# 10 Product designs and physical data

To be able to use physical data in a useful manner, it helps to distinguish physical ergonomic (product) models. As we have to deal with both anthropometric and biomechanical data in physical ergonomics, we make a distinction between A models, B models and P models.

Readers can find more background information relating to this chapter in the PhD thesis '*Op Maat Gemaakt* [Made to Measure]' (Molenbroek, 1994).

☞ In accordance with Lombaers et al. (1985) an 'anthropometric model' (A model) is defined here as an incomplete but targeted and systematic image or simulation of anthropometric aspects of a population.

☞ A 'biomechanical model' (B model) is defined here as an incomplete but targeted and systematic image or simulation of biomechanical aspects of a population.

☞ A 'product model' (P model) is defined here as an incomplete but constantly improving representation of a product, as it is used in the successive stages of the product development process (= design process), with the emphasis on Man-Product Interaction (MPI).

In a similar fashion an AP model (anthropometric product model) and a BP model (biomechanical product model) are used for a combination of an A and a P model or a B and a P model.

The use of an A model or a B model can help at important stages of the design process:

- when generating ideas about new or improved function performers;
- when testing a product concept;
- when preparing a schedule of requirements;
- when specifying the size and shape details of contact surfaces;
- when specifying the details of a mechanical resistance for product use;
- when testing the prototype or final product.

During the creation process, shape, materials, function and usage method are specified in more and more detail. These can evolve even further during product use.

The purpose of an anthropometric or biomechanical product model is giving the designer or the assessor of the product the opportunity to assess a P model with regard to human aspects, such as dimensions, forces, postures and control patterns within the context of important aspects of a particular man-product interaction.

## 10.1 The physical-ergonomic design process

The physical-ergonomic design process is a process whereby the more general design process is limited to that of physical ergonomics, which comes down to selecting, creating and using the A, B, P, AP and BP models (Figure 10.1).

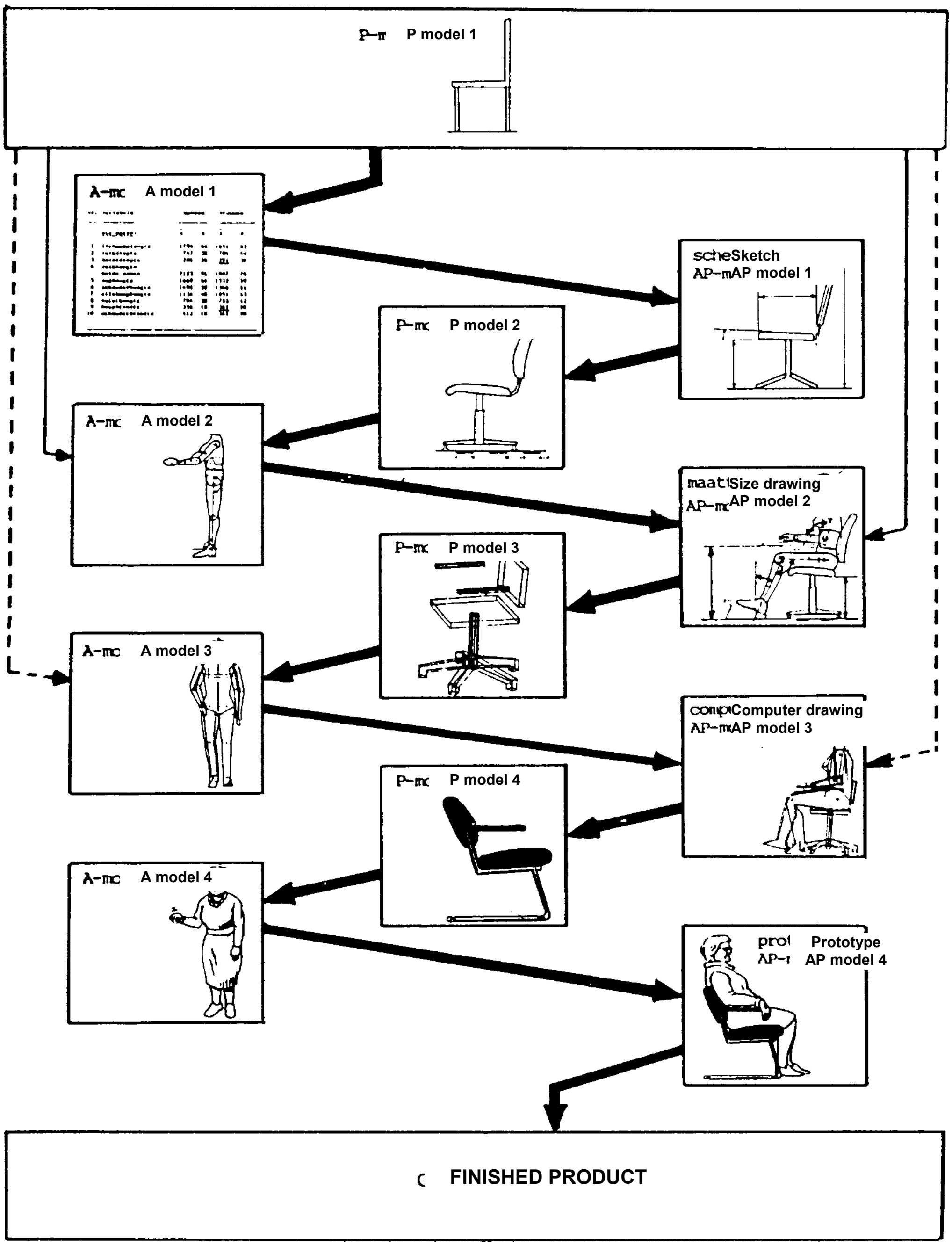


*Figure 10.1 A schematic representation of the anthropometric design process.*

Physical models such as manikins, computer models and test subjects (see Molenbroek (1994) for a list) are obviously more functional than a table. After all, a 'non-static upright' position is difficult to assess using a table, but this is often possible with the other anthropometric models as they include, for example, the angles of or distances between the pivoting points of the skeletal system.

At the earliest stage of the design process the designer/assessor will already have a vague, intuitive but preferably professional image of the product, the user and the interaction in his or her mind. This could be called AP model 0. In a similar fashion as for Man-Product Interaction (MPI) for actual use of an already manufactured product, a process consisting of 'trial and error' and feedback will now occur in the mind of the designer. The difference is that the user will probably adjust his or her actions after the initial confrontation with the product; the designer, however, will adjust the Man-Product Interaction, up to the AP model. This will often be the product model in the relevant stage, sometimes this will be the A model or both. This could be called AP model 1.

The adjustments of P model 1 that result in P model 2 are the result, on the one hand, of a further specification of AP model 1 and, on the other hand, of the revision of the intuitive idea about the nature of the Man-Product Interaction, characterised by aspects such as discomfort, accuracy, speed, safety and fatigue. Due to the number of individually dependent factors that play a role, it is usually difficult to define unambiguous algorithms for the relationship between a set of relevant dimensions in the A model (AM) and the corresponding set of dimensions in the P model (PM). In the same way, a Free-Body Diagram (FBD) can be considered a BP model for the biomechanical aspects.

**Example 1:**
Someone wishes to know which human measurements correspond with a set of wheelchair product dimensions. Two sets of relevant dimensions are the result:

| A model | P model |
|---|---|
| Depth (length) of seat | Distance (length) between buttock and back of the knee |
| Seat width | Hip width |
| Seat height | Popliteal height |
| Backrest height | Acromion height |
| Armrest height | Elbow-bottom height |

**Example 2:**
Someone wishes to know which forces occur in the wheelchair situation in example 1 and realises that, contrary to a physical measurement, a force is a vector and is therefore determined by size and direction.

| M model | P model |
|---|---|
| Body weight | Normal force on seat |
| Position | Frictional force of seat |
| | Normal force on footrest |
| | Normal force on backrest |
| | Normal force on armrest |

The margins between product and human characteristics are or can be determined experimentally. For example, the seat width for spastic children in a electric wheelchair will have to match the hip width more closely but, on the other hand, a certain amount of room will be more comfortable for a manually driven wheelchair (Henze and Staarink, 1989; Steenbekkers and Molenbroek, 1990; Sieuwertsen and Molenbroek, 1990).

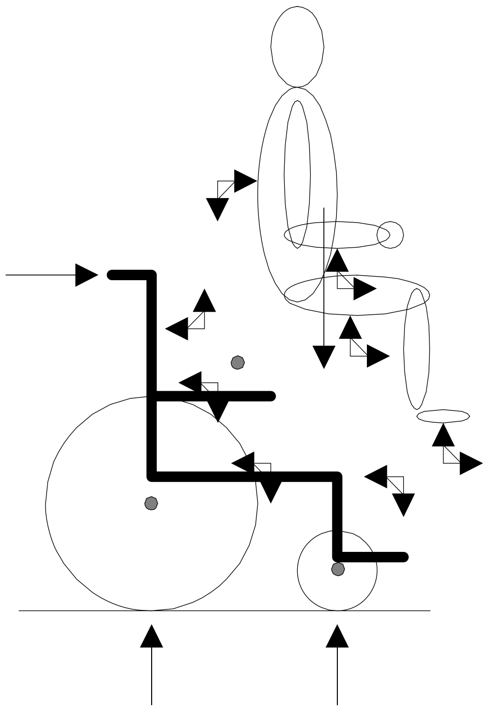

*Figure 10.2 BP model*

One difference between the A model and the P model can be made by a number of additional factors that consist of empirical values, which may be standardised or estimated:

KT for clothing and gear,
HT positional variation, for converting statically measured values into functional measures,
OT other matters such as fatigue, etc.

For each product dimension (PM) and human measurement (AM) that is relevant to the interaction the following will generally apply:

PM = f(AM + KT + HT + OT)

Example: the following applies to a working surface for standing work that requires precision:

AM = elbow height while standing
KT = heel height
HT = 10–20 cm above the elbow due to short line of sight
OT = slumping 3 cm after standing for a long time.

! Not every AP model is equally applicable for each phase of the design process. The anthropometric model that is suitable for each phase of the design is depicted in Figure 10.3.

For a BP model it is of the utmost importance to determine first whether a 2D or a 3D analysis has to be made in view of the directions of the forces that occur.

