

Look around you

- Q2.8) Observe someone performing physical work (for example in a cash register, in a shop, at a gym etc.) – look particularly at the back, the neck, the shoulders and the hands. Is the person performing the work with a good posture, or can you see any signs of asymmetrical loading?
- Q2.9) Clench and open your fists and wiggle your fingers – where is the majority of muscle activity happening as you do this? Try feeling the muscles in the palm of your hand and the underarm while you activate your hands. Where do you think you will feel fatigued if you exert large forces with your hands?
- Q2.10) Hold a pen in the palm of your hand and grasp it in your fist. Then try holding it in extreme flexion and extreme extension – what happens to your ability to grasp the pen tightly?

Connect this knowledge to an improvement project

- When you observe physical work for the first time, try to take note of what movement types (bending, twisting, pushing, pulling, lifting, precision movements) and strength levels (in the back, arms, hands) are required to perform the work to good quality.
- Try to assess if body structures are loaded properly – as in symmetrically, at appropriate force levels and not to the point where they get fatigued.
- Do you observe any risk for fatigue or force overloading?
- Reflect on if physical work demands are appropriate for all ages, sizes and physical conditions of your working population. Who should be able to perform this task? Identify any “critical users” who may not be able to do the task currently.
- Look particularly at hand loading and tools – are they appropriate for all workers? Can anything in the tools be improved to lessen the demand for extreme postures, large force exertion or long exposure times?

Connection to other topics in this book

- All of the theory in this chapter is the foundation for the chapters on Physical Loading (Chapter 3), Anthropometry (Chapter 4), Ergonomics Evaluation Methods (Chapter 8), and Digital Human Modeling (Chapter 9). All of the principles in those chapters are rooted in the basic rules of how much loading the anatomical structures can withstand.

Summary

- The human body is a very complex structure made up of bones, muscles and joints; if loaded in the wrong way it can easily get injured.
- Combined, the skeleton, muscles and joints enable the body to turn chemical energy into motion, withstand forces and perform physical work.
- With the knowledge of basic physical anatomy and how certain structures move and respond to loading, it is possible for engineers to design healthy workplaces with reduced risk for injury.
- Work-related injuries resulting from repetitive static tasks and heavy loading are unfortunately quite a common occurrence, with the highest impact on employees taking sick leave in Europe.
- To avoid pain, discomfort, fatigue or injury the body should be used in its natural position, as close to neutral as possible.
- Most skeletal muscles are attached to the skeleton and enable humans to transfer loads and torques, while protecting the skeleton. Their strength is dependent on age, gender, genetic heritage and training.
- There are two types of muscle fibres: fast twitch and slow twitch. Fast twitch are suited to short fast explosive contractions while slow twitch is better for sustained longer exertions.
- An adult skeleton is made up of 206 bones of varying size and function.
- Joints are structures positioned at the point where different bones connect; they can enable movement in up to three different dimensions.
- Joints are the most complex of the three structures and can take years to heal if injured, or in some cases never fully heal.
- The back is one of the most common areas affected by WMSDs. The spine is made up of a series of stacked vertebrae and discs.
- When sitting or standing the back is being loaded and the discs between vertebrae compress. Excessive or uneven loading can cause discs to rupture, resulting in severe pain or numbness.
- The neck and shoulder complex are also a common area affected by WMSDs. Frequent or static bending of the neck resulting from looking at screens is a common injury trigger.
- The hands and wrists are crucial for carrying out high-precision work tasks, and an injury here has serious implications as it hinders humans from most forms of work.
- The hand and wrist can move in a number of different directions; however, working with them as close to the functional resting position as possible enables the best performance conditions for high strength and good precision.

Notes

- ¹ According to Kuorinka and Forcier (1995), the term *work-related musculoskeletal disorder* excludes accident-related sudden injuries.
- ² If you want to learn more about anatomy and physiology in a more medical sense, the book *Introduction to the Human Body* by Tortora and Grabowski (2004) is warmly recommended. Please see the references at the end of the chapter.
- ³ The brain and nerves
- ⁴ The lungs and oxygenation of the blood
- ⁵ The heart and blood flow
- ⁶ Pumps blood to and from the heart
- ⁷ Transports food and liquid through the gastrointestinal (digestive) system
- ⁸ For this reason, when the body needs to increase its temperature, we shiver involuntarily.
- ⁹ This number may vary, partly due to age, partly due to different conventions of how to count bones in the skull, and partly because some individuals are born with superfluous bones, e.g. extra ribs or vertebrae.
- ¹⁰ See the fact box in section 4.3.4 on hands to read about the condition *carpal tunnel syndrome*.
- ¹¹ There are actually six defined types of joint movements defined by the anatomical structure of the joint, but in this book we simplify it to the principle of movement in one, two, or three dimensions.
- ¹² Also called synovial fluid; it is secreted by an inner synovial membrane in the joint capsule.
- ¹³ However, this is just the structural recovery of the bone; the healing time until the bone is ready to take on the same amount of loading usually requires an extra period of rehabilitation.
- ¹⁴ Also referred to sloppily as “slipped disc”, although this condition does not actually mean that the disc slips per se; it is still a rupture of the gelatinous core.
- ¹⁵ Although the hand (like any other body part) can be deliberately trained to exert high forces given the right exertion-and-relaxation regimen, it is unsustainable to require very high grip strength of a working population that you are designing for.
- ¹⁶ For as you now know, that would mean working at the outer extremes of your joint motion range, where the joint cartilage is thinnest and the internal pressure is highest.

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CHAPTER 3

Physical Loading

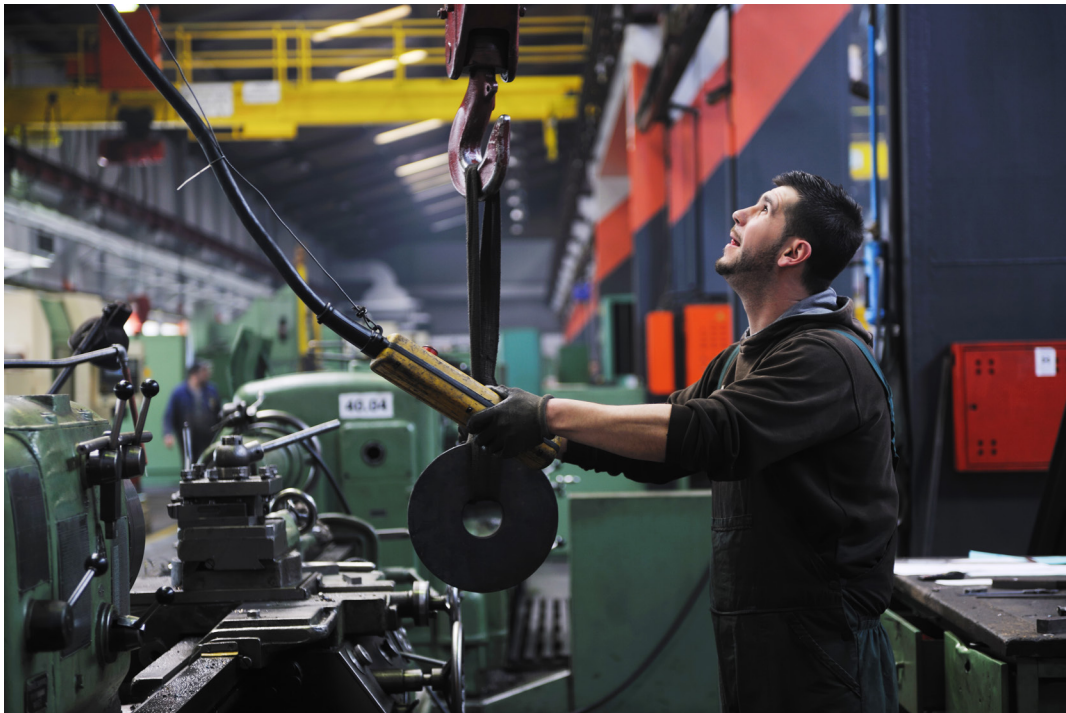


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THIS CHAPTER PROVIDES:

- A description of the three components of loading.
- Descriptions of the body's response to loading.
- A brief overview of simple biomechanics.

How to cite this book chapter:

Berlin, C and Adams C 2017 *Production Ergonomics: Designing Work Systems to Support Optimal Human Performance*. Pp. 49–64. London: Ubiquity Press. DOI: <https://doi.org/10.5334/bbe.c>. License: CC-BY 4.0

WHY DO I NEED TO KNOW THIS AS AN ENGINEER?

This chapter will help you understand how much physical loading is acceptable in the workplaces you design. Based on the knowledge you have acquired in Chapter 2 (Basic Anatomy and Physiology), you now have an understanding of how the body's locomotive structures allow movement and the handling of loads. In this chapter, we turn that anatomical and physiological knowledge into mechanical principles of loading, allowing you to identify, analyse and evaluate the greatest risks for physical injury in the workplace.

One of the great strengths of engineering is the ability to make simplifications in order to calculate how much loading the body is under. If you have limit values available, biomechanical calculations can tell you whether a chosen task, in terms of posture, forces and time, will push the human beyond his or her limits. These simplifications are the basis for most ergonomics evaluation methods, which are explained in Chapter 8.

When you can identify unhealthy physical loading based on principles, you can reason your way into better decisions when choosing design solutions for the workplace.

WHICH ROLES BENEFIT FROM THIS KNOWLEDGE?



For the *system performance improver* and *work environment/safety specialist* striving to identify improvement potentials in a workplace, the previous chapter's anatomical and physiological knowledge may be overwhelming to keep in mind and difficult to separate into analytical components in order to look for risks in a structured way – therefore, this chapter provides an intermediate step along the way to the ergonomics evaluation methods by showing how the body's reactions to loading can be simplified into some main components that can be systematically observed and later targeted in improvements.

3.1. The components of physical loading

As you learned in Chapter 2, Basic Anatomy and Physiology, the body's tissues work together to withstand many different types of biomechanical loading. Exceeding the body's physical ability to handle these loads results in pain and physical injury, which can be either sudden or chronic. But if we regard the problem from an engineering perspective, we need concepts and methods to identify what exactly makes physical loading a risk.

