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Gait Course

Pre-course Reading

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Contents

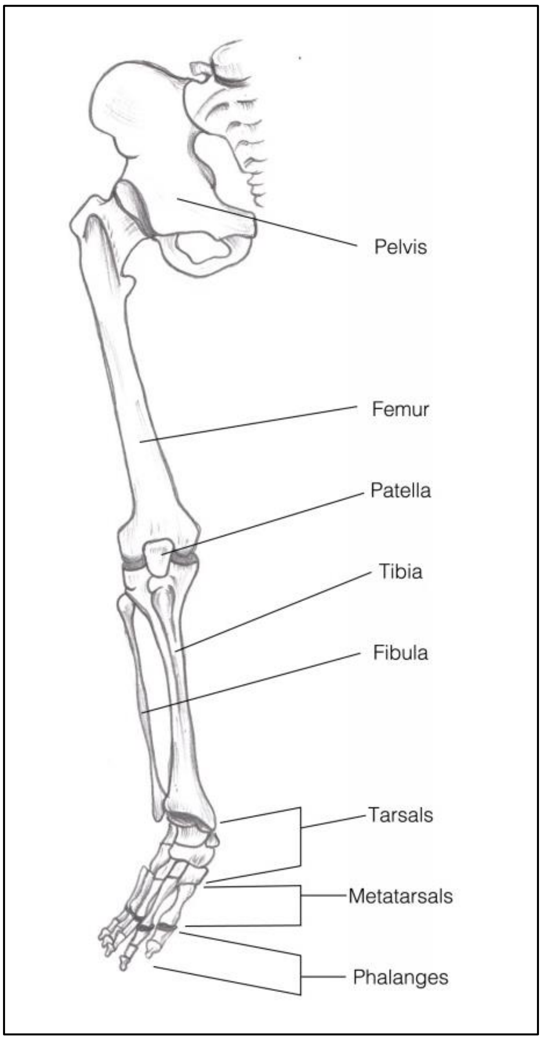
1. Anatomy and Function

*** Contributed by Bertram Muller and Julie Stebbins. Images contributed by Rosalind Bates or Wikimedia, unless otherwise stated. Edited by Gabor Barton.*

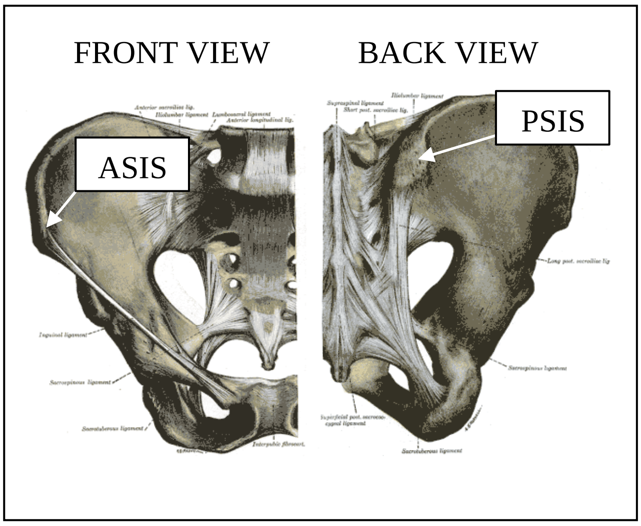
For clinical motion analysis, it is important to understand the underlying anatomy and function of the musculoskeletal system. Whilst it is recommended to study it in more detail, a short summary is given here as a quick reference.

Both skeletal and muscular anatomy is relevant for the study of gait. The skeleton provides structure and support, whilst the muscular system provides force generating capacity. Where either of these is compromised, the gait pattern may also be affected. Only the anatomy and function of lower limbs is presented here, as this is most relevant to gait analysis.

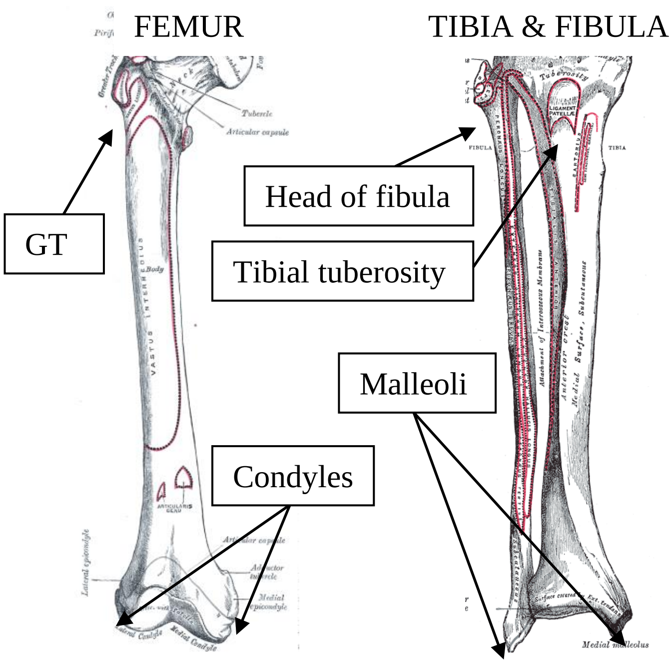
1a. Skeletal Anatomy



Each side of the ***pelvis*** (right and left) consists of three bones, which are fused together by adulthood. Posteriorly (at the back), the pelvis connects with the lower part of the spine (sacrum). The large circular depression on each side (the acetabulum) forms the socket for the hip joint. In gait analysis, there are four bony prominences that are relevant for marker attachment. These are the right and left anterior superior iliac spines (ASIS), as well as the right and left posterior superior iliac spines (PSIS). The ASIS can be palpated at the front of the pelvis, while the PSIS can be palpated at the back of the pelvis.



The ***femur*** is the long bone of the thigh (upper leg). It is the longest, heaviest and strongest bone in the body. The rounded head is encased by the acetabulum of the pelvis, and moves freely within it. The distal (lower) end of the femur forms the upper part of the knee joint. In gait analysis, bony prominences that are generally used for marker placement include the greater trochanter (GT) (which is the bony part that protrudes outwards at the top of the femur) and the condyles (the flared lower ends of the femur). The ***patella*** or knee-cap is the triangular shaped bone at front of the knee joint.



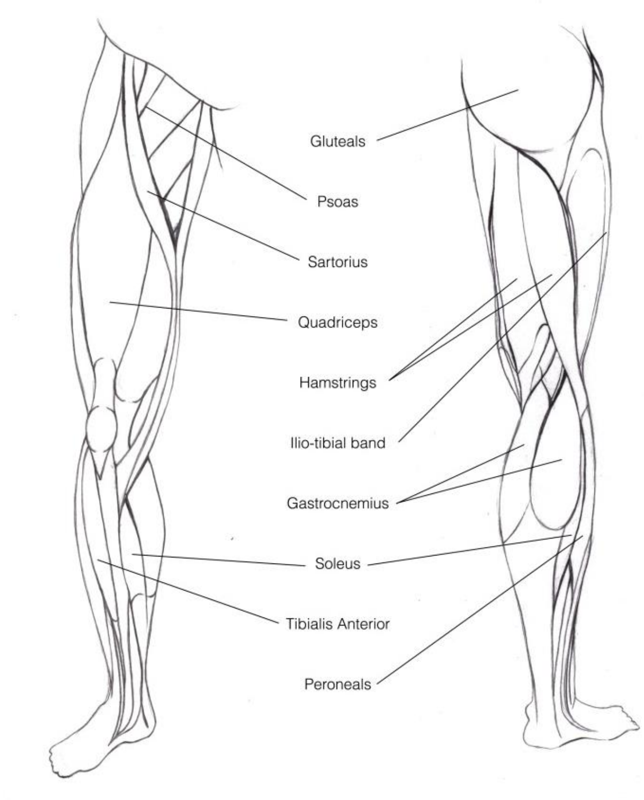
The ***tibia*** and ***fibula*** form the bones of the lower leg or shank. The tibia (shin bone) bears the weight of the body, and forms the knee joint at the upper end, and the ankle joint at the lower end. The fibula is narrower than the tibia, and primarily acts as a site for muscle attachment. Bony prominences relevant to gait analysis include the medial malleolus (lower, medial end of the tibia) the lateral malleolus (lower, lateral end of the fibula), the tibial tuberosity (prominence on the front, upper part of the tibia), and the head (top) of the fibula.

The ankle and foot is made up of 26 bones, which can be divided into the ***tarsals*** (seven cubic-type bones that make up the ankle joint complex and rear-foot), the ***metatarsals*** (five long bones connecting the tarsals with the toes), and the ***phalanges*** (14 bones making up the toes).

1b. Muscular Anatomy

The major muscles of the lower limbs are presented below, particularly those involved with movement during gait. For more information on their function, see “Function of the Muscles and Joints” below:

Skeletal muscles are usually long and narrow. They span the joints of the body, so that when a muscle contracts, it induces movement of the joint. Generally, muscles act in units, rather than in isolation. Muscles that contract together to achieve co-ordinated movement are called *synergists*. *Antagonist* muscles work in the reverse fashion, and oppose movement of each other.