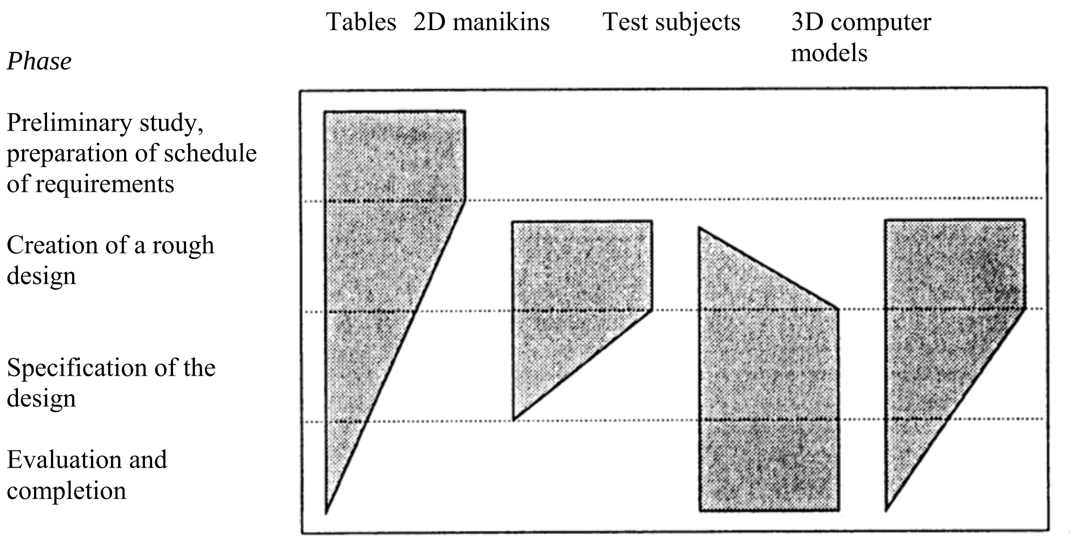


*Figure 10.3 Phases of A models (from Lombaers et al. 1985)*

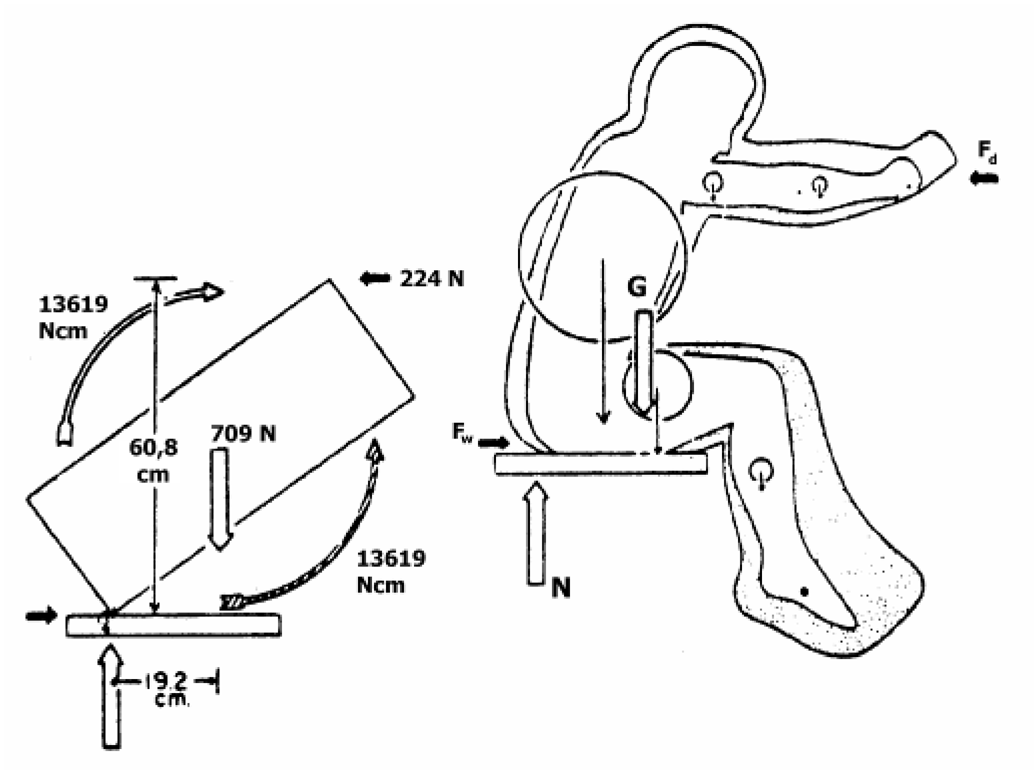


*Figure 10.4 A sitting body in a pushing position and a simplified representation by a balanced block (Dempster, 1955). Fd=pushing force, Fw=frictional force, G=body weight.*
*The following applies for a static equilibrium:*
$\Sigma H = 0 \rightarrow Fd = Fw = 224\ N$
$\Sigma V = 0 \rightarrow G = N = 709\ N$
$\Sigma M = 0 \rightarrow Fd \times 60.8 = G \times 19.2$

It will then be useful to consider the events that precede the determination of a product dimension in a bit more detail; in other words, 'zooming' in on one test of the AP model as it were. The following steps are taken in this case, whereby Figure 10.5 is used as a summary of possible relevant factors for industrial design taken from literature (Molenbroek, 1994).

| No. | Aspect/ factor | Relationship with/ of body | Explanation of size and shape | Important for design |
|---|---|---|---|---|
| 1 | Age | ++ | | Yes |
| 2 | Gender | ++ | | Yes |
| 3 | Ethnicity | + | | Yes |
| 4 | Build | ++ | | Yes |
| 5 | Nutrition | +- | Unpredictable * | Rarely |
| 6 | Secular changes | + | For designs of products with a prolonged life span | Yes |
| 7 | Socio-economy | +- | | Rarely |
| 8 | Clothing/ footwear | + | | Yes |
| 9 | Environment | +- | Included in ethnicity * | No |
| 10 | Laterality | - | Included in ethnicity * | Sometimes |
| 11 | Daily rhythm | - | Superfluous for most applications | Rarely |
| 12 | Illness/ disability | ++ | More research required, especially via limitations | Yes |
| 13 | Genes | +++ | Included in build * | No |
| 14 | Hormones | +++ | Included in build * | No |
| 15 | Position | +++ | | Yes |

+++ = Very closely; +- = Slightly
++ = Closely; - = Hardly
+ = Moderately; * = included in other factors

*Figure 10.5 The estimated importance of anthropometric aspects and factors when designing and assessing products (Molenbroek, 1994).*

! Determining a physical-ergonomic guideline:

1. Describing the demographic characteristics of the group of intended, partially unknown users: numbers per gender, age class and ethnicity, where required, including socio-economic circumstances and possible illnesses or disabilities.
2. Describing and/or outlining the Man-Product Interaction, especially the postures (and quasi-statically therefore also estimated movements), whereby the function of the product has to be performed.
3. Describing the relevant human measurements and the critical values of them: the (anthropometric) designer has to use ergonomic insights here to exclude parts of the population in a substantiated manner, to choose one or more percentile values and to choose between either the production of different types of a product with a difference in size (glasses, helmets, shoes, etc.) or the production of a setting or adjustment option (the seat height of an office chair).
4. Describing the possible additional factors (HT + KT + OT), the values of which depend, among other things, on the function to be performed. The process of systematically obtaining an anthropometric value that is required for and crucial to a design and/or product dimension is depicted in Figure 10.6.

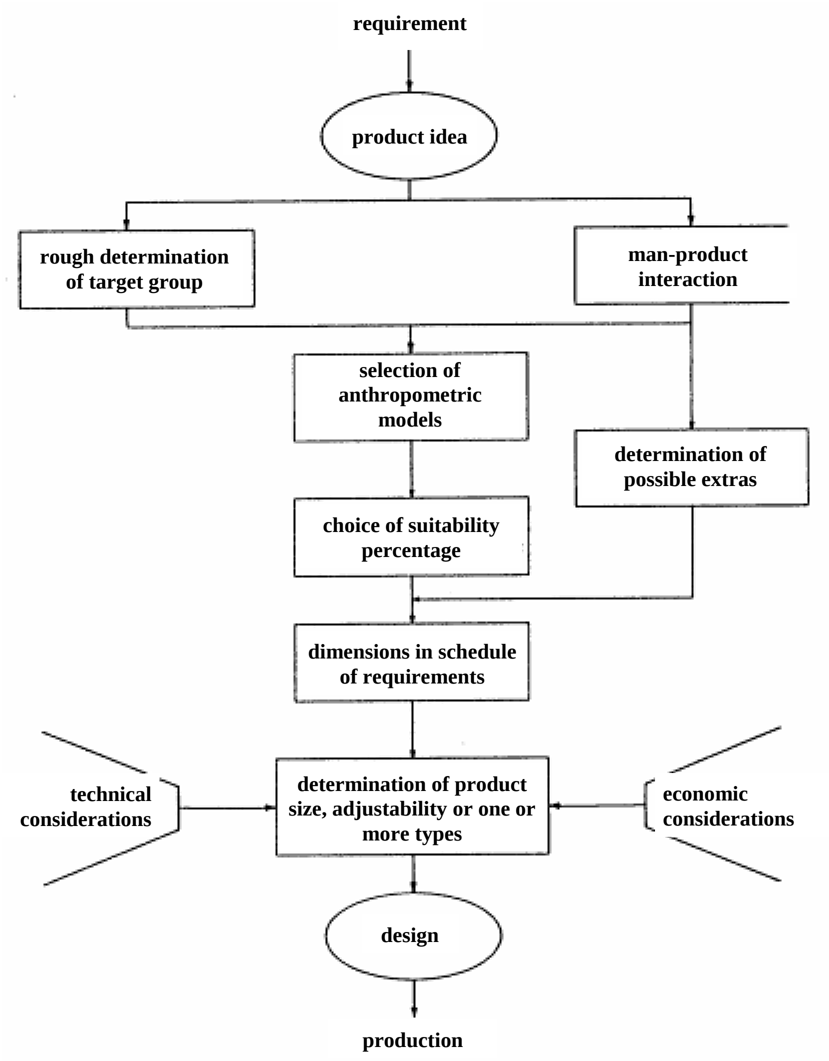


*Figure 10.6 The process of obtaining an anthropometric guideline (Molenbroek, 1994)*

An overview of the most important sources (anthropometric tables) can be found in the Appendix. These also include: KIMA; DINED; GDVV; DUTCHMIL.

**Considerations when using A or B models**

What does the ergonomic literature offer:

- Magazines such as: Applied Ergonomics, Ergonomics, Human Factors or Biomechanics
- Handbooks as listed in Appendix 19
- Internet sites:
  - http://www.dined.nl (refers to the website of the Applied Ergonomics and Design section of the Industrial Design Engineering Faculty)
  - ERGOWEB (general ergonomics)
  - http://tucker.mech.utah.edu
  - HFES Human Factors and Ergonomics Society
  - http://www.hfes.vt.edu
  - Biomechanics Worldwide
  - NvvE *Nederlandse vereniging voor Ergonomie* [Dutch Ergonomics Association] http://www.ergonoom.nl

If nothing can be found in literature, the required value can be estimated using formulas such as those in the DINED table (see Appendix 4 and 18 or www.dined.nl).

If no estimation is possible, small-scale measurements would be obvious with simple equipment and only a few test subjects, but offering sufficient insight for the design of an object with the emphasis on usefulness, efficiency, safety and comfort.

Paragraph 10.2 provides an overview of measuring methods, units and parameters.

**Examples of blunders relating to size or force.**
It is often impossible for wheelchair users to enter aircraft, toilets in aircraft or trains, but also *Kijkshop* in Delft due to an escalator that was installed in 1994.

Changing a car tyre is often impossible for many women; the corresponding wheel nut wrench is only adequate for strong young men.

A jar of apple sauce can often only be opened by strong young men with large hands. The use of an all-purpose opener as a tool for this will also only help a group of people with large hands.

A 6-year-old child is often unable to open the button in a pair of jeans.

## 10.2 Units and parameters

Widely spread causes of confusion relating to study results can be attributed to the use of different units. Here are some recent examples:

| Unit | Pronunciation | SI unit | Conversion to SI |
|---|---|---|---|
| $lbf/inch^2$ (imperial) | Pounds per square inch | Pressure | $0.453\ kg/2.54\ cm^2 = 0.7\ N/cm^2$ |
| kp (German) | Kilopound | Force | 10 N |
| kgf (old Dutch) | Kilogram force | Force | 10 N |

*Figure 10.7 Examples of old units*

The Dutch 1937 *IJkwet* [ Weights and Measures Act] states what units may and may not be used in commerce and refers to the accompanying *Eenhedenbesluit* [Units Decree]. This Units Decree can be updated as a result of a EU Directive. Since 1960 the International System of Units is indicated by SI.

This means that no units other than SI units may be used in commerce (except for a couple of exceptions that have been approved by the Minister); when trading goods and services, for quotations, invoices, manuals, policies, brochures, etc. In practice it does, however, mean that the Minister has approved quite a large number of exceptions. According to the Weights and Measures Act this is allowed if units are used in addition to the corresponding indication in recognised units, as long as the indication in recognised units dominates.

Standardised use (in accordance with NEN 999 or ISO 31) of quantity names and symbols is not required by law, but it is strongly recommended.

The following units are recognised according to the SI system and are called the fundamental units:

| Quantity | | SI unit | |
|---|---|---|---|
| name | Symbol | name | Symbol |
| Length | l,s | metre | m |
| Mass | m | kilogram | kg |
| Time | t | second | s |
| Electric current | I | ampere | A |

| | | | |
|---|---|---|---|
| Thermodynamic temperature | T | kelvin, degree Celsius | K, °C |
| Amount of substance | n | mol | mol |
| Light intensity | I,Iv | candela | cd |

*Figure 10.8 Fundamental units of the SI system*

The derived SI units. These units are derived from the fundamental units in the form of power products.

| Quantity | | SI unit | | |
|---|---|---|---|---|
| name | Symbol | name | Symbol | Derivation |
| Plane angle | α,β | radian | rad | $m.m^{-1}$ |
| Solid angle | Ω,ω | steradian | sr | $m^2.m^{-2}$ |
| Force | F | newton | N | $kg.m.s^{-2}$ |
| Pressure, tension | p | pascal | Pa | $N.m^{-2} = kg.m^{-1}.s^{-2}$ |
| Energy, work | E,W | joule | J | $N.m = kg.m^2.s^{-2}$ |
| Power | P | watt | W | $J.s^{-1} = kg.m^2.s^{-3}$ |
| Illuminance | E | lux | lx | $lm.m^{-2} = cd.sr.m^{-2}$ |
| Luminous flux | Φ | lumen | lm | cd.sr |
| Moment of force | M | newton metre | N.m | |

*Figure 10.9 Derived SI units*

## 10.3 Measuring errors

Repeat measurements performed before and during field tests are a useful method to gain an insight into error sources.
A distinction can be made between:

- One observer measures the random sample several times, as a result of which the intra-observer variation can be considered and analysed;
- Several observers measure the same random sample, as a result of which the inter-observer variation can be considered and analysed.

There are several methods to determine a measure for reproducibility:

a. Among other things, the correlation coefficient between the first and second measurement can be used. As a rule, this should be greater than 0.9.
b. Tanner and Weiner (1949) defined the ‘S-meas’ using a different method. This is the standard deviation of the differences between the paired measurements divided by $\sqrt{2}$. The smaller ‘S-meas’, the greater the reliability of the observer. For random samples of more than 30 the actual measured value will lie between + or – 1.96 * ’S-meas’ in 95% of the cases. The paired intra-observer ‘S-meas’ should also be more or less the same as the paired inter-observer ‘S-meas’. See also Appendix 18.