To make this possible, we adopt the view that:

$$\text{Physical Loading} = \text{posture} \times \text{forces} \times \text{time}$$

Body posture demands that the body's muscles actively work to maintain a position, which is a form of *internal loading*. The posture aspect includes how internal forces are distributed across the different parts of the body (for example, lifting something off the ground with a straightened back engages mostly the leg muscles which are large and strong, while lifting the same object with a bent back loads the upper torso which has smaller, weaker muscles).

External loading occurs as a result of handling weights, e.g. by pushing, pulling, lifting, pressing or dragging something. Generally, when force is counted as a component of loading, we are mainly referring to external loading. In some biomechanical analyses, the weights of the human's own body parts are sometimes also considered a load, especially if gravity influences the chosen posture.

Finally, time factors describe how long, how often or how frequently the body's structures are loaded. Since you now know that the muscles and tissues can work for a limited time until they are fatigued and need to rest, the level of risk depends on whether the exposure is suitable for strength- or endurance-type body structures. The time component most frequently focuses on repetitiveness, which is considered a major health risk because the body's structures are not allowed enough recovery between loadings.

3.2. Posture

Posture denotes how the body is aligned and positioned, especially in states of activity. A posture can occur as a result of consciously choosing how to position the body, or less voluntarily as a result of adapting to available space, tool sizes, visual demands, pain, etc. Posture may be influenced by the contextual factors in Table 3.1.

Good and bad posture

There is a conception of “good” and “bad” posture, stemming from societal norms about keeping the body upright, symmetrical and well aligned. From a work design perspective, good posture is more than keeping your head upright and your back straight – it also includes strong hand postures, equal weight balance between the legs, and deliberately handling external loads close to the centre of the body. As a useful, operative definition for engineering work, we can define good and bad posture as follows:

Good posture is a position where the functional structures of the body are in the best possible position to exert high force or high-precision movements, as required by the work task (Figure 3.1). Indications of good posture are balance, symmetrical distribution of forces on the body parts, and skeletal (rather than muscular) loading.

Bad posture is a position where body is in a weak position to perform physically demanding work. Bad posture puts the body tissues under extra, unnecessary physical load that does not contribute to the task at hand. Indicators of bad posture include positions at the outer range or movement (hyperflexion or hyperextension), asymmetry, imbalance between the legs, slumping, and forced muscular loading rather than skeletal loading.

As stated in Chapter 2, different parts of the body are specialized for different types of movement and loading. For example, the back and legs are excellent at withstanding heavy loads for a long time

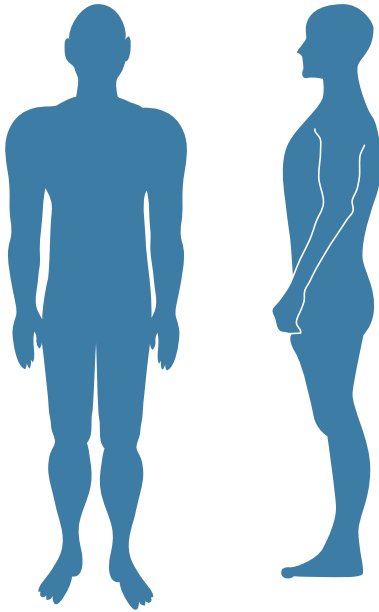
Table 3.1: Factors that may influence body posture.

SPACE	Humans are good at adapting body posture to existing preconditions in order to fulfil a task. This may often involve twisting or turning the body in order to reach, fit into an inconvenient space or avoid touching the surface of materials (example: so as not to scratch the paint job of a car). Therefore, it is necessary to determine how much working space around the task will be enough to avoid unnecessary loading, and whether to design for a minimum amount of space or with safety margins. A related aspect is to consider whether the available space will suit all body types and sizes ¹ .
VISION	An important prerequisite for performing a task is often being able to see what we are doing. If the line of vision is blocked or inconvenient, a human will often move the head, neck or upper torso to improve the line of sight, often bending or twisting. Therefore, visual demands can certainly influence posture. Also, insufficient lighting may have a similar effect even when the line of sight is acceptable, since it may still lead to bending closer to see controls, screen interfaces or instructions. It is a wise safeguard to have a well-lit working environment, particularly to ensure the ability to see ² written information for workers of all ages.
STRESS	A high pace of work or high mental load (demanding tasks or working under pressure to perform) can contribute to feelings of stress. Heightened stress levels often increase muscular tension in the body, leading to a persistent internal loading situation that is static and can lead to fatigue. In some cases, tension from stress leads to cramping up and discomfort or pain. Stress can result from the psychosocial environment, demands of the job, the task speed or perceived mismatch between the task and the human's abilities.
PROTECTIVE CLOTHING	Many environments and tasks demand that the workforce should wear protective gear and clothing – sometimes to protect the human from extreme temperatures, glare, hazardous materials, wetness or dirt (e.g. gloves, glasses, jackets, helmets or visors), and sometimes to protect sensitive products or the environment from humans (e.g. hygiene masks and gloves). From a loading perspective, it is important to consider the additional postural load that these safety measures can bring about. For example, a helmet or visor may be heavy or warm, resulting in extra muscular effort and heat. Another example is that wearing gloves can often reduce surface friction and the sense of touch, leading to compensation with higher grip forces or clumsy use of hand tools. Finally, it is worthwhile to consider that protective clothing can impede both movement and vision.

if loaded in their axial direction, while the hands are highly flexible and responsive instruments of precision work rather than strength. Granted, with training some people are able to increase their force exertion in the hands or the precision of their back and leg movements, but it is generally reasonable to design tasks and workplaces so that they cater to what the body segments are naturally best at.

Causes and consequences of bad posture

Bad posture is often accompanied by initial warning signals in the form of tension, discomfort or pain. It often results from unawareness, ignoring signs of pain or discomfort, or underestimating the impact of low-level long-term loading. There is a conception that there are several ergonomics pitfalls



Good Body Posture

- Feet firmly planted on the ground
- Knees directly above the middle of the ankle joints
- Hips directly above the knees
- Shoulders squarely above the hips
- Head and neck held in a way that aligns the ear directly over the shoulders

Figure 3.1: Characteristics of good body posture (for the purpose of being ready for additional loading)
Illustration by C. Berlin.

or typical scenarios that people often brush off as “not so bad” or just a minor inconvenience, but which may lead to risk for injury. These include:

- stretching to reach
- repeated heavy lifting
- lifting large, bulky, awkwardly shaped objects alone
- high pinch forces
- handling sharp, hot or cold objects
- working with hands above shoulders
- long periods of work holding the same body posture

As mentioned earlier, additional demands (such as seeing, avoiding touching surfaces, psychosocial issues, or compensating for protective gear with posture or force) may be part of these ergonomics pitfalls. Observable work behaviours include bending, pushing, pulling, lifting, hand twisting, unbalanced standing or sitting, and repetitive actions.

Some postures themselves can cause static loading on the body, meaning that forces or torques are applied for so long on the engaged body parts that they are not given sufficient rest. This can lead to fatigue, decreased force/precision performance, and compensation recruitment of extra muscle fibres. In many cases, static loading leads to constant tension in the muscles which can lead to tiredness, discomfort and cramping or even headaches. Such static postures and loading situations include:

- bending the back forwards or sideways
- holding loads in the hands

- stretching the arms out to the sides or raising them above the shoulders
- putting weight on one leg, while the other works (e.g. a pedal)
- standing in one place for long periods
- sitting in one place for long periods (e.g. computer work or driving a car)
- pushing and pulling very heavy objects
- tilting the head forwards or backwards at the extreme end of motion to see
- raising the shoulders

Measuring posture

How, then, can we determine if a posture in itself is harmful? A good rule of thumb is that if a posture is held near the outer range of motion, it is probably not a good position for taking on external forces. For many ergonomics evaluation methods, posture is defined in terms of joint angles between body segments. A “neutral” posture is considered the least amount of loading, and resembles a relaxed, standing, symmetrical body position with the arms hanging along the sides of the body (Figure 3.2). Deviating from this relaxed, standing posture is considered an increase in risk for harmful loading.

For situations where work postures are being observed or assessed manually, rough estimates (based on the expertise of a trained eye) of the joint angles are often sufficient, but for analyses that require more precise values for joint angles, the following measurement methods exist:

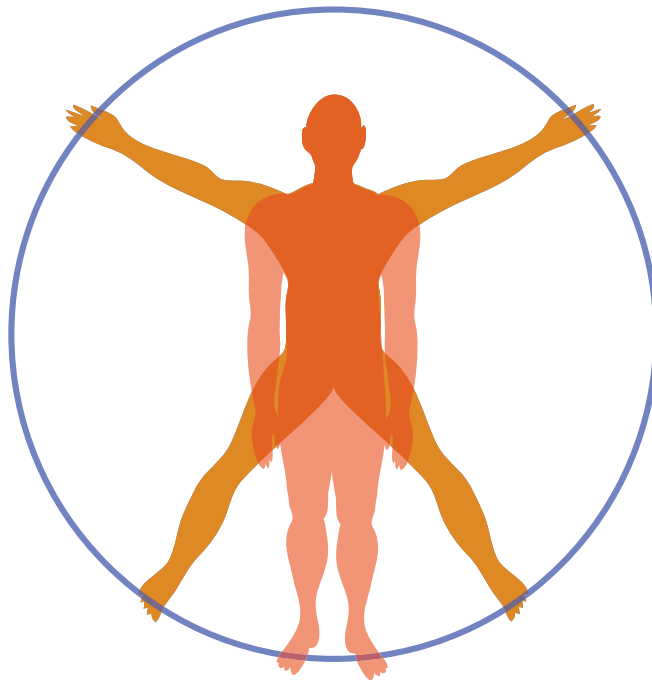
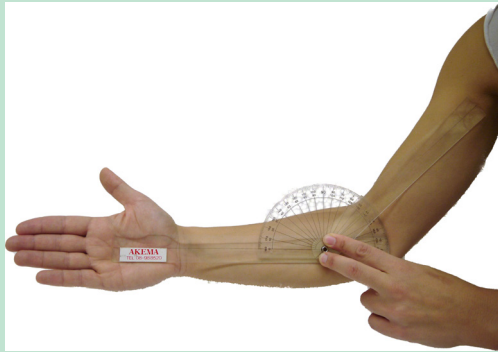


Figure 3.2: The basic “neutral” posture (red), typically considered as the lowest risk for harmful loading, and a near-maximal deviation of limbs (orange) from that neutral position, generating biomechanical torque on most joints. Bending and twisting also lead to deviation from the “ideal” starting posture.

