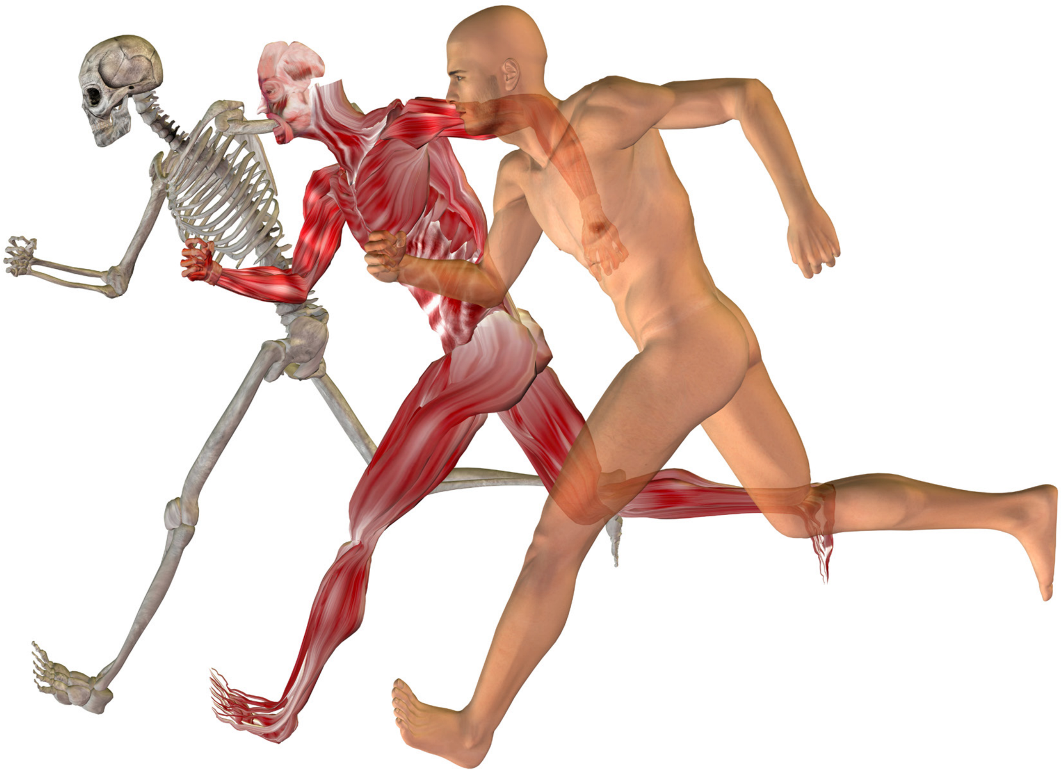
PART I

Understanding the Human in the System

CHAPTER 2

Basic Anatomy and Physiology



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THIS CHAPTER PROVIDES:

- Descriptions of how the different structures of the musculo-skeletal system are shaped (anatomy) and how they work and respond to loading (physiology).
- A description of current injury statistics regarding musculo-skeletal disorders and how big the problem is for production industry.

WHY DO I NEED TO KNOW THIS AS AN ENGINEER?

From a physical point of view, having a basic understanding of the human body's strengths, abilities, and limitations is an important basis for making well thought-out tweaks to the design of the workplace, in order to build work systems that are not a risk to human health or performance. Knowing how your muscles, bones and joints work may seem like a far cry from your engineering work, but it will significantly help your understanding in later chapters where physical loading and methods of ergonomics evaluation are discussed. Another thing this chapter does, is to provide a *limited* description of anatomy and physiology; it will not go into as much detail as an anatomy book, but provides the level of detail needed to understand some of the methods that will be explained later.

If you as an engineer start using ergonomics evaluation methods without first gaining the knowledge in this chapter, the reasoning that those methods are based on would probably remain a mystery. You could still use them, but if you were questioned about their limitations or why you were using them, you would probably not be able to explain their validity, or reason about unexpected results. Knowing about the human body and its strongest and weakest positions can also encourage even an engineer to adopt more healthy movement, posture, loading and sitting behaviours in their everyday life – and *that* awareness is the best basis for becoming a great workplace designer.

WHICH ROLES BENEFIT FROM THIS KNOWLEDGE?

The engineer who acts as *system performance improver* or *work environment/ safety specialist* is likely to observe and analyze actual physical work being performed, before making a recommendation or a design proposal. With knowledge of how the human body functions optimally and how it is limited in strength, stamina and injury recovery, the engineer can avoid building potential risks for MSDs (musculo-skeletal disorders) into the work system. These roles may also interact with workers who complain in an imprecise manner about pain or discomfort, or with medical or health personnel who are not trained in using ergonomics evaluation methods to evaluate risks. With basic knowledge of anatomy and physiology, the engineer can communicate effectively with these stakeholders about risks and possible solutions.

2.1. Musculo-skeletal disorders

Our ability to work – in any way – is completely dependent on our physical health. When we feel unease, discomfort, pain or numbness, we may be able to ignore the body's warning signals and still perform work, but the body will perform slower; with less power, quality and precision; with more errors; and at worst, resulting in serious accidents. A very real problem that is faced by all production industry is when the limit has been passed for what a human body can tolerate, resulting in a worker needing to go on *sick leave,* i.e. be absent from work to recover from physical disability. If the disability affects the worker's physical ability to move and handle loading, then the worker is said to be suffering from a *work-related musculo-skeletal disorder* (abbreviated either as WMSD[1] or just MSD). MSDs are defined as a heterogeneous group of disorders caused by a multitude of potential (physical) factors. Pain, discomfort and fatigue are considered common first symptoms, while more obvious signs of the presence of an MSD include loss of function, limited movement range and loss of muscle power.

The costs of a worker taking sick leave can balloon to huge proportions: not only does the employer in many cases need to cover the worker's sick leave compensation and rehabilitation costs, but there are also the costs of recruitment, training of new personnel and losses of productivity and quality until a new employee has reached the previous worker's level of skill, competence and speed (see chapter 11). All in all, losing valuable, experienced staff due to an unnecessary physical disability is a terrible waste that can be avoided in two steps:

1. Evaluating ergonomic risks
2. Designing workplaces that lessen the strain on the human body

Some potential causes of musculo-skeletal injuries are related to biological and lifestyle characteristics of individuals, and are therefore difficult to anticipate or do anything about using design. Biological and lifestyle-related factors influencing MSDs are shown in Table 2.1.

However, *work-related* MSD causes are possible for an engineer to avoid and are therefore the most interesting ones to identify quickly. Engineers with knowledge of ergonomics should design work and workplaces to minimize the adverse risks of the following:

- forced working postures
- load weight
- static work
- continuous loading of tissue structures
- repetitive working tasks
- time pressure/lack of recovery time
- working technique
- working attitude
- demotivation, stress
- organization

2.2. How big is the problem?

MSDs are the work-related health problem with the highest impact on sickness absenteeism in Europe; they are the cause of half of all absences from work and cost the EU €240 billion each year

Table 2.1: Individual biological and lifestyle-related factors that influence the risk of MSDs.

Biological factors	Lifestyle factors
• Muscular strength • Skeletal strength and bone mineral content • Age, sex, biological measures • Impaired vision, hearing, senses • Pain experience, neuromuscular reactions	• Prior load history, diseases and injuries • Health, training and fitness habits • Social environments (active or sedentary) • Pleasure, comfort and well-being • Chosen working postures • Smoking, alcohol, diet or drugs

in productivity losses (Fit for Work Europe 2013). MSDs are also the work-related health problem with the highest impact on permanent incapacity; 61% of permanent incapacity is due to MSDs (OSHA 2007). Forty-four million workers across the EU have an MSD caused by their work, 30% of those with MSDs also have depression, making it even more difficult for them to stay in or return to work (Bevan 2013). Typically the back tends to be the most commonly affected area of the body (Figure 2.1); 80% of all adults have back pain some time in their working life and 30% of sick

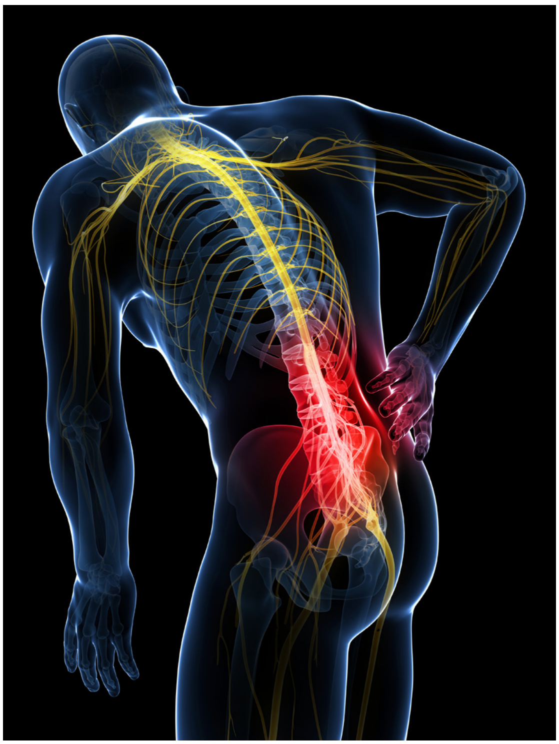

Figure 2.1: Lower-back pain has long been the most common cause of MSD-related sickness.
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leave cases in Sweden are due to back pain (many young people) (Palmer, 2000). Blue-collar workers are at the highest risk for contracting an MSD, with almost 20 times as many employees experiencing an MSD compared to white-collar employees. Of these workers, those involved in manual labour such as trade workers, plant and machine operators and assemblers, are at the highest risk (OSHA 2007).

2.3. The musculo-skeletal system

The primary structures of the human *locomotive* (movement) system are the *skeleton*, the *muscles*, and the *joints*[2] (Figure 2.2). These structures combined allow the human body to move, withstand physical loading and recover when the body's abilities have been exhausted.

These are the structures that are mainly active when performing physical work, although other systems (such as the nervous system[3], the respiratory system[4] and the circulatory system[5]) that are all very important for the human being's ability to function are naturally also affected by physical work. However, this chapter will focus on movement, physical loading and what the locomotive system requires in order to function optimally.