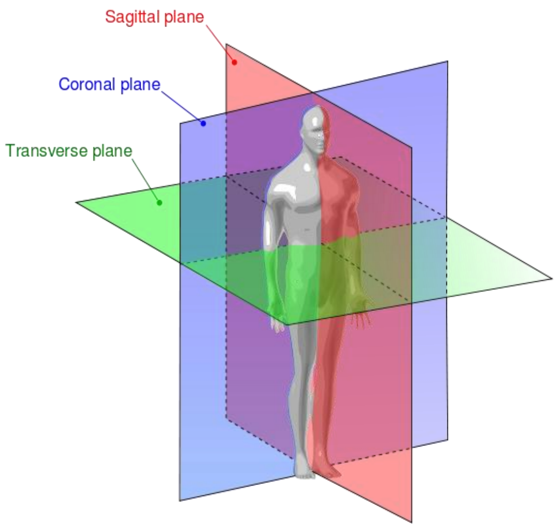


Muscles are generally named according to their shape, location, attachment, orientation of fibres, relative position and function. For example, the ***tibialis anterior*** is a muscle anterior (in front of) the tibia (shin bone). The muscles that move the thigh originate in the pelvis or spine, and attach on the femur. Muscles that move the lower leg originate on the pelvis or femur and attach to the tibia or fibula. Finally, muscles that move the foot originate on the femur or lower leg, and attach on the ankle and foot bones. There are some exceptions to these rules though, we will cover some of these during the course.

1c. Function of the Muscles and Joints

Motion of the human body is commonly defined by using a Cartesian co-ordinate system (i.e. three planes that are all mutually perpendicular) with our surrounding as a reference (absolute vertical and horizontal). This differs from the anatomical co-ordinate system at each joint. Since this is the case, there is no straight forward process to gain absolute information about the true motion at the joints. Instead, an approximation within each plane is derived.

While there are many different models and methods available for representing human motion using motion capture, most models assume each segment of the body is rigid (levers), and neighbouring segments are connected by joints (fulcrum). In order to understand this, it is first necessary to understand anatomical joints and their function.



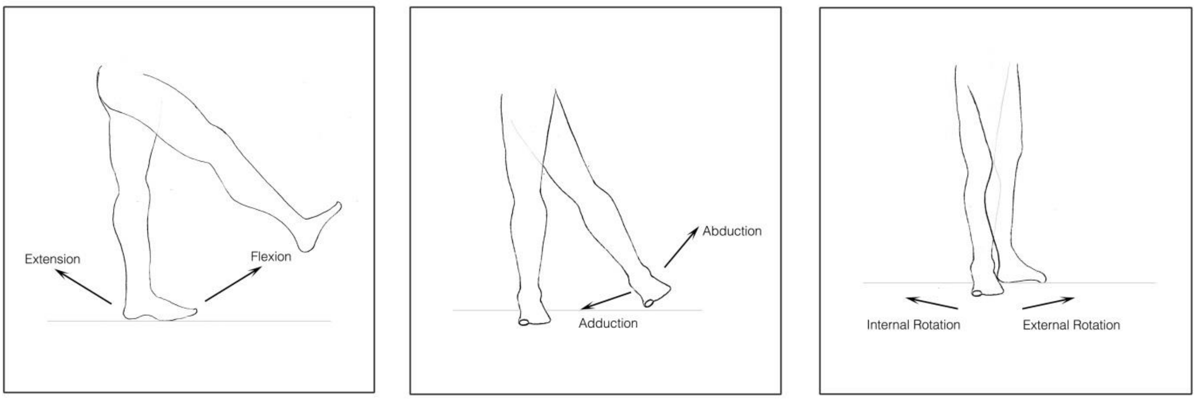
<u>IMPORTANT:</u> The information given in this section provides a quick reference. Joint articulations are presented in a simplified way. Also, function of the joints may sometimes involve more muscles than those presented here, depending on the position of the joint.

The range of movement available at a joint is constrained primarily by ligaments, rather than the shape of the bones. If these ligaments are stretched or ruptured, increased motion within the joint may occur. This internal motion will not necessarily be detected by the standard gait models. When muscles span more than one joint, the range of motion at an individual joint will be dependent on the positions of the other joint(s) that the muscle crosses. More information on this will be given during the course.

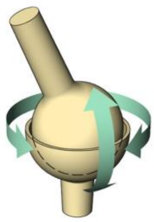
Hip joint

The hip connects the femur to the pelvis and is mechanically defined as a ball and socket joint. While hip motion is in fact multi-planar, it can be described in terms of motion in the three anatomical planes.

However, it should be noted that the anatomical joint coordinate system used in gait analysis differs from that used clinically. When deformities of the bones occur in pathological conditions, the motions that muscles cause may differ substantially from normal motion. One of the main challenges in motion science is the localisation of the hip joint centre from external markers.



The three planes of motion of the hip joint.



Ball and socket joint

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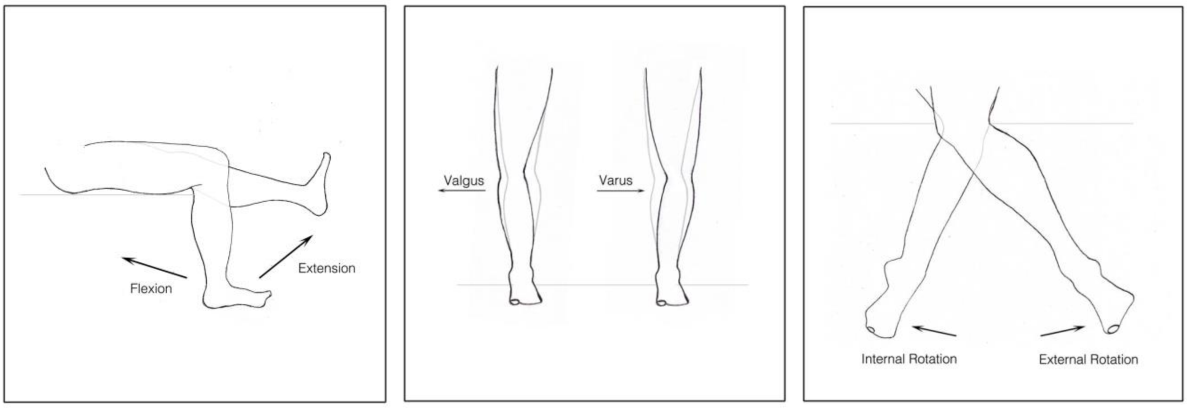
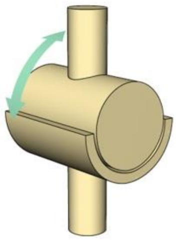
Motion	Main muscles	Normal range (from neutral)
Flexion	Psoas, Rectus Femoris	~130º
Extension	Gluteals, Hamstrings	~20º
Abduction	Gluteus Medius, Sartorius, Tensor Fasciae Latae	~50º
Adduction	Adductor group, Gracilis, Pectineus	~30º
Internal Rotation	Gluteus Medius, Pectineus	~40º
External Rotation	Psoas, Sartorius, Adductor Longus	~50º

Knee joint

The knee joint is the largest joint in the human body and has a complex mechanism. Anatomically, the knee consists of two articulations, femur/tibia and femur/patella. Between the femur and the tibia lie the two menisci (plural of meniscus; fibrous cartilage), which improve the load distribution of the articulation. Motion occurs primarily in the sagittal plane. When knee flexion increases, the stiffness of the joint in the frontal and transversal plane reduces. This allows maximal motion in the other planes at 90º flexion. Active motion does not occur in the frontal plane. However, disruption of the ligaments/tendons around the joint may alter the frontal plane alignment. Another challenge in motion analysis is correctly locating the knee axis position and alignment.



The three planes of motion for the knee joint. In the frontal plane the positional information is given.



Hinge joint
(simplified)

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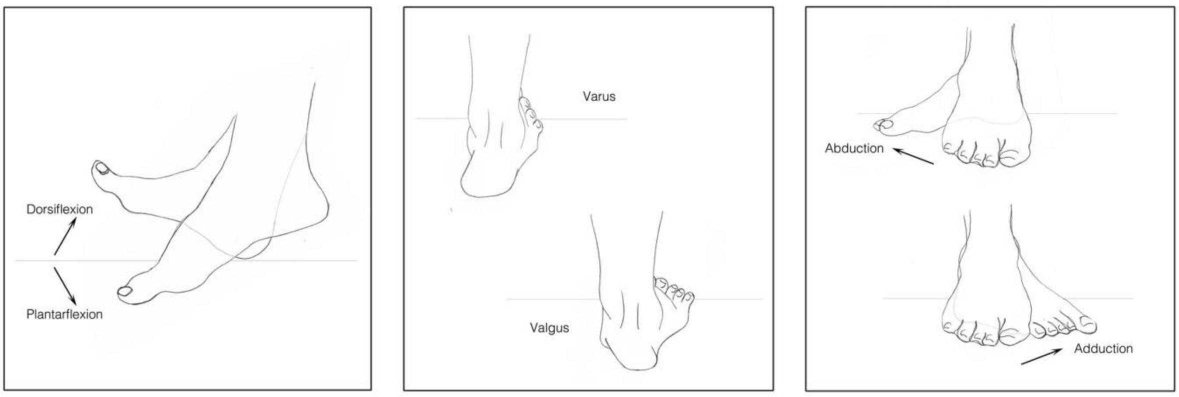
Motion	**Main muscles**	**Normal range (from neutral)**
Flexion	Hamstrings, Gastrocnemius	150º
Extension	Quadriceps	0º
Increased Valgus	*(Tensor Fasciae Latae)*	---
Varus	---	---
Internal Rotation*	Semimembranosus, Semitendinosus	10º
External Rotation*	Biceps Femoris	40º

** Knee at 90º flexion in figure.*

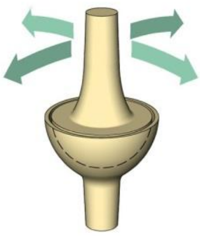
Ankle joint

The ankle joint connects the tibia/fibula with the talus (or astragalus). In contrast to the hip and knee joints, the ankle joint reference of 0º is equal to a 90º anatomical position. This joint allows dorsi- and plantarflexion with the axis between the medial and lateral malleoli. In biomechanical modelling, the ankle joint also includes the subtalar joint (between talus and calcaneus), which allows varus and valgus of the hindfoot, and inversion and eversion of the foot as a whole.