In the study into elderly people by the Institute for Consumer Ergonomics (ICE, 1981 and ICE, 1983) it appeared that the average ‘S-meas’ was 11.6 mm in this case with a standard deviation of 4.9 mm. The minimum value was 4.3 mm for the elbow-wrist distance ($\bar{x}$=253 mm) and the maximum value was 21.9 mm for the ‘elbow width’ ($\bar{x}$=469 mm). The latter, however, means that the actual measured value may be 43 mm above or below it, which can be explained by positional dependence.

In our own study into elderly people in 1982 a form of method a was used. The scatter of the measured values obtained in this way can be described well using the term ‘random error’, which Sittig and Freudenthal (1951) defined as a variable with a normal distribution, an average of 0 and a variance $f^2$, which makes it possible to correct the variance measured $s^2$. The corrected variance will then be $s_1^2 = s^2 - f^2$.

Some variables of the study into elderly people are listed in Figure 10.10.

| | f | s | $s_1$ | $s_1$-s |
|---|---|---|---|---|
| Length | 1.96 | 89.21 | 89.18 | 0.03 |
| Reaching height (when standing) | 15.42 | 124.66 | 123.70 | 0.96 |
| Hip width (when sitting down) | 7.18 | 39.18 | 38.52 | 0.66 |
| Backrest C7 | 6.98 | 27.98 | 27.10 | 0.88 |
| Fist height (when standing) | 4.87 | 49.55 | 49.31 | 0.24 |

*Figure 10.10 Overview of observed and corrected standard deviations for a number of variables that were repeatedly measured (in mm) during the study into elderly people (Molenbroek et al., 1983)*
*f standard deviation of the random error,*
*s standard deviation of the observations,*
*$s_1$ corrected standard deviation,*
*$s_1$ - s the correction that should be applied.*

f in the second column was obtained by taking the average value of 3 standard deviations, each of which was the result of 4 to 6 repeated measurements on 3 people by the same observer.

s in the 4th column matches the s observed in the study into elderly people.
This means that the standard deviation should be corrected using the values in the final column. For the reaching height this means that P1 would turn out to be (2.33 * 0.96) = 2.5 mm lower.

Some examples of random errors are:
- the difference between continuously distributed variables and discrete measured values;
- not taking into account breathing when measuring the waist;
- the difference caused by a test subject not having constant measurements, even in the short term.

Among others, method B is discussed in the literature by Cameron (1984); Kemper and Pieters (1974) and ICE (1981). Kemper et al. found differences expressed in $\bar{x}$ and s varying from 0.004 (0.603) cm for the biacromial diameter to 3.114 (0.929) cm for the thigh circumference. The random sample consisted of 50 boys aged between 12 and 13 who were measured by expert researchers from an institute in Amsterdam and an institute in Zeist using the same measuring instructions. The correlation coefficient between the first and second measurement (coefficient of objectivity) varied between 0.872 for the biacromial diameter and 0.995 for the body weight. Kemper's explanation for the low correlation of the shoulder width was that the position of the shoulder girdle is very difficult to standardise and therefore leads to intra-individual variability. The segment dimensions based on the acromial position (for example, elbow-bottom height, elbow width, etc.) are often less reproducible, as this position results from a random position of the shoulder and therefore does not yield a fixed bone position in the x-y-z body diagram, which conversely is the case for the trochanterion (see Appendix 1 for the location).

## 10.4 Parameters of the human body for physical ergonomics

In biomechanics the body is often considered to be built up of rigid segments that have a volume, a mass and often a constant density. Joints with their complex, double-curved surfaces and their 3D movement paths are simplified into pivoting points. The straight connections between these pivoting points are called 'links' or 'members'. This means that the only property of each link is its size. A segment is an expansion of a link, the properties of which are volume and mass. This makes it possible to create a simplified representation of the human body or part of it in a biomechanical model, which can be used to make predictions. It is always recommended to find out which assumptions were made for the model that the designer is planning to use.

The physical properties (parameters) of that human body or the segments are essential to these models. The less complicated the model, the easier it is to use, but the more assumptions have been made. The best model is reality, but that usually has too many parameters to use for calculations.

Below follows a list of the most important parameters of the human body that are significant for physical ergonomics, divided into their (principal) units. In the following paragraphs it will be explained how to measure these parameters.

**m**

Heights (body height, elbow height when standing, back of knee height, etc.) have a variation coefficient (VC) of 3–5%, in other words, the standard deviation as a fraction of the average is 3–5%.
Widths (hip width when sitting, shoulder width, head width) have a VC of 6–8%.
Depths (breast depth, thigh depth, abdominal depth, etc.) have a VC of 8–10%.
Diameters are sometimes defined whilst assuming a cylindrical body segment.
Circumferences (head, breast, thigh circumference, etc.) have a VC of 6–8%.

The unit that is used to measure this type of data is the metre (m) or units that are derived from it, such as cm and mm. For many design purposes it is sufficient to express the data in cm, possibly with 1 decimal, in order to avoid pseudo-accuracy. A widely occurring misconception in this context is when a computer manikin states dimensions in 8 or more decimals, whilst the data used in it could not have been measured any more accurately than up to approx. 5 mm.

**$m^2$**

Skin surface area, man-product contact surface.
With regard to radiation, heat exchange, moisture level and protection it is useful for designers to know the size of the surface area of body segments.

**$m^3$**

Volume, build as a division of volume. Build could be studied based on the idea that the entire body is made up of volumes of segments. This can be found in the literature relating to computer manikins. Sometimes a truncated pyramid is used for this (e.g. for ADAPS) or ellipsoids of revolution (e.g. for COMBIMAN). For a density of 1 kg/litre the volume will then be equal to the body weight (mass).
Design relevance: protective equipment.

**kg**

Mass, centre of mass, mass moment of inertia and density. Body mass and the distribution of it is highly important for the design of many types of support equipment, but also for areas that study force transmission.

**N**

Force, moment, pressure and friction.
To determine materials and dimensions of product components it must be known how forces are transmitted during man-product interaction. This can be expressed by forces perpendicular or parallel to the product surface.

**Rad, sr, m, $m.s^{-1}$, $m.s^{-2}$, ω, α**

Joint angles or excursions, posture, movement, speed, acceleration.
The quantification of the position of body segments with regard to each other and with regard to a fixed system of coordinates – also as a function of time – requires the use of units for angle and length, speed and acceleration.

**Some indices**

To study and assess build, proportional numbers can be used, for example, the Quetelet index and waist/hip ratio, which have a normal distribution. Other indices such as quotients of percentile values, for example, P95m/P5v only have a normal distribution in terms of length.

## 10.5 Sizes measured in metres (m)

If a designer requires height, width, depth or circumference data, the following steps can be considered:

A. Look for the most recent anthropometric source for the target group (see appendix);
B. if this is not available, you may consider an estimation using formulas listed in the DINED table;
C. if this is not possible, a small-scale study will have to be performed. A number of methods for this will be discussed now.

### *10.5.1 Self-reporting by test subjects within anthropometrics*

Self-reporting by test subjects means that people are asked to measure their body measurements themselves using simple means (usually measuring tape) and a protocol prepared by the researcher. This is done on a large scale by CBS that annually determines body height and body weight in this way. The reason for a written measurement is simple: the cost per test subject is much less. With a high-quality (pre-tested) protocol (among other things, including instructions and illustrations for each variable) this can yield reasonable results, especially for average values.

! The following disadvantages should, however, be taken into account, especially with regard to scatter:

- Low response (in a study into the Long People's Association in 1994, in which 10,000 members were sent a form with DINED measurements, illustrations and instructions, 600 were returned). The distortion as a result of the non-response and self-reporting should be studied by performing a second random sample, which is 'actually' measured.
- There is also a risk of distortion as a result of people entering their desired (average) measurements. It appears that this effect becomes more significant as the measurement in question deviates more from the average (Wichelow and Cox, 1987).
- It is more difficult to exclude measuring errors.

### *10.5.2 Measuring using an anthropometer and measuring tape*

Among other places, this is described briefly in a Dutch Practice Guideline (NPR 2737,1991). Other sources are Roebuck et al. (1975) or Roebuck (1995) and the Anthropometric Source Book (ARP,1978) or Molenbroek (1994).

! Generally speaking, a random sample of 30 people will be sufficient, provided that they do not have to be split up afterwards, for example, into men and women or age groups. One cell of a random sample should contain at least 10 people. This will be sufficient to measure, for example, 'upright fist height' and 'upright hand palm height'. The results can be used to produce a regression equation to predict one based on the other, provided that the confidence intervals are taken into account. Before measuring a protocol with measurement definitions, illustrations and text stating what the test subjects will be told must be prepared first.

## 10.6 Sizes measured in square metres ($m^2$)

The measuring of surface areas is a time-consuming task; many different tricks are often thought up to smartly measure the required area quickly after all. These are a number of 'measuring' methods:

- Wet feet on a tiled floor easily show the contact area with the floor.
- To measure the entire surface area of the body, the test subject is usually carefully covered in a thin layer of material, which is then removed from the body and measured.

3 methods can be found in literature (Knussmann,1988):

a. Using strips of graph paper that are laid over part of the body as a grid, after which the millimetres are counted;
b. The part of the body is divided into simple geometric shapes, which are then covered in paper. Plaster casts are sometimes made first to be able to check the measurements easily.
c. The material that has been placed on the part of the body is weighed.

- Ultrasound imaging is used to measure the diameter of the thorax of a foetus in the womb. A pen is used to trace the circumference of the thorax, whereby each coordinate is stored and the surface area is therefore known.
- The Man-Product Interaction surface can be measured easily using a carbon copy sheet, by drawing the circumference (for hands and feet this is still highly relevant with regard to the design of gloves or shoes).

**Data**
Data relating to human surface area measurements can be found in/determined with the following sources:
According to Damon (1966) the table by Sendroy and Cechini from 1956, see Appendix 9, provides a good description; he validated this with 107 test subjects. The average difference was only 2% (350 $cm^2$). The range of surface areas measured for foetuses to heavy people was between 500 $cm^2$ and 3.08 $m^2$.

The formula by DuBois from the 1920s is simple, but it is criticised a lot in the literature: $A = 71.84 * G^{0.425} * L^{0.725}$ with G in kg, L in cm and A = surface area in $cm^2$.

The more recent formula by Haycock from 1978 (Knusmann, 1988) is based on an accurate study of 18 test subjects from premature babies to adults and reads as follows: $A = 0.024265 * G^{0.5378} * L^{0.3964}$ with A in $m^2$, G in kg and L in cm.

| Segment | Relative surface area |
|---|---|
| Head and neck | 11 |
| Torso | 31 |
| Arms | 20 |
| Legs | 38 |

*Figure 10.10 Rough percentages for the skin surface area of segments.*

## 10.7 Sizes measured in cubic metres ($m^3$)
Volume is one of the few parameters that can be measured for both the entire body and for segments of living test subjects. The methods applied are:

a. measurement of body surface area ($m^2$ * height),
b. submersion,
c. optical measurement.

**Re a**
Dempster (1955), for example, used a pantograph to measure the circumference of thighs in two places with a distance h in between. He then obtained surface areas A1 and A2 using a planimeter. Formula (1) then provides a rough estimation of the volume of this segment.

$$V = h/3 (A_1 + A_2 + \sqrt{(A_1 + A_2)}) \quad (1)$$

Contini (1972) used ellipsoidal cross-sections. As a result of this formula (1) becomes (2):

$$V = 0.778/2 (O_1 + O_2)2 * h. \quad (2)$$

$O_1$ and $O_2$ are the respective circumferences with h the in-between distance.

**Re b**
When using submersion the volumes are determined using the amount of liquid displaced. Usually the tangible bone points of Martin are used as markers for the interface between two adjoining segments. Measurements according to this method were performed, among others, by Dempster (1955), Drillis

and Contini (1966) and Bernstein (1967). Figures 10.11 and 10.12 list a number of results in an absolute and relative sense.

| Segment | Range (litres) | x | SD | CV |
|---|---|---|---|---|
| Hand | 0.328 - 0.428 | 0.384 | 0.035 | 9.5 |
| Forearm | 1.055 - 1.296 | 1.175 | 0.084 | 6.5 |
| Upper arm | 2.094 - 3.047 | 2.412 | 0.334 | 7.8 |
| Entire arm | 3.512 - 4.583 | 3.971 | 0.376 | 6.8 |
| Foot | 0.670 - 1.105 | 0.895 | 0.175 | 19.6 |
| Lower leg | 2.263 - 3.272 | 2.818 | 0.399 | 14.2 |
| Thigh | 4.750 - 8.456 | 6.378 | 1.464 | 22.9 |
| Entire leg | 8.338 -12.788 | 10.091 | 1.758 | 17.4 |

*Figure 10.11 Segment volumes in litres (Drillis and Contini, 1966)*

| Segment | Range (%) | x (N=12) | SD | CV | x endotypes (N=3) | x ectotypes (N=2) |
|---|---|---|---|---|---|---|
| Hand | 0.47 - 0.62 | 0.566 | 0.052 | 9.60 | 0.517 | 0.623 |
| Forearm | 1.47 - 1.78 | 1.702 | 0.112 | 6.96 | 1.536 | 1.776 |
| Upper arm | 2.98 - 3.53 | 3.495 | 0.192 | 5.87 | 3.426 | 3.120 |
| Entire arm | 4.93 - 5.79 | 5.730 | 0.299 | 5.54 | 5.481 | 5.519 |
| Foot | 1.04 - 1.35 | 1.297 | 0.155 | 12.53 | 1.184 | 1.410 |
| Lower leg | 3.59 - 4.30 | 4.083 | 0.276 | 7.02 | 4.100 | 3.825 |
| Thigh | 6.92 -10.77 | 9.241 | 1.486 | 16.79 | 8.949 | 6.925 |
| Entire leg | 13.17-16.86 | 14.620 | 1.599 | 11.40 | 14.233 | 12,160 |

*Figure 10.12 Segments volumes as a percentage of body volume*

☞ A special form of submersion for the entire body is plethysmography. Here the test subject holds his or her breath and steps into an air cylinder, whereby the pressure difference is a measure for the volume.