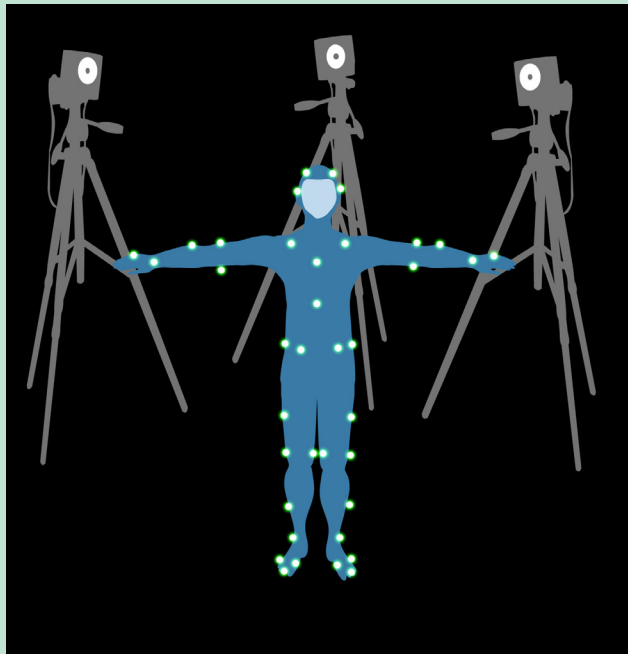
Illustration by C. Berlin.



Goniometers^a are graded tools used to measure angles between body segments.

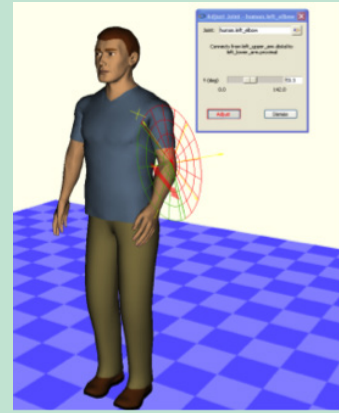


Inclinometers are electronic devices that can be mounted to body segments to continually log and measure the “leaning” or inline of body parts in different positions.



Motion capture has been used primarily by the film and games industries to record the motions of a real human being performing movements. Early motion-capture technologies often involved attaching electrodes with wires to different body segments. Today, this is usually done by one of two ways: 1) *visual motion capture*, where the person is strapped with reflective visual markers, and recording of the person’s movements is from all angles, using several different cameras simultaneously, and 2) *wireless motion capture*, where digitally connected sensors with inclinometers are oriented to a 3D coordinate system in a computer and wirelessly transmit human movement as the recording progresses. The result in both cases is a file that registers how the markers move relative to each other in a 3D space. This recording can be imported into ergonomics evaluation software, and joint angles and various risk levels can be easily deduced from...

...**Manikins**^b, which are 3D representations of humans in a 3D CAD environment that can be posed and made to move. Since manikins are frequently used to evaluate posture and ergonomics, exact joint angles are generally easy to obtain from the software that the manikin is used in.



^a Images by C. Adams (Goniometers and Inclonometers) and C. Berlin (Motion Capture).

^b © 2016 Siemens Product Lifecycle Management Software Inc. Reprinted with permission.

3.3. Force

Force in itself is only a risk if it exceeds the limit loading values of the body's structures. Some of these limits are determined by materials science values for body tissues, but a certain degree of ability to handle large forces actively can be influenced by training, health status, nutrition levels and genetic preconditions.

In static mechanics, a force is traditionally thought of as a vector arrow with a certain magnitude and direction, acting on a point. But to study the impact of real-life loading forces, we need a more nuanced vocabulary to do justice to forces. Table 3.2 shows some different terms by which we can characterize force.

Table 3.2: Terminology concerning forces.

MASS	The inert weight of objects that are not in motion, expressed in kg or lb.
DYNAMIC FORCES	Forces that have variation in magnitude and direction, engaging different muscle groups and leading to aerobic (oxygen-based) processes in the muscles.
STATIC FORCES	Forces that affect a limited muscle group for a sustained period of time, allowing little or no rest and recovery. This leads to discomfort, fatigue and anaerobic processes (production of painful lactic acid) in the muscles.
REPETITIVE FORCES	A special case of static loading, these are forces that are short in duration, but occur so frequently that the muscles are not able to relax in between loadings, meaning that their overall load is equivalent to a static force.
EXTERNAL FORCES	External forces often occur as a result of handling objects by pushing, pulling, lifting, lowering and carrying.
INTERNAL FORCES	Internal forces arise when the body's muscles strive to maintain a posture, either as a reaction to external loads or because of higher internal pressure at the extreme ends of our range of motion.



Figure 3.3: Force gauge for measuring push and pull force. The readout is often given in N.
Photograph by C. Adams. All rights reserved.

Measuring force

As with posture, rough estimates can go a long way, but it is often necessary to get a value on the force being applied to judge its risk impact. A very rough yet effective method is to use weigh scales (such as bathroom scales or luggage scales with a hook, Figure 3.3) to measure push and pull forces expressed in kilograms or pounds. This can then be roughly approximated into force expressed in Newtons by multiplying the gravitational factor 9.82 m/s^2 . For more exact force measurements, force gauges for measuring pushing or pulling motions can be used (see Figure 3.3).

3.4. Time

Time factors can significantly influence the occurrence of work-related MSDs and make a seemingly small and harmless load into a risk for long-term injury due to wearing out the body. Primarily, it is important that loading from tasks must be suitable for the body tissues that are engaged and that they are allowed sufficient rest and recovery between exposures. Exposure can be defined as the time duration that the body's structures are actively engaged in order to perform a task, usually in order to sustain a force or torque.

Table 3.3: Terminology of time exposures.

REPETITIVENESS	<p>Repetitiveness, also known as “monotonous work”, is thought of as the potentially most harmful time exposure factor. Generally, the magnitude of force is not the problem with repeated loading; the lack of recovery is. Since repeated motions affecting the same muscle groups lead to little or no time for rest, this type of exposure is considered equivalent to static loading.</p> <p>Definitions in scientific literature vary regarding limit values for repetitiveness, but many definitions count the number of “same” actions that occur every 30 seconds (Zandin, 2001).</p> <p>Repetitiveness can be either measured as the speed at which the operator carries out the tasks, or it can be measured in terms of the number of movements or posture changes per shift.</p>
FREQUENCY	Frequency designates the number of occurrences per time unit that a muscularly similar action occurs. Repetitiveness is often expressed in terms of frequency.
CYCLE TIME	The inverse of frequency is the cycle time, i.e. time duration per completed motion or task.
ENDURANCE TIME	The period of time before fatigue sets in; until that time, the body tissues can tolerate constant or repeated loading and still function to a satisfactory level of speed, precision and/or strength.
FATIGUE	The state where musculo-skeletal structures are loaded to the extent that they can no longer exert sufficient force, speed, precision or motion range anymore. At this stage, rest must begin to achieve recovery and rebuild safety margins against physical injury.
RECOVERY	The state where musculo-skeletal structures are free of discomfort, tiredness and pain related to exposure, and are once again ready to take on loading.
RESUMPTION TIME	The time it takes between reaching the stage of fatigue and when the worker feels ready to resume the activity or task.
CUMULATIVE LOADING	Cumulative loading is the notion that load exposures add up over time, and that some injury risks are difficult to identify unless the loading is considered over different time perspectives. This is especially true if there is routinely insufficient rest or recovery. For example, load risks may not be evident when studying cycle times of ~30 seconds, but may emerge if the loading is considered over an hour, over a shift, over a day, a month... all the way up to an entire working life. For some manual labour professions, certain types of loading may have a significant physical impact over the course of a working life.
VARIATION	The main remedy against harmful time exposures is to introduce variation – this means doing a variety of different tasks after each other to avoid repetitive motions. It is believed that even if muscular activity remains high, spreading out the loading on different body structures gives the different muscle groups a chance for relative rest and recovery.

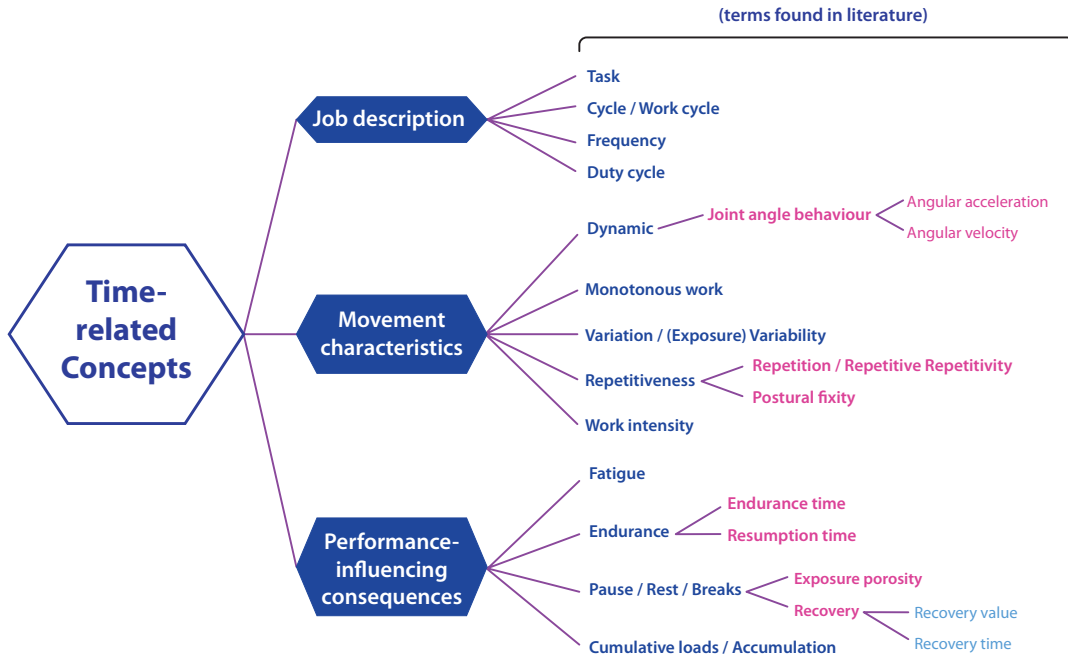


Figure 3.4: A hierarchy of time-related factors that can be used to describe production assembly work. (Adapted from Berlin & Kajaks, 2010).