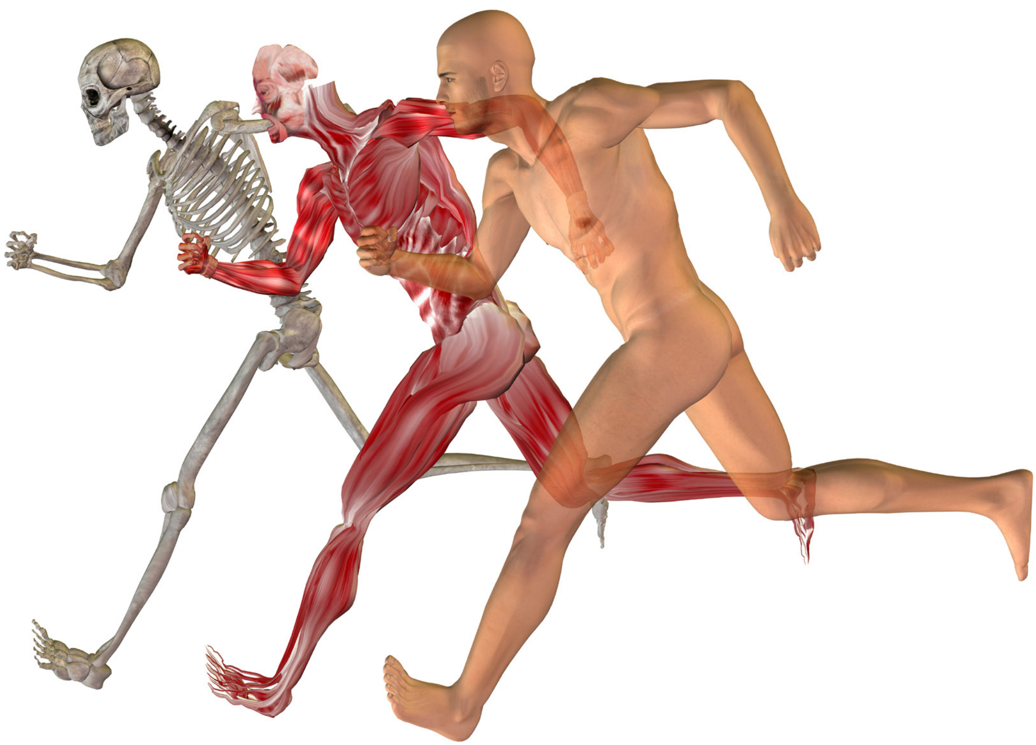


Figure 2.2: The musculo-skeletal (or locomotive) system consists of skeletal muscles, bones and joints.

Together, the skeleton, muscles and joints allow the human body to turn chemical energy into motion, to withstand physical forces and perform physical work in a way that is simultaneously dynamic, stable, flexible and adaptive. All of the structures are made up of living materials, so our body is constantly adapting to the loading and movements that we expose it to, making it better suited to perform those activities by becoming stronger and more stable. Unfortunately, it is also possible to load the body in such a way that we wear down or break the structures that make up our locomotive system. In order to avoid this and ensure that we design work and work systems that allow the human body to perform at its strongest, we need to know something about how each of these structures are shaped, how they move, how they respond to loading and regenerate.

2.4. The muscles

There are many different types of muscles in the human body, as shown in Figure 2.3. In the locomotive system, skeletal muscles convert chemical energy into contractions, thereby producing motion and mobility, stabilizing body positions, producing heat and helping to return deoxygenated blood to the heart. As the name suggests, most skeletal muscles are attached to the skeleton (via fibrous tissues at the ends called tendons) and are dedicated to moving it. This differentiates skeletal muscle tissue from cardiac muscle[6] and smooth muscle[7], which are not under our voluntary control.

Some skeletal muscles have specific functions, for example the postural muscles keep the posture of our body and head upright while we are awake, without any need for active control from our

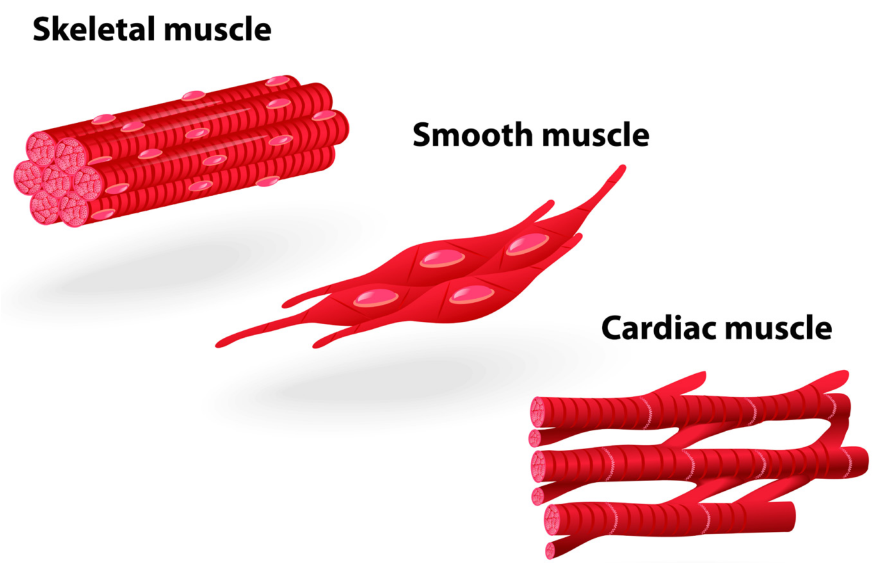


Figure 2.3: Muscle types: skeletal, smooth and cardiac.

brain (although in states of extreme fatigue, we lose control over our postural muscles, which explains the term "nodding off" to sleep). It is our skeletal muscles that allow us to transfer loads and torques, and the strength of our muscles varies depending on our age, sex, genetic heritage and training habits.

Definitions of how to count the number of muscles in the body vary, but they number in the hundreds (about 600 individual muscles) and they make up 40 to 50% of our body weight. Many muscles function in opposing pairs called antagonists, meaning that their contractions result in movements that work against each other. So when one antagonist is maximally contracted, the other one is – by definition – in a state of relaxation to allow the movement (see Figure 2.4). Examples of antagonists at work include bending and straightening of the knee or the arm, pointing and flexing the foot, or alternately bending the back outward and inward. For high-precision movements, the body controls a sophisticated and sensitive balance of contraction and relaxation between antagonists.

To stay balanced and well-aligned, the body generally needs to develop equal strength between antagonists; for example, some symptoms of back problems may actually have to do with weak stomach, or core musculature, rather than just the back muscles.

Healthy muscle tissue has four characteristics:

- *Excitability,* which is the ability to respond to stimuli
- *Contractility,* which is the ability to shorten and thicken (contract) when stimulated

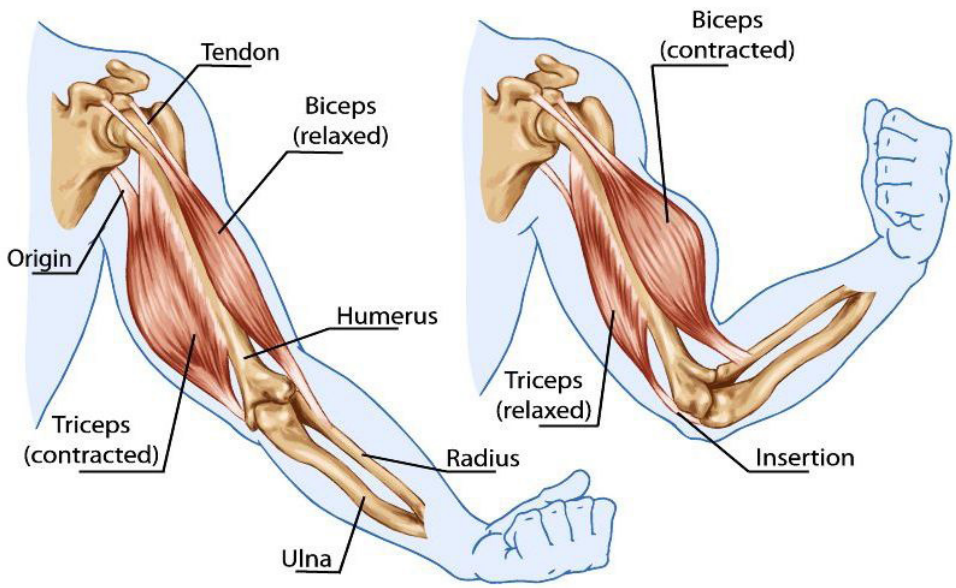


Figure 2.4: Antagonistic pair – biceps and triceps.

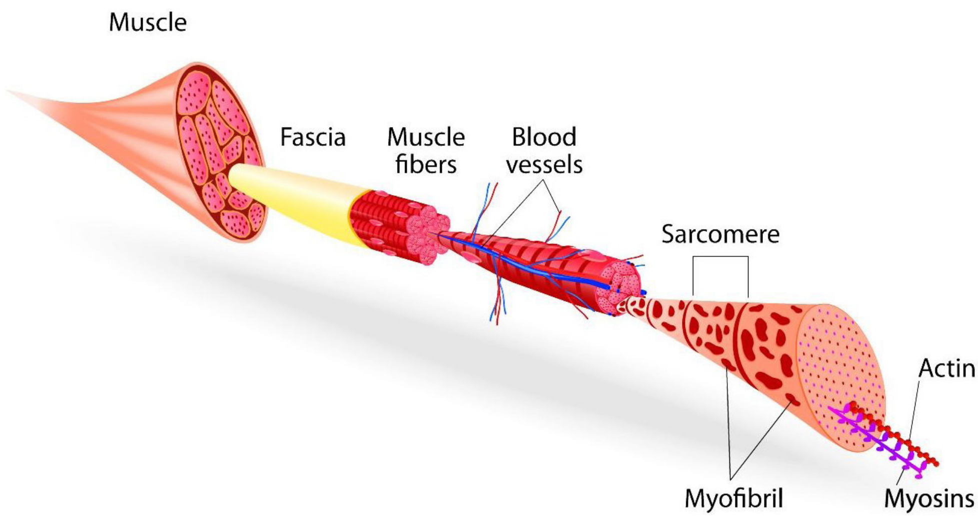


Figure 2.5: The structure of a skeletal muscle.