**<u>Re c</u>**
Optical methods for determining body surface areas and volumes are moiré topography and stereo photogrammetry. These require little effort by the test subject because they do not involve contact.

☞ Moiré topography:
For this method lines are projected on the test subject using an accurate lattice; the camera that now views the body through the lattice will register contour lines due to the moiré effect. Both mono and stereo pictures can be made of this. By digitising the contour lines the desired volumes will be obtained using the above formulas.

☞ Stereo photogrammetry:
For stereo photogrammetry shots are taken using two photo cameras that are placed next to each other. The shots obtained can be used to determine contour lines point by point. This technique has developed rapidly in the past decades with annual conferences, whereby the researchers Herron and Coblentz could be regarded as the founders. One of the current examples is the set-up of Jones in Loughborough, whereby 12 cameras are used to register the test subject in 3D whilst he or she slowly turns on a base. The data obtained in this way can be used, among other things, to cut a copy of the test subject in foam. In the first place this set-up is intended as an aid for the clothing industry, which also funded it.

The volume estimation can obviously also be used to study the shape of the body. For the well-known somatotypology by Sheldon (Figure 10.13) it can then be established that the relative volume distribution differs considerably.

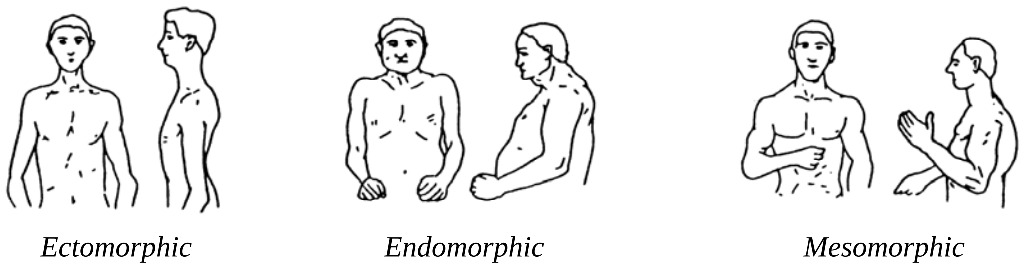


*Figure 10.13 Somatypes of Sheldon.*

For endomorphic people (examples are apple or pear-shaped types) the volume of the head, torso and limbs individually is greater than for mesomorphic or ectomorphic people. For mesomorphic people (an example is a body builder) the emphasis lies on a greater volume of the upper torso segment and the proximal sections of the limbs. For ectomorphic people (with little fat and muscles) the volume of all segments is below average.

The development of the build from child to adult can also be described very well in terms of volume. Roughly speaking a chubby baby changes into a sausage-shaped adolescent. In Figure 10.14 this phenomenon is expressed as a function of age.

If the curve is extrapolated to a more advanced age, you can see that it bends to the left and downwards due to the fact that elderly people are smaller and lighter than a 25-year-old.

## 10.8 Density and (centre of) mass

### 10.8.1 Density

Density is usually expressed in kg/litre and varies between 1.03 and 1.14 kg/litre for people. The highest value is found in the distal segments such as hands, fingers and toes, which mainly consist of bone. The lowest density is found in the more proximal parts of the body, such as the torso.

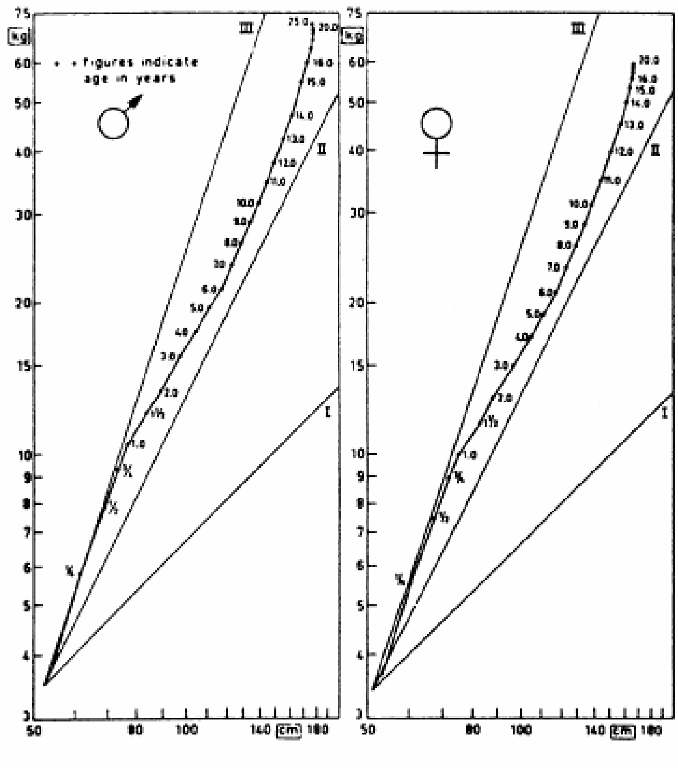


*Figure 10.14 Van Wieringen 1972*

| Type of tissue | Density in kg/litre |
|---|---|
| Skin | 1.10 |
| Muscle | 1.06 |
| Fat | 0.96 |
| Bone | 1.4 - 1.9 |

*Figure 10.15 Densities in the human body*

| Segment | Density |
|---|---|
| Upper arm | 1.081 |
| Forearm | 1.122 |
| Hand | 1.144 |
| Thigh | 1.069 |
| Lower leg | 1.095 |
| Foot | 1.100 |
| Head and neck | 1.111 |
| Torso | 1.030 |

*Figure 10.16 Average segment density (in kg/litre) (Drillis and Contini, 1966)*

Density is determined for an important part by the amount of fat (see also indices), which can be estimated using skin fold measurements. In literature the skin fold of the triceps is usually regarded as a good indicator for the percentage of fat of the entire body (see overview in PhD thesis by Molenbroek, 1994).

For example, if HPT = triceps skin fold and HPS = subscapular skin fold, the following applies according to Pascale (1956):
d = 1.0923 – 0.00202 * HPT
d = 1.0896 – 0.00179 (with d in kg/litre)

According to Baskirew (1954) density is also a function of the different amounts of tissue:
d = 1.07554 – 0.00191 $D_1$ + 0.00055 $M_1$ – 0.0019 $B_1$
$D_1$ = % fat;
$M_1$ = % muscular tissue;
$B_1$ = % bone tissue.

Dupertuis et al. (1950) found that for American men:
d = 1.094 – 0.119 x.
x = $1^{st}$ Sheldon component (= endomorphy = a measure for the roundness of the body).

The quickest way to find d is the approximation according to the formula by Contini (1972):
d = 0.6905 + 0.0297 * H * $W^{-1/3}$
H = body height in inches (= 2.54 cm)
W = body weight in pounds (= 0.453 kg)
D = density in kg/litre.

This formula can be verified by entering your own weight and height. For example, for someone who weighs 100 kg (220 pounds) and has a height of 185 cm (72.4 inches) the density is 1.04 kg/litre.

In the long term density increases with age and body height. In the short term a variation of 2% can occur by eating food and excreting waste products. Due to breathing the volume of the torso constantly changes by 3–4 litres for adults. As a result of this the density can vary around 5% (Boyd, 1933).

**Measuring methods**

The above data was taken from corpse measurements, as mass can only be determined after segmentation. The measuring method is then quite simply determining the quotient of the measured mass and volume of the segment in question. Problems may occur when determining a good representative random sample of corpses and when determining the interfaces between the segments. In the past Dempster was one of the few who succeeded in performing this preparation of segments in an accurate manner and for reasonable numbers (Dempster, 1955). See also Mass and Volume.

## 10.8.2 Mass in kg

The mass of segments cannot be measured separately for living test subjects. This means that people have to rely on corpse measurements here as well. The number of test subjects for this type of study is limited (5 on average). In Roebuck (1975) you can find a short list of authors (see Figure 10.17).

| Source | Average |
|---|---|
| Head | 7.8 |
| Torso | 47.2 |
| Entire arm | 5.4 |
| Upper arm | 2.9 |
| Forearm and hand | 2.5 |
| Forearm | 1.8 |
| Hand | 0.8 |
| Entire leg | 17.1 |
| Thigh | 10.8 |
| Lower leg and foot | 6.3 |
| Lower leg | 4.6 |
| Foot | 1.7 |
| Total | 100.0 |

*Figure 10.17 Weights of segments (average values) as a percentage of body weight by several researchers (Roebuck et al., 1975)*

☞ The Borelli balance and a given centre of mass can also be used to determine the mass of a segment as well (see Figure 10.18).

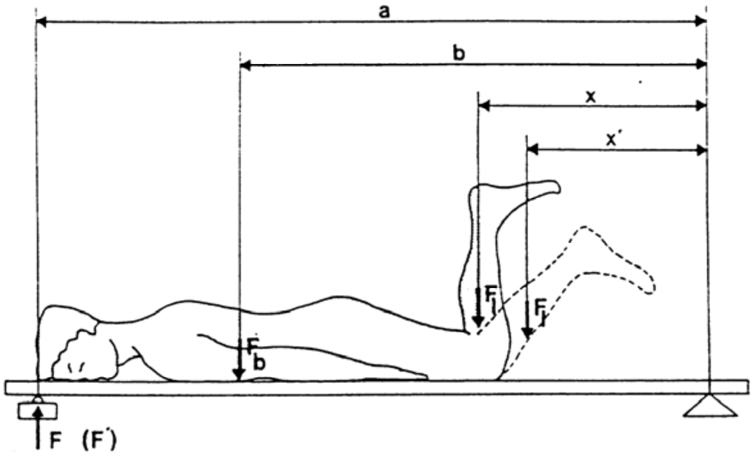


*Figure 10.18 Determination of the mass of the lower leg and foot using a Borelli balance*

If the test subject (in the figure) changes the position of the lower leg, the following applies:

$\Delta F = F - F' = (F_1 * (x - x')) / a$ or $m_1 = a * \Delta F / ((x - x') * g)$

$\Delta F$ = change in force measured
a = force absorber – pivoting point distance
g = gravitational acceleration
x – x' = horizontal displacement of the centre of mass
$F_1$ = gravitational force acting on the segment
$m_1$ = mass of the segment

These studies showed that distal limbs are relatively heavier for men than for women. Male thighs are relatively lighter than female thighs; this applies to a lesser extent to lower legs, whilst the opposite is true for feet. A modern method was demonstrated, among others, by Jensen. He created a 3D computer model to which he assigned a density function. This allowed him to determine segment parameters.

A slightly easier method is sometimes applied using 3D dummies that are used in crash tests for cars. A part of the body with a certain length and weight is copied in clay first to give it a similar outward appearance. Afterwards the density is modified by drilling holes until it matches the literature data. Then measurements can be performed for the missing segment parameters.

### 10.8.3 Centre of mass (com)

☞ The determination of a segment com involves more or less the same difficulties as the determination of segment masses. Both parameters are therefore usually applied at the same time. The easiest measurement is determining the com of the entire body. In the past a balancing table was used for this purpose (following Borelli, 1679), but nowadays a force platform (with piezo elements) is able to register small changes in position as a function of time. An example of the application of the latter is a neurological test, whereby the number of seconds and the type of movement are measured while standing on one leg; for example, before and after medical treatment and with open and shut eyes to study the posture.

