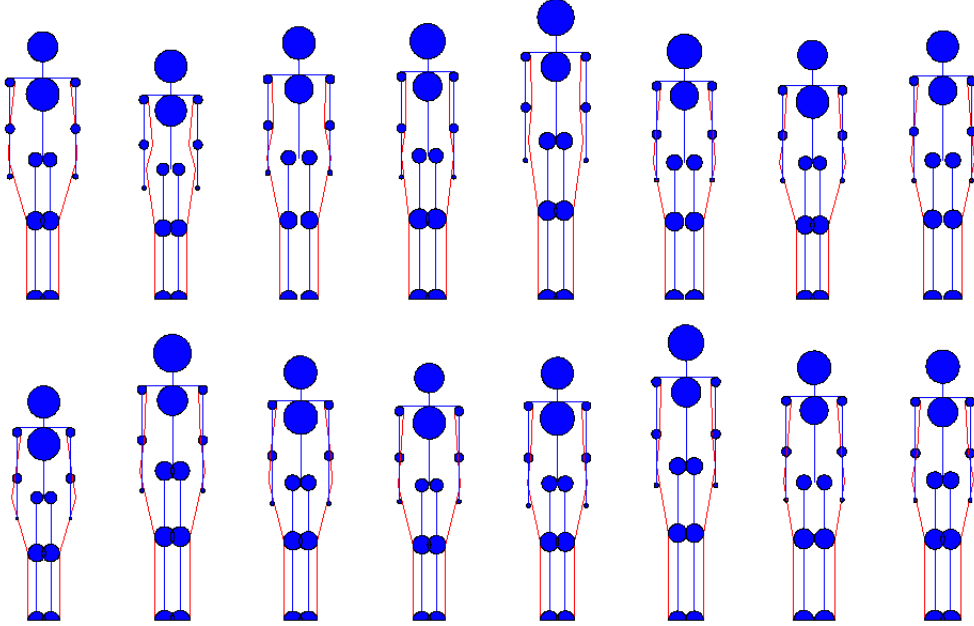


Figure 5: Examples of skeleton models

assume that the knee is circular and that the joint is positioned in the middle. The relevant distances are then found as shown in equation (2):

$H_p$  = popliteal height - known  
 $D_p$  = popliteal depth - known  
 $D_k$  = knee depth - known  
 $R_k$  = knee radius - to be found  
 $L_{ll}$  = lower leg dimension - to be found  
 $L_{ul}$  = upper leg dimension - unknown value

$$\begin{aligned}
 D_k &= L_{ul} + R_k \\
 D_p &= L_{ul} - R_k \\
 \Rightarrow \\
 R_k &= (D_k - D_p)/2
 \end{aligned} \tag{2}$$

and

$$\begin{aligned}
 H_p &= L_{ll} - R_k \\
 \Rightarrow \\
 L_{ll} &= H_p + (D_k - D_p)/2
 \end{aligned}$$

Other assumptions are made, such as in the calculation of the chest depth. In this it was assumed that the majority of the increased circumference (the dimension given in the data set) would be on the front and sides of the body and we are only interested in the depth



between the centre and back. In this case we assume that the circumference of the ribcage is the minimum possible, e.g.  $mean - 3 * sd$ . This was also allowed for in the calculation of the anthropometric values. A full list of the methods used to find the dimensions and the assumptions required are included in the supplementary information.

This gives us a skeleton model with additional body proportions as shown in figure 5. We will refer to the body length dimensions as (head to toe) neck length ( $L_n$ ), torso length ( $L_t$ ), upper leg length ( $L_{ul}$ ) and lower leg length ( $L_{ll}$ ). The joint radii will be referred to as head radius ( $R_{hd}$ ), shoulder radius ( $R_s$ ), hip radius ( $R_{hp}$ ), knee radius ( $R_k$ ) and foot radius ( $R_f$ ). Additional proportions include the padding ( $P$ ), which is the thickness of the layer of tissue around the hip, total mass of the test model and the centre of mass of each limb, which used data from [23].

### 3.3 Positioning the Skeleton

The next task was seat the skeleton in the chair. This needed to be as natural as possible within the bounds of the simplified model, as all the later calculations would be based on the position of the skeleton. This was calculated in the  $x$ - $z$  plane with the assumption that the skeleton was positioned symmetrically.

#### 3.3.1 The Chair

To position the skeleton we require a simplified model of the chair; two lines in the  $x$ - $z$  plane. The first represents the seat and is set between  $(0,0,seat\ height)$  and  $(seat\_end\_x,0,seat\_end\_z+seat\ height)$ , where seat height is parameter 1 and seat\_end\_x and seat\_end\_z are found using the seat length and seat recline parameters (2 and 5 respectively). The second line is the back and is between  $(0,0,seat\ height)$  and  $(back\_end\_x,0,back\_end\_z+seat\ height)$ , with the back variables similarly calculated from parameters 3 and 4. In addition a line at height 0mm was used as the floor and another at height 750mm to represent a desk or table.

#### 3.3.2 Hip Placement

The first point positioned was the hip joint. Since there are many ways to sit in a chair, it was decided that the hip joint position would be fixed near the back of the chair to ensure all the chairs would be tested in the same manner. Therefore the chairs are always tested with the test skeletons fully seated and not 'perched' on the edge of the chair.

The point at a distance of  $R_{hp}$  from both the seat line and back line was found. This point was then moved forward by  $P$  to account for the tissue layer covering the hip. Padding was not added between the seat line and the hip as it was assumed that this layer was compressed or moved out from under the hip. The remaining tissue thickness was included in  $R_{hp}$ .

#### 3.3.3 Leg Placement

The method used to position the legs was to minimise the height of the centre of mass of the two sections. A range of 100 positions for the upper leg was found from when the knee was tangent to the seat line to a position at an angle of  $\frac{1}{2}\pi$  from the back line. Similarly a range of 100 lower leg positions was found from 0 (straight leg) to  $\frac{3}{4}\pi$  (leg bent). A matrix of size  $100 \times 100$  was found where element  $(n, m)$  contained the centre of mass of the entire limb with the upper leg in position  $n$  and lower leg in position  $m$ . Two other matrices with the positions of the knee and foot at the relevant angles were also found.

The next stage of calculation was to find the positions that could not exist, e.g. those where the legs passed through the seat or floor. As the minimum angle of the upper leg was

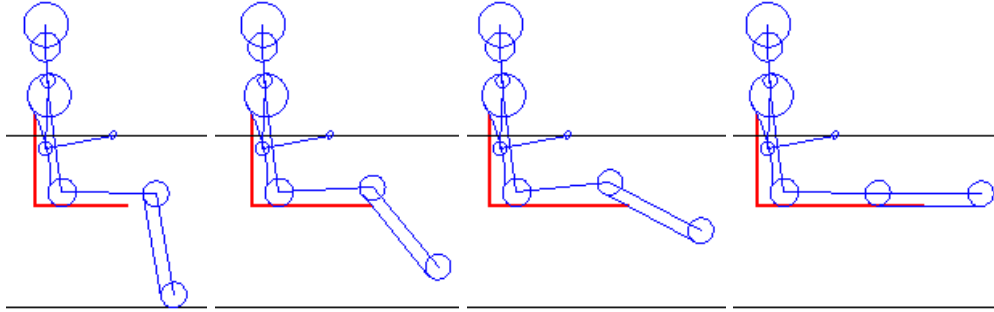


Figure 6: Position of legs as the seat length increases

when the seat was tangent to the knee and hip it was assumed that the upper leg would not pass through the seat or floor and so it was sufficient to test the lower leg.

To check for intersections between the floor and the lower leg, the  $z$  value of the foot position was considered. If the  $z$  value was less than  $R_f$  then the foot would be passing through the floor. The elements in the centre of mass matrix where this was the case were removed by setting the element to  $NaN$  ('Not-a-Number' in Matlab,  $NaN$  elements are ignored when applying functions such as max and min).