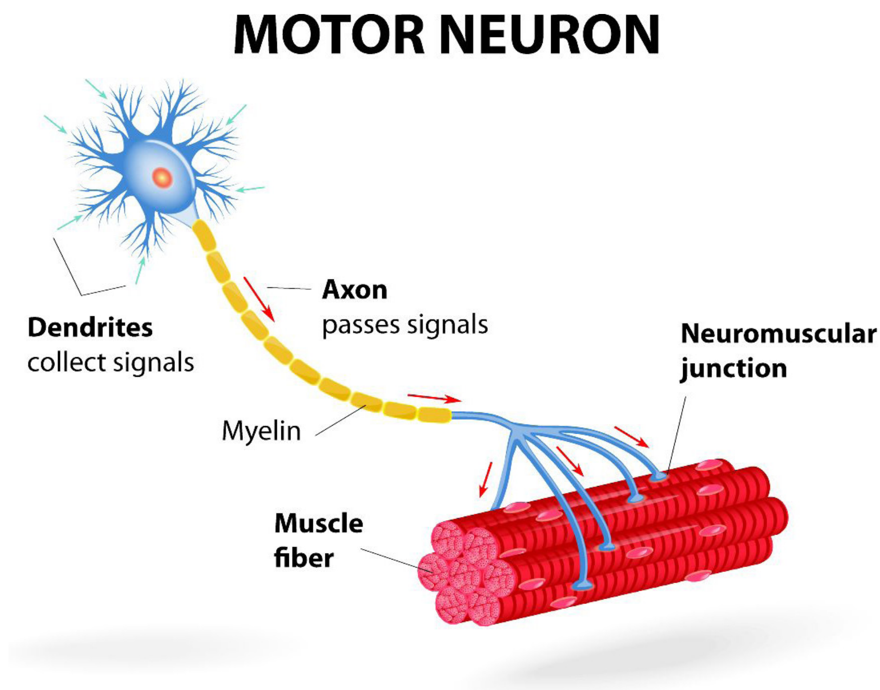


Figure 2.6: Structure of motor unit.

- *Extensibility*, which is the ability to stretch without being damaged
- *Elasticity,* which is the ability to return to its original shape after any form of physical loading

On a cellular level, muscles consist of clusters of long, thread-like cells called muscle fibres that measure about 2–150 mm long and 10–110 micrometres thick; see Figure 2.5.

Muscle fibres are in turn bundled into motor units, a group of cells that respond to voluntary signal impulses from the brain by contracting until the motor unit is fully, 100% contracted. This reaction of a motor unit (sometimes called "firing") can never be partial, so it is said that motor units are recruited one by one by the brain, until there are enough to perform the task. Motor units vary in how many muscle fibres they contain, and what type of movements and force generation they are adapted to. Each motor unit consists of one motor neuron and all the muscle fibres it contracts. The structure of a motor neuron is shown in Figure 2.6.

A *contraction* of a muscle can be explained as a chemical process that leads to a shortening and thickening of each motor unit, resulting in the production of force exertion and heat[8].

Generally, muscle fibres behave differently when stimulated by nerve impulses and can be classified into two types: Type I (slow-twitch fibres, suited for prolonged work and high endurance) or Type IIa or IIb (fast-twitch muscle fibres, suited for quick, explosive, brief movements). They are characterized by the type of physical loading or movement that they are best adapted to. Most people are born with a genetically determined proportion of Type I and Type II muscle fibres, but it is possible through physical training and nutrition to influence the proportions of different muscle fibre types. The differences in characteristics of these muscle fibres are described in Table 2.2.

Table 2.2: Main differences between different muscle fibre types.

Type I: Slow-twitch, aerobic	**Type IIa: Fast-twitch A, intermediate**	**Type IIb: Fast-twitch B, anaerobic**
• Adapted to high-endurance continuous contractions, work for a long period of time • Low force production • Slow contraction time • Small motor unit size • Not fatigued easily • Plenty of blood vessels and myoglobin = good supply of oxygen • Aerobic; requires plenty of oxygen to generate muscle fuel • Red in colour (due to high blood vessel content) • Predominant in marathon runners and cyclists	• Adapted to fast, short- term contractions • High force production • Fast contraction time • Large motor unit size • Quickly fatigued • Intermediate number of blood vessels and myoglobin • Mix of aerobic and anaerobic processes to generate muscle fuel • Red in colour	• Adapted to extremely fast, explosive contractions • Very high force production • Very fast contraction time • Large motor unit size • Fatigues very quickly • Low number of blood vessels and myoglobin • Completely anaerobic processes (no oxygen), burns glycogen to generate muscle fuel • White in colour • Predominant in sprinters, high jumpers

2.5. The skeletal system

The skeleton is made up of about 206 bones[9] (in an adult) which allow the human body to withstand its own weight with little or no muscular effort involved to stay upright and aligned (Figure 2.7). Apart from this, the most important functions of the skeletal system include:

- To serve as a rigid structure of mechanical stability, to support soft tissues and serve as attachment points for muscles
- To protect vital organs (brain, heart, lungs, spinal cord) and nerves
- To break down and regenerate bone (bone cells continually do this)
- To produce blood cells (in the red bone marrow)
- To assist in movement (skeletal muscles move bones) by making force and torque transfer efficient
- To store minerals (particularly Calcium (Ca) and Phosphorous (P))
- To store chemical energy (triglycerides, in the yellow bone marrow)

In a locomotive sense, the skeleton consists of a number of specialized bones suited for different purposes and loading profiles. The way the skeleton is designed, with an upright spinal column and long extremities with different bone widths and sizes, is the result of evolutionary requirements for human survival and development, in terms of structural strength, mobility, and flexibility. For example, the lower extremities (the legs) are quite wide and strong, and evidently suited for strength and stability in the lengthwise direction of the long bones (the femur over the knee, the fibula and tibia under the knee), greatly enabling us to stand, walk and run. Conversely, the arms (the upper extremities) consist of smaller, more complex bones that are developed to have maximum mobility and high precision, but (comparatively) low strength. This is because human survival has been highly dependent on our ability to move quickly and endure a lot of standing and walking, but also to use our hands as high-precision sensors and tools, causing a development of intricately attached small bones.

Some bones do not have the long shape and form of those in the extremities; some appear to be more like small, tightly clustered bones that are connected tightly and often form a base for complex-functioning body parts, particularly the bases of the feet and hands. In the hands, these bones are known as the *carpals* (*carpus* is Latin for wrist) and they form protective armour around a number of blood vessels, nerves and important tendons that allow finger movement. These all pass through a narrow passage in the wrist known as the *carpal tunnel*.[10] The corresponding clusters of bones at the base of our feet are called the *tarsals* (Latin for ankle). On both the hands and the feet, the bones that extend out to our fingers and toes are known as *phalanges*.

Since it contains blood, bone cells, energy and minerals, bone is a living material with a capacity to adapt itself to the type of loading it is under, and the body is continually breaking down or regenerating bone. It is essential to load the skeleton in order for bones to grow (this stimulates increased development of collagen fibres and more deposition of minerals, making the bones thicker and stronger) – if the bones are not placed under any type of stress, the body's processes of breaking down and reabsorbing bone materials overtakes the bone generation and the bones brittle and weak – a well-known phenomenon among old people, people who are bedridden long periods of time and astronauts due to weightlessness. This condition of bone fragility, where bone resorption processes outpace new bone development and mineral deposition, is known as osteoporosis. Such bones become so brittle and weak that a very small force application may break them, for example resulting in a hip fracture just from sitting down too quickly.

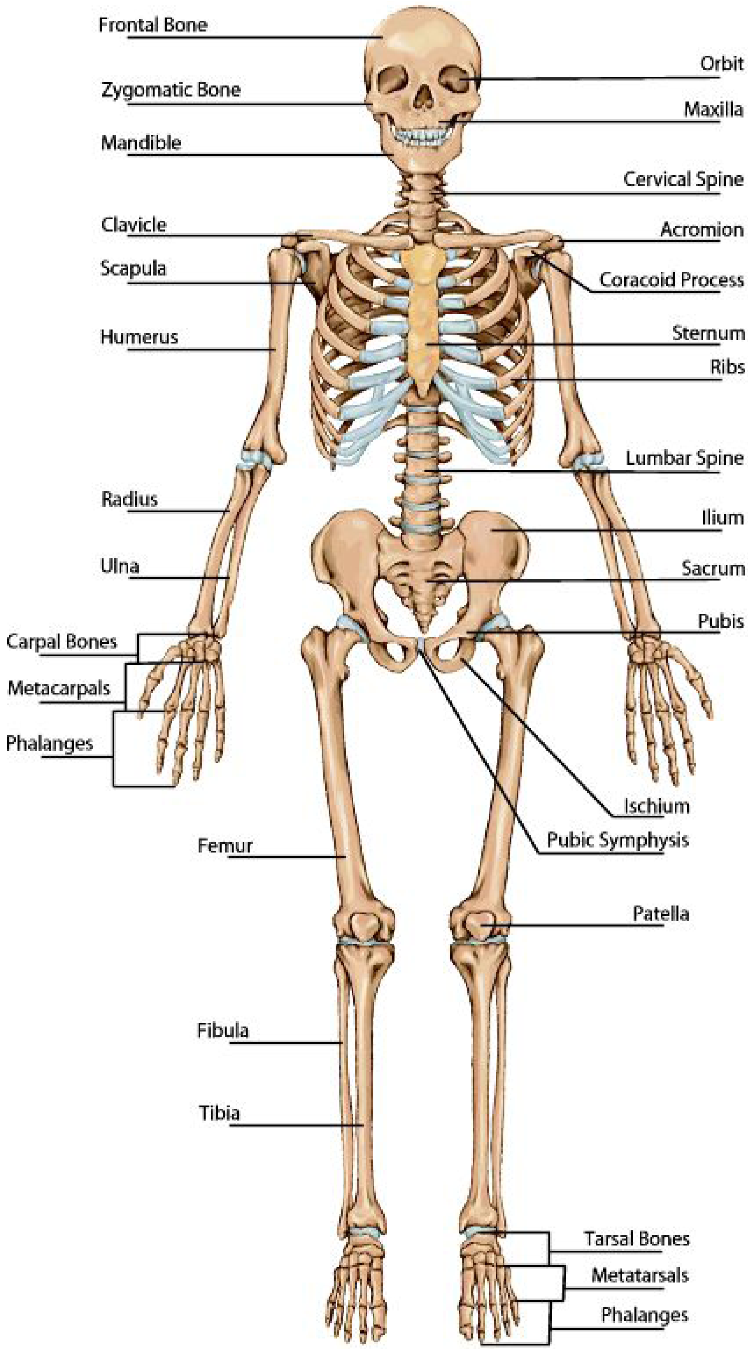


Figure 2.7: Structure of the skeleton.