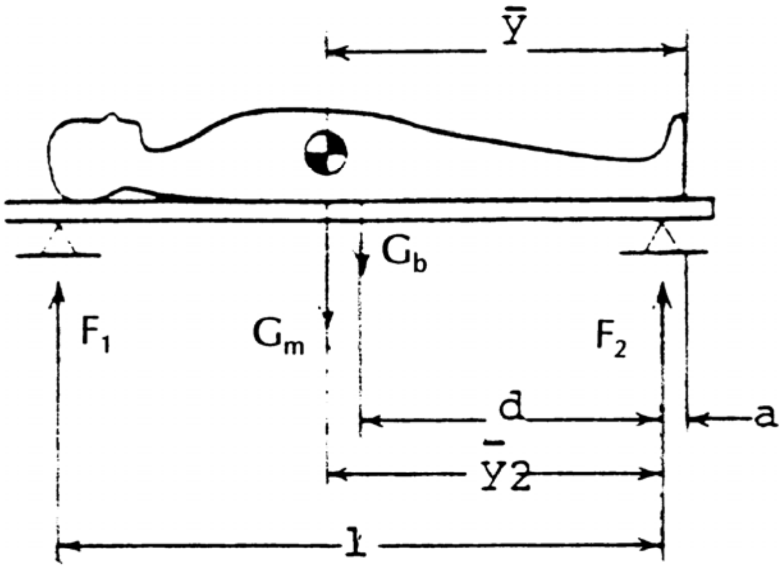


*Figure 10.19 Determination of the centre of mass of the body using two balances (Roebuck et al., 1975).*

The classic work by Braune and Fischer (1889) was performed as a result of the need to determine the location of the com of foot soldiers in relation to their gear.

$F_1$ = force measured in measuring cell 1
$F_2$ = force measured in measuring cell 2
$G_m$ = body weight
$G_b$ = weight of plateau

$\Sigma M = 0$
$G_1 * l - G_m * y_2 - G_b * d = 0$
$G_m = F_1 + F_2 - G_b$
$y_1 = y_2 + a.$

It is important to know that each position results in a different com. Using the pendulum method Santschi et al. (1963) determined the com of various standard positions. They performed this in a highly accurate manner and are therefore still quoted regularly today.

Their long pendulum limited the required angular rotation to 1 degree from the centre. As a result of this the movement of the com by internal movement of organs remained limited. The oscillation periods were large compared to the rate of breathing, which meant that this effect could also be neglected. The results of Santschi et al. are depicted in Figure 10.20 and 10.21.

The results are based on data from 66 people with an average weight of 66 kg and an SD of 9 kg; the average height was 176.3 cm with an SD of 7.4 cm.

The positions of the centres of mass in relation to the body were defined as follows (for the surfaces see Figure A in Appendix 1):

☞ • A frontal surface that touches the back contour; this yields L(X) in Figure 10.21.
☞ • A sagittal surface through one of the anterior superior iliac spines (this is the clearly noticeable bump at the front of both iliac bones; in Appendix 1 the anterior iliospinal point); this yields L(Y) in Figure 10.21 and it also equals half of the bispinal width.
☞ • A transverse surface that touches the head; this yields L(Z) in Figure 10.21.

Centres of mass of segments are taken either from corpse measurements or approximations. One of the approximation methods consists of using the formulas of Clauser et al. (1969), who performed 99 anthropometric measurements before segmenting a corpse. This yielded regression equations about the location of the com of segments in relation to external anthropometric measurements. Trotter and Gleser (1952) also performed measurements prior to segmentation; they used American soldiers before (when they were still alive) and after (when many returned as corpses) joining the front of the Korean War in the early 1950s. Their results were used by Dempster for the preparation of a functional limb system (Dempster, 1955), on which most current human computer models are still based.

The results of Clauser are depicted in Figure 10.22 (Roebuck et al., 1975).

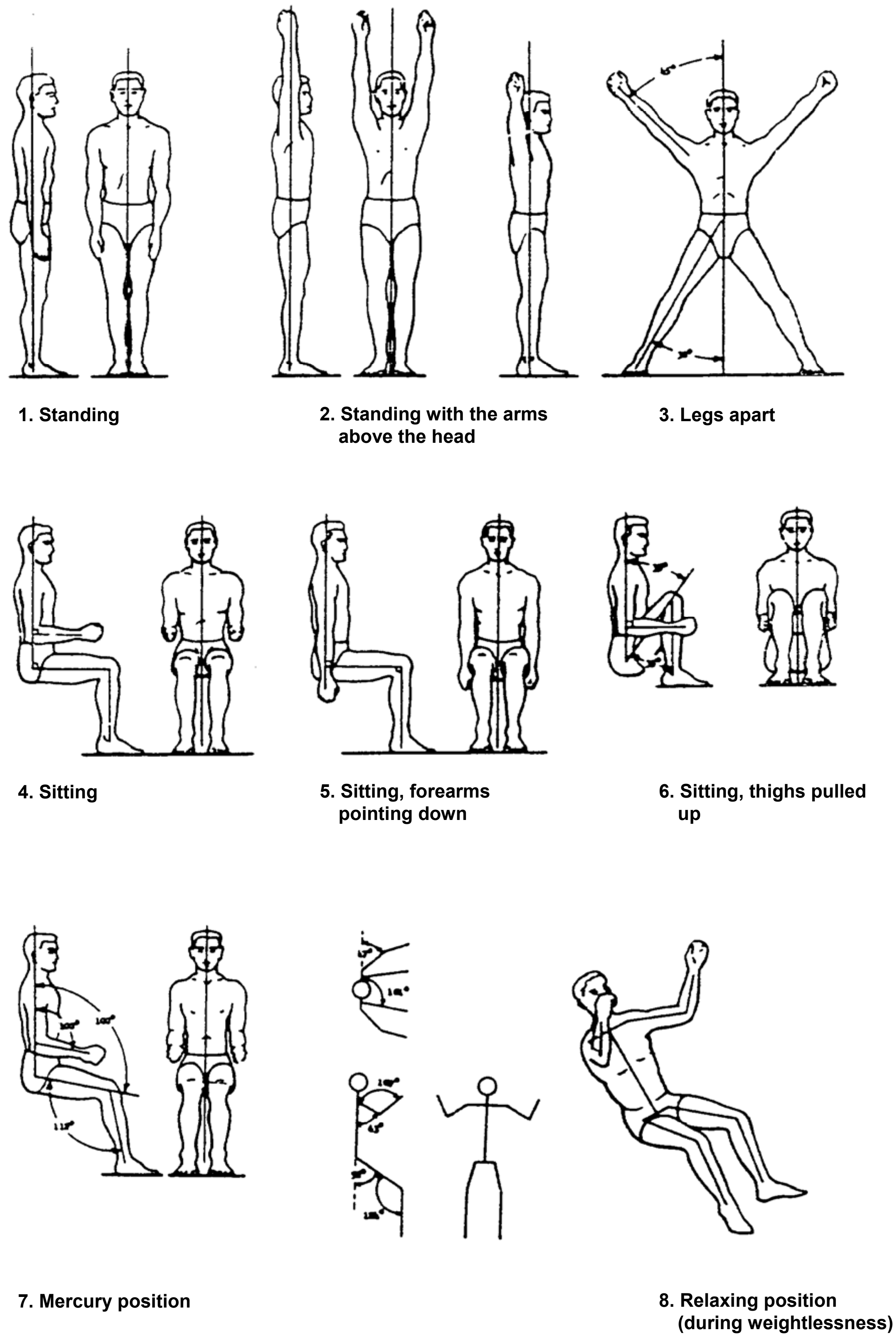


*Figure 10.20 Standard positions (Santschi et al., 1963)*

| | Position | | Location of the centre of mass (cm) | |
|---|---|---|---|---|
| | | | Average | SD |
| 1. | Standing | L(X) | 8.9 | 0.51 |
| | | L(Y) | 12.2 | 0.99 |
| | | L(Z) | 78.8 | 3.68 |
| 2. | Standing with arms | L(X) | 8.9 | 0.56 |
| | above the head | L(Y) | 12.2 | 0.99 |
| | | L(Z) | 72.2 | 3.38 |
| 3. | Legs apart | L(X) | 8.4 | 0.48 |
| | | L(Y) | 12.2 | 0.99 |
| | | L(Z) | 72.4 | 4.82 |
| 4. | Sitting | L(X) | 20.1 | 0.91 |
| | | L(Y) | 12.2 | 0.99 |
| | | L(Z) | 67.3 | 2.89 |
| 5. | Sitting, forearms | L(X) | 19.6 | 0.86 |
| | down | L(Y) | 12.2 | 0.99 |
| | | L(Z) | 68.1 | 2.95 |
| 6. | Sitting, thighs | L(X) | 18.3 | 0.94 |
| | pulled up | L(Y) | 12.2 | 0.99 |
| | | L(Z) | 58.7 | 1.98 |
| 7. | Mercury position | L(X) | 20.1 | 0.86 |
| | | L(Y) | 12.2 | 0.99 |
| | | L(Z) | 68.8 | 2.89 |
| 8. | Relaxing position | L(X) | 18.5 | 0.84 |
| | (during weightlessness) | L(Y) | 12.2 | 0.99 |
| | | L(Z) | 69.9 | 3.66 |

*Figure 10.21 Centre of mass locations for eight standard positions (Santschi et al., 1963).*

| Segment | Average |
|---|---|
| Entire body | 41.3 |
| Head | 42.0 |
| Torso | 41.4 |
| Entire arm | 43.0 |
| Upper arm | 46.7 |
| Forearm and hand | 55.9 |
| Forearm | 41.5 |
| Hand | 36.1 |
| Entire leg | 40.9 |
| Thigh | 43.4 |
| Lower leg and foot | 49.3 |
| Lower leg | 41.8 |
| Foot | 44.2 |

*Figure 10.22 Positions of segment centres of mass (average values by 5 researchers for a total of 27 corpses); the distance to the proximal end of a segment expressed as a percentage of the segment length (Roebuck et al., 1975). See the approximation by Williams (1962) in Figure 11.9.*

### 10.8.4 Moments of inertia (I in kg.m$^2$)

The pendulum method by Santschi et al. (1963) also made it possible (see above under centres of ☞ mass) to determine the mass moment of inertia (I) (your knowledge of mechanics should tell you that this basically equals 'mass times distance squared' with the unit kg.m$^2$). These appeared to correlate closely (r = 0.77–0.98) with body weight and body height. This means that the data and regression equation (Figure 10.23) by Santschi et al. can only be used for target groups whose height and weight variations are limited.

☞ Another method for determining I is the 'quick-release method', which is mainly suitable for forearms and lower legs (Figure 10.24). For this method it is assumed that, when a force F is applied at a distance d from the centre of rotation, the segment will be subject to an angular acceleration (φ) of:

$$F.d = I.\varphi$$

If the moment and the angular acceleration are measured, it will be easy to determine I.
Among other things, Appendix 13 includes the results of the research by Dempster on 8 corpses. Until then only two corpses had been measured properly. Hardly any new data has been added between 1955 and the present. This gives a significant added meaning to the work by Dempster (1955).

| Position | Moments of inertia (gram x cm$^2$ x 10$^6$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $\bar{X}$ | SD | R | SEE | Regression equation | | |
| Standing | X | 130.0 | 21.8 | .98 | 4.73 | -262.0 | +1.68S | +1.28W |
| | Y | 116.0 | 20.6 | .96 | 5.96 | -240.0 | +1.53S | +1.15W |
| | Z | 12.8 | 2.5 | .93 | 0.95 | -0.683 | -0.044S | +0.279W |
| Standing (arms above the head) | X | 172.0 | 29.5 | .98 | 6.36 | -371.0 | +2.39S | +1.63W |
| | Y | 155.0 | 28.6 | .96 | 7.79 | -376.0 | +2.38S | +1.47W |
| | Z | 12.6 | 2.1 | .86 | 0.98 | 1.6 | -0.038S | +0.234W |
| Legs apart | X | 171.0 | 30.6 | .98 | 5.54 | -399.0 | +2.51S | +1.69W |
| | Y | 129.0 | 24.1 | .96 | 7.06 | -305.0 | +1.91S | +1.29W |
| | Z | 41.4 | 8.9 | .93 | 3.19 | -114.0 | +0.677S | +0.484W |
| Sitting | X | 69.1 | 10.6 | .92 | 4.53 | -104.0 | +0.637S | +0.804W |
| | Y | 75.4 | 13.1 | .92 | 5.10 | -153.0 | +1.01S | +0.669W |
| | Z | 37.9 | 6.6 | .97 | 1.64 | -59.6 | +0.34S | +0.502W |
| Sitting (forearms pointing down) | X | 70.5 | 11.0 | .91 | 4.50 | -89.0 | +0.574S | +0.771W |
| | Y | 77.0 | 13.6 | .92 | 5.28 | -144.0 | +0.913S | +0.802W |
| | Z | 38.2 | 6.7 | .97 | 1.54 | -60.8 | +0.341S | +0.514W |
| Sitting (thighs pulled up) | X | 44.2 | 6.8 | .89 | 3.16 | -38.2 | +0.242S | +0.529W |
| | Y | 43.0 | 6.6 | .77 | 4.14 | -25.1 | +0.193S | +0.449W |
| | Z | 29.7 | 5.8 | .92 | 2.26 | -34-4 | +0.146S | +0.509W |
| Mercury position | X | 74.4 | 10.6 | .93 | 4.24 | -107.0 | +0.699S | +0.768W |
| | Y | 85.1 | 15.8 | .94 | 5.61 | -198.0 | +1.27S | +0.794W |
| | Z | 38.7 | 6.3 | .96 | 1.85 | -50.9 | +0.297S | +0.492W |
| Relaxing position (weightless) | X | 104.0 | 15.0 | .96 | 4.20 | -120.0 | +0.788S | +1.13W |
| | Y | 99.8 | 15.0 | .94 | 5.13 | -157.0 | +1.08S | +0.879W |
| | Z | 40.6 | 6.1 | .96 | 1.74 | -53.4 | +0.346S | +0.440W |