Illustration by C. Berlin, based on Berlin & Kajaks (2010).

3.5. Interaction of posture, forces and time

It is important to remember that the interaction between posture, force and time may sometimes increase or decrease the total risk (increased probability and severity of injuries) considerably. It is for instance not necessarily true that lifting heavy weights is always a risk; this is acceptable as long as it is done infrequently (to ensure recovery) and with good posture. In contrast, small, persistent loadings over a long time period can be much more harmful than they seem, because weak structures that are constantly nearing fatigue can “drag along” neighbouring body structures into compensating with muscular tension.

Sometimes, the nature of the task can also influence whether loading is harmful or not. Often it is a question of whether the three components are of a suitable magnitude. You learned earlier that high-precision work with the hands is not good to combine with maximum force. It then follows that different hand postures or grips are ideal for high-precision or high-power work respectively. However, some postures alone will raise the risk greatly – working with highly flexed or extended wrists is both harmful and ineffective, since most extreme-range postures lead to nerve and tendon entrapment and provide a weak position for transferring force.

To describe the risk levels of these factors combined, the *cube model*³ (Sperling et al., 1993) gives each of the loading components three criteria levels of severity (where 1 = low risk and 3 = high risk) showing which combinations may result in harmful loading or injuries. Figure 3.5 shows that a high level on just one out of three components may be acceptable as long as the value is lower than 6,

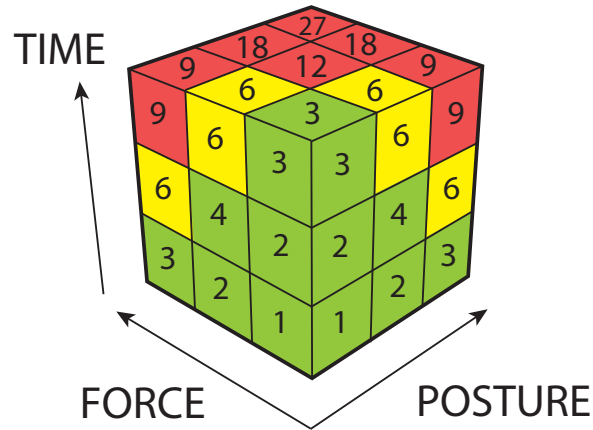


Figure 3.5: The cube model, showing how different combinations of posture, forces and time result in different risk levels. (Adapted from Sperling et al., 1993).

Illustration by C. Berlin, based on Sperling et al. (1993).

(green zone), while a combined level that is higher lands in the yellow (6 and above, but under 9) or red zones (9 and above), indicating that the load must be reduced (red) or at least investigated (yellow).

3.6. Other factors influencing physical loading

Some additional non-anatomical factors in a work environment may affect physical loading in a way that engages all three loading components or combinations of two of them.

Table 3.4: Factors that may have influence on body posture.

VIBRATIONS	Vibrations are a special form of loading; different body tissues have different resonance frequencies and therefore have different sensitivity levels to vibration forces. The body spends the entire times it is exposed to vibration compensating muscularly for small external forces that act in opposite directions on the body. This compensation tension can lead to sustained strain, over time resulting in cumulative trauma disorders.
ENVIRONMENTAL FACTORS	Cold, heat and humidity can affect contact comfort, grip friction, forces required, avoidance of burning or chill, etc.
NON-RIGID MATERIALS HANDLING	Rubber, fabric, cables, etc. are often large, floppy, sometimes elastic and difficult to manage in a consistent standard way. Extra force exertion may be necessary due to friction, dragging material on the floor, elastic behaviours and entanglement. It is also difficult to measure the forces required, both during carrying and during assembly.
HIGH-PRECISION WORK	High-precision work increases demands on performance and requires extra suitable working conditions and postures in order to be executed efficiently and with high quality.

THE “CINDERELLA HYPOTHESIS”

Hägg (1991) proposed a theory of cumulative loading known as the “Cinderella Hypothesis”, named after the fairy tale character that was always “first to rise and last to go to bed”. This theory aims to explain why there is a risk for injury even when humans perform tasks with low forces over prolonged time duration.

The basic idea is that when a motion occurs and the muscle contracts, certain low-threshold (weak) motor units are recruited first (with other stronger ones successively joining in as the motion continues) and are deactivated last. This means that when motions are repetitive, some muscle fibres run a greater risk of injury, because even though the motion stops briefly, the first recruited fibres remain constantly activated at low loads, meaning that there is no recovery. This leads to fatigue, pain and possibly cumulative strain injuries. This theory helps to explain low-load musculo-skeletal problems in the neck, shoulders and wrists, such as mouse arm and writing cramps.

3.7. Biomechanics

This book only gives a very brief overview of biomechanics, for the purpose of introducing you to the basic assumptions and simplifications behind many ergonomics evaluation methods. It is not intended to be extensive, so it will only bring up some very simple examples. To read more extensively on the subject, please consult a dedicated textbook of biomechanics, such as Knudson (2007).

3.8. Applying mechanics to the human body

The human body is made up of many different tissues (bone, muscles, nerves, ligaments, etc.) that all have different mechanical properties, for example limit values for loading and strain. Furthermore, they can move in a three-dimensional range of motion during loading. However, it is possible to simplify calculations of how much the body can be loaded using simple laws of mechanics, and by considering motions in a simplified way: by studying the forces and torques acting on the body at different “before” and “after” positions in a two-dimensional plane. The biomechanical calculation is often made with loading on a specific body part as reference, and generally, there is a limit value for how much force or torque that body part can safely withstand. However, since exact biomechanical calculations are extremely complicated, a simplified equation must be built on many assumptions. To be able to trust the simplification of the physics acting on the body, the limit value for how much a body part can be loaded should be calculated conservatively – in other words, the safety of the body is ensured by considering its weakest link.

Some basic assumptions (or simplifications) made in biomechanical calculations are that:

- Skeletal bones are considered as rigid bodies (no plasticity).
- Joint motions are considered in one direction.

- There is no friction in the joints.
- Torque is considered to affect only one muscle or muscle group in one direction.
- There are no antagonistic muscle forces.
- The mass of the body segment is calculated as a percentage of total body weight.
- Body weight and measures for centre of gravity are taken from anthropometric literature data.

Stress, strain and trauma

In a biomechanical sense, stress is defined as potentially harmful loading. Stress is usually the result of forces or torques acting on the body structures, up to the point of strain, meaning that the structures experience deformation as a result of the loading. This in turn goes to the point of trauma, which means that the structures fail or break. Every tissue in the human body has its limit value of stress that it can withstand before failure. As long as loading is beneath that value, the structure is safe, but above it, risk for injury is present.

Study questions

Warm-up:

- Q3.1) What is the difference between internal and external loading?
- Q3.2) Name some causes of bad posture that may arise from the work task and work environment.
- Q3.3) What is the difference between dynamic and static loading?

Look around you:

- Q3.4) Find some videos online (for example on YouTube.com) showing physical assembly work tasks; can you use the posture/forces/time triad to identify risks for unhealthy physical loading?
- Q3.5) Reflect on your own working life as a student, engineer or the like. What are the typical postures, forces and time frequencies of exposure that occur in your daily life? Are you at risk for unhealthy loading?

Connect this knowledge to an improvement project

- When observing physical work, look for recurring posture-, force- and time-related risk occurrences.
- Try to identify the root cause – in the task or environment – that may cause or contribute to the previously mentioned risk exposures.

- Ask operators why certain behaviours are adopted. If there is a known reason, this will perpetuate the risky behaviour and should be addressed. What function does the answer to that “why” fill?

Connection to other topics in this book:

- Some ergonomics evaluation methods (Chapter 8) specifically target one or more of the risk factors of posture, forces and/or time. When choosing a method, consider that:
 - Many methods are purely posture-based (Chapter 8), meaning that they may exaggerate the severity of the posture if it is not frequently occurring.
 - Time-related evaluation methods are not commonly covered; at least not with observation-based methods that you can perform on-site. Usually some assumptions are needed.
 - Force-related evaluation exists and is well backed up scientifically, but many of these guideline rules are limited to a specific population (for example, by being valid mostly for men), so it is worthwhile to be aware of how anthropometry (Chapter 4) dictates how relevant these methods are.

Summary

- Physical loading is a combination of posture, force and time.
- Posture dictates how the body is aligned and positioned and is influenced by space, vision, stress and protective clothing.
- To maintain a certain posture the muscles must actively work; this is a form of internal loading.
- A good functional working posture is one in which the body is balanced, forces are symmetrically distributed over the body and external loads are held close to the body while both feet are firmly planted on the floor.
- Bad demanding postures, where there is an imbalance between the legs, extensive muscular loading and movements at the outer range should be avoided where possible.
- A neutral posture where the body is relaxed and symmetrical with the arms close to the body is considered to involve the least amount of loading.
- Static loading when forces and torques are applied for prolonged periods of time without sufficient rest should be minimized.
- Excessive static loading can lead to fatigue, decreased performance levels, constant tension in the muscles and discomfort.
- Forces are only an injury risk when they exceed the loading value of the body's structures.
- Static forces affect a limited muscle group for a sustained period of time with little or no rest and recovery.
- Dynamic forces have variation in magnitude and direction, engaging different muscle groups.