The normal position of the foot is about 0º to 6º in valgus. Technically, no rotation occurs at the ankle joint, however foot rotation relative to the external environment (around the ankle axis) can be achieved by hip rotation (knee extended) or by knee rotation (knee flexed). Joints in the midfoot (tarsals/metatarsals) can also contribute to foot rotation. Foot rotation is also called abduction/adduction or in-toeing/out-toeing.



The three planes of the motion of the ankle.



Ellipsoidal joint
(simplified)

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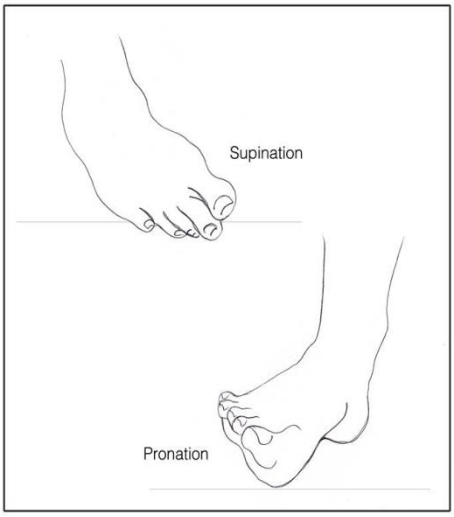
Motion	Main muscles	Normal range (from neutral)
Dorsiflexion	Tibialis Anterior	~30º
Plantar flexion	Gastrocnemius, Soleus, Tibialis Posterior	~50º
Eversion	Peroneus Longus and Brevis	~15º
Inversion	Tibialis Anterior, Soleus, Tibialis Posterior	~30º
Rotational foot position	---	0º-20º

Foot motion

The foot is a highly complicated mechanism and in biomechanical modelling is often very simplified. This is due to the number of bones within the foot, and the difficulties in measuring the internal motion of these bones. For this reason, the ankle joint is typically represented by hindfoot motion. The foot is structurally divided into hind-, mid- and forefoot. The most visible motion occurs at the forefoot in the frontal plane with pronation of around 15º and supination of around 35º. Other motions occurring within the foot are very subtle, but no less important. The main function of the foot is to provide stability over different surfaces. Biomechanically, the windlass mechanism is very important: when the big toe is extended (e.g. at toe off), the plantar fascia compresses the calcaneum, tarsals and metatarsals together forming a bone block, which is able to withstand the stress of the body weight.



In general, the foot is modelled as a single segment for the above mentioned reasons. Clinically, this is unsatisfying, especially when deformity and increased internal motion between the hind- and forefoot occurs. In this case, different foot models need to be applied.

2. Terminology

*** Contributed by Mike Walsh (CRC, Dublin) and Reinald Brunner. Edited by Gabor Barton.*

2a. Gait Cycle Definition

Walking or bipedal gait in the human being is the mechanism by which the human body is transported using coordinated movements of the major lower limb joints. This locomotion requires the co-ordination of the neurological and the musculoskeletal systems to convert the essentially vertical movements of the lower limbs into a smooth forward movement of the head and trunk, which allows the eyes to remain relatively steady throughout the process. Many disorders of the musculo-skeletal and nervous systems result in significant interference with gait which make it difficult to participate in normal human activities. One of the basic purposes of clinical gait analysis is to define these difficulties and to suggest remedial intervention.

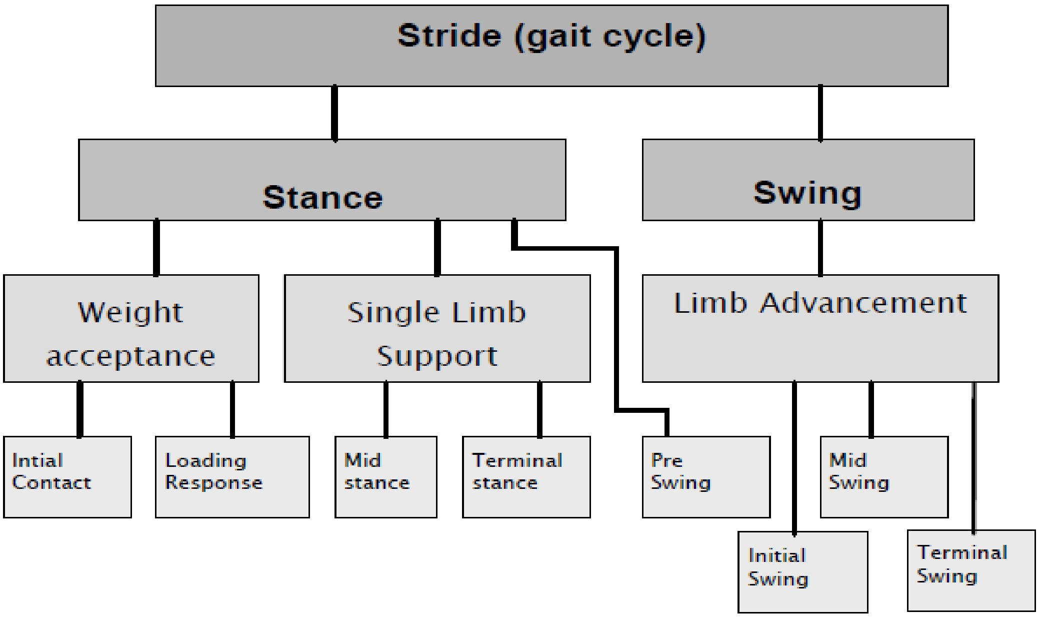
Before attempting to define pathological gait, one must first understand normal gait. The purpose of this material is to introduce basic terminology which is used to describe human gait.

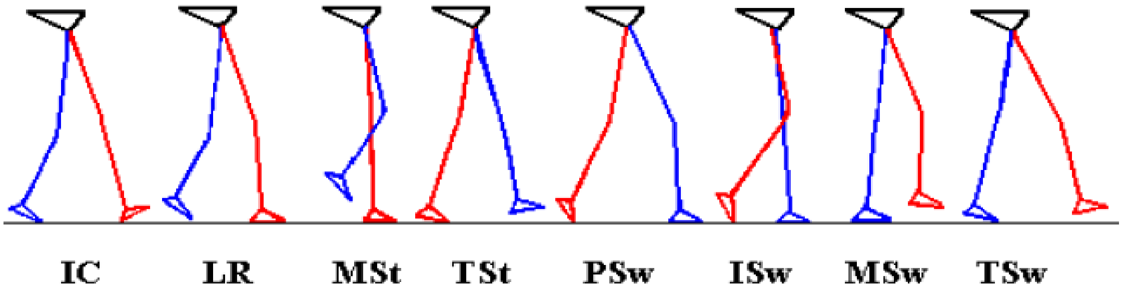
Gait Cycle

Walking involves repetitious patterns of movement resulting in each foot periodically moving from one position of support to the next. These movements are cyclical in nature and occur over and over again, step after step. This cyclical quality of walking allows us to zone in on one unit of this cycle for the purposes of describing gait. Hence, when describing human gait, it is conventional to do so in terms of the **gait cycle**. Because the moment of floor contact is the most readily defined event in the sequence of movements that is walking, this action is conventionally chosen to mark the beginning of the gait cycle. Any event in the cycle could be chosen. **A complete gait cycle or stride begins when one foot strikes the ground and ends when the same foot strikes the ground again.**

Phases and Events

The gait cycle is divided into two major phases, **stance phase**, and **swing phase**. **Stance phase is defined as the period of time when the foot is in contact with the ground**. It begins with **initial contact**, which in normal gait is with the heel and ends at **toe off** when **swing phase** begins. **Swing phase is defined as the period of time when the foot is not in contact with the ground**. It occurs from toe off until the foot strikes the ground again.





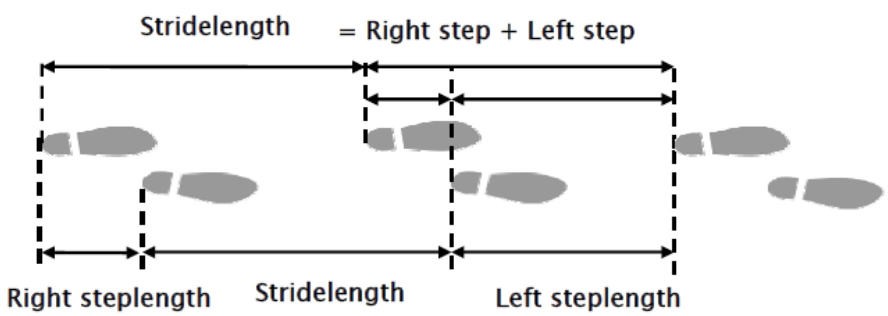
If we define the period of time for a complete gait cycle as 100% **(normalisation)**, then each of these events in the gait cycle is defined sequentially as occurring in specific percentages of the cycle. **Initial contact** is defined as occurring at **0%** and **100%** of the gait cycle. During normal walking, **toe off** occurs at approximately **60%** of the cycle. Therefore, **stance phase** represents approximately **60%** of the cycle and **swing phase** makes up the other **40%**.