*Figure 10.23* *Moments of inertia in eight standard positions, averages and standard deviations (x and SD) around the X, Y and Z axis through the centre of mass (see Figure 10.20). R is the multiple correlation coefficient for body height (S in cm) and body weight (W in kg); the relevant regression equations are also given with SEE being the standard error of the estimation (Santschi et al., 1963).*

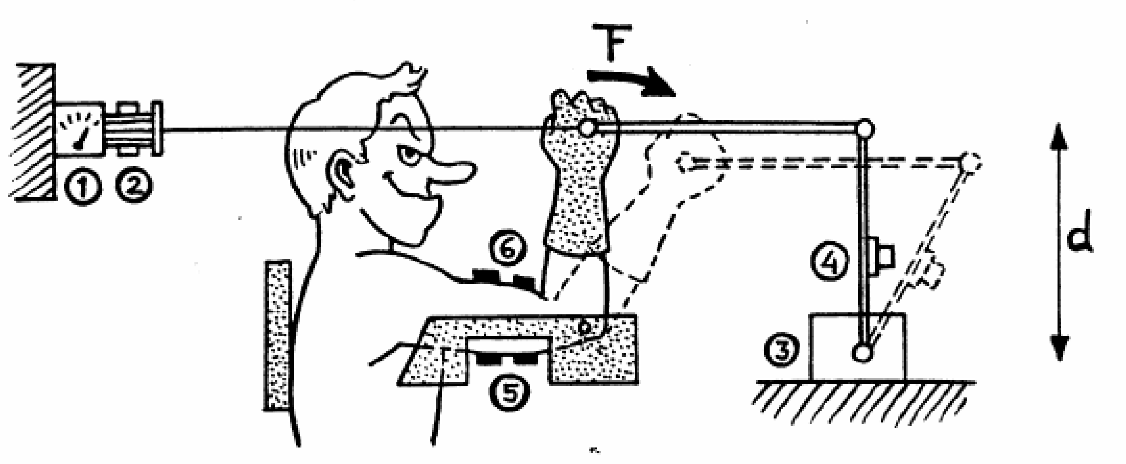


*Figure 10.24* *Quick-release experimental set-up (drawing by Industrial Design Engineering student Bart Kip):*
*(1) display of force absorber,*
*(2) electromagnet,*
*(3) angle and*
*(4) acceleration meter,*
*(5) surface electrodes for triceps and*
*(6) biceps (Bouisset and Pertuzon, 1968)*

## 10.9 Force, moment, pressure and friction

### *10.9.1 Force*

A certain level of force needs to be exerted when using most physically supporting products. In many cases the MPI has not been optimised here. The reason for this may be:

- Insufficient knowledge on how to obtain data relating to forces;
- if certain forces are unknown in the literature, people are unaware of how to estimate or measure them;
- the existing data is applied incorrectly.

In this paragraph we will discuss the sources and measuring methods.

**Sources**

1. PhD thesis by Daams (1994): this states in a well-ordered and standardised manner what they themselves and many other researchers who met a number of criteria (these included that the random sample, test set-up and assignment had to be reported to test subjects) have measured.
2. Anthropometric Source Book: volume I contains useful data about tensile and pushing forces in a sitting position for adult men and women. The measured values are expressed as percentile values and the measuring equipment is described. Lifting: see chapter 'handles and loads' of the NIOSH programme in the Physical Ergonomics Section Laboratory.
3. Burandt (1978) also presents a simple table, whereby average values for 30-year-old young men can be converted into a different age group and/or gender.
4. Human Scales (Diffrient et al., 1974–1978): easy to use for an initial indication, but it should be noted that these details always have to be verified with a different source or with your own measurement using a weighbeam or balance. For example, the explanatory notes of Human Scales state that the maximum lifting force is 1300 kg; this was taken from the Guinness Book of Records by adding the values for the Olympic weightlifting champion for pulling, pressing and jerking.
5. Ergobase: this is a computer programme in the laboratory of the Physical Ergonomics Section that can be used to find both measurements and forces of mainly American origin.

**Related factors**

Factors that are related to the exertion of forces are further specified in Figure 10.25: gender, age, build, laterality, fatigue, training, motivation and environmental factors.

Test subjects appear able to achieve a considerably higher maximum if they are instructed to build up the force gradually at a rate they determine themselves. Kroemer and Howard (1968) experimentally found that, for single-handed sideways pushing, the peak values were 65% higher than the minimum maximum values.

| | |
|---|---|
| 1. Measuring instruments | - Specification (function; type; manufacturer; calibration)<br>- Attachment to the test subject<br>- Output method (digital/analogue; units) |
| 2. Position of the force vector | - Coordinates of the origin of the force<br>- Direction of the force exerted<br>(for dynamic force exertion both as a function of time; in that case also:)<br>- Movement of all masses involved |
| 3. Test subject | - Which population<br>- Anthropometric data |
| 4. Posture of the test subject | - Position relative to the measuring instrument (see 1)<br>- Body segments and muscles involved<br>- Posture while exerting the force<br>- Support of the body (reactive forces) |
| 5. Method by which force was exerted | - Description of instructions issued to the test subjects; if no instructions were issued then at least:<br>- Method by which force was to be exerted (build-up method; what to do once the target was achieved; how long to maintain this)<br>- Time interval between successive tests<br>- Number of repetitions<br>- Exercises/training |
| 6. Motivating factors | - Selection of test subjects<br>- Voluntary or mandatory participation<br>- Method of payment<br>- Knowledge about the aim of the experiment<br>- Knowledge about the experimental procedure<br>- Feedback on performance delivered<br>- Supervision during the experiment<br>- Encouraging factors (cheers; rewards; competition; audience)<br>- Limiting factors (danger; fear of injury; adverse environmental conditions; fatigue; lack of interest; audience). |

*Figure 10.25 Checklist for reporting force measurements (Kroemer and Howard, 1986)*

## Some incorrect designs for force exertion

When packaging jam the manufacturer will base the design on the *Jambesluit* [Jam Decree] of the *Warenwet* [Commodities Act]. This states that the centre of the lid must be 1 mm below the edge, to indicate that it is 'vacuum-sealed'. Unfortunately it does not state that it is to be opened by the $P_3$ or the $P_{5women}$ until the expiry date has passed. Berns (1981) found that around 4 Nm is required to open a jam jar, whilst the $P_5$ value is around 1 Nm. The fact that the measured values have a large scatter is shown by the fact that an athletic senior achieved 12 Nm in our laboratory with our mechanical jam jar, which is built as an electronic force absorber.

Every car comes with a wheelnut wrench that in principle every driver should be able to use to change a tyre. The weakest among us appear completely unable to do this and that is not surprising with a handle length of 20 cm instead of 100 cm.

## Measuring methods

The simplest instruments for measuring forces within the reach of designers are weighbeams and scales. Both types cannot be used unless they are calibrated first. This means that at least two points on the scale must be compared to a standard. Officially the *Nederlands Meetinstituut* [Netherlands Measuring Institute] in Delft is the only organisation that does this according to the *Wet op het IJkwezen* [Weights and Measures Act]. For small-scale studies within the design process this can also be done in a simple manner. The first calibration point is the zero point (this is also called stopping). The second point should preferably lie around the measuring range to be expected. The easiest way to verify this is by using commercially available ‘calibrated weights (to be recognised by the pieces of lead)’.

It then appears that scales for people can sometimes have an error of 5 kg at 100 kg. Sometimes a ‘calibration graph’ must then be drawn as a correction method, indicating the relationship between the measured and the calibration values.

To measure the pushing force of a person in a particular position the scales can simply be placed on the interface between hand and wall. By taking a photograph or slide at the same time it will be possible to measure the angles afterwards and it will be easy to draw a Free-Body Diagram.

If one pair of scales is not sufficient because of the measuring range (usually 150 kg), several scales can be linked in parallel or in series. This principle also applies to weighbeams, which can normally be used to pull a maximum of 10 or 50 kg. Figure 10.26 illustrates how 3 Industrial Design Engineering students measured tensile and pushing forces of 100 children for their design of the Flying Dutchman.

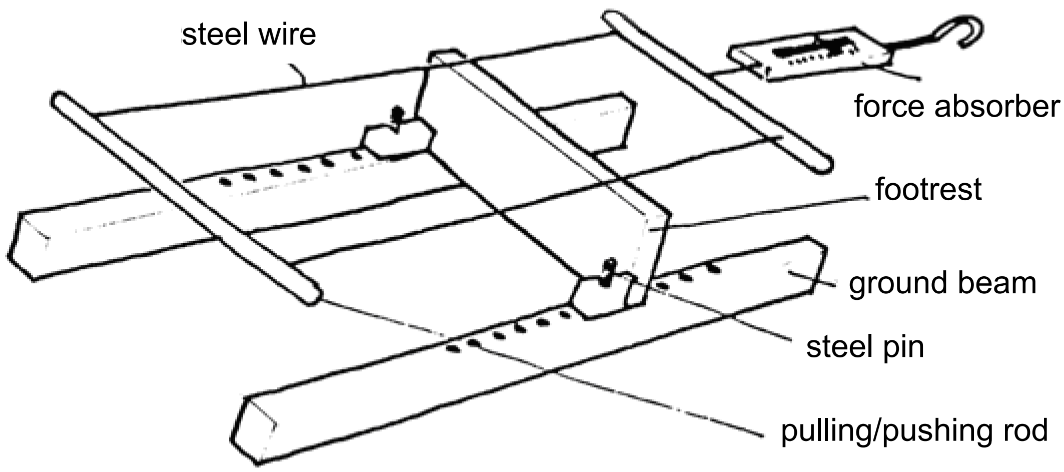


*Figure 10.26 Test set-up of 3 third-year Industrial Design Engineering students for a research project into forces exerted by children (Frank, Han and Spangenberg, 1985).*

For small (finger) forces it is also possible to build a more simple set-up using a balance and weights.

**Isometric, isotonic, static or dynamic**

☞ A great deal of muscle research has been performed in laboratories under isometric circumstances, in other words, at a constant muscle length. This is a study into one muscle and has limited importance ☞ for designers, as this occurs rarely in practice. Isotonic means at a constant muscle tension, but this term is often used incorrectly. Even if a body segment moves against a constant resistance the muscle tension will change due to the changing muscle length (Figure 10.27) and the changing mechanical advantage for the muscular force exerted.

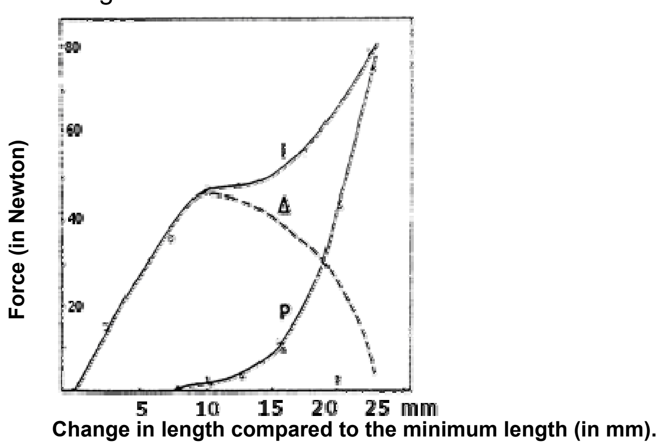


*Figure 10.27*
*Force-length diagram*

The difference between static and dynamic forces is, however, important to designers:

☞ 1. During static force exertion the length of the contracting muscle does not change. The forces are in equilibrium.

☞ 2. During dynamic force exertion the length of the contracting muscle does change.
   - For concentric contraction the muscle length is reduced (back muscles when lifting);
   - For eccentric contraction the muscle length is increased while the force is exerted (back muscles when bending over).

An interesting example of a practical study into forces exerted on playground equipment was performed by two Industrial Design Engineering students together with TNO Building and Construction Research for the preparation of a standard (Van de Kerk and Voorbij, 1995). The random sample consisted of over 200 children aged 4–12. When pushing their feet against a bar from a sitting position with a back support it appeared, among other things, that forces of up to 2000 N occurred.

### 10.9.2 Pressure, tension and torsion

To measure forces that are exerted strain gauge technology, piezo elements or capacitive measuring elements are often used in laboratories. These are expensive methods; for example, a glass platform with 4 piezo pressure sensors and charge amplifiers, power supplies, recorders and displays will easily require a budget of over € 25,000.