- Forces can be both internal and external.
- Time factors describe how long, how often or how frequently the body's structures are loaded.
- Repetitiveness is one of the most harmful time factors, when repeated motions affect the same muscle groups with no time for rest.
- Fatigue is the state at which musculo-skeletal structures are loaded so much that they can no longer exert sufficient force, speed or precision.
- Rest is key to enable the body to recover from fatigue so it can function normally again.
- Variation of body postures and applied loads coupled with sufficient recovery time is very important during work.
- Applying principles of mechanics to the human body is known as biomechanics and can be used to calculate what loads the body can withstand.

Notes

- ¹ We explain how to consider different body sizes in Chapter 4: Anthropometry.
- ² We explain how to consider vision and lighting in Chapter 12: Environmental Factors.
- ³ Although the Cube Model was originally developed to evaluate hand/wrist loading when using hand-held tools, the logic of interaction between these loading risk components is applicable for the entire body.

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CHAPTER 4

Anthropometry



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THIS CHAPTER PROVIDES:

- Theory on statistical variation in human populations.
- Design procedures for selecting critical users to design for.

How to cite this book chapter:

Berlin, C and Adams C 2017 *Production Ergonomics: Designing Work Systems to Support Optimal Human Performance*. Pp. 65–82. London: Ubiquity Press. DOI: <https://doi.org/10.5334/bbe.d>. License: CC-BY 4.0

WHY DO I NEED TO KNOW THIS AS AN ENGINEER?

Perhaps you have heard of something called the “average person”. If you take anything with you from this book, let it be the knowledge that the average person *does not exist*. At least, the average person is not somebody you can or should design workplaces or equipment for. While it is possible to have average height, average grip strength or average weight, there are too many possible individual combinations of biological variations to design for any “standard” person, and sometimes the “middle” or mean is not where the statistical majority of people are found. Instead, most workplaces need to be designed for a range of needs from a population of people, ranging from small to large sizes in a number of different ways. This is the best way to accommodate as many system users as possible.

In other words, this chapter transfers the focus from the needs and capabilities of the *individual*, to the needs of the collective – so that our engineering solutions become useful for a *population*. Anthropometry is the study of statistical variation of human body dimensions and its implications on design. This concerns everything from workplaces, tools, vehicles and medical packaging to clothing. For an engineer, a helpful design input is to know the measurements of “critical users” whose specific needs must be met by the workplace design dimensions in order for them to be able to work in the most effective, productive and risk-free way.

WHICH ROLES BENEFIT FROM THIS KNOWLEDGE?



The *system performance improver* gains an understanding for the range of worker body sizes, strengths, etc. that the workplace and its equipment needs to be dimensioned for, especially for future recruits or an aging population. The *work environment/safety specialist* will be able to identify workplace risks and improvement potentials that are caused by a mismatch between worker size, strength, etc. and available equipment. The *purchaser* will be able to better understand the business sense in investing money in adjustable solutions that fit more workers (in spite of the perceived higher cost at the purchase stage), but may require a business case example and consideration of benefits for the whole workforce to be convinced. The *sustainability agent* will be able to connect ergonomics very clearly to demographic developments and align the design of the workplace to social sustainability concerns, such as readying the workplace for future workers.

4.1. Designing for the human

It is important for work environments to be designed according to the characteristics of the human body. Anthropometry is the branch of science that deals with human body measurements; its name comes from Greek, where *Antropos* means human and *Metrikos* means measurement. As a discipline, anthropometry dates back for centuries with many people taking an interest in the proportions of the human body.

We have previously discussed how the human body reacts to loading, and in Chapter 8 we introduce a number of tools and methods to evaluate workplace situations and identify areas for improvement, so now theoretical knowledge based on the physical characteristics of the human body will be discussed to aid in making improvements and redesigns.

There is a large variation in body size from one person to the next, with people having unique proportions across each body segment. There is significant variation in body size between different populations, genders and nationalities, which makes the design of equipment and workstations challenging, but this must be taken into consideration, especially when designing for an international environment. For example, a piece of equipment designed to fit 90% of Americans may suit 90% of Germans, but only 65% of Italians and 45% of Japanese, if we look at the size ranges in those local populations. However, populations also change over time, reflecting the effects of migration and genetic developments, so the best bet is to design your work equipment or environment for a range of populations and to use as recent databases as possible.

When it comes to designing for the human, the “one size fits all” approach rarely provides satisfaction for all involved. Just as the clothing industry takes variation into consideration by providing a range of sizes to meet everyone’s diverse needs, a number of considerations must be made to enable a diverse range of people to all use one workstation setup. In reality, there are very few work environments that are custom designed and tailored to one specific individual (Formula 1 cars are one of the rare exceptions). While individually designed workstations would probably promote healthier working practices, they would be extremely expensive and impractical. Instead, it is necessary to

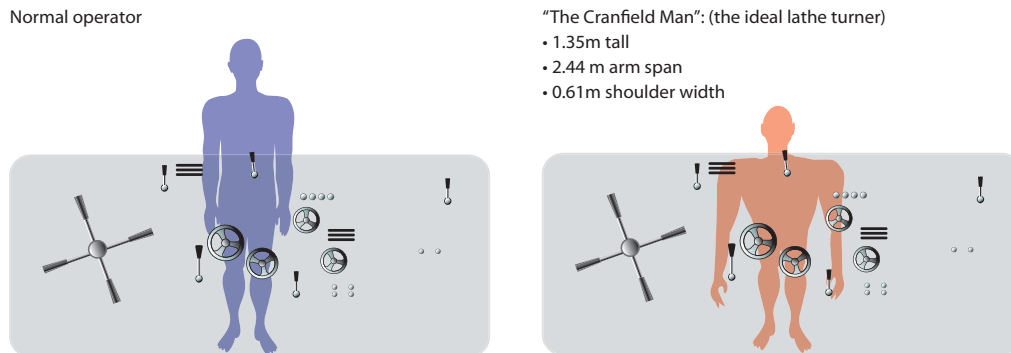


Figure 4.1: The “Cranfield man” on the right illustrates the mismatch between real operator measurements and a machine’s controls (Eastman Kodak Company, 1983).

Image by C. Berlin, inspired by Eastman Kodak Company (1983) and Kroemer (2010).

select appropriate sizes for different aspects of the design, taking into consideration the variations in body measurements across populations, so a solution for the majority of the population is achieved. Anthropometric data plays a key part in this process of optimizing a design to maximise its use and value for the greatest number of users.

A study at the Cranfield Technology Institute highlighted the issue of humans not being considered during the design of a lathe, when they calculated that the ideal operator for one such machine would be 1.35 m tall, with an arm span of 2.44 m and a shoulder width of 0.61 m in order to operate the machine and turn the handles (Singleton, 1964).

4.2. Terminology

Glossary of statistical terms

NORMAL DISTRIBUTION	Also known as Gaussian distribution – when a set of data measurements follows a bell curve with a high frequency of occurrences around the mean and few values at the extremes.
PERCENTILE	Percentage point on the measurement distribution; the cutoff point in a population at which that percentage has a certain characteristic limit measurement, and the rest do not.
CORRELATION	When a strong relationship exists between different body measurements; i.e., if one measurement moves toward an extreme, then so does another. This relationship can be determined using statistics. The value r is used to indicate if the correlation between measures is positive (both measures move in the same direction) or negative (when one increases, the other decreases). The value $r = 1$ indicates a maximally positive correlation, $r = 0$ is no correlation, and $r = -1$ indicates a negative correlation.
POPULATION	Term to describe a particular group of people of interest who have been selected due to a certain characteristic, e.g. age, nationality or gender.
VARIATION	Difference within a particular body measurement across populations.
BIVARIATE	Concerning the design of solutions where two measurement variables are taken into account simultaneously.
MULTIVARIATE	Concerning the design of solutions where several different measurement variables are taken into consideration simultaneously.

4.3. Static (structural) measurements

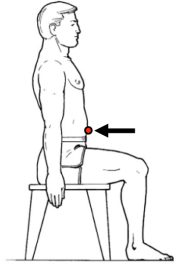
There are two different types of anthropometric measurements: static and dynamic.

Static measurements describe dimensions and distances that are taken while people are in a defined, unmoving position. Measurement points known as *landmarks* (see Figure 4.2) are positioned over the human body and measurements are taken in a straight line from one landmark to another.

Static measurements are very specifically defined and include stature, eye height, sitting height, buttock-to-knee length, etc., as shown in Figure 4.3.

While these dimensions are relatively easy to obtain, they have limited value when designing workplaces since the body rarely adopts such predetermined specific positions during real work.

Abdominal point, anterior: The most protruding point of the relaxed abdomen on a sitting participant.



Acromion, right and left:

The point of intersection of the lateral border of the acromial process and a line running down the middle of the shoulder from the neck to the tip of the shoulder.

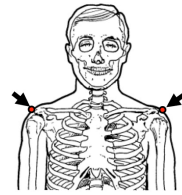


Figure 4.2: Two examples of definitions of landmarks for static measurements (Slightly modified figure from Gordon et al. 2014 p. 20).

Image permissions for Figures 4.2 and 4.3 granted by U.S. Army Natick Research, Development, & Engineering Center. The images have been slightly modified from the originals (in 4.2 surrounding table lines are removed, and in 4.3 the figure labels are moved to the side).