If we take a gait cycle for a particular lower limb, (**ipsilateral limb**), then during that gait cycle **contralateral (the opposite side) toe off occurs at 10%** of the cycle and **contralateral heel strike occurs at 50%**. This means that during walking there are **two periods of double support**, when both feet are on the ground. Each of these periods constitutes about **10%** of the cycle. The **first period of double support** occurs immediately after initial contact. The **second** occurs just prior to toe off. The first period of double support is referred to as **loading response** and is a period of deceleration when the shock of impact is absorbed, and body weight is transferred from one lower limb to the other. This is followed by a period of **single stance** occupying about **40%** of the cycle, during which the opposite limb is going through a swing phase. In walking, **single support** on the stance side must be equal to the period of swing on the opposite limb. The period of **single stance can be sub-divided into mid stance and terminal stance. Mid stance** occurs from 10% to 30% of the gait cycle and is a period of body progression over a stable foot. Stability of the lower limb is an important feature of this phase. In normal gait mid stance ends when the body weight is aligned over the forefoot. **Terminal stance** occurs from 30% to 50% of the gait cycle, beginning with **heel rise** and ending with **initial contact** of the contralateral limb. During this phase the body weight is progressed beyond the supporting foot. In stance, the second period of double support is called **pre-swing**. It begins at about 50% of the gait cycle and lasts until **toe off of the stance side**. **Pre-swing** of the ipsilateral stance limb is equivalent to **loading response** on the contralateral limb and is equal in time. During pre-swing, the limb moves from a position of general extension into flexion and although a stance phase, it is functionally important for limb advancement by preparing the limb for swing. **Toe off** marks the beginning of the **swing phase** of walking. **Swing** is generally divided into three phases: **initial swing, mid swing** and **terminal swing**. **Initial swing** occurs from 60% to 73% of the cycle and is a period of limb advancement and clearance of the foot. It begins when the foot is lifted from the floor and ends when the swinging foot is opposite the stance foot. **Mid-swing** occurs from 73% to 87% of the cycle and ends when the swinging limb is forward, and the tibia is vertical with the main functional objectives again being foot clearance and limb advancement. **Terminal swing** is the final phase of the gait cycle and is a period of deceleration and preparation for the next ground contact.

All of these phases and events of a single gait cycle normally occur during a period of just over one second. It is important to note that although we generally refer to one side when defining our terminology, that the same terminology also applies to the other side which in normal gait is half a cycle behind or ahead. Thus, the first period of double support for the ipsilateral stance side refers to the second period of double support for the contralateral limb. Since normal gait is symmetrical, it is important to remember all of these relationships. In pathological gait an asymmetrical pattern very often exists. For example, in a unilateral antalgic gait, the single support time may be reduced in the painful limb which would also be reflected in a reduced swing time of the normal limb because a person wants to spend as little time as possible with all of the body weight being supported only by the painful limb.

2b. Spatio-Temporal Parameters

Further characterisation of human walking can be done with **distance or spatial measurements** such as **step length** and **stride length** which can be combined with temporal parameters such as **walking velocity** and **cadence**. Spatial parameters are best visualised using footprints.



Step length is defined as the longitudinal distance between the two feet generally expressed in meters (m). It is the distance from a point of contact of one foot with the ground to the following occurrence of the same point of contact of the other foot with the ground. In normal walking the **right step** length is defined as the distance measured from heel strike of the left foot to heel strike of the right foot. The **left step** length is defined as the distance measured from the heel strike of the trailing right foot to heel strike of the leading left foot. **Step time** is the time taken for one step and is measured as the period of time from an event of one foot to the following same event of the other foot, expressed in seconds (s).

Stride length is the distance covered during a complete gait cycle and represents the sum of the right and left step lengths. Stated differently, it extends from the initial contact of one foot to the following initial contact of the same foot.

Note: In normal walking, the right and left step lengths are symmetrical and a stride length measured from the left foot must equal the stride length measured from the right foot for a person to walk in a straight line. This rule in relation to symmetrical stride lengths still holds in pathological gait, however, it is perfectly possible for the two step lengths to be different. For example, in a step-to gait, if the left foot is moved forward and the right foot is brought up beside it, rather than in front of it, then by definition the right step length will be zero. This can sometimes cause great confusion but it is merely a consequence of the definition used for step length. The main point to remember is that if asymmetry exists, then this is not normal, and we must explore further to elicit the cause of this asymmetry.

Step width is defined as the medio-lateral distance between the feet which is typically measured from the ankle joint centre. Only a few centimetres for non-pathological subjects, this value can increase to as much as 15 or 20 centimetres in patients with balance problems such as cerebellar ataxia or athetoid cerebral palsy.

Cadence is the number of steps taken during a given amount of time, usually steps per minute.

Walking velocity is expressed as a distance over time relationship, measured in m/s or m/min and is the rate of change of linear displacement along the direction of progression measured over one or more strides. A child and an adult can walk at the same velocity, but the child has a shorter stride and therefore a faster cadence. Walking velocity is generally constant after about age five or six. However, as the lower extremities grow longer, step length increases and cadence slows. This continues until growth is complete.

Natural walking velocity is the velocity of walking which is voluntarily assumed and is generally the most efficient in terms of energy consumption for that person.

2c. Segments, Movement Planes and Joint Angle Definitions

Segments

A segment is simply a part of the body that stays “solid” or “rigid”. For the purposes of understanding and modelling human lower limb movement such as walking the simplest model of the human body assumes that the lower limbs move as seven segments: the pelvis, two thighs, two shanks or legs and two feet. There is general consensus in the gait analysis community about the definition of the different segments, although the precise details vary a little. The simplest way to visualise a segment is as a triangle. One point and a line segment can define this triangle and define the plane in which the body segment lies. The lower limb segments are generally defined as follows:

Pelvis segment
Point – midpoint of two PSISs
Line – from right ASIS to left ASIS

Thigh segment
Point – hip joint centre
Line – knee joint axis

Leg/Shank segment
Point – knee joint centre
Line – ankle joint axis

Foot segment
This is often defined not as a triangle but as a line passing along the long axis of the foot. Some models define it as a triangle with the point being the ankle joint centre and a line being offset from the lateral border of the foot.

There will be more about segment definitions and modelling during the course, including alternative definitions of segments to those proposed above.

Movement Planes

Motion of the limbs is generally described using reference planes.

1. The **sagittal plane** divides the body/segment into right and left sides.
2. The **coronal/frontal plane** divides the body/segment into front and back halves.
3. The **transverse plane** divides the body/segment into upper and lower halves.

Sagittal plane movement of the lower limbs (looking at the body from the side) involves anterior or posterior tilting of the pelvis, flexion/extension movements at the hip and knee and plantar/dorsiflexion movements of the ankle joint.

Coronal plane movement (looking at the body from the front and behind) involves obliquity or the pelvis, abduction/adduction of the hip and varus/valgus at the knee.

Transverse plane movement (looking at the body from the ceiling) involves protraction or forward rotation and retraction or backward rotation at the pelvis, internal/external rotation at the hip joint, internal/external rotation of the tibia and in turning or out turning of the foot.

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3. Pathology Relevant to Clinical Gait Analysis

*** Contributed by Julie Stebbins. Edited by Gabor Barton.*

3a. Cerebral Palsy

Definition

"A group of permanent disorders of the development of movement and posture, causing activity limitations that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, perception, cognition, communication and behaviour, by epilepsy and by secondary musculoskeletal problems." (1)

In simple terms, Cerebral Palsy (CP) is a condition caused by damage to the brain during fetal development and around the time of birth. It affects around 2 out of every 1000 live births. It results in many and varied problems as described above, depending on where and to what extent the brain has been injured. In many cases it causes a detrimental effect on walking, due to deficits in muscle control and secondary deformity. This ranges from very mild to severe problems, and some even lose the ability to walk altogether. Gait problems vary across the population, but some similarity is seen according to the type of CP. Broadly, this can be classified as those with bilateral involvement (diplegia) and unilateral involvement (hemiplegia).

Clinical and Gait Problems

(1) Spasticity

Cerebral Palsy disrupts the signals from the brain to the muscles. One manifestation of this is muscle spasticity, which is an increased velocity-dependent resistance to muscle stretch. It is caused by a lack of inhibition and results in excessive contraction of the muscles. Since it is velocity-dependent, it is most evident during gait at points in time when limb segments are moving most rapidly. For example, as the knee rapidly flexes in preparation for swinging the leg through. As a result, knee flexion is limited, and clearance of the foot may be poor.

(2) Muscle tightness / contracture

If spasticity persists over a period of time, it can result in structural changes to the muscles; in particular the muscles may reduce in length relative to the underlying bone. During gait, this can cause persistent flexion, when a joint can no longer fully extend. For example, a common problem in cerebral palsy is when the knees stay in a flexed position, causing a "crouch" type gait pattern.

(3) *Weakness*

Another problem associated with CP is muscle weakness. During gait, a threshold level of muscle strength is required to keep the body upright. When muscle weakness is present, the body must compensate by altering the gait pattern. A typical gait pattern associated with weakness in the hip muscles is when the upper body sways side to side to maintain the centre of mass over the supporting leg.

(4) *Torsional deformity of the long bones*

If muscle spasticity and tightness is present during growth, it can cause deformity of the growing bones. Torsional deformities of the long bones of the leg are common in CP. This can result in an in-toeing or out-toeing gait pattern.

(5) *Foot deformity*

Foot deformity is present in around 90% of people with CP. While there is a large variety of types of deformity, the two most common are planovalgus and equinovarus deformity. Planovalgus deformity is when the arch of the foot is excessively flat, and the foot turns outwards. Equinovarus deformity represents the reverse of the above, where the foot is plantar flexed and turns inwards. Deformity of the foot can have many detrimental effects on gait, as it disrupts shock absorption, reduces propulsive power, and causes mechanical alignment problems.

Further Reading

To find out more about CP and the effect this condition has on gait, the following references may be helpful:

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3b. Spina Bifida

Definition

“Spina bifida occurs when the spinal cord, surrounding the nerves and / or spinal column fail to develop normally during the first month of pregnancy, resulting in an incomplete closure of the spinal column. Spina bifida occurs in one of every 1000 births – the most common permanently disabling birth defect in the U.S.” (1).