Movement image analysis is often performed using these Kistler measuring platforms: inertial forces during movement can be obtained via video analysis, but data relating to the reactive ground forces using this kind of platform are required for calculating the equations of motion within a particular cross-section of the human body to be studied. This type of research has shown that the vertical bone forces in the knee joint are around 3G (G=body weight) for normal walking; these can increase up to 5G when climbing stairs and up to 15G when jumping off a vaulting box.
This type of measuring platform provides the magnitude, the direction and the point of origin of the reactive ground force. One disadvantage of the piezo elements is that the measured values dissipate after a while; this is why they have to be recorded straight away.

The strain gauge technique is more commonly used to measure forces when pushing, pulling and twisting hands, fingers or feet. For this method a thin-walled cylinder is covered in strain gauges according to the Wheatstone bridge. When placed under a load even the tiniest movement along the length is converted into a change of tension that can be read on a display. This technique is directionally sensitive and therefore sets strict requirements for the attachment of handles or pedals. However, by using a well-considered protocol of what the instructions for the test subjects will be (‘only push, do not bend’), a lot of measuring errors can be prevented.
Capacitive measurements can be used very well to register pressure and pressure distribution. One of the zones of the human body that has often been the subject of research relating to pressure distribution is the bottom. An easy methods consists of the use of cuff sphygmometers. The Oxford Pressure Monitor (OPM) also uses the same method. A number of bags filled with air under a given pressure are placed at the man-product interface (in this case bottom-chair). The pressure difference is then indicated by the gauges of the sphygmometers, or via a printed list of measured values for the OPM.

A disadvantage of these methods is that the sitting comfort, and therefore also the Man-Product interaction, is affected by the measurement. Additionally, the OPM only uses 12 bags of air for the measurement area. In our laboratory (Physical Ergonomics Section) the development of a measuring mat, whereby for each square centimetre the vertical force is measured as a function of time, has already been underway for a number of years (Moes, 1995). The measured values of the pressure distribution of a person sitting on a bicycle saddle can be displayed all at once on a monitor in the form of a constantly changing mountain landscape. The shear stress is being investigated at the Medical Faculty in Rotterdam in the laboratory of the Biomedical Physics and Technology department of Prof. Snijders.
Both methods are still experimental at this point.

### 10.9.3 Friction

☞ There is useful friction (when writing, walking, skating and braking or rolling), but there is also detrimental friction (wear of gears and tyres or a graze after falling). It is good to realise that, in principle, friction always involves 3 media: two materials and an intermedium. The intermedium can be air (dentist's drill), but it can also be oil (hydraulic bearing) or clothing (person sitting on a chair). The properties of each of these three and their interaction determine the nature of the friction. In the ideal situation the following applies:

$W = f. N$

W = frictional force in N,
f = coefficient of friction, depending on the roughness of the surface
N = normal force in N perpendicular to the surface.

Below is a brief summary of a general problem involving friction that is used in mechanics, applied to a block (this may just as well be a human in a static state) with a side length 2a; a force F is exerted horizontally on the left side of the block at a distance p from the ground. The block will move along the horizontal floor or tip over edge b (bottom right).

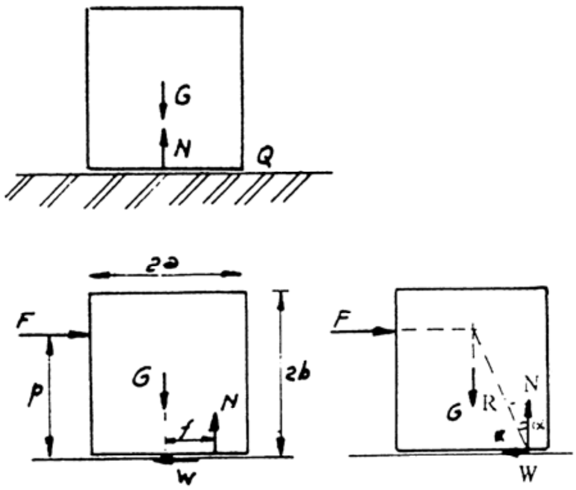


*Figure 10.29 a Coefficients of friction between shoes and the floor of various materials*

| Floor | Leather | Neoprene | Crepe |
|---|---|---|---|
| Soft rubber | .92 | 1.13 | .89 |
| Smooth rubber | .44 | .70 | .65 |
| Wet + slippery concrete | .97 | .62 | .59 |
| Lacquered hardwood, dry | .53 | .35 | .75 |
| Idem, wet | .67 | .35 | .30 |
| Vinyl/linoleum | .65 | .73 | .81 |
| Idem, wet | .60 | .41 | .52 |
| Asphalt | .57 | .49 | .88 |
| Idem, wet | .66 | .43 | .49 |
| Hard rubber | .53 | .80 | .80 |
| Idem, wet | .77 | .44 | .55 |
| Brushed steel | .24 | .24 | .54 |
| Idem, wet | .28 | .34 | .34 |

*Figure 10.29 b Coefficients of friction between shoes and the floor of various materials*

As F increases the block will slide or tip over edge b.
When sliding the maximum value of W is $W_0$ and the acceleration is:

$\ddot{x} = (F - W_0)/m$
If tg $\alpha_0 = W_0/N$, then $W_0/G = \mu_0$

If the block tips over before W has reached its maximum value $W_0$, the line of action of N will be acting on edge b; the following will then apply:

$I_b \cdot \varphi = F.p - G.a$
(here $N \neq G$ and $W \neq F$)

What will happen depends on the ratio F/G:
For: $F/G < \mu_0$ → block does not move or starts to tip over
For: $F/G < a/p$ → block slows down or slides

The block is more likely to slide than tip over if $\mu < a/p$
The block is more likely to tip over than slide if $\mu > a/p$

An example of a complex MPI situation, whereby friction between various interfaces plays an important role is the situation whereby someone who is sitting on a chair leans back and then bends forwards; this is also called 'shirt push' or 'shirt-removal effect' (see Figure 10.30).

In this situation the torso rotates using the line between the hip joints as the rotational axis, whilst the clothing covers a greater distance by rotating around the axis through the seat bone and/or via the curve of the buttocks over the seat.

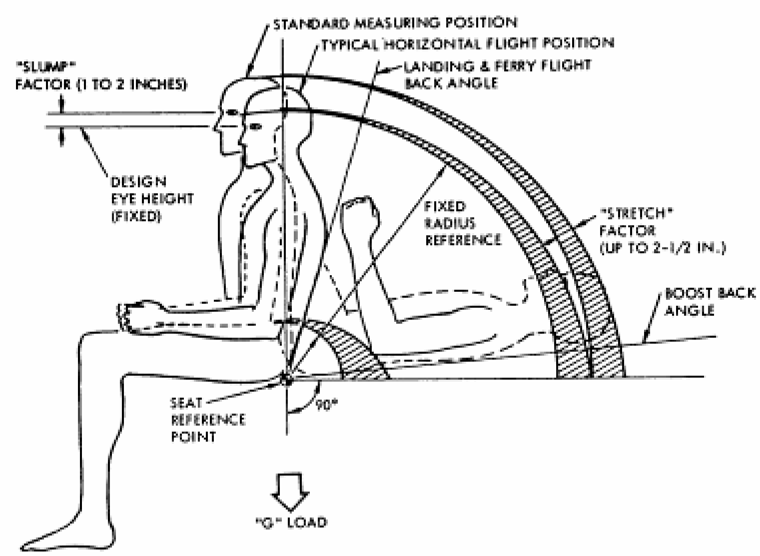


*Figure 10.30 Anthropometric dimension changes as a function of back angle in earth gravity (Roebuck et al., 1975)*

## 10.10 Joint excursions, posture, movement, speed and acceleration

### 10.10.1 Joint excursions

☞ The term joint excursions (see Appendix 15) is not very well-known outside of industrial design; people then normally speak of joint travel, movement options or 'body joint motions'. In addition to this, people usually mean the maximum joint excursion (R.O.M.: range of movement) when measuring. When applying the data people prefer to use comfortable angles. Data relating to comfortable angles is, however, rare or unavailable. As an anthropometric quantity joint excursion should be treated as a measure of length, which often has a normal distribution and which can be expressed in parameters by an average value and a standard deviation. Compared to a measure of length, however, more problems occur:

- the maximum joint excursion depends on clothing, training and occupation or hobby;
- contrary to many measures of length, joint excursions are often greater for women than for men;
- the maximum joint excursion is smaller on the basis of someone's own muscular action compared to when forced by external forces;
- comfortable joint excursions are difficult to define and depend, among other things, on posture and the gravity exerted on the segment in question; during the ergonomics practical at Industrial Design Engineering it appeared that the instruction 'which angle are you able to maintain for 5 minutes' resulted in 70% of the maximum angle;
- joints do not have a single centre of rotation, but the collection of momentary centres of rotation often lies along a path that can be described mathematically (involute or screw axis); as a result of this the distance between two centres of rotation (= usually the segment length) is theoretically also made a function of the angular rotation of the segments;
- movements in two or more neighbouring joints tend to affect each other, which means that the maximum flexion of these different joints will be less than the sum of that of the individual joints.

In the literature various attempts have been made to standardise joint excursion (among others, see Roebuck et al., 1975). The method used here is also called the SFTR method. During a literature search an Industrial Design Engineering student drew up an overview of what was known for each joint and then recorded this according to the SFTR method (Vellinga, 1984).

S = movement in the sagittal plane (see for anatomic terminology Figure A in Appendix 1);
F = movement in the frontal plane;
T = movement in the transverse plane;
R = rotational movement.

The excursion is recorded as follows: + 180 F -30; this means 180 degrees outwards in the frontal plane and 30 degrees inwards. In this case the data is related to the abduction/adduction of the upper arm in the shoulder. These values are always based on the anatomical posture (see Appendix); this means standing upright with the arms hanging by the sides and the hand palms facing forwards.

**Measuring methods**

The most widely used instrument is the goniometer or an automated version of it. It is not easy to position the goniometer along the centre line of a segment or on the rotational centre of a joint.

If joint excursion is to be measured on a large scale it won't be long before a modified instrument is developed for every joint. For example, to register head movements a helmet-like construction with a number of lines that indicate the median, transversal and frontal planes is very useful.

Another principle is the 3D position meter (EDI), which makes electronic readings possible. This instrument must be held against a segment in position A and position B; the instrument then calculates the difference between the two angles, assuming that the movement took place in one and the same plane. The advantage of this is that you do not need to identify a centre of rotation. The downside, however, is that it is slow and errors occur quite regularly.

A fourth method is recording the movement on video and digitising it afterwards. As more adequate frame grabbers are being introduced (to convert images into data) and as the test subjects only need to put in a limited amount of their time, this method is quickly gaining popularity. In some software packages a segment only needs to be indicated once, after which the digitisation of the other images of the same segment is performed automatically.

A fifth method is the use of 3D digitisers, such as OPTOTRAK (present in the laboratory of the Ergonomics and Use department for the PhD projects, among others, of Graaf (1994) and Van der Vaart (1995)) or PRIMAS (developed at the Faculty of Physics). By attaching markers to the limbs the cameras (2 or more) automatically convert the movements into x, y and z coordinates or, where required, angles.

**Joint excursion data**
The table by Lange (see Appendix 15) is probably the most widely known, but its downside is that it does not provide percentile values and it is unknown how these were measured and in which target group. It has been included nevertheless, as it is still quite commonly used.

The second table (Appendix 11) includes data by Staff (1983) and Houy (1982), who worked with automatic goniometers and wrote an extensive overview of literature. Her test subjects were around 100 female students from the University of Texas. The sources she used to compare her results are also stated in this table.

**Eyeball excursion**
This means: what are the movement options of the line of sight, which are used to describe the size of the field of vision (field of view). Figure 10.31 shows an example of an eyeball excursion, as measured by the Industrial Design Engineering student Abke Geels (1985).

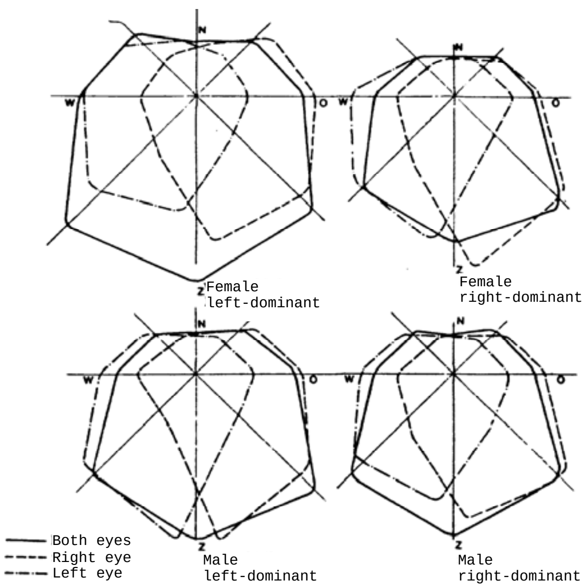


*Figure 10.31 Comparison of the left and right eye with both eyes, whereby the median (M) is shown (Geels, 1985)*

The heads of the test subjects were fastened in a holder at around 1 metre from a vertical board with good lighting. From the periphery cards with series of letters were moved to the centre of the board. The coordinates of the point at which people were able to read the card were recorded. This resulted in typical diagrams like the one in Figure 10.31.
Some related aspects (line of sight, field of sight, fixation point, fovea, field of vision, field of eye, eyeball excursion field) can be found on page 42 in the report by Geels.