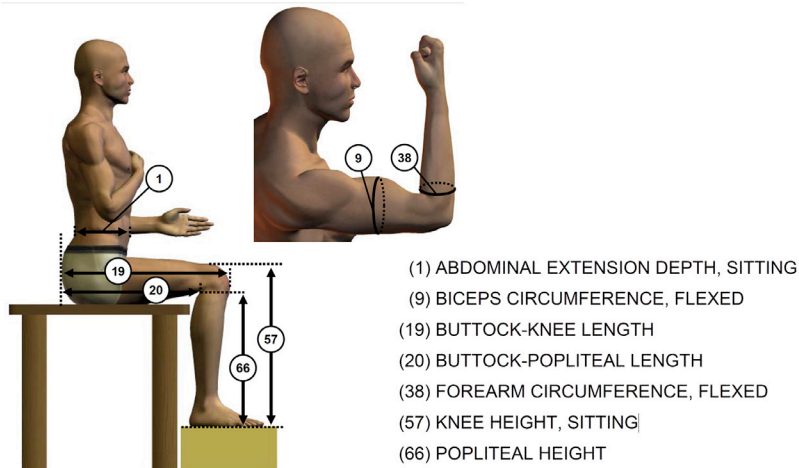


Figure 4.3: Static measurements (Slightly modified figure from Gordon et al. 2014 p. 402).

4.4. Dynamic (functional) measurements

Functional measurements concern dynamic positions, providing information about the necessary space required to carry out certain movements. While these measurements are more relevant to the design of workspaces, the data available in databases is usually very specific to particular work scenarios, so care should be taken when basing designs on such measurements. Examples of dynamic measures include ranges of reach (see Figure 4.3), clearance (how much space a person or body part takes up in relation to an object's boundaries, e.g. when passing through a doorway), strength measurement, etc. Obtaining and measuring functional measurements is more difficult than static measurements,

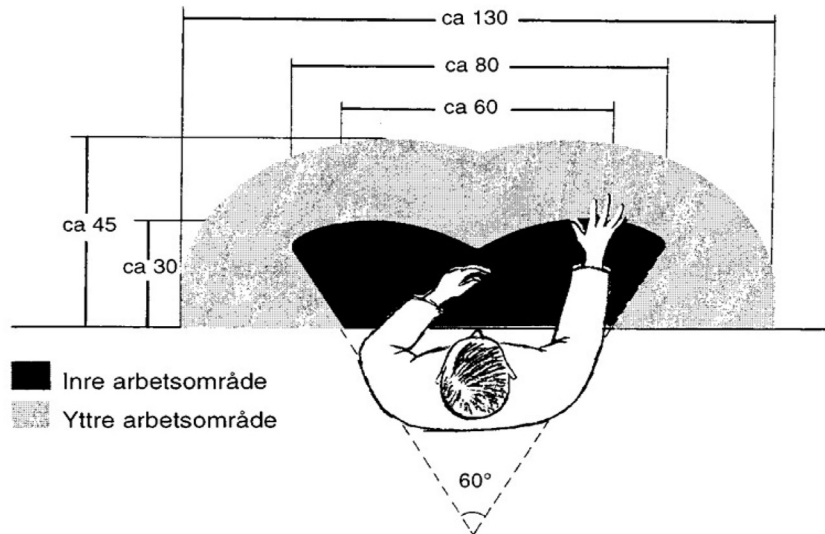


Figure 4.4: Dynamic measurements: reach distance design guidelines (Swedish Work Environment Authority, 1998).

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since many measures involve multiple body actions and movements in concert. For example, dynamic reach may include bending towards an object as well as extending the arm. This makes the act of standardizing the measurement quite complex, and thus databases of such measures are not easily verified.

4.5. Normal distribution and percentiles

Figure 4.5 shows a typical distribution of anthropometric data for stature (height). The distribution follows a bell curve, which in statistical terms is known as a “normal” or Gaussian distribution. In such a distribution, the mean, median and mode values are the same.

This curve is almost symmetrical about the highest point, which is the mean (average) height and the most probable height to occur (given it has the highest frequency), so 50% of the population in question are shorter than the mean and the other 50% are taller. In contrast to the high frequency of people close to the mean height, there are few very tall or very short people, as can be seen from the two tails of the curve. To better understand what percentage of the population have a certain stature, the x-axis can be split into sections, where each section or division is known as a percentile. Percentiles can be calculated if both the mean and standard deviation of a group of measurements is known. If someone has 5th percentile stature, it means they are taller than 5% of the population, while someone with 95th percentile stature would be taller than 95% of the population (with only 5% of the population being taller). The concept of percentiles can be applied to any measurement of the human body, including non-visible measures such as hand strength. While a lot of anthropometric measurements can be approximated using a normal distribution curve, this is not the case for weight, depth, width and strength measurements. A person's percentile measurements are rarely consistent

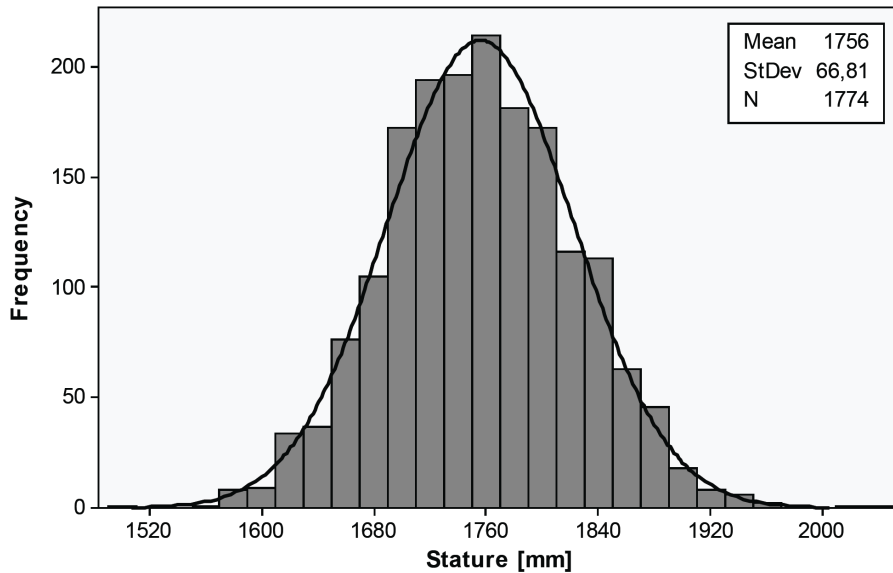


Figure 4.5: Normal distribution plot of stature (in Brolin, 2012; based on data from Gordon et al., 1989). Image reproduced with permission from E. Brolin. All rights reserved.

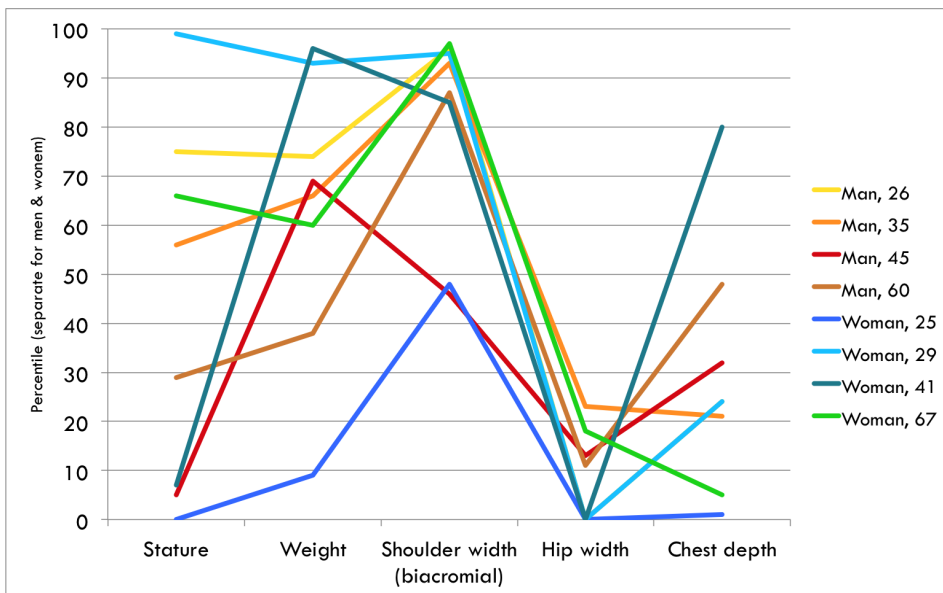


Figure 4.6: Variation in individuals' measurements – note that each individual person's combination of measurements fall into widely different percentile ranges!

Image by C. Berlin, based on data from Heinz et al. (2003) and Hanson et al. (2009).

across their entire body; while they may be 80th percentile in stature, they would be unlikely to be 80th percentile in all other measurements. As can be seen from the sample set of measurements in Figure 4.6, people with constant percentile values for a number of dimensions are rare, and therefore it is not meaningful to assume that a consistently “average” person exists or could be representative for the needs of a population.

Using the concept of percentiles, it is possible for designers to decide from the outset exactly which portion of the population they want their solution to be suitable for. In ergonomics and the design of workplaces, the extreme measurements are considered the most interesting, as these are the boundary attributes that could cause a design to be unsuitable and “not fit” the intended workforce. Generally when selecting which data to base designs on, one should ask the question:

“Who will be excluded from this solution if I select these measurements and what are the implications?”

However, care should also be taken, as designing for the extremes can mean that the solution is sub-optimal for the majority who aren’t considered extreme.

4.6. Correlations

Some body measurements are closely related; for instance, eye height is, logically, closely connected to stature. However, this is not the case with all measurements; for example, head circumference shows no such relationship with stature. Statistically speaking it’s possible to determine how strong a relationship exists between different sets of data using the Pearson correlation coefficient (r). This measure provides information about the level of dependency between two variables, giving a value between -1 and 1, where 1 is a perfect positive correlation, 0 is no correlation and -1 is a negative correlation (e.g. as one variable increases the other variable will decrease at the same rate. For example: the more time you spend at work, the less time you spend at home).

Generally where anthropometry is concerned, measurements need to demonstrate an r value of at least 0.7 for them to be considered correlated (Figure 4.7 and Figure 4.8).

It is valuable to understand how measurements across populations and body segments differ and how anthropometric data sets have come to be. Relationships between some measurements of the US air force showed that correlation exists between: stature and overhead reach, stature and wrist height, stature and sitting height, and stature and span. So while stature is the easiest measurement to obtain, it is not sufficient in many cases to use it as a predictor for other measurements. Care should be taken to generalise this information as it comes from a very specific group. Given that there is not a direct relationship between all measurements, it is not possible to add percentile values together.