The spinal level of the defect determines, to a large extent, the effect on walking gait. Lesions at the 12th thoracic level allow for limited ambulation abilities while lesions at lumbar levels 1 through 4 promote limited household ambulation. Moving distally, lesions found at lumbar level 5 and below most often obtain community walker status (2).

Clinical and Gait Problems

(1) Skeletal Deformity

A number of factors contribute to skeletal deformity, including imbalanced skeletal growth, mechanical instability, and neurological abnormalities (3). Malalignment of the lower limb reduces walking efficiency, by compromising mechanical lever arms.

(2) Sensory Loss

Loss of sensation in the lower body is common in spina bifida. This can have a significant effect on gait, reducing proprioceptive ability and balance reactions.

(3) Weakness and hypotonicity

Weakness is a significant problem in spina bifida, due to compromised innervation of the muscles. For example, weakness of the plantar flexors causes inability to maintain an upright lower leg. Consequently, the leg collapses forward, causing a “crouch” gait pattern (2). Hip abductor weakness is also common, leading to lateral trunk sway during walking.

(4) Spasticity

Spasticity occurs in a sub-set of those with spina bifida. It can add to the gait problems seen above by reducing available range of motion at a joint. In some cases, spasticity of lower limb muscles can contribute to excessive anterior pelvic tilt and reduced hip extension, limiting stride length and forward progression.

(5) Contractures

As with cerebral palsy, muscle contracture can also occur in spina bifida. A common muscle contracture seen in this population is contracture of the knee flexors, leading to a crouch gait pattern.

(6) Foot deformity

Equinovarus foot posture is commonly seen in spina bifida, which limits walking ability. However, hyperpronation can also be seen in this population. Orthotic management is required to maintain walking ability in the presence of foot deformity.

(7) Spinal deformities

Deformity such as scoliosis and kyphosis (rounded upper back) are commonly seen in this population. This can have an effect on both the efficiency of gait, as well as the ability to maintain upright posture.

Further Reading

To find out more about spina bifida and the effect this condition has on gait, the following references may be helpful:

1. http://www.gillettechildrens.org
2. http://www.oandp.org
3. Spina Bifida: Management and Outcome**,** By M. Memet Özek, Giuseppe Cinalli, Wirginia June Maixne
4. http://www.gcmas.org/sites/default/files/spina_bifida_position_paper.pdf
5. Broughton, N. & Menelaus, M. (1998). *Orthopaedic Management of Spina Bifida Cystica.* Saunders Ltd.

3c. Hemiparesis following stroke

Definition

A stroke is a sudden interruption in the blood supply of the brain. According to the World Health Organization, 15 million people suffer stroke worldwide each year. Of these, 5 million die and another 5 million are permanently disabled. Most strokes are caused by an abrupt blockage of arteries leading to the brain (ischemic stroke). Other strokes are caused by bleeding into brain tissue when a blood vessel bursts (haemorrhagic stroke). Because stroke occurs rapidly and requires immediate treatment, stroke is also called a brain attack. When the symptoms of a stroke last only a short time (less than an hour), this is called a transient ischemic attack (TIA) or mini-stroke [1].

A stroke can damage the corticospinal tract in the supratentorial region of the brain. Damage to these descending motor pathways results in a characteristic set of signs and symptoms, which are collectively termed the 'upper motor neuron (UMN) syndrome'. These signs include contralateral loss of muscle force and motor selectivity, exaggerated deep tendon reflexes, and increased muscle tone, in short referred to as 'spastic hemiparesis'. Contractures can emerge due to muscular imbalance around joints [2]. Of those who survive the acute phase about 11% are unable to walk and 55% have moderate to severe walking disabilities. Hence relearning to walk is relevant for a large group of the total stroke population. For most of the patients, in the early stage, movements cannot be performed or the co-ordination of movements has lost its smoothness. It is thought that after several weeks novel co-ordination patterns will evolve.

Gait Problems

Spasticity
A stroke disrupts the signals from the brain to the muscles. One manifestation of this is muscle spasticity. In stroke, spasticity is most evident in the calf muscles and thigh muscles causing an equinus of the foot and limited knee flexion. As a result, foot clearance may be poor.

Muscle tightness / contracture
As with all central neurological disorders, muscle contracture also occurs in stroke. A common muscle contracture seen in this population is contracture of the calf muscles causing excessive plantar flexion at the ankle and consequently a hyperextension of the knee during stance phase.

Weakness
Another problem associated with stroke is muscle weakness. A typical example of muscle weakness in stroke is the so-called dropfoot caused by weakness of the dorsiflexors of the ankle.

Foot deformity
Foot deformities are common in people with stroke. While there is a large variety of types of deformity, the most common is the equinovarus deformity. Planovalgus deformity is when

the arch of the foot is excessively flat, and the foot turns outwards. Equinovarus deformity represents the reverse of the above, where the foot is plantar flexed and turned inwards. Deformity of the foot can have many detrimental effects on gait, as it disrupts shock absorption, reduces propulsive power, and causes mechanical alignment problems.

Further Reading

To find out more about Stroke and the effect this condition has on gait, the following references may be helpful:

1. http://www.strokecenter.org/patients/about-stroke/stroke-statistics/
2. Jorik Nonnekes, Nathalie Benda, Hanneke J R van Duijnhoven, Frits Lem, Noel L W Keijsers, Jan Willem Louwerens, Allan Pieterse, Gerbert J Renzenbrink, Vivian Weerdesteyn, Jaap H Buurke, Alexander C.H. Geurts MD PhD. Improving the gait pattern in patients with chronic unilateral supratentorial upper motor neuron syndrome: a step-wise approach. Submitted
3. Olney S.J, Richards C.L. Hemiparetic gait following stroke. Part I: Characteristics. Gait & Posture 1996; 4: 136-148.
4. Richards C.L, Olney S.J. Hemiparetic gait following stroke. Part II: Recovery and physical therapy. Gait & Posture 1996; 4: 149-162.

3d. Arthritis

Definition and Gait Problems

Arthritis is an inflammation of the joints and can be systemic (rheumatoid arthritis) or localised to specific joints (osteoarthritis). It is a chronic condition characterised by breakdown of the cartilage within the joint. Cartilage normally functions as a cushion between the bones; when this breaks down, the bones grind against each other, causing pain, stiffness and swelling. Limited range of motion at the joints, as well as pain, can cause significant gait abnormalities. Many gait deviations seen in arthritis are compensatory changes, adopted to avoid pain.

3e. Duchenne Muscular Dystrophy

Definition and Gait Problems

Duchenne Muscular Dystrophy is an X-linked genetic disorder, and therefore affects only males. The incidence is about 1 in every 3500 live births. Over time, muscle fibres break down and are replaced by fibrous or fatty tissue, causing progressive muscle weakness. Regular steroid injections may help slow this progression in weakness. The gait pattern is characterised by attempts to compensate for muscle weakness, and includes excessive trunk sway, walking on toes, and a wide base of support.

4. Fundamentals of mechanics (online video and slides)

Below are the slides of the talk. Watch the narrated Powerpoint presentation at https://vimeo.com/cineurope/review/360214327/cad0450581.

Mechanical Concepts

Adam Shortland PhD

One Small Step Gait Laboratory,

Evelina Children's Hospital,

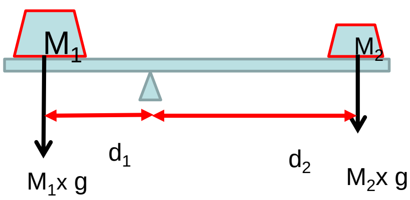
Guy's & St Thomas' Trust

London

ESMAC Gait Course

Outline

- Linear motion
- Angular motion
- Centre of Rotation
- Forces/Moments
- Mass/Mass moment of inertia
- Induced Accelerations
- Some examples



$M_1 \times g \times d_1 = M_2 \times g \times d_2$

Learning Outcomes

At the end of this session the student should be able to have a basic appreciation of the biomechanical factors that influence human movement

Scalar is a quantity that possesses only magnitude. Examples are mass, time, length, density and temperature.

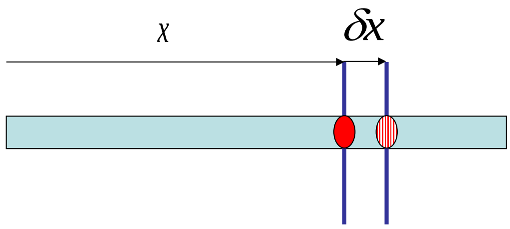
Vector is a quantity that possesses both magnitude and direction. Very often a vector is represented by an arrow. Examples are velocity, force and acceleration. Vectors can be represented by bold letters or letters with an arrow drawn above them: **F** or $\vec{F}$

Kinematics study movement of bodies without considering the forces that cause the movement. Eg position, displacement, velocity, acceleration.

Kinetics study movement taking the forces that cause the movement into account. Eg power.