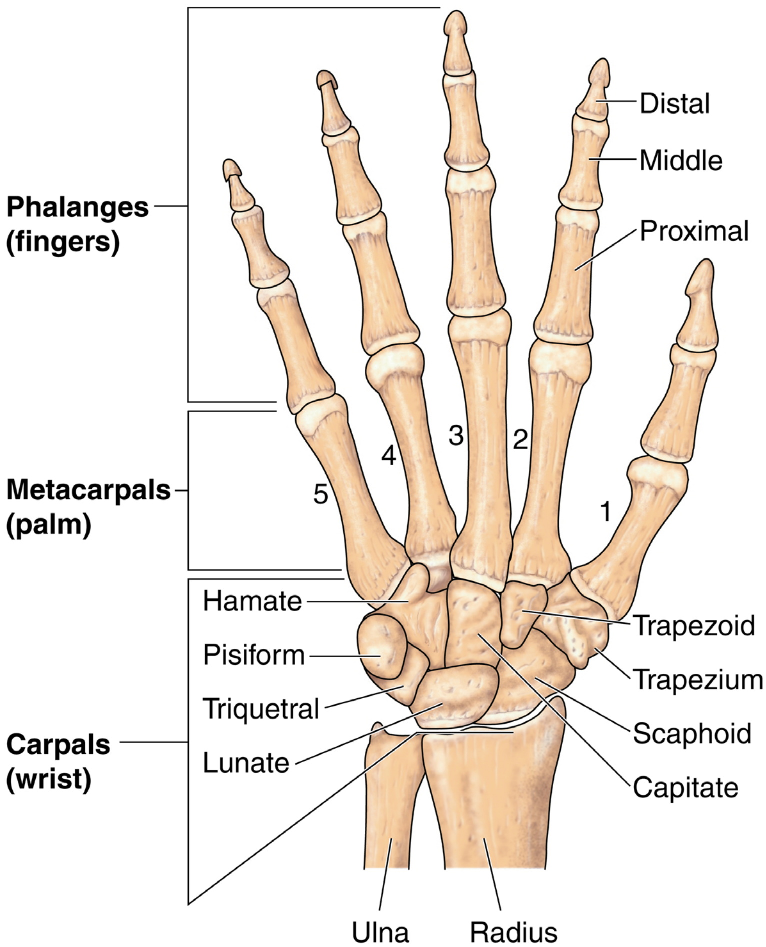


Figure 2.8: Anatomy of the hand.

2.6. Joints

Joints are the structures that appear at the points of contact linking bones to other bones, to cartilage or to teeth. Some joints are simply links between two bones without permitting movement at all, while others are specifically designed to permit movement, or at least a bit of flexibility[11]. Joints that allow movements in one dimension (translation, or "gliding" movement) may for example be found between the smaller bones in the wrist or where the ankle meets the foot. Two-dimensional joints, in many cases also known as hinge joints, allow rotation of bones relative to each other and are found, for example, in the elbows, knuckles and knees. Finally, three-dimensional joints permit the greatest range of movement in several dimensions, and are for example found at the base of the thumb (a so-called saddle joint) or at the shoulder and hip joints (ball-and-socket joints).

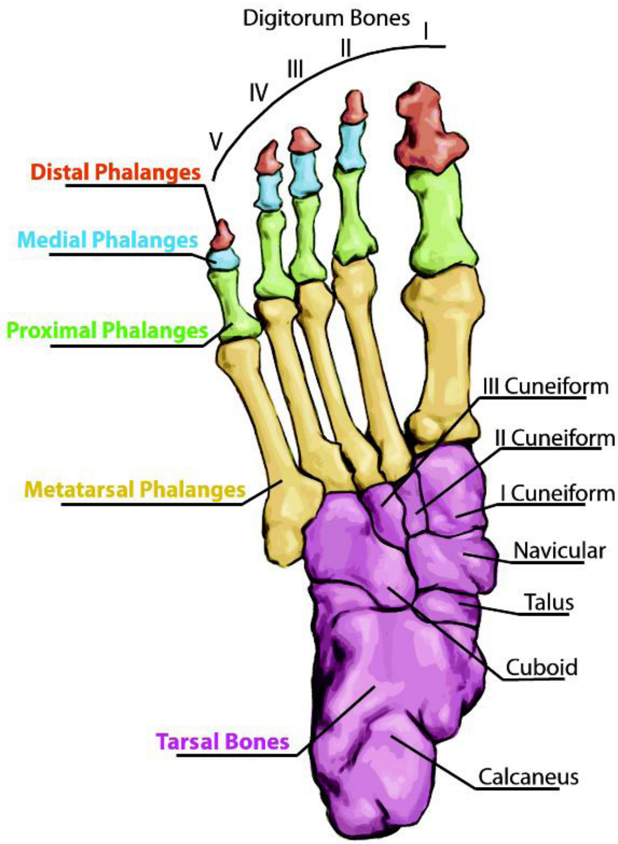


Figure 2.9: Anatomy of the foot.

The type of joint that permits movement in one, two or three degrees of freedom is called a synovial joint. Such joints are always between articulated bones (bones that meet and form a joint) whose ends are covered by a bendy, tough layer of articular cartilage, which reduces friction when the bone ends move (translate or rotate) relative to each other. Synovial joints always have a synovial cavity in which the bone ends move against each other, and are surrounded by a capsule filled with *joint fluid*[12] that lubricates the articular cartilage and allows even smoother movements with less friction between the bone ends. The capsule is covered by an outer layer of dense, tough connective tissue that is flexible enough to permit movement, but strong enough to keep the bones from dislocating. Depending on which joint it is, there may also be a presence of ligaments, which are bundles of fibrous connective tissue that are especially designed to withstand high strains.

Due to their complexity and the presence of many complicated and fragile structures passing through them, joints are particularly sensitive to injuries caused by physical loading in extreme positions.

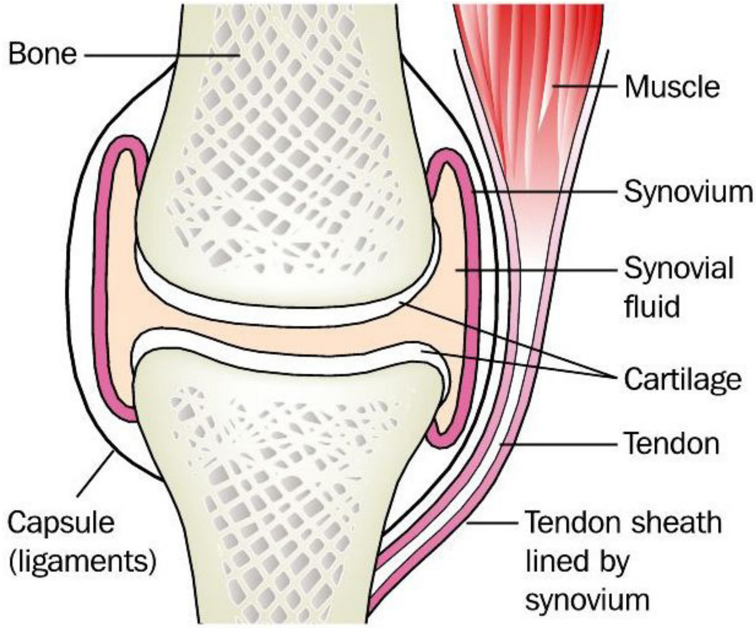


Figure 2.10: Structure of a two-dimensional joint.

The cartilage at the end of articulated bones is thickest in the middle, meaning that working in extreme joint angles may result in wear and tear on the thinnest part of the protective cartilage layer.

As we age, the risk for joint problems and injuries increases due to a number of factors:

- Decrease in the production of synovial fluid, reducing both the lubrication of the joint cartilage and the transportation of unwanted substances away from the joint
- Articular cartilage between the bones becomes thinner
- Individual genetic and lifestyle factors
- Life-long wear and tear on the joint
- The fibrous ligaments around the joint capsules lose flexibility and become shorter, reducing the protection against movement-related injury and bone dislocation

2.7. Injuries and healing

When it comes to withstanding physical loading, the body is protectively structured in such a way that:

- The skeletal muscles protect the skeleton.
- The skeleton protects the inner organs.
- The joints protect blood vessels, tendons, muscles and nerves that run through them, but are also the most fragile structure of the three.

When any of these three structures are subjected to increasing mechanical forces, it is said that they are placed under *strain* until they can no longer withstand the force, and then they break. This stage is called *trauma*, and it means that the structures are injured and need time to heal before they can perform normally and take on more physical loading.

The muscle tissues are soft and can cushion the body (up to a point) from applied forces. The supply of plenty of blood flow, allowing the transport of nutrients and removal of unwanted materials, means the healing of mild to moderate muscle injuries typically takes place in a matter of weeks – more severe strains can take months.

The skeletal bones are excellently suited to withstand long-term loading in numerous directions (Figure 2.11) and static loads (such as the weight of our own body when we stand up), but because they have less blood flow and the required mineral deposits to create new bone take a long time to deposit, bones take longer to heal when injured. Injuries (breaks) in bone structures are called fractures, and usually heal in a matter of 5 to 6 weeks[13]. Additionally, healing times vary considerably depending on a number of factors, such as the injured person's age and general health, the site and severity of the fracture, the type of bone that has been fractured, proximity to a joint, infections, etc.

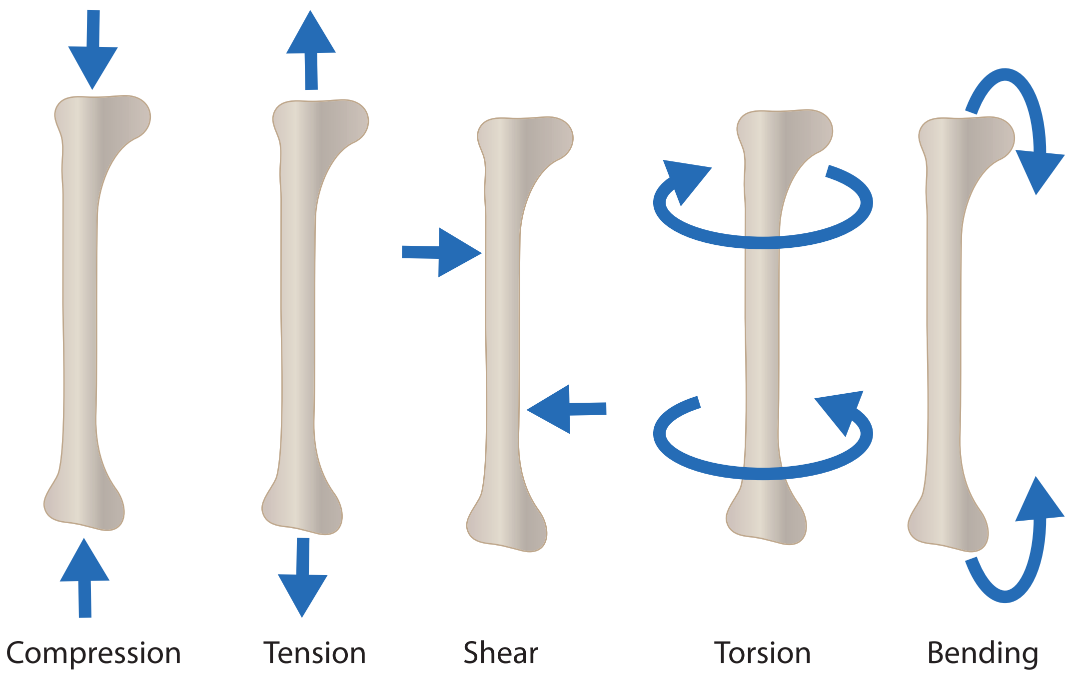


Figure 2.11: Different types of mechanical loading on bones. The first two types act in the lengthwise direction of the bone, which it is well suited to withstand, but the others (shear, torsion and bending) bring greater injury risks.