4.7. Multivariate design

Typically it is not sufficient to only take one body measurement into account when designing workstations; rather, a number of different measurements are considered. This is known as multivariate design, and when the design of a solution only takes into account two measurements it is known as bivariate design.

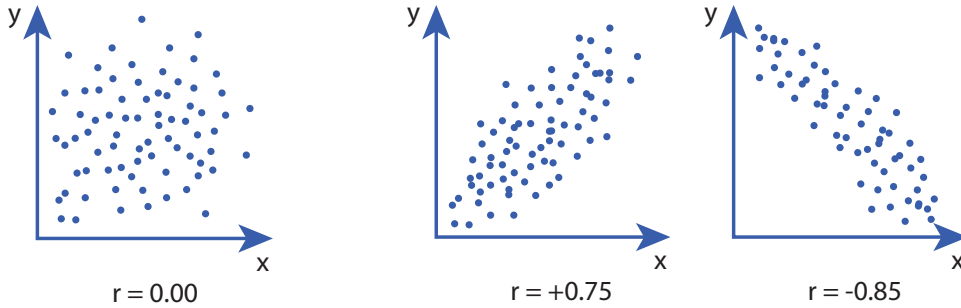


Figure 4.7: Uncorrelated measurements.
Images by C. Berlin.

Figure 4.8: Correlated measurements.

In cases where more than one measurement is used by the designer and a 5th percentile to 95th percentile approach is adopted, the reality is that the dataset actually excludes more than 10% of the population, as can be seen in Figure 4.8.

The design is in fact only suitable for those who fall within the squared area that only contains 82% of the population, thus excluding 18%. By adding a third measurement, a multivariate case is introduced and the percentage of the population accommodated by the design will be even less. This can be plotted on a 3D graph.

4.8. Variation

While almost every human body has the same “biomechanical layout”, there is significant variation in body sizes and proportions between individuals. The main reasons for variation between anthropometric data are due to:

- data management
- intra-individual variations
- gender
- nationality
- age

Data management

The first reason for variability between measurements has nothing to do with physical variation between groups, but is actually due to poor data management. By not adopting standardized methods and utilizing illogical procedures while taking, analyzing and organizing measurements, errors can easily occur. This results in unusual measurements that don't accurately represent reality. Should you encounter any measurements which are significantly different from any other published data set then extra care should be taken when designing workplaces based on such numbers.

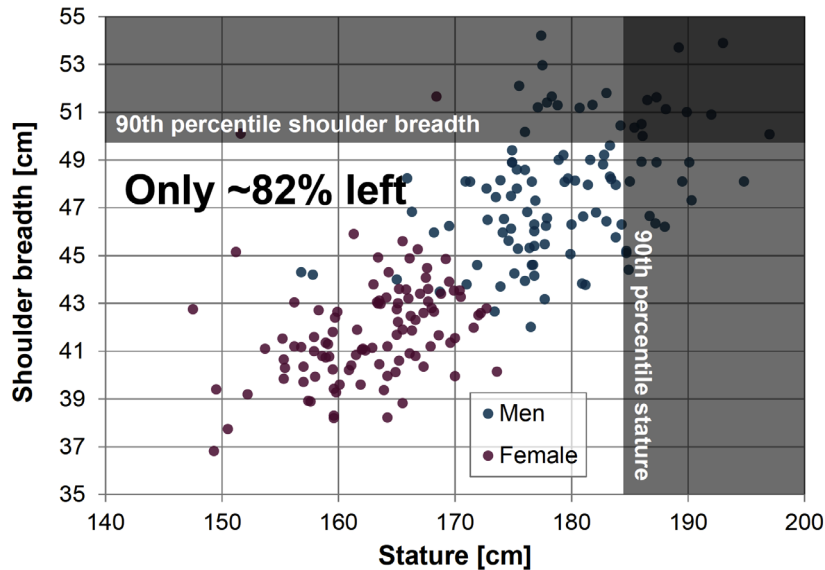


Figure 4.9: Bivariate frequency distribution of stature and weight – note how the 90th percentile principle of exclusion in two uncorrelated measurements ends up excluding about 18% of the population (Brolin, 2013).

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Intra-individual variations

It is not uncommon for variation to exist within individuals over short periods of time. As discussed in the Chapter 3, the spinal discs thin over the course of the day, meaning that individuals are taller in the morning. Significant changes in diet, state of health or exercise routines can also contribute to intra-variations over short time periods.

Gender

Between (biological) genders, significant variation in body sizes can be identified. Typically, females have lower measurement values than men across the gender-separated spectrum of most body measurements (Figure 4.9), with the width of the hips being an exception. Another obvious variation between genders is the difference in body anatomy, which sometimes requires separate standardization principles for how to measure specific (usually static) dimensions. Variations also exist in the degree of muscularity, level of oxygen consumption and the location and quantity of body fat. Given the increasing number of women in the industrialized workforce today compared with the past few decades, it is important that workplaces are designed to suit the characteristics of both men and women. Figure 4.10 highlights the variation in stature between genders.

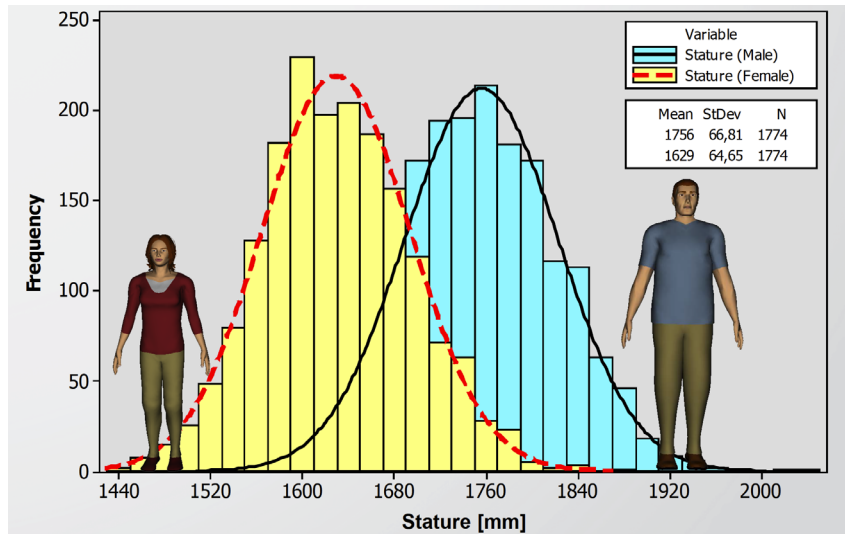


Figure 4.10: Variation in stature between genders (Brolin, 2013).

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Nationality

Differences in nationality also contribute to variation between data sets. For instance a piece of equipment designed to fit 90% of the male US population would roughly fit 90% of Germans, 80% of Frenchmen, 65% of Italians, 45% of Japanese, 25% of Thais and 10% of Vietnamese workers. Given the increasing rate of diversity in the workplace, it is important to ensure that people from a number of geographic locations can work together in a healthy and safe environment. When designing for a European population, it has been common practice to take Dutch males and Italian females as the two extremes of the size spectrum.

Age

Age is another factor that plays a significant role in the variation between populations and measurements. Humans tend to be at their physical peak between 20–25 years old; at around the age of 30, some deterioration starts to occur, which becomes more prevalent in the later years (65 plus), as shown in Figure 4.10. These deteriorations typically mean: lower muscular and skeletal strength, reduced oxygen consumption, poorer eyesight and hearing, and increased sensitivity to vibrations, heat and cold. With increasing age, changes in stature have also been observed with spinal disc compression over time, leading to decreased height (see Figure 7.8). Given the increasing aging population in the workforce, it is important that these factors are considered in the design of workstations to maximise performance and minimise injury risks.

In addition to differences between various populations at a fixed time, it is also interesting to note changes in measurements over time. These days it's common for children to grow to be taller than their parents; this is in line with a recognized trend that people today are typically taller than their ancestors. An increase in stature of 10 mm per decade in Europe and North America during the 20th century has been observed. Increased weight over time in certain populations has also been identified over the past century.

Given the high degree of variation between populations, it is not possible to design workstations that will be suited to the entire population, so it is generally accepted to disregard the extreme ends of the spectrum and design for 5th–95th percentile. Given that muscle and skeletal strength varies due to age, gender and health status, it is necessary to design workplaces and tools where muscular strength exertion is optimized, so the most efficiency can be achieved at the lowest level of effort.

4.9. Methods for measuring body dimensions

To ensure accuracy across data sets and avoid poor data management and unreliable data, measurements are collected by professional physical anthropologists following standardized procedures where possible. Historically data has been collected manually using a combination of tools including rulers, anthropometers (a device used for measuring body segments), goniometers and calipers (Figure 4.12). However, with recent developments in technology full-body laser scanning, this is becoming increasingly popular, enabling all surfaces of the human body to be captured quickly in three dimensions. Measurements are taken in a number of predetermined postures, without shoes on and with as few items of clothing on as possible, to gain as accurate a representation as possible.

4.10. Anthropometric datasets

Extensive work has been carried out to measure different populations and obtain complete data sets that can be statistically analysed then scaled to provide an accurate representation of an entire

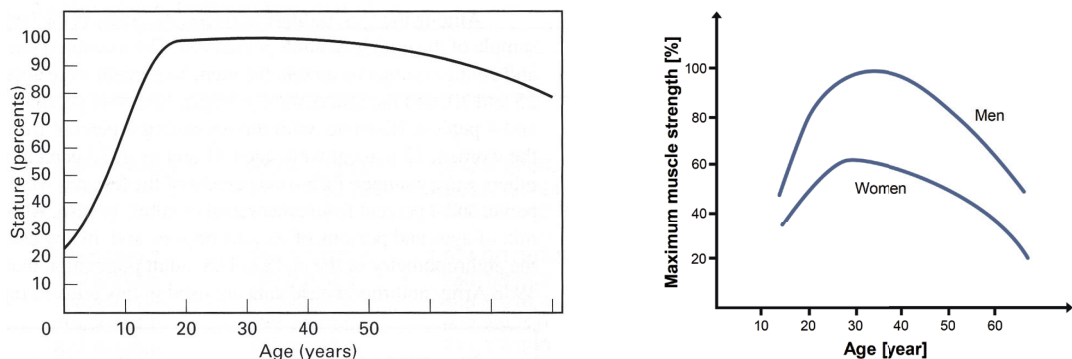


Figure 4.11: Variation in stature and muscle strength over time as a human ages (figures from Brolin, 2013).