For intersections between the lower leg and the seat we first find a line tangent to the circles representing the knee and foot. This will be the back of the leg in our model. We then ensure that the seat front does not intersect this line. We found the point of intersection using the line-line intersection method from Wolfram<sup>6</sup> and then tested to see if the  $x$  value of the point of intersection was smaller than the end of the chair.

After removal of the impossible positions the minimum of the heights of the remaining centre of mass points was found. This was the position used in our model. This produced quite a natural movement of the legs; while the seat was shorter than the underside of the legs, the legs either rest on the floor or if the chair is too high dangle vertically. However as the seat gets longer, the knees are raised to allow the feet to drop slightly. Eventually, when the chair approaches the sum of the lengths of the lower and upper leg, the leg straightens out and rests full on the seat. This is shown in figure 6.

The final height of the feet from floor level is recorded as the first of our practicality measures.

### 3.3.4 Back and Head Placement

The back and head positions were found in a similar way to the leg method, this time minimising the effort required to keep the body in position. There are also 3 joints to consider; the hip, shoulder and neck, creating a 3 dimensional matrix of points.

First the range of motion of all the joints was found. The range of the hip joint was between the angle of the back and an angle of  $\frac{1}{4}\pi$  leaning forward. Due to the length of the torso, 500 points were taken in this range to ensure a small spacing of possible positions of the shoulder joint. The shoulder range was between  $\frac{1}{4}\pi$  forwards and  $\frac{1}{8}\pi$  backwards with 100 points and the neck range was  $\frac{1}{8}\pi$  forwards and  $\frac{1}{4}\pi$  backwards with 50 points. These

<sup>6</sup><http://mathworld.wolfram.com/Line-LineIntersection.html>

angles were chosen as estimated range of motion limits, only the neck range was taken from a data source (the DINED dataset [8]). It was assumed that positions at the extremes of the range of motion would be more uncomfortable, therefore the range estimates were chosen to be smaller than the potential full range. As with the back these were used to construct matrices of the positions of the joints for every angle in the range. Three matrices of effort values were created, one for each joint.

After the posture is finalised the angle between the eyes and the horizontal is measured as one of the practicality traits. We assume the eye line is perpendicular to the neck.

**Joint Effort** In this model the joint effort used to position the back and neck is not directly related to a real force, it is based on observations on how people sit in response to real forces acting on them. Examples of the skeletons sitting are given in figure 11.

Two main factors were identified that could change the effort value. The first was the force due to gravity. It was assumed that when the centre of mass of an object was directly above the joint then all the force was travelling down the spine and this would not cause twisting of the joint. However, if the centre of mass was moved away from the vertical then part of the force down would begin to try and pivot the body around the joint and muscles would have to compensate for this force to prevent the body slumping over, therefore increasing the effort. The second factor was the use of the seat back to prevent pivoting, e.g. if you are leaning against a backrest then it is the back and not your muscles that are preventing you from pivoting further. To model this, we found the points where the back or head was within a tolerance value of the back line and made the relevant joint effort 0 at those points. Details of the calculation used to find proximity to the back is given in the spine section below.

To produce a slight hunch when seated a muscle is modelled along the back of the shoulder joint. The resting position of this muscle is in a slouch position. When the skeleton is hunched further the effort of this muscle is increased according to Hooke's law ( $F = kx$  [24]). Similarly the effort is also increased as the back straightens to vertical. A balance is therefore found between the muscle's resting position and the vertical spine, creating a slouch. How these factors interact can be seen in figure 7.

As with the legs, positions where the body passes through the back of the chair were removed. The calculation of these positions is found in the spine section. We find the minimum effort and set this as our position.

**Spine** One way the back is more complex than the legs is the spine. While the legs can be modelled as straight bones whatever their position, the back changes shape as it flexes. It was decided that modelling all 33 vertebrae and their ranges of motion was too complex for the purposes of this model. Instead the flex of the spine was modelled by a single joint in the shoulders. However as the spine is close to the surface of the back and creates the profile in contact with the chair an approximation of its shape is required. By profile we refer to the external shape visible from our side view.

The human spine has 5 regions; cervical, thoracic, lumbar, sacral and coccygeal[25]. However as the sacral and coccygeal vertebrae are within the profile of the hip bone we do not need to model them here. In figure 8 we see that in the vertical position the cervical and lumbar regions have an outward curvature and the thoracic region has an inward curvature. However in the slouched posture the thoracic region becomes straight or even outwardly curved. Based on these observations we use the existing hip and shoulder radii as the lumbar and cervical regions respectively and introduce a new curve to represent the variable thoracic spine. As this is the only part modelled separately we will refer to it as the spine.

For simplicity we model the spine as an arc of a circle. A circle can be defined using three points. We select the first point where the spine meets the hip, taken as a point on

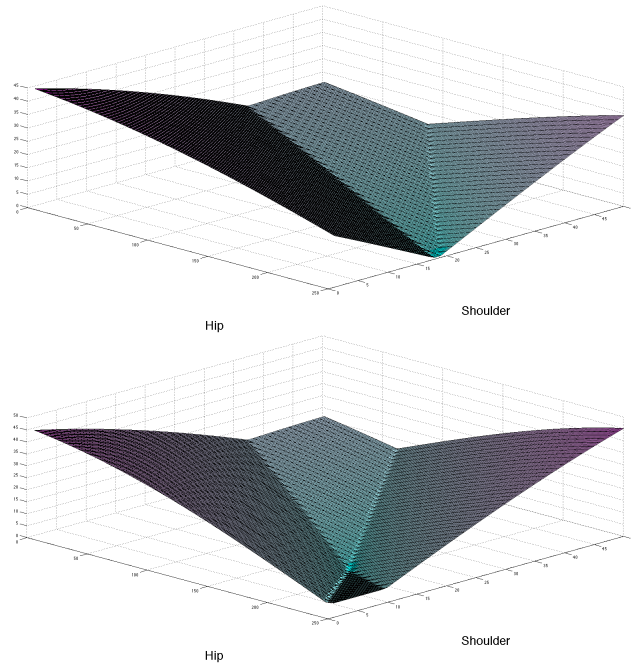


Figure 7: The potential effort values for the shoulders at two set head angles. The two lines are caused by the pivot force minimum when the back is vertical and the muscle force minimum at its resting position. How these lines intersect creates the minimum value

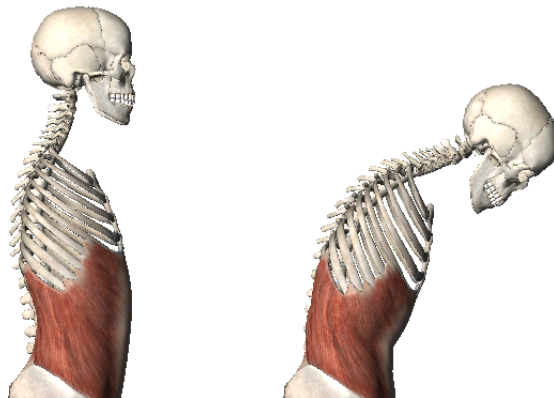


Figure 8: Spine shape in vertical and leaning positions. Graphics from Visible Body Muscle Premium [26]

the hip radius at angle  $\frac{1}{4}\pi$  from the skeleton's back angle. The other two points are on the shoulder radius with a position determined by the position of the neck joint and another perpendicular to the line between that point and the shoulder joint. This definition creates the shape that we desire, when the skeleton is slouched it produces an outward curve of the spine and when it is vertical (or resting straight against the back) it has an inward curve.

This additional curve creates new positions which would be impossible due to intersections between the body and chair. These are found and removed from the potential positions. It also creates new points where the weight is supported by the seat back and these also need to be found. For the cases where the back curves out we find the minimum distance between the seat back line and the centre of the circle of the spine arc (using a method from Wolfram<sup>7</sup>). If this distance is less than the radius of the spine curve and the closest point on the back line is not outside the bounds of the back, then we set the effort points to *NaN*. Similarly we can find those points where the radius is the same as the distance ( $\pm$  a tolerance) and set their effort value to 0. When the back curves in the seat back will only come into contact with the spine if the seat back is not long enough to reach the shoulders. Leaning backwards into such a short back did not appear to be a natural position and no values are set to 0 in this case. However we still test for intersections and remove the effort values accordingly.