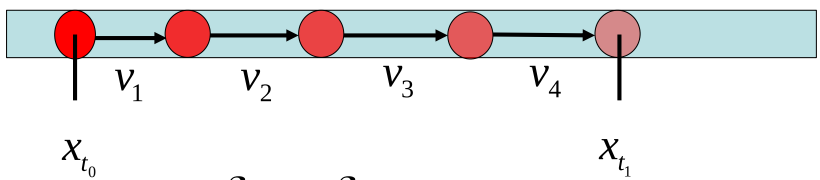
You may also have heard of this as **dynamics** (hence terms such as *dynamometry* for force measurement)

Movement of a point along a line – differentiation



$$v \approx \frac{\delta x}{\delta t} \qquad v = \lim_{\delta t \to 0} \frac{(x + \delta x) - x}{\delta t} = \frac{dx}{dt} = \dot{x}$$

Movement of a point along a line – integration



$$\delta x \approx v.\delta t$$

$$x_{t_1} - x_{t_0} \approx \sum v_i.\delta t$$

$$x_{t_1} - x_{t_0} = \int_{t=t_0}^{t=t_1} v.dt$$

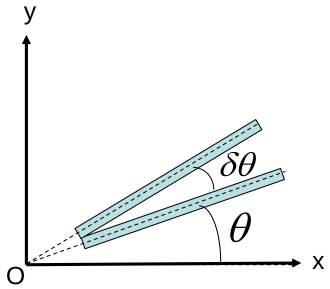
Similarly, for acceleration

$$a = \lim_{\delta t \to 0} \frac{(v + \delta v) - v}{\delta v} = \frac{dv}{dt} = \dot{v} = \frac{d^2 x}{dt^2} = \ddot{x}$$

$$v = \int a \cdot dt + C$$

$$v_{t_1} - v_{t_0} = \int_{t_0}^{t_1} a \cdot dt$$

Angular Motion



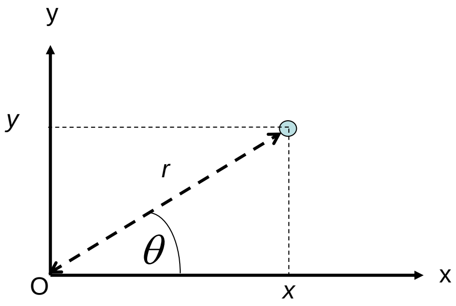
$$\omega = \lim_{\delta t \to 0} \frac{(\theta + \delta\theta) - \theta}{\delta t} = \frac{d\theta}{dt} = \dot{\theta}$$

$$\alpha = \lim_{\delta t \to 0} \frac{(\omega + \delta\omega) - \omega}{\delta t} = \frac{d\omega}{dt} = \dot{\omega} = \ddot{\theta}$$

Where θ is the angle between the body and some axis in radians (rads), is the angular velocity in rads/s and ω is the angular acceleration in rads/s/s.
A good example of a motion that could be describing the angular movement of a limb segment around a joint.

Position of a point in a plane

- We can calculate the position of a particle in terms of in Cartesian or polar co-ordinates



$$x = r.\cos\theta$$

$$y = r.\sin\theta$$

Movement of a point in a plane - Cartesian

In Cartesian co-ordinates for *x*:

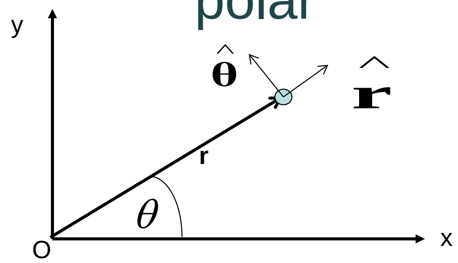
$$v_x = \dot{x} = \frac{dx}{dt}$$

$$a_x = \dot{v}_x = \frac{dv_x}{dt} = \ddot{x} = \frac{d^2x}{dt^2}$$

Similarly for *y*. In vector notation:

$$\mathbf{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix}; \quad \mathbf{a} = \begin{pmatrix} a_x \\ a_y \end{pmatrix}$$

Movement of a point in a plane - polar



$\mathbf{r} = \hat{\mathbf{r}} \cdot r$ where $\mathbf{r}$ is the vector describing the movement of point P; where $\hat{\mathbf{r}}$ is the unit vector in the direction of $\mathbf{r}$ and where r is the magnitude of $\mathbf{r}$

If we consider a unit vector perpendicular to the x - y plane, $\hat{\mathbf{k}}$. We can construct a unit vector $\hat{\boldsymbol{\theta}}$ which is the cross - product of $\hat{\mathbf{k}}$ and $\hat{\mathbf{r}}$ i.e.

$$\hat{\boldsymbol{\theta}} = \hat{\mathbf{k}} \otimes \hat{\mathbf{r}}$$

Vector calculus

$$\hat{\mathbf{r}} = \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \quad ; \quad \hat{\boldsymbol{\theta}} = \begin{pmatrix} -\sin\theta \\ \cos\theta \end{pmatrix}$$

$$\dot{\mathbf{r}} = \dot{r}\begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} + r\dot{\theta}\begin{pmatrix} -\sin\theta \\ \cos\theta \end{pmatrix}$$

$$\dot{\mathbf{r}} = \dot{r}\hat{\mathbf{r}} + r\dot{\theta}\hat{\boldsymbol{\theta}}$$

$$\ddot{\mathbf{r}} = \ddot{r}\hat{\mathbf{r}} + \dot{r}\dot{\theta}\hat{\boldsymbol{\theta}} + \left(-r\dot{\theta}\dot{\theta}\hat{\mathbf{r}} + (r\ddot{\theta} + \dot{r}\dot{\theta})\hat{\boldsymbol{\theta}}\right)$$

$$\ddot{\mathbf{r}} = \left(\ddot{r} - r\dot{\theta}^2\right)\hat{\mathbf{r}} + \left(2\dot{r}\dot{\theta} + r\ddot{\theta}\right)\hat{\boldsymbol{\theta}}$$

A special case - motion in a circle

When we are considering the rotational motion around a joint in 2D we often make the assumption that the motion around the joint is circular (a good example when that assumption is made is for the knee joint).

In circular motion, the radius does not change and if the angular velocity is constant the results for radial and tangential acceleration reduce to:

$$a_r = -r\dot{\theta}^2 = -\frac{V^2}{R}$$

$$a_t = 0$$

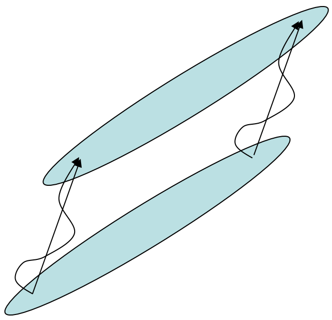
Rotation and Translation of a rigid body in 2D

Rigid body - the distance between any two points on the body remain constant.

Position and Orientation in a plane is defined by a minimum of 3 co-ordinates (x, y, θ).

Therefore a rigid body moving on a plane has 3 degrees of freedom

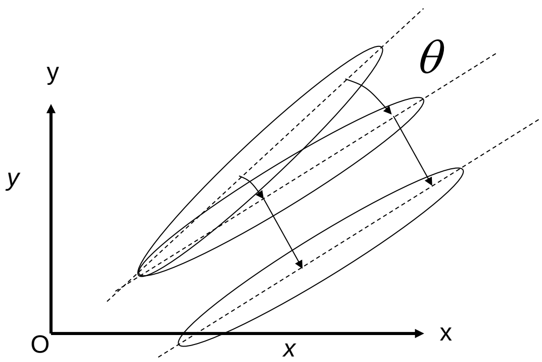
Translation



In a translation, all the points within the rigid body undergo the same vectorial transformation in x and y.

Of course this translation could be quite complex!

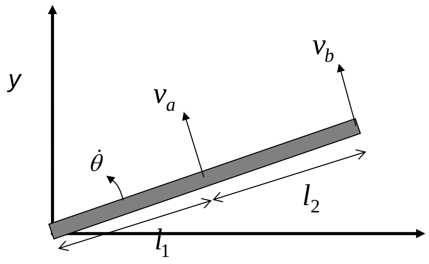
Rotation



Any *transformation* of a rigid body in a plane can be expressed as a combination of a *rotation* and a *translation*

Transformations

Under a *translation* velocities and accelerations of points within the body are identical, whereas under *rotation* velocities and accelerations are a function of the distance between the point and the centre of rotation.



$$v_a = l_1\dot{\theta}$$

$$v_b = (l_1 + l_2).\dot{\theta}$$

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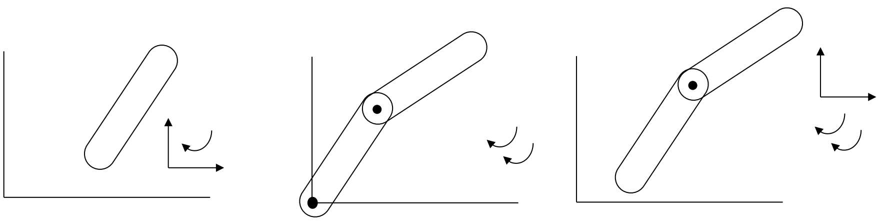
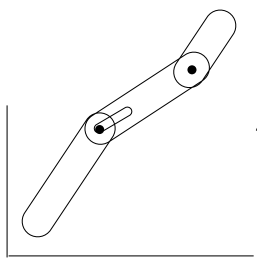
Degrees of freedom (in 2D).





The no. of degrees of a connected system is

$$f = 3n - 2p - q$$

? Where n is the no. of connected bodies, p is the no. of joints that remove 2 degrees of freedom (they have 1 degree of freedom) and q is the no. of joints that remove 1 degree of freedom (they have 2 degrees of freedom). What are maximum number of degrees of freedom of a body moving in 3D space?