Image reproduced with permission from: E. Brolin. All rights reserved.



Figure 4.12: Examples of equipment for anthropometric measurements: anthropometer (top) and calipers (bottom). Figures from Gordon et al. 2014 p. 11.

Image permission granted by U.S. Army Natick Research, Development, & Engineering Center. The images have been slightly modified from the original (figure labels removed and some cropping).

population. However, obtaining large amounts of accurate data and recruiting people for body measurement is no easy task, and with emerging population trends, data can become obsolete. Datasets representing civilian populations are quite limited, but there is substantial data available from the US military. Historically the military has always had a wealth of available data, as numerous measurements were systematically taken by paid and qualified medical personnel for uniforms, weapons, vehicles and other equipment. However, given that the majority of soldiers are young, fit, healthy and historically male, it is difficult to generalise such data and create an accurate picture for the rest of the population. While hand, head and foot measurements are reportedly similar for both soldiers and civilians alike, other data shows little similarity. Some databases containing datasets for various populations are available; *Bodyspace* by Pheasant & Haslegrave (2006) is one of the most popular textbooks in this field, containing a number of measurements from anthropometric surveys.

Various online databases also exist, for example:

- openenerg.com/psz/
- antropometri.se
- dined.io.tudelft.nl/dined/
- openlab.psu.edu

4.11. Design principles

Usually, it is not feasible to design workplaces to suit everyone perfectly from the shortest to the tallest, so a decision needs to be made about which members of the population will be eliminated. A commonly accepted rule is that the extreme sizes are eliminated and designs are based on measurements from 5th percentile females up to 95th percentile males; however, as we have already seen in the case of multivariate design, this can mean more than 10% of the population is excluded, so it is not sufficient to apply one standard rule; rather, it depends on the specifics of each design case. When designing workplaces they should be suited to both male and female Europeans aged between 18 and 70. In reality it isn't sufficient to only take into account anthropometric data; one must also consider behavioural patterns of people in different environments. This is why observations and participatory ergonomics are key sources of input during redesigns.

There are certain principles that can always be applied when designing for specific situations, which will be discussed in more detail below:

- Designing for the extremes
- Designing for adjustability
- Designing work heights

4.12. Designing for the extremes

When designing workspaces it's important to ensure there is enough space for employees to move around, especially given the varying nature of assembly tasks. So in this case the design should be based on values for the 95th percentile male so that there is sufficient space to accommodate their arms and legs and clearance above their head level so they aren't constantly hunched over. At the other end of the scale, where the issues are reaching components on the work surface and the strength needed to carry out the tasks, datasets corresponding to 5th percentile females should be used. Theoretically, adopting such a design philosophy should accommodate workers with body measurements closer to the median; however, testing and simulations should be done to confirm this before implementing the workplace. Guidelines exist to aid in the design of workplaces, e.g. the AFS (*Arbetskyddsstyrelsens Författningssamling*) guidelines from the Swedish Work Environment Authority (Figure 4.13).

4.13. Designing for adjustability

In some instances it is not possible to accommodate everyone across the size spectrum; in such circumstances, adjustable equipment with varying height ranges should be added to the workstation. Where adjustable workstations are impractical, non-slip platforms are another possible addition to enable a more diverse workforce to work at the same workstation.

4.14. Designing work heights

One of the key areas that you have to consider when designing workstation layouts is the working height. Given the high degree of standing work on the production line, this is an attribute that affects

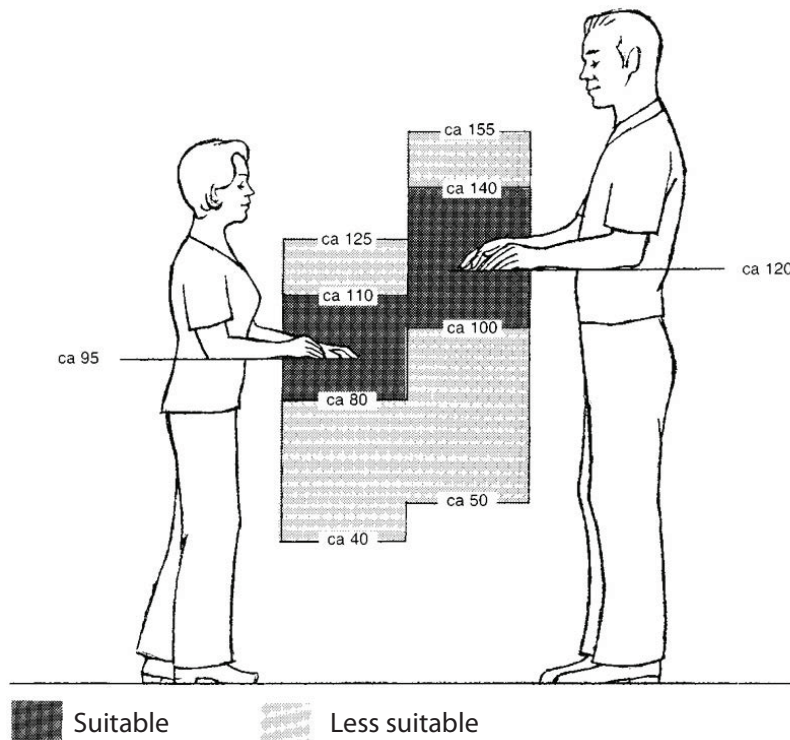


Figure 4.13: Workplace height design guidelines showing that the overlap between the tallest and shortest workers' ideal work heights may be rather slim (Swedish Work Environment Authority, 1998).

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all members of the workforce, so care should be taken to get it right and eliminate any injury risks. As discussed in Chapter 2, the shoulder is a complex structure prone to injury, so having workplaces set too high will force workers to continuously lift up their shoulders or work for prolonged periods with their arms extended above shoulder level. However, if the workstation is too low, the worker will be bent forwards and loading their back, which can also be an injury trigger. Adopting a body position like the one shown in Figure 4.13, with the arm bent at a right angle at the elbow, is regarded as the best option for light work. If a higher degree of precision is necessary, then the working height should be slightly higher, enabling the worker to see exactly what they are doing without straining their neck. For heavier work involving physical exertion the working height should be lower. Given that the component being assembled has its own height and that fixtures are often used to hold it in place, the workbench should be set at a height that takes this into account – meaning that while on its own the workbench might appear to be too low, but in reality while the worker is carrying out their assembly tasks it will be appropriate. Given that too high a workstation could lead to shoulder injuries, while too low a working height could result in back injuries, it is crucial to select the appropriate measurements to maintain an efficient and healthy workplace. An AFS guideline from the Swedish Work Environment Authority exists to aid in the design of workstation reaches and heights as shown in Figure 4.4 and Figure 4.13.

Steps for using anthropometric data in workstation design

1. Identify the necessary body dimensions needed for each element of the workspace design. For instance, hand length affects handle size, and eye height is relevant for information displays.
2. Identify the specific population of interest (age, gender, nationality) and determine suitable percentile ranges for each measurement.
3. Find a suitable anthropometric database with relevant measurements, if one is not available you may have to extrapolate data from another dataset or collect your own measurements.
4. Make a model of the proposed design based on the selected data; both physical models and computer simulations can be used to test the design.
5. Evaluate whether one fixed design will be sufficient, or if adjustable equipment needs to be added to accommodate the whole working population.

Study questions

Warm-up:

- Q4.1) Why would you choose to base measurements on a particular anthropometric database, such as one of the ones listed in section 4.4? Give at least two reasons.
- Q4.2) Explain what it means to “design for the 5th to 95th percentile” of a population.
- Q4.3) Explain the difference between static and dynamic body measurements.
- Q4.4) Name two examples of normally distributed body measures.
- Q4.5) Name two examples of non-normally distributed body measures.
- Q4.6) Why would it be a bad idea to design a workplace based on a fictive person with “average” measurements?
- Q4.7) What is a “critical user”?

Look around you:

- Q4.8) See if you can find examples of certain elements in a work environment that are not designed for a range of body sizes.
- Q4.9) Go into a kitchen – can you list elements of the environment that appear to have been designed with a particular body size in mind? Can you think of reasons why those measurements were decided upon? Who would have difficulty using the kitchen?

Connect this knowledge to an improvement project

- Think about the range of users who will use the workplace you are designing. Who are the tallest and shortest? The strongest and weakest? The most and least mobile (in terms of movement?). List the “extremes” for each task.
- List the critical tasks and the demands they place on human (or machine) performance – what are the maximum and minimum strength requirements? Reach distances? Hand clearances?
- Decide on whether you should design the workplace to offer adaptability (being able to change reach distances, work heights, choosing different size hand tools, etc.) or to design for a “critical user” for whom the work becomes impossible if the dimensions are not adapted to them.

Connection to other topics in this book:

- Knowing what tasks are typical in this workplace (Chapter 7) will help you figure out the requirements for strength, reach, manoeuvring space, clearance for hands, etc.
- Some ergonomics evaluation methods are only guaranteed to be valid for a certain population – for example, the NIOSH lifting equation is based on strength limits that have been measured mainly for males, so the method is only said to be 75% valid for females. For more, see Chapter 8.

Summary

- Work environments should be designed according to the characteristics of the human body, based on anthropometric data.
- Body measurements are described in terms of percentiles and what percentage of a defined population has which measurements.
- Variation between measurements is due to: poor data management, inter- individual variation, gender, nationality and age.
- Databases containing a wealth of measurement data collected using manually methods or body scanning, exist to aid designers.
- There is no such thing as the “average person” in all respects, so it is not a good idea to design workplaces based on their measurements.
- Design to exclude as few people as possible.

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