The inverse of the radius of the spine arc was used as a measure of the curvature of the spine. This is our first comfort measure.

**Resulting Behaviour** We can see how all these factors are used to define the space in which our skeleton can be positioned and how this affects its posture. In figure 9 we see how each additional factor changes the hip effort space (for fixed neck angle) and therefore the potential position of the skeleton.

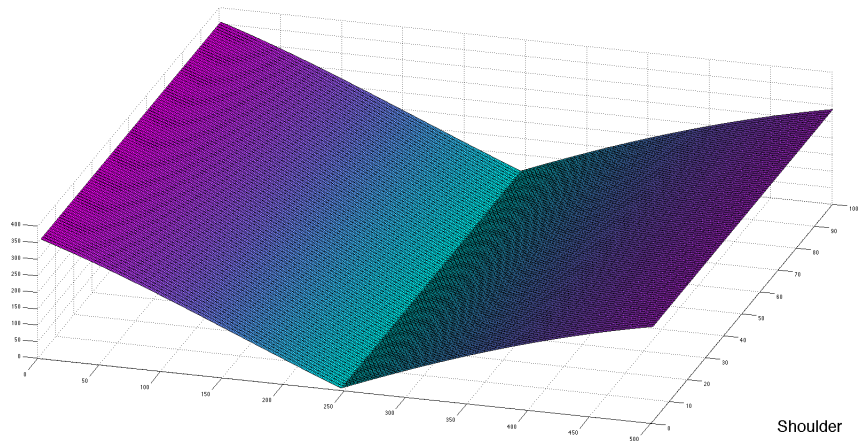
With all the factors in place the skeleton has 3 main positions: If the back is sufficiently long so that the head and shoulders can both be in contact then the skeleton leans back, creating an inward curve to the spine (figures 11b, 11d, 11f and 11h). If the back is too short and the head can no longer be in contact with the back then the skeleton takes one of the other two positions; leaning backwards, so that the hip effort is 0 with the head lifted into a near vertical position at the minimum of the shoulder and neck efforts (figures 11a, 11c and 11e), or sitting upright at a slight slouch (figure 11g) as the effort to support the head at that angle becomes higher than the benefit of resting the shoulders against the seat back. If the seat back is so short as to prevent the back resting against it the skeleton will automatically sit up in the final position.

**Arms** The final part of the model to position is the arms. The arms are studied so that we can see how the arms would be positioned if the skeleton was to be working at a desk or table. As before all possible positions of the joints (elbow and hand in this case) were found. The positions that did not result in the hands being at desk level (750mm) were then removed. In addition any positions that had the arms pass through the back of the chair were also removed. To select the arm position that required the least effort the height of the centre of mass was once again minimised.

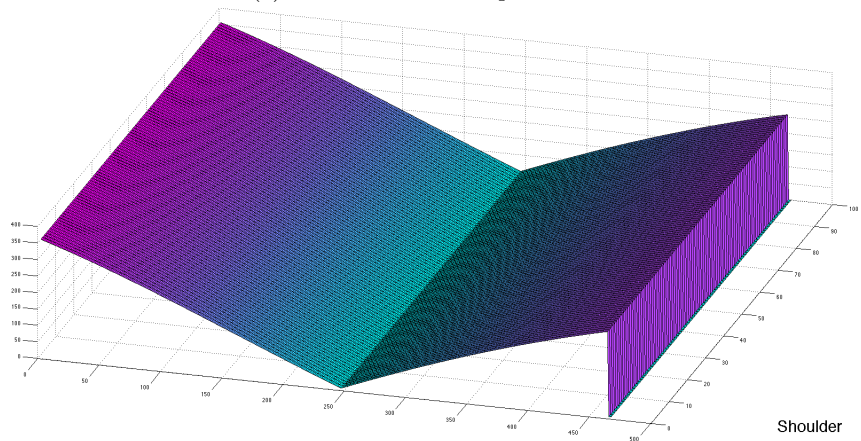
The difference between the arm angles and the preferred angles is found. The preferred angle of the lower arm is parallel to the desk and the preferred angle of the upper arm is at right angles to the lower arm. The differences of these two angles are summed and this value is another practicality measure.

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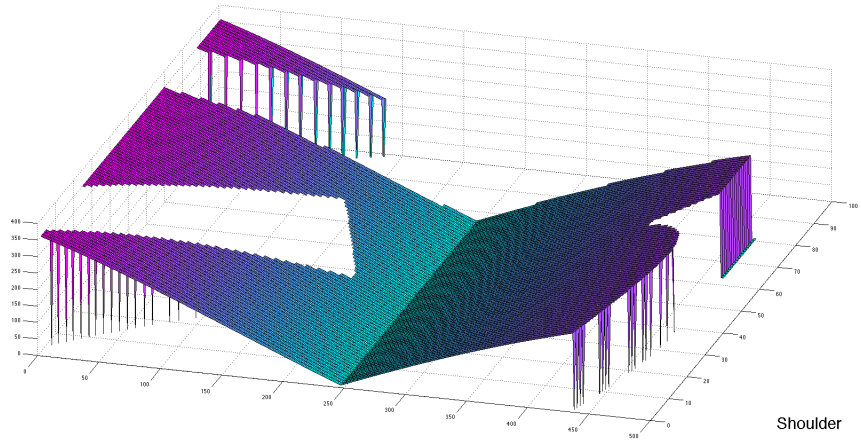
<sup>7</sup><http://mathworld.wolfram.com/Point-LineDistance3-Dimensional.html>



Hip  
(a) Effort to overcome pivot effect

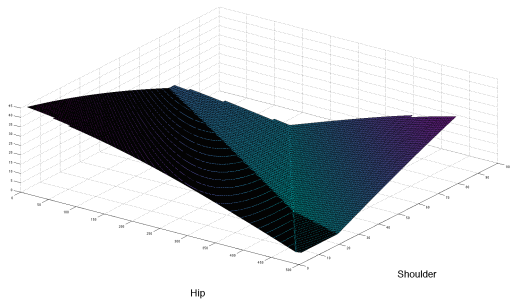


Hip  
(b) Shoulders resting on seat back give 0 effort, Shoulders passing through chair removed

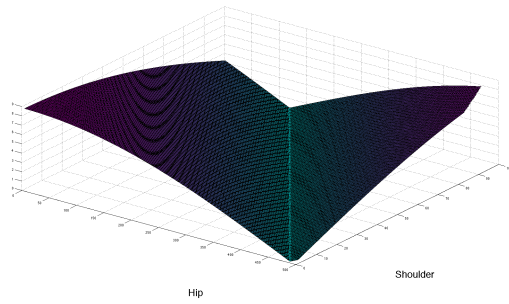


Hip  
(c) Spine resting on seat back given 0 effort, Shoulders passing through chair removed

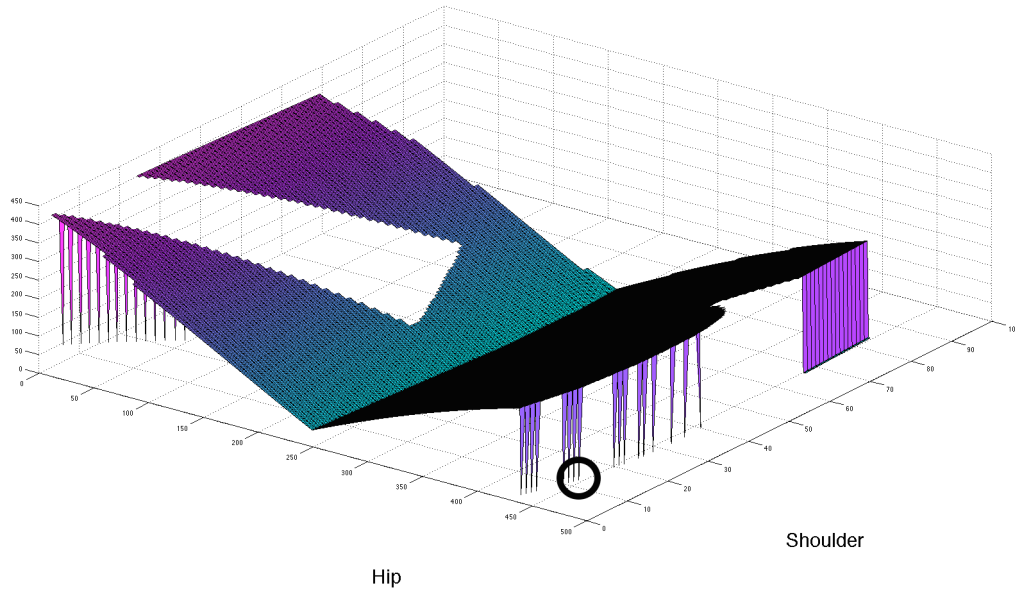
Figure 9: Illustration of how the hip effort is modified by effort factors