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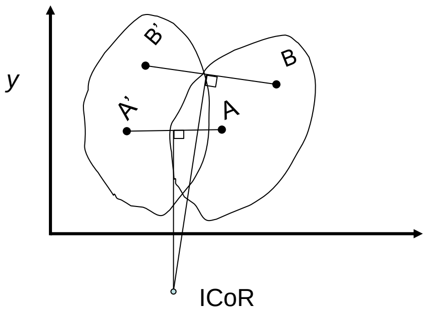
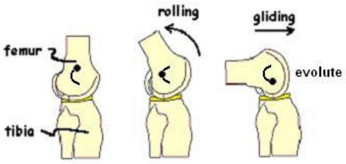
Instantaneous centres of rotation





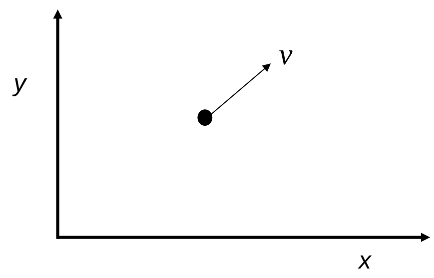
We can describe any instantaneous movement of a rigid body in a plane by a rotation around a instantaneous centre of rotation.
The position of the CoR could be calculated by calculating the intersection of the perpendicular bisectors of two lines AA' and BB' on a rigid body at two successive points.

Newton's Laws

Newton's Laws apply to the motion of a particle in a non-inertial (non-accelerating) frame.

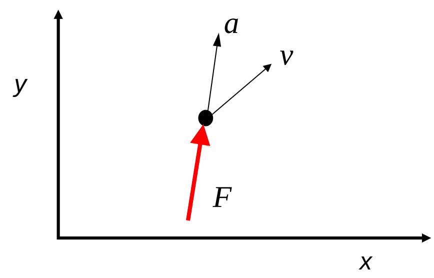
Newton's 1st Law

If no force is applied, the velocity of a particle remains unaltered.



Newton's 2nd Law

When a force acts on a particle the acceleration of the particle is proportional to the magnitude of the force applied

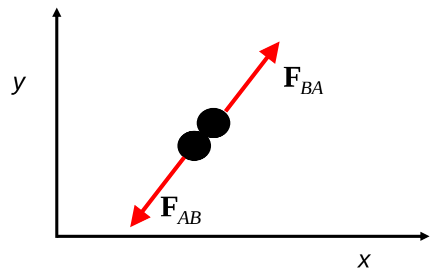


$$\mathbf{F} = km\mathbf{a}$$

$$\mathbf{F} = m\mathbf{a}$$

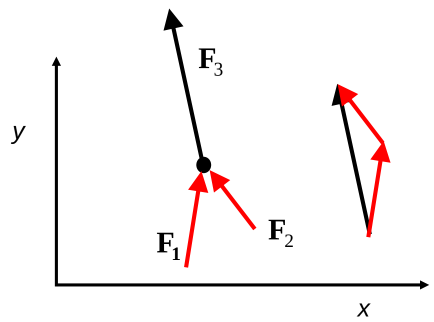
Newton's 3rd Law

When two particles (A and B) are in contact the force applied by B on A is equal in magnitude and opposite in direction to that applied by A on B



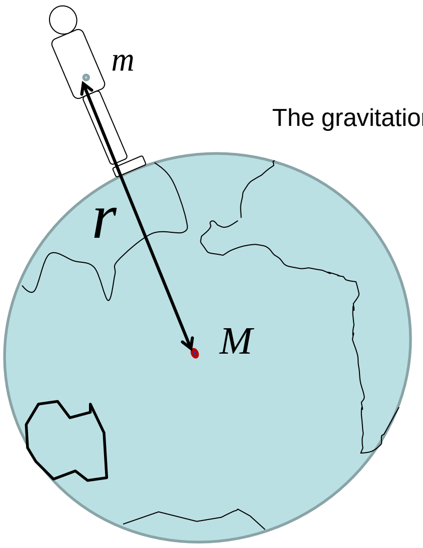
Force continued

If a number of forces act on a particle the resultant force is the vector sum of the forces.



When the external forces add up to zero, the particle is said to be in equilibrium

Acceleration due to gravity



The gravitational force between two objects is given by:

$$F = \frac{GMm}{r^2}$$

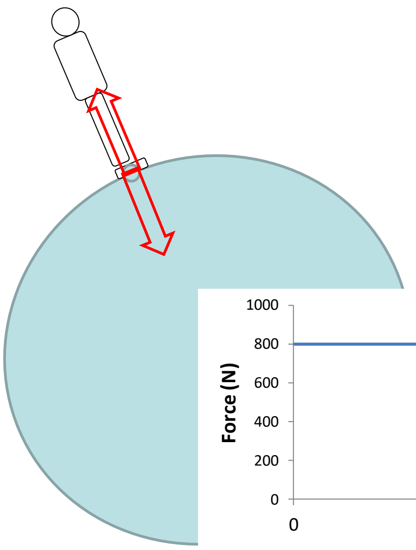
and

$$F = ma$$

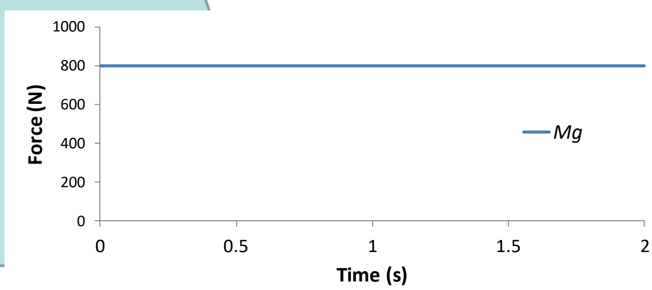
so

$$a = g = \frac{GM}{r^2} \approx 9.81\text{ms}^{-2}$$

Newton's 3rd Law



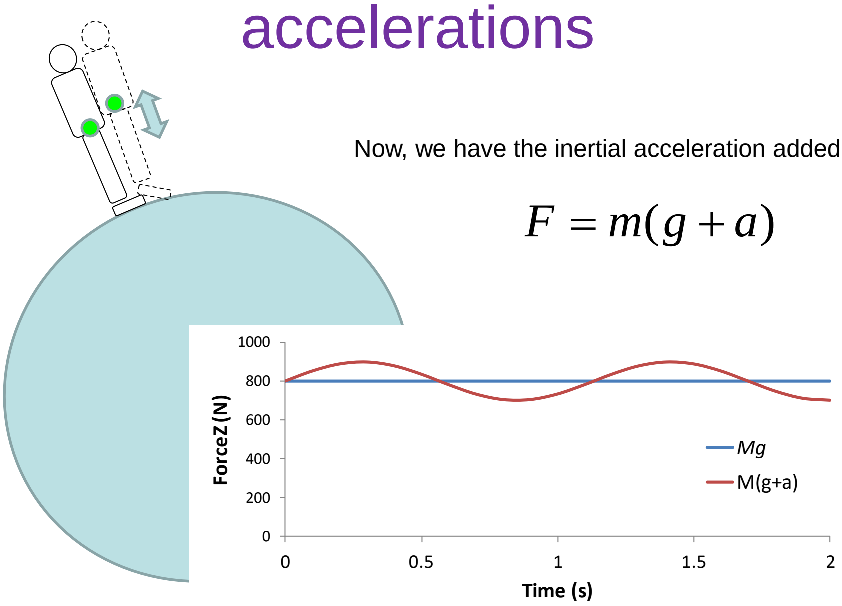
For any two bodies in contact (A and B), the force applied on body A by body B is equal in magnitude and opposite in direction to that applied by A on B.
So in this case the earth generates an equal and opposite force on the body.
In gait circles, this opposite force or REACTION is known as the GRF or Ground Reaction Force.



Forces due to inertial accelerations

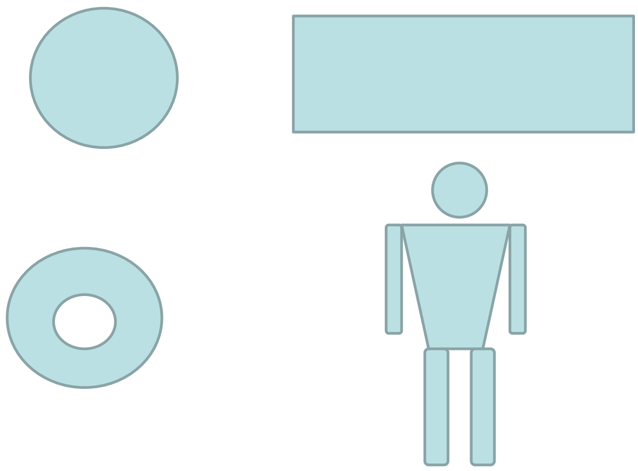
Now, we have the inertial acceleration added

$$F = m(g + a)$$

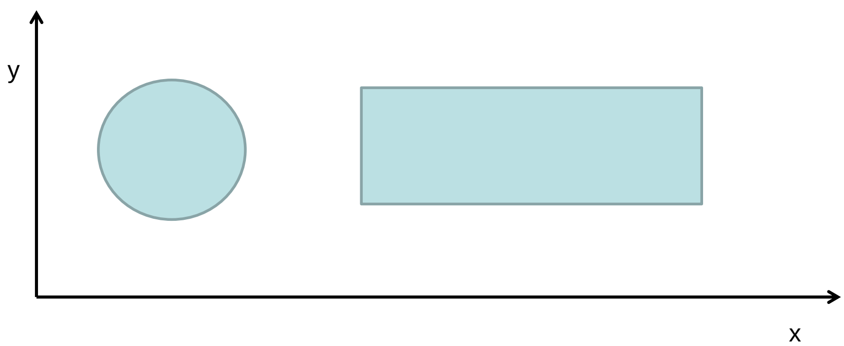


Centre of Mass

Where is the Centre of Mass?