## 10.11 Indices

An index is regularly used in ergonomics to assess two or more related variables. Examples are:

- Quetelet index ($G/L^2$);
- Cranial index (100*width/length);
- Leg height/torso height;
- Hip width/shoulder width;
- Waist circumference/hip circumference, or waist/hip ratio

All of these are mathematical operations on body measurements and they usually have a normal distribution as well. Other indices like the ones in the DINED table, which are operations on percentile values of body measurements, no longer have a normal distribution.
The textbook of Physical Anthropology according to Martin (Knussmann, 1988) contains an overview of a large number of indices. Some examples of reference values are:

**Hip width/shoulder width**

| | |
|---|---|
| Trapezoidal | ≤ 0.699 |
| In between | 0.700-0.749 |
| Rectangular | ≥ 0.750 |

**Quetelet index**

This is also referred to as QI or as BMI (Body Mass Index) in English literature. There is no doubt about the units for this index: body weight G in kg, divided by the square of the body height L in metres (see also the 'education' section of www.dined.nl). The Dutch National Health Council has set limits to which a 'healthy weight' is subject. These limits are the following:

| | |
|---|---|
| 18–20 kg/$m^2$ | tendency to be underweight |
| 20–25 kg/$m^2$ | healthy weight |
| 25–27 kg/$m^2$ | tendency to be overweight. |

A great deal of research is performed into the Quetelet index with regard to nutrition and the risk of dying. These types of reference values appear to be time-dependent (which actually means fashion-dependent). This was the result for the Broca index (healthy weight equals body height in cm – 100): G = L – 100 kg. Martin (1926) wrote in his textbook that this applied for $155 < L < 165$ cm. In later editions this had to be revised as the number of people with a height of more than 165 cm was constantly growing. The indices also appeared to depend on culture (being well-rounded was in fashion around 1900), on ethnicity and somatotype. A recent diagram is shown in Appendix 16. By using a ruler it can be used to read both the QI and an estimation (SE=4%) of the fat percentage for a particular height and weight in an easy manner.

**Fat mass**

According to Garrow et al. (1986) the QI appeared to have a useful relationship (r=0.955) with the amount of body fat (FM).

FM = (0.713 * QI – 9.74) * L2 , kg of fat mass for women.
FM = (0.715 * QI – 12.1) * L2 , kg of fat mass for men.
For children and elderly people these reference values appear to be invalid.

**Skin folds**

The amount of fat is usually determined by measuring the skin fold thickness. In literature, however, this method is highly criticised (reproducibility is low, the frequency distribution is skewed, people must be well-trained to measure this correctly). The sum of the four skin folds (biceps, triceps, subscapular and supracristal) has a close correlation with the fat mass. There are tables (Durnis and Ramahan, 1967) in which people can read the fat mass, depending on gender, age and skin fold thickness.

If you want you can have your fat percentage measured in the ergonomics lab of Industrial Design Engineering (Delft University of Technology).

**Apple and pear-shaped**

Ashwel et al. (1985) came up with the term 'apple-shaped' for people with a lot of abdominal fat and 'pear-shaped' for people with a lot of fat on the hips. She studied the amount of fat using CT scans and, among other things, defined the 'Waist circumference / Hip circumference' (W/H) index. This makes it easy to determine the location of the fat; it should be considered a supplement to the QI. This is because the QI does not differ between a body builder with broad shoulders and narrow hips and someone with an apple-shaped figure if both their height and weight are the same.

Note 1: April '99 – UK National Ballet excludes English people due to being pear-shaped.
Note 2: see also under endomorphy 10.12

**Reference values**

| Location of fat | W/H (waist/hip circumference) |
|---|---|
| Lower body (pear) | < 0.75 |
| Normal | 0.75–0.85 |
| Upper body (apple) | > 0.85 |

**2005 overweight situation in NL**

Research by the Framingham Heart study showed that people who are overweight (3.2 years) and obese (7.0 years) die sooner than people with a normal weight.

Male and female smokers died 6.4 years and 5.2 years sooner, respectively, compared to non-smokers. Obese smokers died 3.5 years sooner on average. Smoking or overweight shortens your life by more years than all cardiovascular diseases together and about twice as many as all forms of cancer!

- The absolute waist circumference is currently considered to be the best indicator for health
- Overweight means a Quetelet Index or Body Mass Index of 25–30 $kg/m^2$
- Normal weight means a BMI of 18.2–25
- ☞ Obesity (adiposity) means a BMI > 30 (obesitas is Latin for 'eating a lot')
- See also: www.framingham.com/heart
  www.dined.nl (under education)
  www.dikke-mensen.nl

## 10.12 Somatotypology

The theory by Sheldon was already mentioned briefly in paragraph 2.6 (volume). This was based on subjective observation, but his assistants Heath and Carter objectified and quantified the idea of using a number of indices to summarise the variation in human form. Carter & Heath (1990) reported on the state of 'Somatotypology' in an extensive and painstaking manner.

! According to Carter & Heath people do not have one somatotype that they keep their whole life, which is what Sheldon claimed in the past, but they pass through an interconnected series. The somatotype is indicated by 3 indices, for example, 171 is a very athletic type; 711 is a well-rounded (fat) type and 117 is a very skinny type. According to Sheldon these three digits were always between 1 and 7, whereby the number indicates the score for the first component (endomorphy), the second component (mesomorphy) or the third component (ectomorphy). Every person has a particular score for each component throughout his or her life, which can shift slowly in relation to the others.

Carter & Heath gave a maximum score of 9. Figure 10.32 indicates the path travelled within a somatocard by children on average.

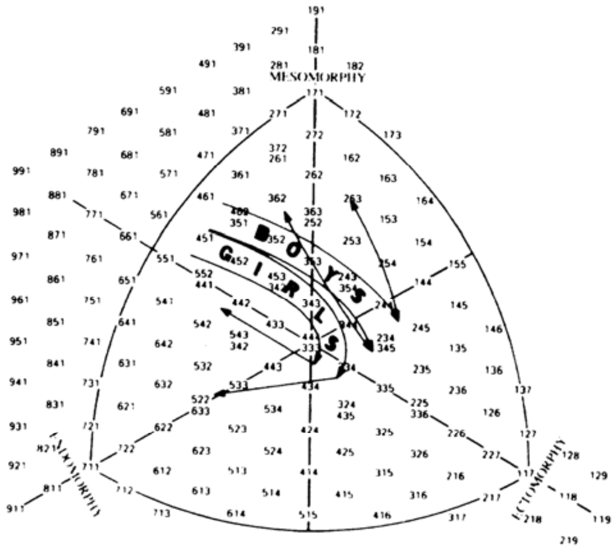


*Figure 10.32 Growth: the path within a somatocard (Carter and Heath, 1990).*

Boys shift from endo-mesomorphic to ecto-mesomorphic. During puberty with increasing muscle mass and completion of ossification the mesomorphic component strengthens and the ectomorphic component weakens. Girls start out with a similar path along the somatotypes: from endo-meso to ecto-meso and the central somatotypes; during puberty and afterwards they move towards a well-balanced endo-mesomorphy. Studies relating to dieting or sporting children have shown that the more ectomorphic types are more stable. In general, however, it appears that the somatotypes of most children do change slightly.

## Regression equations according to Carter & Heath

### 1. Endomorphy

Endomorphic score = $-0.7182 + 0.1451\,(X) - 0.00068\,(X^2) + 0.0000014\,(X^3)$
with X = the sum of the triceps, subscapular and iliac skin folds.

X must be multiplied by 170.18/body height in cm to obtain an endomorphic score, which is corrected for body height (Figure 10.33);

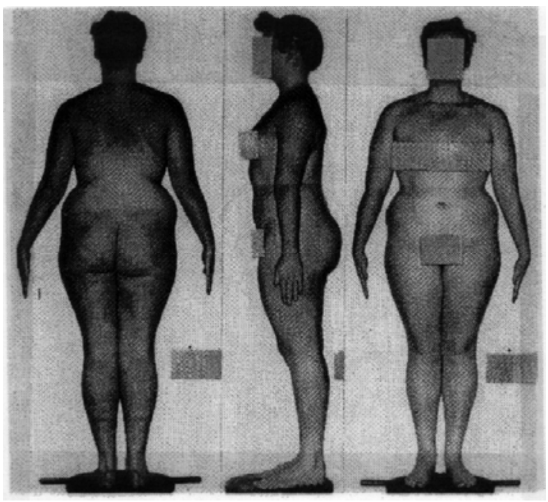

*Figure 10.33 31 yr, 171.5 cm, 100.5 kg, 11.16 (36.89), 4-9-0.5 (Carter and Heath, 1990).*

## 2. Mesomorphy

Mesomorphic score = (0.858 * humerus width) + (0.601 * femur width) + (0.188 * corrected arm circumference) + (0.161 * corrected calf circumference) – (body height * 0.131) + 4.50

Circumference correction = circumference in cm – skin fold in cm (see Figure 10.34);

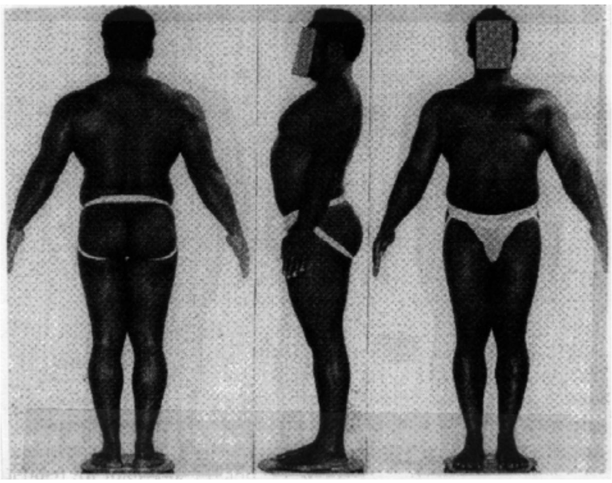

*Figure 10.34 19 yr, 172.8 cm, 86.0 kg, 11.84 (39.15), 7.5-4.5-1.5 (Carter and Heath, 1990).*

## 3. Ectomorphy

Ectomorphic score = HWR * 0.732 – 28.58
HWR = height-weight ratio, using the formula in which the body height (L in cm) is divided by the cube root of the body weight (G in kg): $L/\sqrt[3]{G}$.

If 38.25 < HWR < 40.75 → Ecto = HWR * 0.463 – 17.63
HWR < 38.25 → Ecto = 0.1

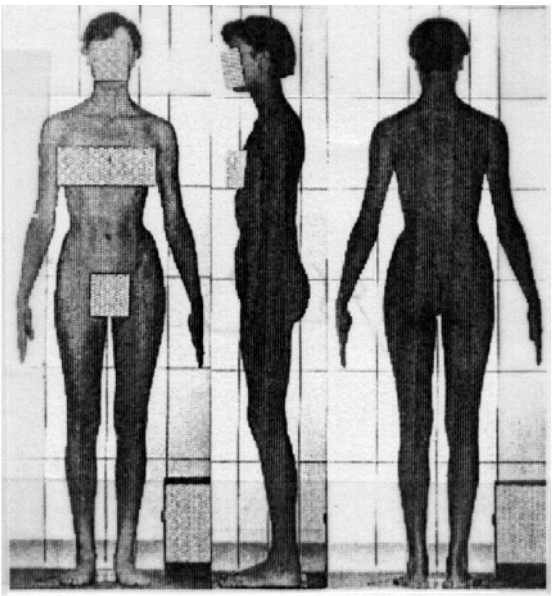

*Figure 10.35 18 yr, 178.2 cm, 56.0 kg, 14.09 (46.58), 3.5-2-6 (Carter and Heath, 1990)*

The above scores are called anthropometric somatotype scores; these are the best objective estimations of a somatotype.

Using the HWR table (height-weight table), the photograph and the anthropometric scores, an experienced ‘somatotypist’ will be able to determine the final somatotype.

**Design relevance of somatotypes**

It does not take long to determine the 10 required anthropometric variables, but it does require a certain level of training. Future research should show whether a smaller number of variables, for example, the series: weight, height, waist and hip circumference, age and gender will already allow designers to distinguish enough between types of build.

For industrial designers a 3-digit classification system together with the HWR list and the prevalence of each type, for example, for each professional group appears to be a useful tool.

CAD programmes such as ANYBODY, CADPEOPLE, MANNEQUIN, ADAM and JACK, whereby the designer can choose between 3 rough somatotypes, are already available. Keeping the above in mind the designer will be able to consider these types of possibilities a little more critically.

## 10.13 Conclusion

In the above an overview was presented of the data and measuring methods that can be important for designing, studying and assessing physically supporting products, components or systems. To an ever increasing degree it can be seen that special small-scale measurements and experiments are performed in product development processes to increase the quality of use of the design.