(a) Final Shoulder Effort



(b) Final Neck Effort



(c) All Efforts including Hip Effort from 9c giving final minimum (circled)

Figure 10: Shoulder and Neck efforts and the combination that gives the final position. The skeleton seated in this position is shown in figure 11f

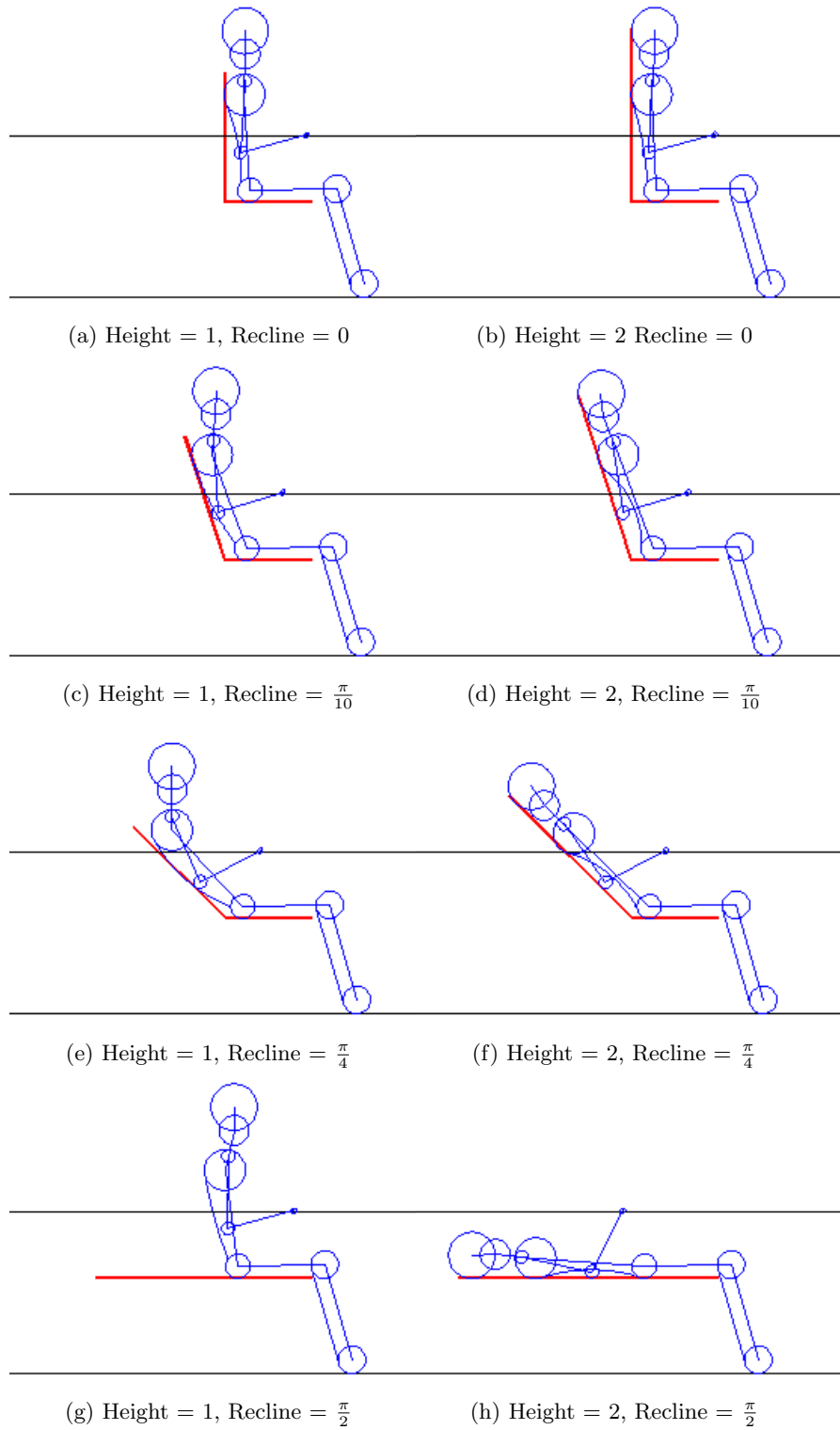


Figure 11: Example of the movement of the skeleton as the back changes length and angle



### 3.4 Pressure Modelling

To find the peak pressure a pressure map that resembles those seen in previous research is required. Observations of seat pressure maps in both commercial and academic literature indicates that the distribution of pressure is roughly symmetrical, with the highest concentration under the hips. As the distribution is not uniform a similar gradient is required to ensure that the peak pressure is high enough, however the exact distribution is not as important as in the cases where pressure sores are a concern.

We aim to find a model that has peak pressure in the 20 kPa–40 kPa range for a flat padded seat cushion, with improvement when a contoured cushion is used. We have no base line maximum for an unpadded seat but the peak pressure should be higher, based on observations of unscaled comparative maps. We are looking for a peak below the hips, unless the shape of the seat creates a pressure peak at another point.

#### 3.4.1 Chair Surface

To test how the pressure changed between different chairs we need to have a chair surface to analyse. To model the pressure in Matlab a matrix where each element represents a  $1mm \times 1mm$  square is used. As with the SketchUp model the cross-sections and their depths and positions are used to create the chair surface. The cross-sections are imported into Matlab as a list of  $x, y$  coordinates.

A width curve is interpolated as a vector of width values at every  $1mm$  step along the chair from the cross-section's widths and positions. Then for each element of this matrix a copy of the cross-section coordinates is created, with the  $y$  coordinate scaled by the relevant width value and the  $x$  value scaled by the depth of the cross-section. The coordinates are then interpolated to find the  $1mm$  steps. The different cross-section copies are combined by weighting the copy by its proximity to its original cross-section. A depth vector (found in a similar way to the width vector) is used to smooth the curve. All the areas not covered by the seat are set to  $NaN$ .

From the chair surface two other maps are found that are used in the calculation of the pressure. The first of these is the angle map, this is found by calculating the difference in height value between two neighbouring elements in the  $y$  direction. The other map is the padding depth. This is found by subtracting  $10mm$  from the height map (this depth is assumed to be structural), with any negative values set to 0. If the chair is to be a material that is not padded (e.g. wood or metal) the padding map will be zero everywhere.

#### 3.4.2 Pressure of the Legs

One of the most important things to consider with the pressure map of the legs is the effect of the pelvis. As seen in figure 12 the shape of the pelvis means that the part of the hip known as the Ischial Tuberosity (IT) takes most of the weight and as it is much closer to the surface of the skin it also causes the highest pressures.