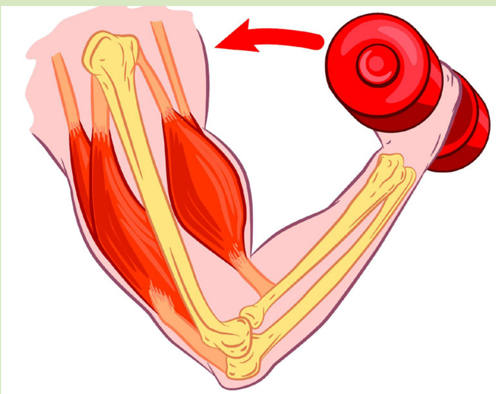
Illustration by C.Berlin.

Joints are the most complicated and fragile structures of the three, partly because they consist of many different kinds of tissues and structures, but also because they are supplied with the least amount of blood flow (particularly ligaments). For this reason, injuries to joints can take months to years to heal, and depending on the age at which the injury is sustained, damages may be permanent. So, the priority order for work design is to avoid unnecessary risk of injuries first to joints, then the skeleton, then the muscles.

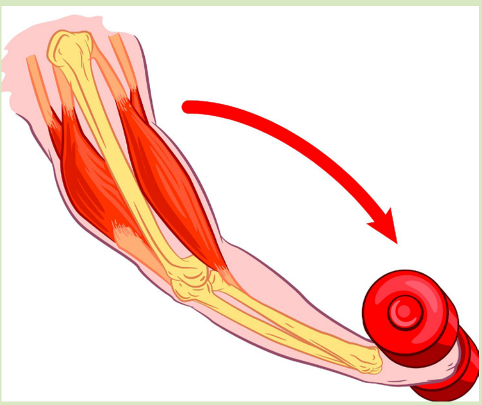
2.8. Movements

When the different functional tissues of the locomotive system work together, the body generates *movement*. The study of human movement is known as *kinesiology*. There is some useful standard terminology that is used in medical science to describe different types of movement, in terms of directions and orientation. Most human movements consist of bending or twisting motions that change the joint angles between different body segments. Some movements are coupled, in the sense that pairs of muscles work against each other to "do and undo" each other's respective movements (for example, bending and straightening the arm is, simply put, the work of two antagonistic muscles; the biceps and the triceps). The following terms are a helpful framework to describe motions.

Glossary For Movement, Organized by Coupled Motions[a]

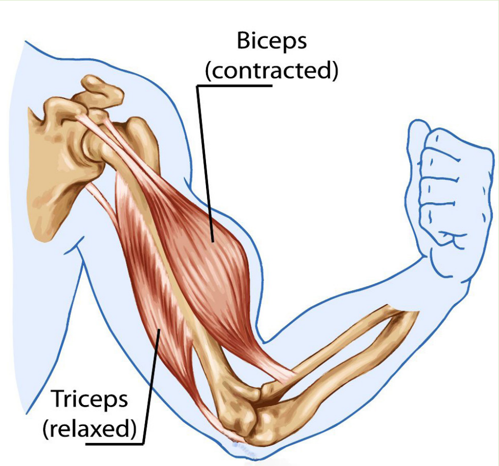


CONTRACTION – when muscles use chemical energy and nerve impulses to pull together muscle fibre components so that the muscle becomes shorter and thicker, generating force exertion, movement and heat.



RELAXATION – when the contraction of muscle fibres is released, so that the muscle fibre components disengage from each other and the muscle becomes longer, more elastic and stops exerting force.

[a] Image permissions granted by: NoPainNoGain/Shutterstock.com (Contraction and Relaxation), stihii/Shutterstock.com (Antagonistic movement), and Kues/Shutterstock.com (Flexion).

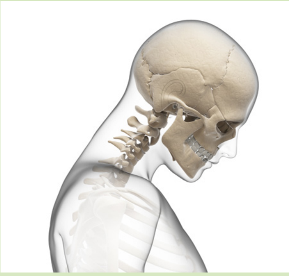


ANTAGONISTIC MOVEMENT – when a pair of muscles coordinate complex movement by working in opposite directions; when one contracts, the other releases.

FLEXION – a movement at a synovial joint that results in a decreased angle between two body segments (e.g. curling the biceps); alternately, think of it as curling in toward the body's midline.

EXTENSION[B] – a movement at a synovial joint that results in an increased angle between two body segments (e.g. straightening the arm); alternately, think of it as "uncurling", away from the body's midline.

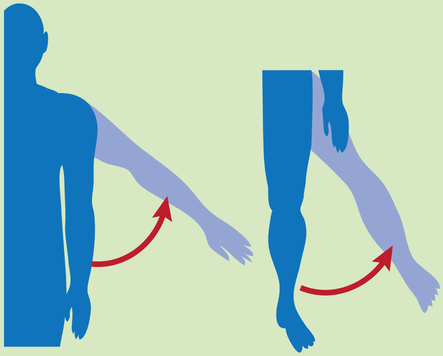
Hyperextension



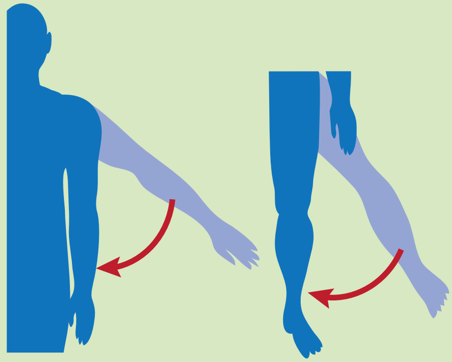
Hyperflexion

HYPERFLEXION and **HYPEREXTENSION** – flexion or extension "beyond anatomical position" towards the edge of movement range; usually beyond healthy loading limits (due to high pressure on the joints), but also usually prevented by resistance from the arrangement of ligaments and bones.

[b] Images reproduced with permission from: MetCreations/Shutterstock.com (Extension), Sebastian Kaulitzki/Shutterstock.com (Hyperextension and Hyperflexion), and C. Berlin (Abduction and Adduction).

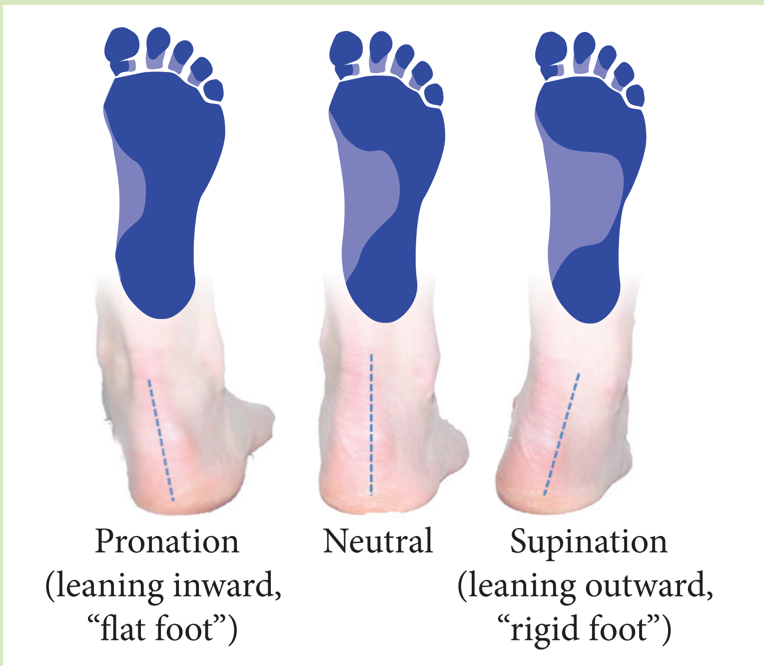


ABDUCTION – (for extremities, i.e. arms and legs) movement that brings the limb away from the body's midline, for example lifting the leg sideways.



ADDUCTION – (for extremities, i.e. arms and legs) movement that brings the limb inward, closer to the body's midline.

(Right foot)[c]



PRONATION – twisting motion

a) for feet: the ankle leans inward with weight pulling down the arch (also called "flat foot")
b) for hands: the palm is facing down and the radial (thumb) side is turned inward.

SUPINATION – twisting motion

a) for feet: the ankle leans outward, with weight on the outside of the foot and a high arch.
b) for hands: the palm is facing up and the ulnar (little finger) side is turned inward.

[c] Image by C. Adams and C. Berlin.

Another useful distinction between movements is whether they are *static* or *dynamic*. *Static* movement (or loading) usually means that the muscles' motor units are engaged for a long, sustained period of time (or in frequent repetition) without rest and recovery, until the point of fatigue (which occurs after a long time). Static movements are especially hazardous when they occur at low intensity, because then it is easy to ignore them or write them off as "not such a big load". Static work can involve keeping body parts still, small movements of part of the body for a long time while carrying out a task, or upholding an external load. Examples include working with arms above shoulder height, using a computer mouse and carrying heavy grocery bags.

Dynamic movement, on the other hand, is characterized by large, swiftly changing movements that may often involve great speed and/or large force exertions. While this type of movement may be a bigger risk for sudden trauma to the locomotive tissues (such as torn muscles or ligaments), this type of loading is also characterized by much more loading variation, leading to relatively frequent rest and recovery while different muscles take turns being loaded. In comparison, static loading can gradually wear down locomotive abilities due to the constant loading of the same muscles, pressure on the same body structures, etc.

A good rule of thumb from a health perspective is that both these movement types can help the body become stronger and more prepared for high loading, provided that there is sufficient rest and recovery for the body to replenish the needed oxygen and energy via the blood, and to transport waste products from the locomotive tissues. This is what distinguishes risky workloads from intentional physical training: although both can push the body to its loading limits, a work environment may sometimes allow little or no time for recovery, while physical training is designed to alternate between loading the body and letting it recover.

Simply put: Dynamic loading with breaks and variation is mostly good and strengthening, while static loading with few breaks risks being harmful and weakening.

2.9. Musculo-skeletal complexes

As previously mentioned, certain parts of the body are frequently represented in MSD injury statistics. It is worthwhile to get to know some of these musculo-skeletal complexes and their strengths and weaknesses better.

2.10. The back

The back is a complex entity consisting of active and passive tissues. The active tissues (skeletal muscles) voluntarily move the back by bending or rotating it, and the passive tissues (bones, joints, ligaments and intervertebral discs) take up structural and external loading.

The spine

The spine is made up of a series of stacked bone structures called vertebrae (singular: vertebra). Between each vertebra is a layer of tough fibro-cartilage that encases a soft, gelatinous, highly elastic disc (called an *intervertebral disc*). These discs allow extra movement flexibility and help the body absorb vertical shocks. Together they form a flexible, strong column, whose moveable parts (Figure 2.12) are usually grouped into three sections: the cervical (neck) spine, the thoracic (chest cavity) spine and the lumbar (lower back) spine.

The spine's function is to:

- Protect the spinal cord and nerves (which run through it from the brain to the rest of the body).
- Support and hold the head.
- Allow trunk mobility by being able to rotate and bend forward, backward and sideways.
- Transfer loads and torques from things we push, pull, carry and lift.
- Serve as a point of attachment for the back musculature and ribs.

Whenever we are awake and active, the weight of our body and our activities cause *spinal loading,* which leads to compression of the intervertebral discs. As long as the body is erect and the spine is in its natural S-curve shape, the discs can take this very well since they are loaded with even and symmetrical pressure. However, if the back is bent and subjected to external loading (such as when

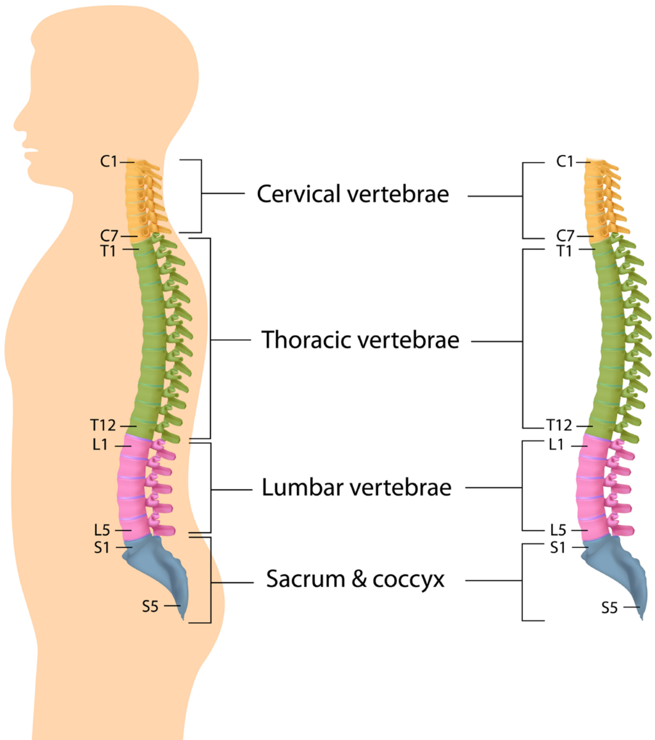


Figure 2.12: The cervical, thoracic and lumbar regions of the spinal column. The sacrum and coccyx – also known as the tailbone – are not part of the moveable spine.

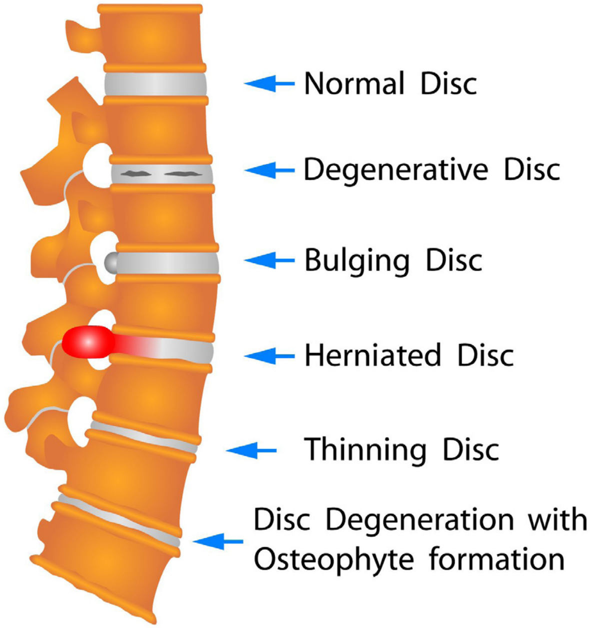


Figure 2.13: Different spinal disc conditions.

a person's back is bent and they are trying to lift something up), the discs are compressed with high pressure only on one edge.

In a worst-case scenario with too-high force, wear and tear from daily loading and/or age, the fibro-cartilage casing can bulge or break and the gelatinous disc can rupture, a condition sometimes referred to as a *herniated disc*[14] (Figure 2.13). This can cause great pain and/or numbness if the disc rupture comes in contact with a nerve root or the spinal cord; but the condition normally settles by itself (by the body reabsorbing the disc fragments) in a matter of one to six months.

Sitting, standing and lying down

The natural shape of the spinal column, when we are standing, is an S-shaped curve when viewed from the side. This shape is possible when there is no imbalance, twisting or bending in any direction; it occurs when the head, hips and feet are vertically aligned and symmetrical. When the spine is positioned this way, the passive structures (the vertebrae, ligaments and discs) are at their strongest alignment and the body is in its absolute strongest condition (from a posture perspective) to take on physical loading. Posture strongly influences the spinal loading and disc compression, in terms of loading on the lumbar (lower) spine, the difference between standing and sitting is significant. According to Kroemer and Grandjean (1997 p. 73), if we normalize the loading from standing in an erect, relaxed position with the naturally occurring S-curve to 100% compressive loading, then relative to that pressure in the lower back:

- Sitting down with a straight back corresponds to 140% loading.
- Sitting down in a slouch or leaning forward corresponds to up to 190% loading.
- On the other hand, lying down brings down the compressive loading to 24%.

This difference in compressive loading provides a clue to why it is so important to get sufficient amounts of sleep – not only does the body need to recuperate and the mind work subconsciously with processing information, the discs in our back also need a chance to return to their uncompressed, round form in order to be ready for another day's work as flexibility enablers, loading relief and shock absorbers.

2.11. The neck

Technically, the neck is a very flexible continuation of the cervical (upper) spine (Figure 2.14). It connects our head to the shoulder complex, allows flexibility of movement, and is an attachment point for several small and large postural muscles that keep our head erect. However, the neck deserves special attention since it is an area of the body that is highly complex, sensitive and prone to injury. An injury to the neck may cause severe impairment, since many nerves run through it. The head weighs about 8% of a human body's weight (about 4.5–5 kg in an adult), and is a special condition of loading for the neck, especially in cases where the head is not held erect.

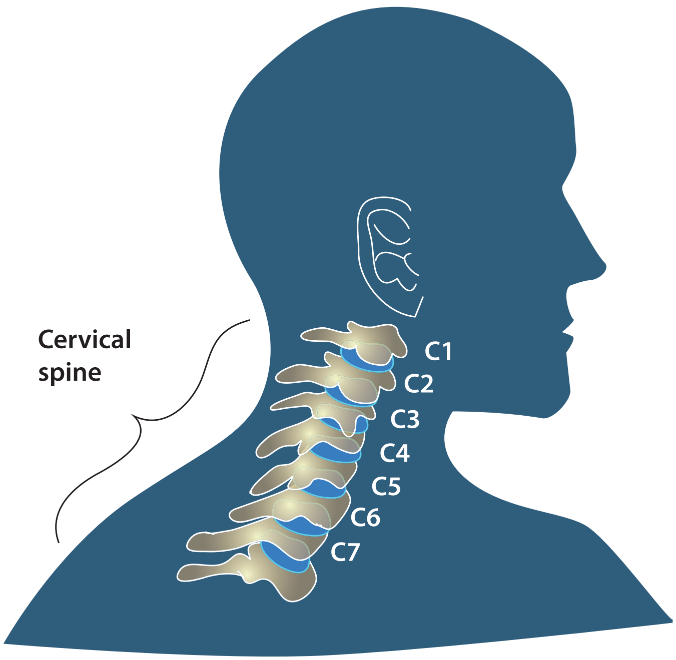


Figure 2.14: The cervical spine (C1–C7) that supports the neck.
Illustration by C. Berlin.

Neck injuries and problems tend to arise due to the following situations:

- Frequent or static bending for long periods of time – for example when using smart phones or tablets – causing shear forces between the vertebrae, as well as high muscular tensile (stretching) loads.
- Extreme extension of the head causing biomechanically dangerous loadings.
- Whip-lash injuries (often caused in traffic accidents) – hyperextension followed by sudden hyperflexion.

The neck and shoulders, being so closely connected, are often co-dependent in their function and movements, and work-related tension or pain in either structure may easily spread to or affect the other. Small injuries that propagate this way often lead to compensation by the other structures, resulting in even greater pain. Quite frequently, a combination of neck and shoulder problems is overrepresented in WMSD statistics, and long periods of sick leave are required. Some occupational groups at risk for neck-shoulder complex injuries are often exposed to static and repetitive loads when working; such as computer and office workers, cashiers, light manufacturing industry workers, health service workers and truck drivers.

2.12. The shoulders

The shoulder is a very complex anatomical structure that allows great freedom of movement, but is also sensitive to developing pain and injuries. Since it is connected to large muscles both in the front and back of the body, as well as several more weak muscles connected to the neck and arms, the bones of the neck-shoulder complex are completely dependent on the balance and alignment of the muscles and fascia (binding tissue) that tie them together.

The arm/shoulder joint is flexible in three dimensions thanks to the presence of four different joints in the shoulder area (Figure 2.15).

- The joint at the arm-to-shoulder connection, a ball-and-socket joint called the *glenohumeral* joint.
- The joint between the collarbone (clavicle) and the top of the shoulder blade (scapula), called the *acromioclavicular* joint.
- The joint between the collarbone and the middle of the ribcage (the sternum), called the *sternoclavicular* joint.
- The joint between the shoulder blade (scapula) and the back *scapulothoracic* joint (where the scapula meets with the ribs at the back of the chest).