We will use the sinusoidal load distribution given by Solidworks<sup>8</sup> as the basis to our model. This assumes that any point on a half circle has a vertical load of  $F_0 \sin^2 \theta$  where  $\theta$  is the angle from horizontal.  $F_0$  is found using equation (3).

$$\text{Total Force} = F_0 \sum_{i=1}^n \sin^2 \theta_i \quad (3)$$

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<sup>8</sup>[http://help.solidworks.com/2013/English/SolidWorks/cworks/c\\_Bearing\\_Load\\_Distribution.htm](http://help.solidworks.com/2013/English/SolidWorks/cworks/c_Bearing_Load_Distribution.htm)

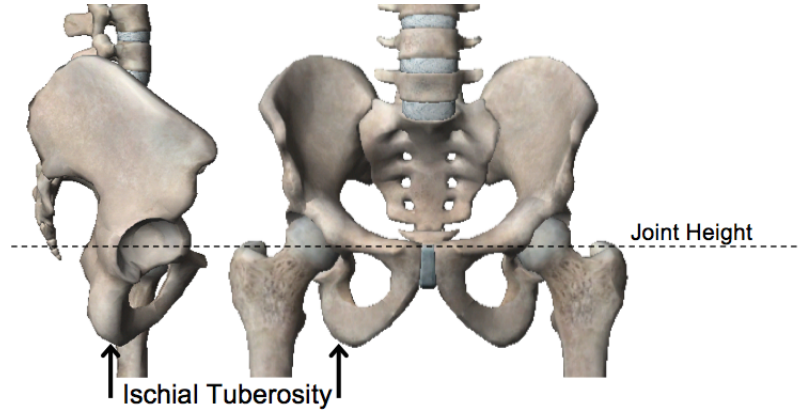


Figure 12: Height of the Hip Bones. Graphics from Visible Body Muscle Premium [26]

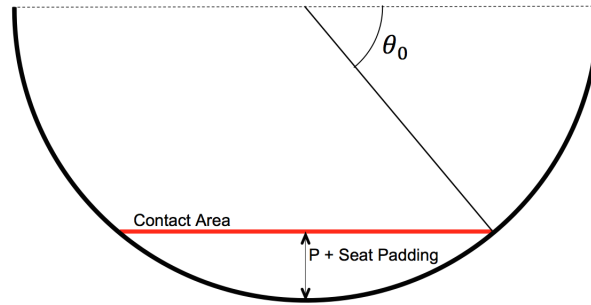


Figure 13: Finding the contact area of the leg.

**Pressure of the Leg Mass** The leg is modelled as having a circular cross-section. This cross-section is of constant radius of  $R_k$  in the lower leg and  $R_k$  increasing to  $R_{hp} + P$  for the upper leg. The buttock itself is modelled as a half sphere of radius  $R_b = R_{hp} + P$ . A matrix is created for the area of the leg with one element representing a  $1mm \times 1mm$  square and for each position we find the value of  $\theta$  for the leg at that point. This value of  $\theta$  is then adjusted using the angle of the chair that it is in contact with using the chair angle map generated in the chair model.

The area of the pressure map is reduced by estimating the area of contact between the leg and seat. The value of  $\theta$  is found at the edge of a segment as shown in figure 13. This segment is assumed to be the volume created by the compression of the tissue and any padding on the chair. Therefore the height of the segment is  $P + \text{Seat Padding}$  (from the padding map as shown in the chair model above). Any points where the angle is less than  $\theta_0$  are then set to 0.

Once the angle  $\theta$  has been finalised  $\sin^2 \theta$  is calculated at each point to create the distribution. The distribution matrix is then piecewise multiplied by the normalised height map from the chair model. This has two effects, first it increases the pressure over high areas relative to low areas, second it sets areas not over the seat area to 0. Additionally we multiply by a vector that adjusts for the distribution of weight over the area. If the centre of mass of the leg is half way down the leg this vector will be constant, but if the weight is moved backwards then the pressure at the front is reduced relative to the back. If the leg is lifted off the seat then part of this vector will be 0.

The total force for the leg mass is the percentage of the mass contained in the upper leg

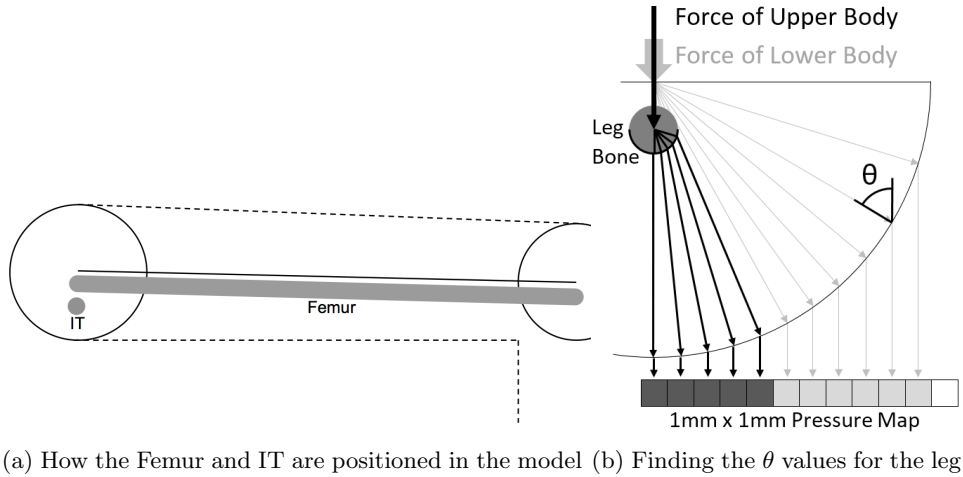


Figure 14: Layout of the simplified model

according to Winter [23] multiplied by acceleration due to gravity ( $9.81m/s^2$ ). If the lower leg is not resting on the floor the mass of the lower leg is added to that of the upper leg and the centre of mass of the entire limb is considered. The distribution matrix is normalised by dividing by the sum, then it is multiplied by the total force. Finally it is multiplied by 1,000,000 to convert to the pressure SI unit Pascals.

**Pressure of the Body Mass through the Skeleton** It is assumed that the weight of the upper body is carried through the skeleton. Two parts of the skeleton are then modelled; the Ischial Tuberosity (IT) and the femur. The femur is modelled as a cylinder of radius  $20mm$  with rounded ends throughout the middle of the leg and the IT is modelled as a sphere also of radius  $20mm$  in the centre of the buttock. We see in figure 14a that they are assumed to be lower than the centre of the leg cross-section. This difference in depth is  $P+Seat$  Padding as in the calculation of contact area.

The transfer of force through the leg is then calculated as follows: For each  $1mm$  cell a line is traced from the outside surface of the leg to the centre of the leg to see if this line passes through the underside of either the IT or the femur (figure 14b). If it does,  $\theta$  of the leg bone at this point is used as the  $\theta$  value for that cell.

This is done for the femur and IT separately. The IT uses a depth of  $R_b - (Weight * 0.52 + 8.16)/2$ , where  $R_b$  is the radius of the buttocks. This value is calculated using data from two papers; Cheung and Tam [27] and Makhsous et al [7]. Cheung and Tam showed that the thickness of tissue over the IT had a linear relationship with body weight, the values of 0.52 and 8.16 were calculated from their results. However their testing was done in a sitting position with no pressure. Makhsous et al studied the relationship between the thickness of tissue in a sitting position and a sitting position under pressure. Their results show a significant reduction in tissue thickness over the IT. Exact values were not given in the paper but the graphs indicate a reduction of approximately half of the thickness, hence the calculated value is divided by 2.

The rest of the process continues as for the leg mass except the existing contact area is used rather than testing the new  $\theta$  against  $\theta_0$ . The mass used this time is the mass of the upper body adjusted to remove any weight carried by the seat back.