The arm joins the upper body in the shoulder area, where it can be abducted, adducted, rotated, flexed and extended. The movement ability is dependent on the healthy function of the joints, muscles, neck and spine. In particular, the ball-and-socket joint between the shoulder and arm is the type of joint that allows movement with 3 degrees of freedom, but this comes at a cost; since the head of the arm bone only has a shallow fit in its socket, meaning that the main stability in the shoulder depends on the rotator cuff muscles and shoulder ligaments to stay stable. Since joints are the most injury-sensitive tissue in the locomotive system, this unfortunately also makes the shoulder as a whole vulnerable in terms of being easily dislocated, inflamed or worn out. It is stabilized by the collaboration of weak muscles, ligaments and the ball-and-socket joint.

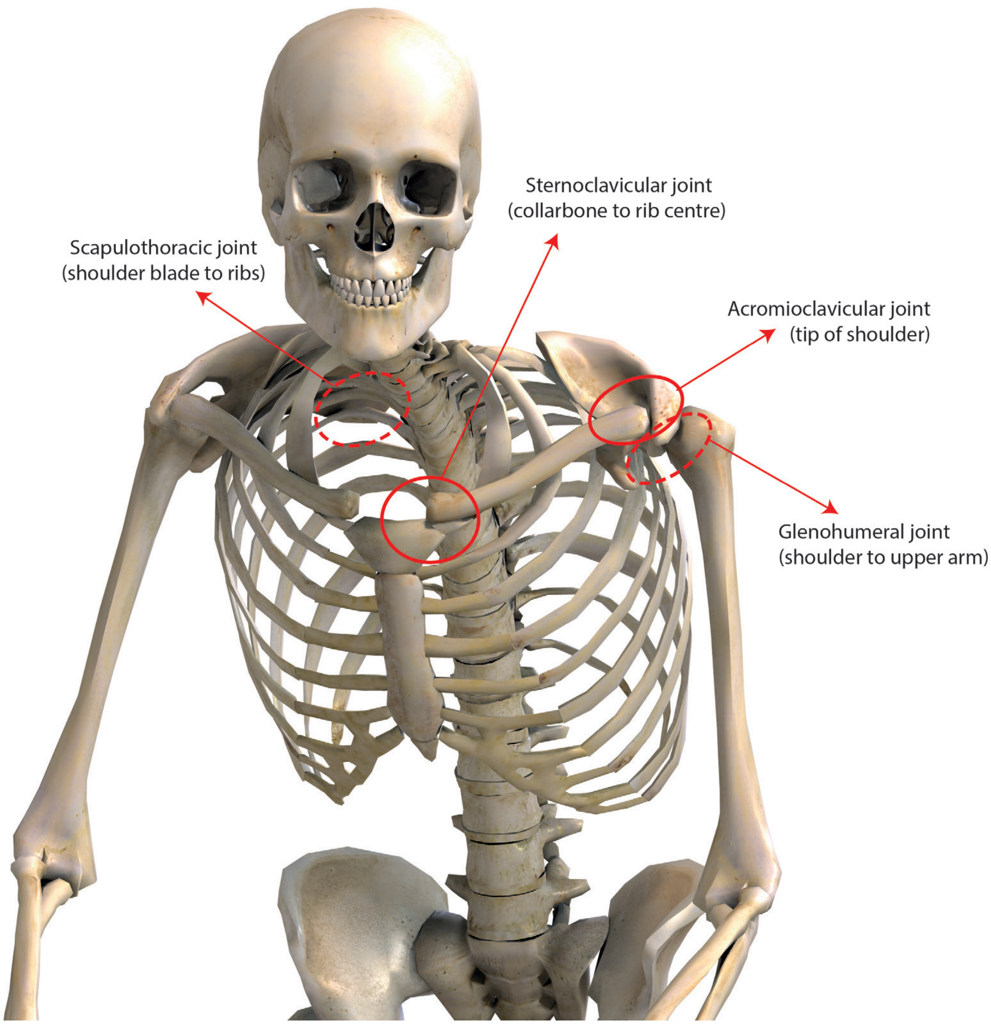


Figure 2.15: Structure of shoulder joints.

Illustration by Ralf Juergen Kraft with modifications by C. Berlin. Permission granted via Ralf Juergen Kraft/ Shutterstock.com.

If pain or injury starts in one part of the shoulder, it is likely that surrounding structures start to compensate by tensing up. This leads to static loading, which in turn can result in pain and discomfort spreading to other parts of the body than where the pain originated. At worst this can result in inflamed, swollen tissues, decreased blood flow, decreased freedom of movement, deformation of muscles and tendons, and impingement (constriction or squeezing in tight spaces) of nerves. Several small muscles and tendons also run through narrow spaces in the shoulder joint and can be vulnerable to high pressure caused by posture.

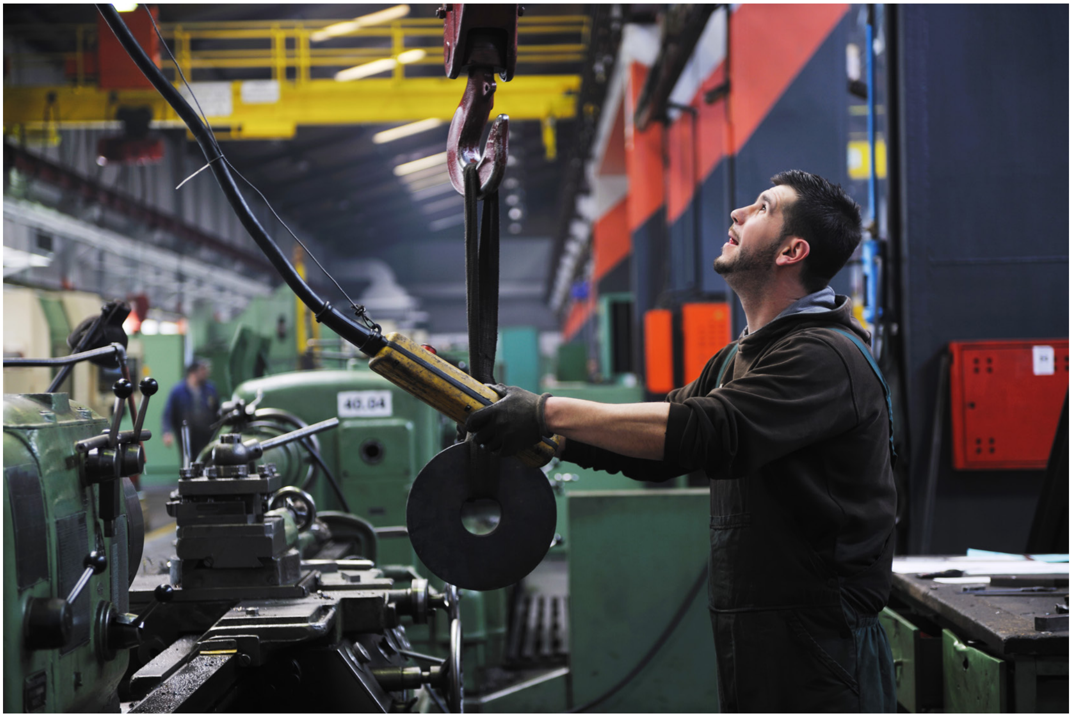


Figure 2.16: There are many ergonomic pitfalls that may cause injury in the workplace.
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Some classical pitfalls that may cause shoulder pain and injuries include the following (Figure 2.16):

- forward flexion of the shoulders
- work with arms above shoulder level
- work with arms outside the body area
- raised shoulders
- repetitive work
- static work loads
- prolonged work with low static loads

2.13. The hands

The hands and wrists are particularly critical for a human being to be able to work. For most of us, the hands are a tool for working, sensing and self-expression. The hand, wrist and arm form a complex and sensitive structure together, that can get easily overloaded or injured during physical work. An injury to the hands has serious consequences since it generally hinders human beings from carrying out most types of work.

The skin of the hand has 17,000 receptors for sense (including cold and heat receptors and nerve endings, some of which are stimulated by fine hairs), which allow us to respond to touch, pressure, pain, heat and cold by adapting our exerted force and movement precision. The hands are also used to convey emotions, personality and body language; imagine (or better yet, try) a conversation where the hands are not used. In most social settings, this would remove an important dimension from communication and probably be considered rather odd behaviour.

The bones, muscles and joints of the hand are primarily adapted for high-precision work and are not anatomically suited for exerting high force[15]. Therefore, it is very important to design work that allows the hand the best possible conditions to exert force and precision. This includes the correct design of hand tools, for comfort, skill and precision during work. The possible motions of the hand (see Figure 2.17) include flexion and extension (for both the fingers and the wrist), deviation (sideways wrist bending) and the twisting motions *pronation* and *supination*.

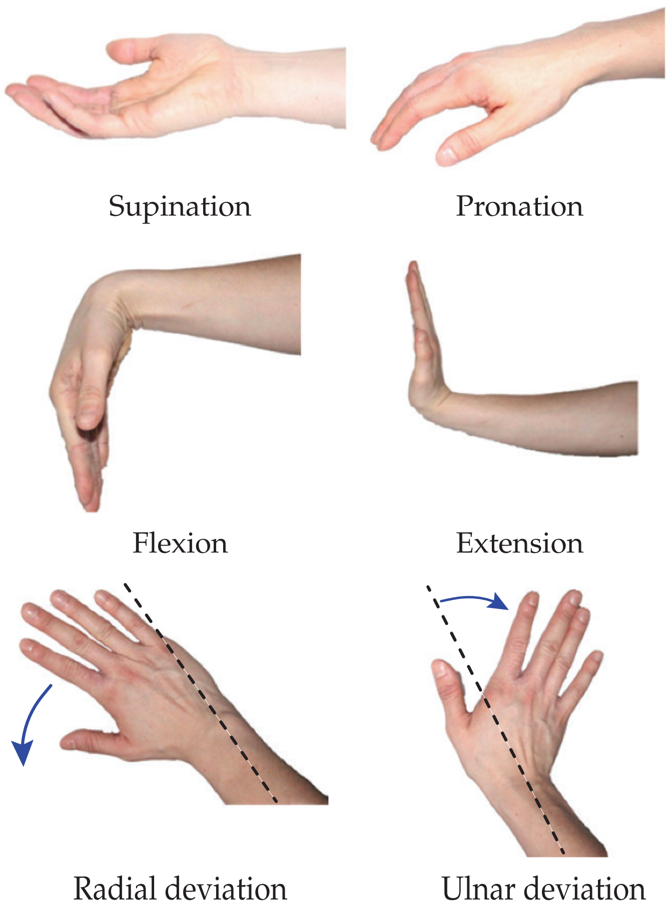


Figure 2.17: Motions of the hand and wrist.

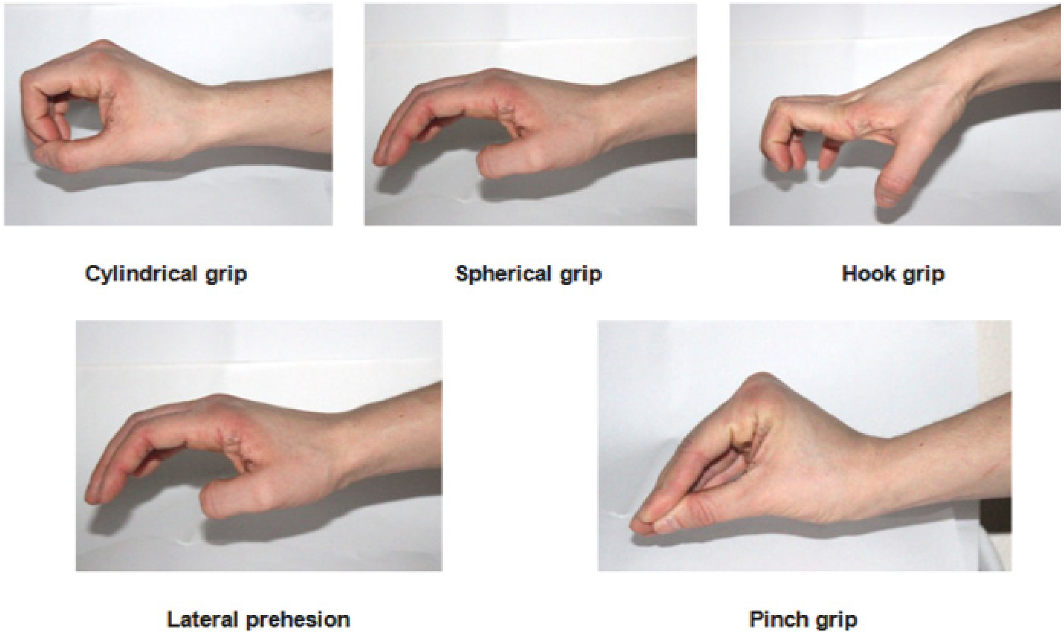


Figure 2.18: Overview of the gripping functionality of the hand.

The hand is also an important grip tool that has different functional positions depending on what level of power and precision is needed for a task. See Figure 2.18 for an overview of grip types.

It is important not to overload the complex structures of the hand by unnecessary twisting and bending[16] while working or handling loads. The hand has a functional resting position, in which the wrist is straight, the muscles are relaxed, the fingers lightly curled, and the pressure in the carpal tunnel (the narrow passage in the wrist that encases the median nerve and several tendons) is at its lowest. As much as possible, work for the hands should be designed as close to the functional resting position as possible, since both the strength and the precision of the hand decrease drastically at the extreme ends of our movement range, as shown in Figure 2.19 and Figure 2.20.

Some typical work-related problems that may result in injury or impairment of the hand's function include:

- repetitive tasks
- high forces
- punctual pressure on a small area
- incorrect grips
- vibrations
- cold and heat
- extreme positions during work (e.g. ulnar deviation combined with supination)
- incorrect design of hand tools

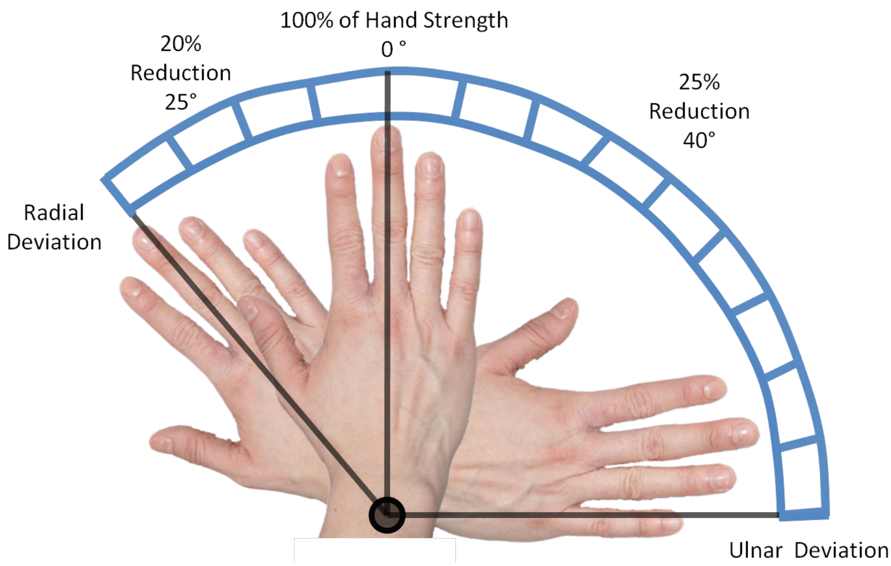


Figure 2.19: Reduction of hand strength at different angles of deviation.

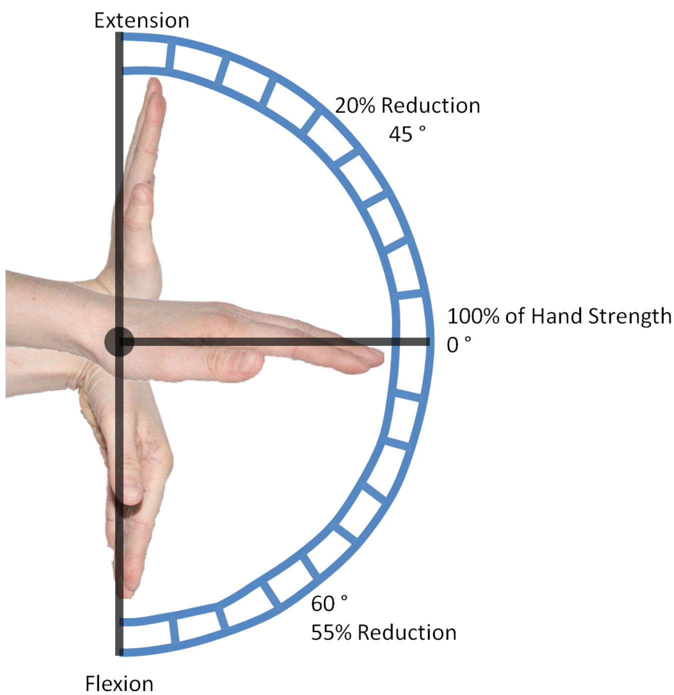


Figure 2.20: Reduction of hand strength at different angles of flexion/extension.

Designing hand tools

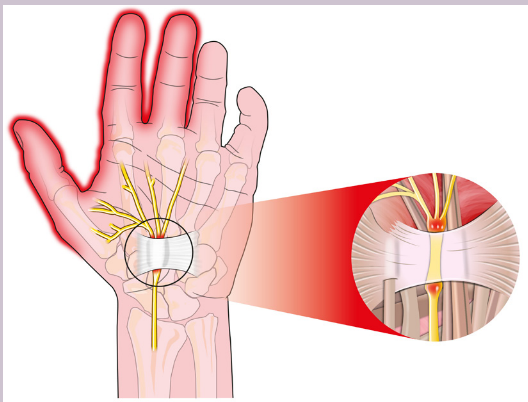
When working with hand tools, the hand should be as close as possible to its functional resting position, to ensure good conditions for strength and precision development. Good design that focuses on this minimizes the risk for long-term consequences like injuries and discomfort. It is also worthwhile to consider the context and working environment for hand tools; for example, the ability to grip a tool is affected by the use of gloves or protective clothing; by temperatures that make the tool uncomfortable to use; by vibrations; or by substances or humidity that might make surfaces, materials and tools wet, slippery and/or dirty. Reduced friction may significantly reduce grip and control over a tool. For example, medical equipment should be able to withstand exposure to blood and chemicals, while wooden handles on tools may be excellent for bare hands, they aren't for gloved ones.

When designing hand tools, ask these questions:

- Who is going to use the tool, and for what purpose?
- What is the function – what task is to be solved?
- Are there differences to consider in the design population, e.g. between sexes (male/female grip strength ranges) or cultures (preferred hand for different activities)?
- What anthropometric data is useful (e.g. different sizes, left/right hand prevalence etc.)?

HAND INJURIES

Carpal Tunnel Syndrome (CTS)[a]
This condition is caused by highly repetitive work in extreme positions, in combination with high force development. The median nerve, which runs through the space in the wrist called the carpal tunnel, gets pinched due to increased pressure. This leads to numbness, tingling, decreased function and weakness in the area around the nerve, and the fingers that are affected by the median nerve (the thumb and three middle fingers). Similar symptoms can be had for radial and ulnar nerves. Treatment of CTS depends on the severity, but non- surgical treatment usually includes wearing a supportive wrist splint to prevent the wrist from bending.



Inflammation in tendons[b]
Tendon inflammation is a condition where movement of the wrist and fingers is painful due to a sense of pressure and swelling at the knuckles. It is the result of irritation in the tendons' sheaths, caused either by highly repetitive finger work or sharp edges on hand tools. One symptom, known as "trigger finger syndrome", is an inability to flex and extend the thumb and forefinger in one smooth movement – instead, the movement is hindered until it "snaps" into position. Medical language distinguishes between *tendonitis* (inflamed tendon) and *tenosynovitis* (inflamed tendon sheath).

White fingers[c]
"White fingers" is a condition with numb, tingling fingers, where blood flow is so decreased that the fingertips turn white. The condition may be hereditary, in which case it is called "*Raynaud's Syndrome*" (therefore, it is important to determine the individual's medical history) or it may be the result of a MSD caused by hand-arm vibration. The greatest risk for contracting this injury occurs at frequencies between 50 and 150 Hz. When caused by work, it is also called *vibration white finger* (VWF), *hand-arm vibration syndrome* (HAVS) or *dead finger*. However, it is sometimes hard to distinguish from Raynaud's syndrome, where the characteristic white fingers appear due to biological or non-work- related causes. Symptoms include: discoloured, pale white fingertips, especially in cold temperatures; numbness and prickling sensations in the fingers; and a decreased motor function and sense of touch.

Study questions

Warm-up

Q2.1) What are the three main tissue structures of the human locomotive system and what are their functions?

Q2.2) What structures make up the active and passive parts of the spine?

Q2.3) Why is it important for the back to get a good night's sleep?

Q2.4) Why is the shoulder area particularly sensitive to joint injury?

Q2.5) Why should you try to lift heavy objects with your leg muscles rather than your back?

Q2.6) Why is it risky to perform physical work in extreme positions?

Q2.7) Why is it not considered ergonomically risky to perform strenuous physical exercise with maximal force exertions and working until fatigued, as you would at a gym?

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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