We now show some example pressure maps from the model along with their maximum pressure values. Figure 15 shows the pressure of a 75 kg (11.8 Stone), 180 cm (5.9 Feet)

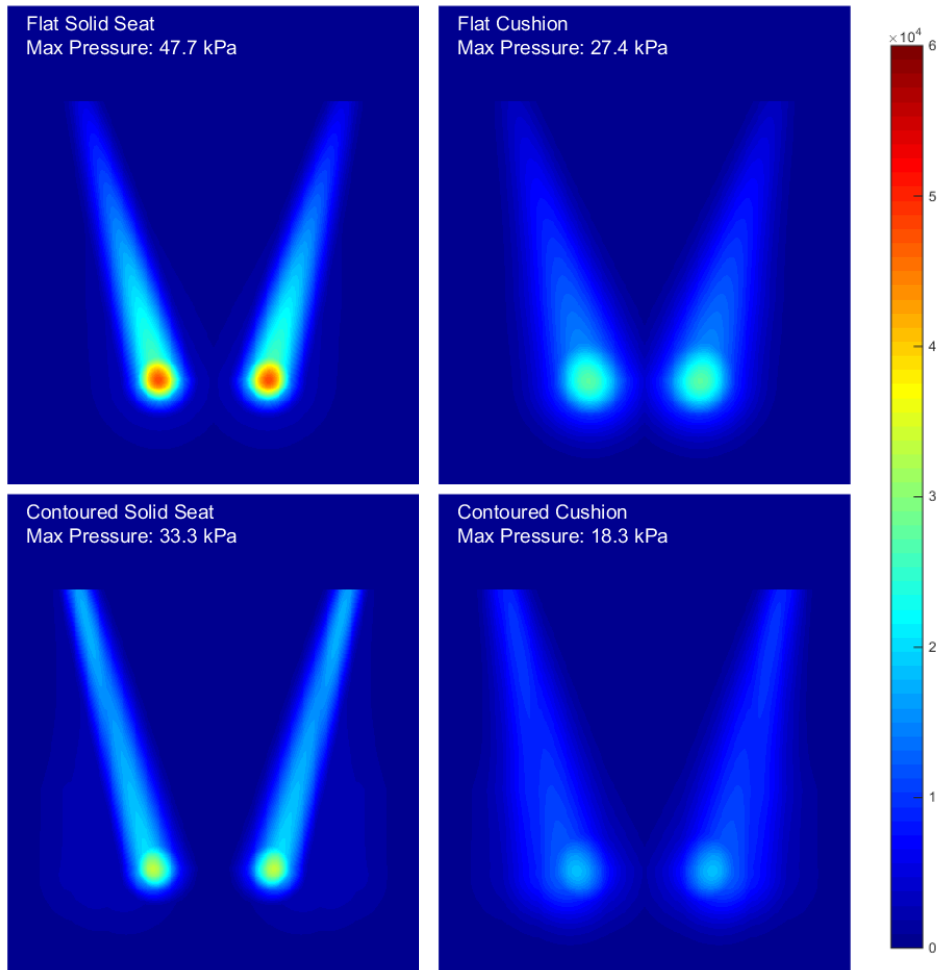


Figure 15: Pressure maps produced by our simulation of a 75 kg, 180 cm tester seated on 4 different seats. Pressure distribution can be compared with figures 1 - 3

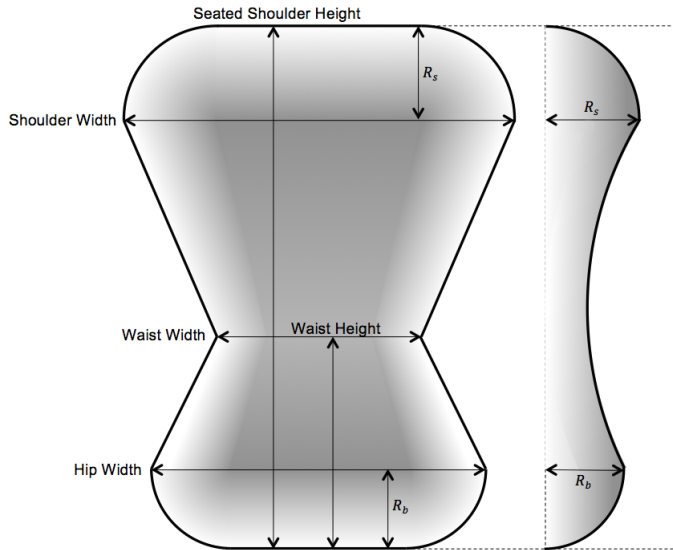


Figure 16: How the back model area (left) and height (right) are formed from the relevant dimensions

person sitting on a variety of seats. This is the same height and mass as the tester in Wagnac et al [14]. Their simulation gave maximum values of 23.6 kPa for a flat cushion and 16.5 kPa for a contoured cushion. Our simulation gives a similar difference between the contoured and flat cushions and the solid seats have higher pressures for both shapes as expected.

### 3.4.3 Pressure of the Back

The pressure of the back against the chair is less well represented in the literature. We choose to make a very simple model that will respond to the back or head leaning on a small or hard area. As the bones in the back (such as the spine, shoulder blades and ribs) are close to the surface and cover the majority of the area we do not model the bones and flesh separately in the back. The shape of the back is modelled as shown in figure 16 and the same method used as for the legs. Notable differences include the calculation of the surface area, where padding value  $P$  was set to  $5mm$ .

If the head also rests on the seat back then the pressure of the head is calculated separately. If it does not rest on the seat back then the mass of the head is added to that of the torso. The weight pressing on the seat back depends on the angle of the back with the rest transferred to the seat.

## 4 Summary

The ergonomic model presented here allows nine ergonomic factors of the chairs (described in table 1) to be tested. The simulations were not designed to be highly accurate and many assumptions and simplifications have been used. However it is capable of assessing chairs directly from the parameters without human input. This is done fast enough to enable the collection of a large quantity of data - something not possible with more sophisticated simulations or collection of real data.

The time improvement over examples in the literature was substantial; 3.2 seconds per chair, per user, improved from 30 minutes for Grujicic et al [15]. This allowed us to produce

Table 1: Properties of Chairs used in this Work

No.	Description of Measure	Type
1	Angle of elbow and shoulder away from ideal	Practicality
2	Angle of eye line away from horizontal	Practicality
3	Height of foot above floor	Practicality
4	Pressure of body against back	Comfort
5	Pressure of body against seat	Comfort
6	Curvature of Spine	Comfort
7	Maximum Width of Chair	Efficiency
8	Maximum Length of Chair and User	Efficiency
9	Angle between Chair Back and User's Back	Efficiency

a useful dataset of 12000 chairs over several days.

Despite the simple model, the simulations produce pressure maps and peak values that are within the range that appears in the literature. The target posture of the skeleton was not drawn from sources, but rather the experience and observations of the author. The reader is invited to judge the postures presented in figures 6 and 11 against their own experience.

The ability to test large numbers of chairs - both good and bad - allows us to study the effect of individual parameters on each ergonomic property, Further work will be done to study this, using machine learning.

## References

- [1] NHS Live Well: ‘How to Sit Correctly’: <http://www.nhs.uk/Livewell/workplacehealth/Pages/howtositcorrectly.aspx>
- [2] Gutierrez, E.M., Alm, M., Hultling, C. and Saraste, H.: Measuring seating pressure, area, and asymmetry in persons with spinal chord injury. In: European Spine Journal, Vol 13, Issue 4, pp 374-379 (2004)
- [3] CDC: National Health and Nutrition Examination Survey (NHANES) Anthropometry Procedures Manual.
- [4] NASA Man-Systems Integration Standards Volume 1, Section 3: Anthropometry and Biomechanics. <http://msis.jsc.nasa.gov/sections/section03.htm>
- [5] Civilian American and European Surface Anthropometry Resource Project CAESAR: <http://store.sae.org/caesar/>, (2014)
- [6] Clauser, C.E.: Weight, Volume, and Center of Mass of Segments of the Human Body. Technical Report No. AD-710 622, Air Force Systems Command, Wright Patterson Air Force Base, Ohio. (1969)
- [7] Makhsous, M. et al.: Tissue Thickness overlying Ischial Tuberosity in a Simulated Sitting Posture measured on MRI machines. RESNA (Rehabilitation Engineering and Assistive Technology Society of North America) Conference 2009. (2009)
- [8] TU Delft DINED Anthropometric Database: <http://dined.io.tudelft.nl/dined/full>

- [9] Drury, C.G. and Coury, B.G.: A Methodology for Chair Evaluation. In: Applied Ergonomics, Vol 13, Issue 3, pp 195–202. (1982)
- [10] Openshaw. D.S.: Predicting and Quantifying Seated Comfort and Discomfort using Objective and Subjective Measures. PhD Thesis, University of Iowa. (2011)
- [11] Wachslar, R.A. and Learner, D.B.: An Analysis of some factor influencing Seat Comfort. In: Ergonomics, Vol 3, Issue 4, pp 315–320, Taylor and Francis. (1960)
- [12] Lanzotti, A., Trotta, M. and Vanacore, A.: Validation of a new index for seat comfort assessment based on objective and subjective measures. International Conference on Innovative Methods in Product Design. Venice, Italy (2011).
- [13] Todd, B.A. and Thacker, J.G.: Three-dimensional computer model of the human buttocks in vivo. In: J Rehabilitation Res. Dev., vol 31, no. 2, 111–119 (1994)
- [14] Wagnac, É., Aubin, C.É. and Dansereau, J.: A New Method to Generate a Patient-Specific Finite Element Model of the Human Buttocks. In: IEEE Transactions on Biomedical Engineering, Vol 55, Issue 2, pp 774–783. (2008)
- [15] Grujicic, M. et al: Seat-cushion and soft-tissue material modeling and a finite element investigation of the seating comfort for passenger-vehicle occupants. In: Materials & Design, Vol. 30, pp 4273–4285. (2009)
- [16] Zhu, H.: Modeling of pressure distribution of human body load on an office chair seat. Masters Thesis. Department of Mechanical Engineering, Blekinge Institute of Technology, (2013)
- [17] Northwest Regional Spinal Cord Injury System, University of Washington: Picture this ... Pressure Mapping Assessment for Wheelchair Users.[http://sci.washington.edu/info/forums/reports/pressure\\_map.asp](http://sci.washington.edu/info/forums/reports/pressure_map.asp). Accessed 23–11–2015.
- [18] Brienza, D.M., Karg, P.E. and Brubaker, C.E.: Seat Cushion Design for Elderly Wheelchair Users Based on Minimization of Soft Tissue Deformation Using Stiffness and Pressure Measurements. In: IEEE Transactions on Rehabilitation Engineering. Vol. 4, Issue 4, pp 320–327. (1996)
- [19] Reed et al.: Survey of Auto Seat Design Recommendations for Improved Comfort. Technical Report, University of Michigan Transportation Research Institute. (1994)
- [20] Reed, K. and Gillies, D.: ChairMaker - A Parametric Chair Modelling Program. Imperial College London, 2016, 15pp. Report no. 2016/3
- [21] Herman Miller: The Art and Science of Pressure Distribution. <http://www.hermanmiller.com/research/solution-essays/the-art-and-science-of-pressure-distribution.html>
- [22] Dirken, J.M.: Ontwerpen voor Gebruikers. In: Productergonomie, Delft University Press. (2004)
- [23] Winter, D.A.: Biomechanics and Motor Control of Human Movement, 4th Edition. John Wiley & Sons, Inc. (2009)
- [24] BBC Schools: GCSE Bitesize Hooke's Law. [http://www.bbc.co.uk/schools/gcsebitesize/science/add\\_aqa/forces/forceselasticityrev2.shtml](http://www.bbc.co.uk/schools/gcsebitesize/science/add_aqa/forces/forceselasticityrev2.shtml). Accessed 30/01/2016

- [25] Drake, R.L., Vogl, W. and Mitchell, A.W.M: Gray’s Anatomy for Students. Elsevier. (2005).
- [26] Visible Body Muscle Premium [http://www.visiblebody.com/muscular\\_overview/](http://www.visiblebody.com/muscular_overview/)
- [27] Cheung, A.C.H. and Tam, E.W.C.: Relationship between Body Weight and Tissue Thickness over the Ischial Tuberosity and the Sacrum. RESNA (Rehabilitation Engineering and Assistive Technology Society of North America) Conference 2003. (2003)

## Supplementary Information

### Parameters used in the ChairMaker

The tables in this section list all of the parameters used in the final version of the ChairMaker along with a brief description of their physical effect. The numbering corresponds to the numbering used within the ChairMaker program.

Table 2: ChairMaker Proportion Parameters

No.	Name	Notes
1	Seat Height	Height is to the back of the seat, Seat Recline will change the height of the front when it is non-zero
2	Seat Length	Length of the seat in the direction of Seat Recline.
3	Back Recline	Angle of back away from vertical
4	Back Height	The length of the back in the direction of Back Recline
5	Seat Recline	Angle of Seat away from horizontal
6	Seat Width	Width of the seat cross-section
7	Back Width	Width of the top of the back, actual back cross-section widths may be altered by the Corner Width
8	Corner Width	Width of the corner cross-section if the seat and back are in 1 piece (number of back pieces is 0). Otherwise this is the width of the base of the back and the back of the seat.
18	Seat Depth	Depth of the seat cross-section
19	Corner Depth	Depth of the corner piece, only used if the seat and back are in 1 piece
20	Back Depth	Depth of the back cross-sections
21	Gap	Size of gap between seat and back, only used if the seat and back are separate
29	Leg Width	Scale of the leg cross-sections
30	Base Size	Ratio of the leg positions on the floor to the Seat Length and Width



Table 3: ChairMaker Texture Parameters

No.	Name	Notes
23	Seat Texture	Choice of texture for seat from predefined set shown in next section
24	Back Texture	Choice of predefined texture for back, not used if seat and back are combined
33	Leg Texture	Choice of predefined texture for legs

#### 4.1 DINED DATA

We use the following values from the DINED 2004[8] data set of Dutch adults, figure 17 shows where the measures were taken and table 5 give the values. Some of these required adaptation as we need slightly different measurements in order to calculate the dimensions of our model. These adaptations and the assumptions that allowed us to find them are given in table 6.

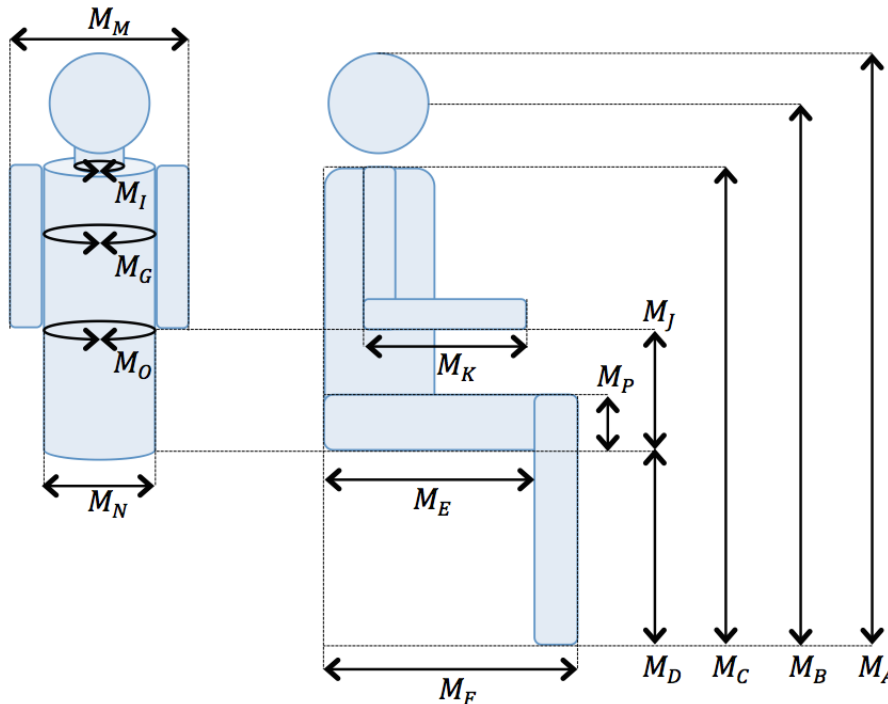


Figure 17: Location of DINED Measures

#### 4.2 Calculation of Dimensions used in Model

We use the DINED values to find the dimensions of the body we will use to test the chairs. We first find values of the measures by deciding on a test subject’s age, gender, weight and height. Weight and height are initially given as Gaussian random numbers with mean 0 and standard deviation 1. These are then used to influence other parameters, if the height is less than 0 then all the limb lengths are likely to be lower than average for the age and gender.

Table 4: ChairMaker Form Parameters

No.	Name	Notes
9	Seat Rounding	When set to 1 the seat is constructed with only 1 cross-section at each end. When set to less than 1 the seat has 2 pieces at each end and the outermost piece is reduced by the Seat Rounding value
10	Back Rounding	As Seat Rounding for all back pieces
11	Vertical Support	Number of uprights between the back and seat. If this value is greater than 1 and the leg type is suitable the legs extend upwards, becoming 2 of the verticals.
12	Seat Shape	Choice of predefined cross-section, combined with the unifying shape to make the seat cross-section
13	Corner Shape	Choice of predefined cross-section, combined with the unifying shape to make the corner or back of the seat cross-section
14	Unifying Shape	Choice of predefined cross-section used to ‘even out’ the change between cross-sections
15	Back Shape	Choice of predefined cross-section, combined with the unifying shape to make all the back cross-sections
16	Seat Weight	Distance away from the middle of the innermost cross-sections, used only when Seat Rounding is less than 1.
17	Back Weight	As Seat Weight, used in each back piece
22	Back Pieces	Number of horizontal pieces in the full back length. When this value is 0 the seat and back are combined
25	Seat Lip	Used to change the angle of the front piece of the seat.
26	Leg Type	Switches between the 3 predefined leg types
27	Leg Join	Distance between the seat sides and the top of the legs
28	Leg Shape	Leg cross-sections
31	Connections	Creates joined up legs. The location of the join changes with Leg Type
32	Curve	Makes the Lofting between the cross-sections more curvy. The cross-sections are also moved to ensure the overall form has the same proportions.

If the weight is greater than 0 then parameters such as mass and waist circumference will be greater than average. A list of which parameters are affected by the height and weight values is given in table 7. These were chosen to represent which dimensions are derived from a measure, they were then adjusted if too much (or little) variance was observed at certain points. For example the values used to generate the head size have very little individual variance as skull size does not vary as much as other dimensions.

Once we have all the measures for a test subject we then find the dimensions for constructing the model. The calculations used to find these dimensions is given in table 8.

Table 5: DINED Values (in mm unless otherwise stated)

Label Measure	20–30 F	20–30 M	31–60 F	31–60 M	60+ F	60+ M
	Mean SD	Mean SD	Mean SD	Mean SD	Mean SD	Mean SD
$M_A$ Sitting Height	888 36	957 39	865 31	925 35	833 35	900 37
$M_B$ Eye Height Sitting	779 32	842 39	764 31	814 35	733 35	791 35
$M_C$ Shoulder Height Sitting	582 29	624 34	565 29	612 31	544 30	596 31
$M_D$ Popliteal Height	441 25	497 31	434 26	481 32	428 27	473 28
$M_E$ Buttock–Popliteal Depth	497 28	522 30	499 27	503 27	492 27	499 25
$M_F$ Buttock–Knee Depth	610 32	651 33	613 28	631 32	610 30	625 28
$M_G$ Breast Circumference	948 97	963 73	1013 119	1044 102	1130 135	1038 111
$M_H$ Hip Height Standing	952 47	1045 61	932 42	990 54	911 43	964 46
$M_I$ Neck Base Circumference	429 32	476 30	447 35	497 37	458 33	483 32
$M_J$ Elbow Height Sitting	251 27	262 28	230 30	253 28	213 27	237 29
$M_K$ Elbow–Grip Length	325 19	364 20	321 15	352 21	318 18	347 18
$M_L$ Hand Thickness	25 3	28 2	27 5	29 3	27 5	29 3
$M_M$ Shoulder Breadth	422 23	470 25	424 28	461 24	413 23	448 21
$M_N$ Hip Breadth Sitting	402 27	388 29	414 31	397 26	410 34	398 24
$M_O$ Waist Circumference	790 110	858 80	863 130	949 108	970 138	958 117
$M_P$ Thigh Clearance	153 14	154 17	145 15	144 12	139 14	135 13
$M_Q$ Body Mass (kg)	66 9	80 14	70 11	82 12	69 10	8 9

Table 6: Other Dimensions used based on DINED Data

Label Measure	Mean	SD	Assumption
$M_R$ Chest Skeleton Depth	$\frac{M_{G\_Mean}}{\pi} - 3 \cdot \frac{M_{G\_SD}}{\pi}$	$\frac{M_{G\_SD}}{10 \cdot \pi}$	Chest is circular and that the majority of depth increase is due to tissue on the front of the body
$M_S$ Neck Depth	$\frac{M_{I\_Mean}}{\pi} - 2 \cdot \frac{M_{I\_SD}}{\pi}$	$\frac{M_{I\_SD}}{10 \cdot \pi}$	Neck is circular and that the majority of depth increase is due to tissue on the front of the body
$M_T$ Waist Height Sitting	$M_{J\_Mean}$	$M_{J\_SD}$	Waist is level with the elbow
$M_U$ Waist Breadth	$\frac{M_{O\_Mean}}{\pi}$	$\frac{M_{O\_SD}}{\pi}$	Waist is circular
$M_V$ Hip Bone Breadth	$M_{N\_Mean} - 3 \cdot M_{N\_SD}$	$\frac{M_{N\_SD}}{10}$	The majority of breadth increase in the hips is due to tissue.

Table 7: Weights used for Height, Weight and Individual variation in dimension generation

Label	Measure	Individual	Height	Weight
$M_A$	Sitting Height	0.9	0.0	0.1
$M_B$	Eye Height Sitting	0.9	0.0	0.1
$M_C$	Shoulder Height Sitting	0.9	0.0	0.1
$M_D$	Popliteal Height	0.9	0.0	0.1
$M_E$	Buttock–Popliteal Depth	0.6	0.3	0.1
$M_F$	Buttock–Knee Depth	0.6	0.3	0.1
$M_H$	Hip Height Standing	0.8	0.0	0.2
$M_J$	Elbow Height Sitting	0.8	0.0	0.2
$M_K$	Elbow-Grip Length	0.8	0.0	0.2
$M_L$	Hand Thickness	0.8	0.0	0.2
$M_M$	Shoulder Breadth	0.8	0.0	0.2
$M_N$	Hip Breadth Sitting	0.0	0.8	0.2
$M_P$	Thigh Clearance	0.0	0.8	0.2
$M_Q$	Body Mass	0.0	0.9	0.1
$M_R$	Chest Skeleton Depth	0.6	0.3	0.1
$M_S$	Neck Depth	0.0	0.8	0.2
$M_T$	Waist Height Sitting	0.8	0.0	0.2
$M_U$	Waist Breadth	0.0	0.8	0.2
$M_V$	Hip Bone Breadth	0.8	0.0	0.2

Table 8: Dimension Calculation

Label	Dimension	Calculation
$L_n$	Neck Length	$M_B - M_C - R_{hd} + M_R/2$
$L_t$	Torso Length	$M_C - R_{hp} - M_R/2$
$L_{ul}$	Upper Leg Length	$M_H - (M_D + R_k) - R_{hp}$
$L_{ll}$	Lower Leg Length	$M_D + R_k$
$R_{hd}$	Head Radius	$M_A - M_B$
$R_s$	Shoulder Radius	$M_S$
$R_{hp}$	Hip Radius	$(M_P - P)/2$
$R_k$	Knee Radius	$(M_F - M_E)/2$
$R_f$	Foot Radius	$R_k$
$P$	Padding	$M_N - M_V$
$L_{ua}$	Upper Arm Length	$M_C - M_J - 30mm$
$L_{la}$	Lower Arm Length	$M_K - 30mm$
$R_e$	Shoulder Joint Radius	$30mm$
$R_e$	Elbow Radius	$30mm$
$R_{hn}$	Hand Radius	$M_L$