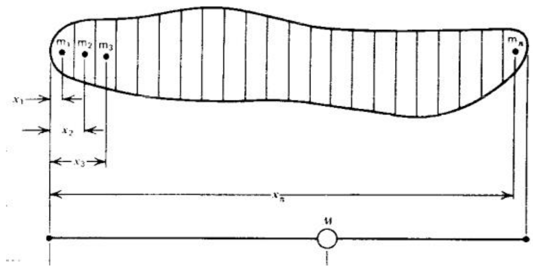
Where is the Centre of Mass?



$$X_{com} = \frac{X_{com\_A} * M_A + X_{com\_B} * M_B}{M_A + M_B}$$

There is a similar equation for Y_{com}

The Centre of Mass of Any Body

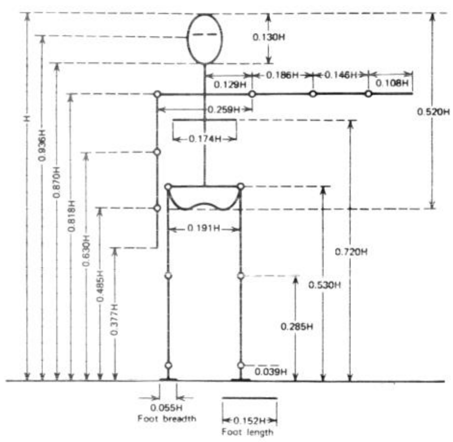


Consider gravity acting on a mass, *M*, split up into little vertical segments. Clearly, the equivalent point at which the force acts is given by:

$$x_{com} = \frac{\sum_i m_i.g.x_i}{M.g} = \frac{\sum_i m_i.x_i}{M}$$

There is a similar result for y_{com}!

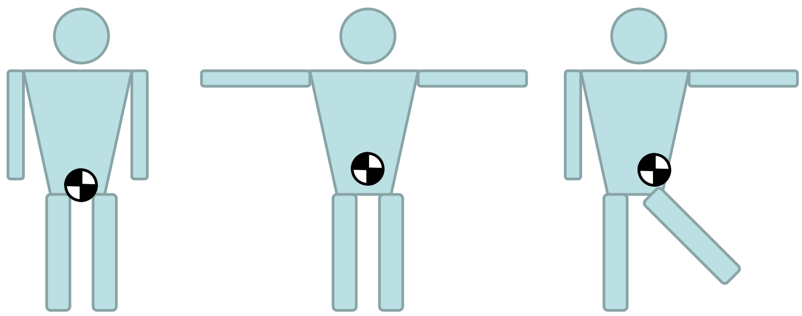
Anthropometrics



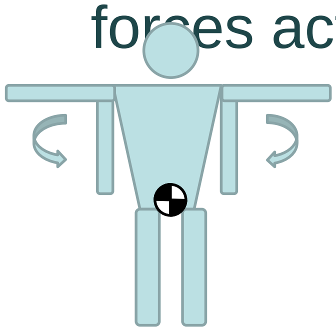
Segment	Segment Mass /BodyMass	Centre of Mass/ Segment Length (proximal)
Trunk	0.497	0.5
Hand	0.006	0.506
Forearm	0.016	0.43
Upper arm	0.028	0.436
Foot	0.0145	0.5
Leg	0.0465	0.433
Thigh	0.1	0.433
Head & Neck	0.081	0.5

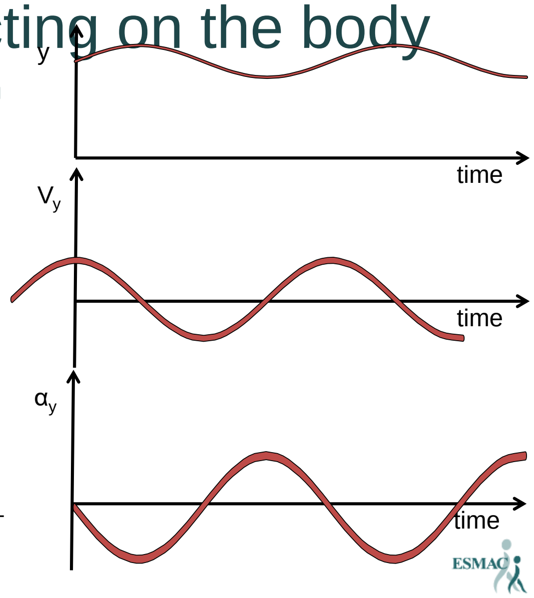
Work out the position of the CoM of this figure if the origin of the coordinate system is on the floor halfway between the subjects feet where y is ↑ and x is →.

CoM depends on body configuration
Guess where the CoM is!



Movement of the CoM is important in determining the forces acting on the body

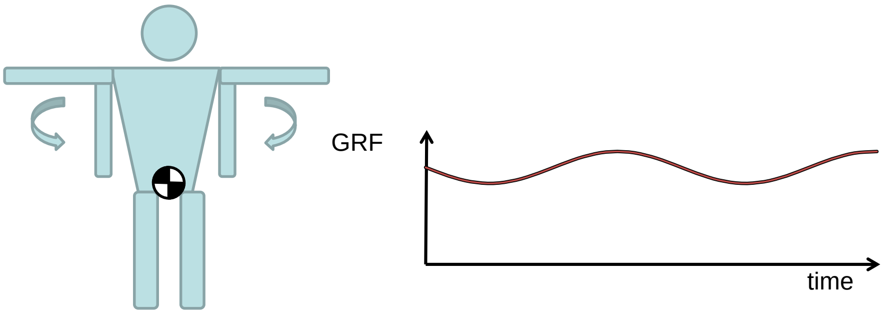




$$v_y = \frac{dy}{dt} = \frac{y_{i+1} - y_i}{\Delta t}$$

$$a_y = \frac{dv_y}{dt} = \frac{v_{y_{i+1}} - v_{y_i}}{\Delta t}$$

Can you predict the GRF of the bouncy man?



Energy

Mechanical Work and Energy

Work and energy are related but different things. Energy is a measure of the body at *one moment in time*. For example a mass, that is h metres above the surface of the earth and is travelling away at a velocity, v, from the surface of the earth has at that instant mgh amount of potential energy (the amount of energy associated with a gravitational force field of the earth) and $0.5mv^2$ worth of kinetic energy. The total energy of the body are these two variables summed.
Work is the *transfer of energy between bodies* or the energy flow from one body to another. For example, when the mass lands some of the energy will be transferred to the earth and some may be retained in the mass. In this process work is done by the mass on the earth (or energy flows from the body to the earth).

Forms of energy

$$E_{TE} = E_{PE} + E_{KE} + E_{CHEM} - \int Q$$

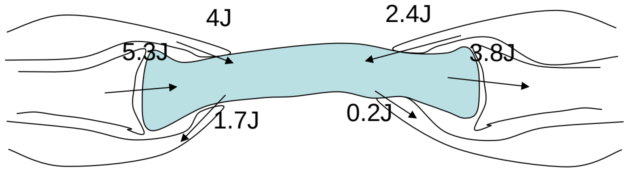
where E_{TE} is the total energy, E_{PE} is potential energy, E_{KE} is the kinetic energy, E_{CHEM} is the energy stored in chemical resources (like ATP in muscles), and Q is the heat flow.

Potential energy may be from energy stored as a function of its position in a force field or as a strain energy such as in a spring. Kinetic energy can be stored in translational and rotational form.

If the segment is inert then E_{CHEM} is 0, and if there is no friction or viscosity then $Q = 0$.

Law of conservation of energy

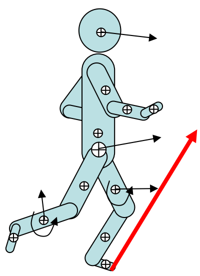
A body will only change its total energy if there is a flow of energy out of that structure into an adjacent structure, such as from a muscle in one body segment to another segment. The total change in energy of a body segment is equal to the algebraic sum of energy changes in and out of the segment.



Can you work out the the change in energy of the highlighted segment? If these changes take place on 20ms calculate the power flow to the segment.

Internal and external energy

External energy is that associated with the dynamics of the body's CoM (its potential and kinetics energy).
Internal energy is summed energy of all the segments relative to the CoM of the connected body, for instance:



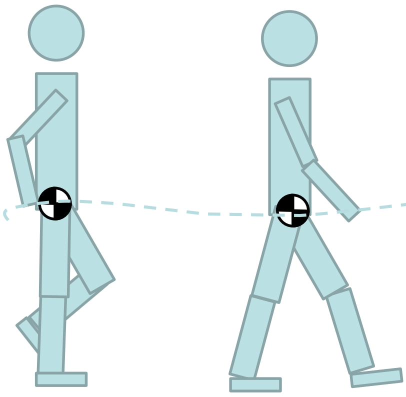
Kinetic Energy

$$KE_{body,trans} = \tfrac{1}{2} m_{body}.v_{com}^2 + ?$$

Potential Energy

$$PE_{gravity} = m.g.h_{CoM}$$

Walking up and down CoM and energy



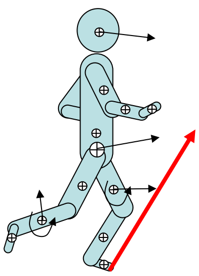
Mechanical Energy Summary

- The mechanical energy of segmented body comprises Kinetic & Potential Energy terms.
- Energy may be transferred between body segments.
- Energy may be transferred between types e.g. KE<=>PE.

Answer these questions

- Estimate the change in PE during a gait cycle.
- Do you think the maximum change in PE is the same as the maximum change in KE?
- To maximise efficiency how could change in PE and KE be related. (Hint: we like to move forward)
- Derive an expression for the efficiency of walking

External & Internal Kinetic Energy



External Kinetic Energy

$$KE_{body,trans} = \tfrac{1}{2} m_{body} . v_{com}^2$$

Internal Kinetic Energy

$$KE_{seg,trans} = \tfrac{1}{2} m_{seg} \left| \mathbf{v}_{\mathbf{com,seg}} - \mathbf{v}_{\mathbf{com,body}} \right|^2$$

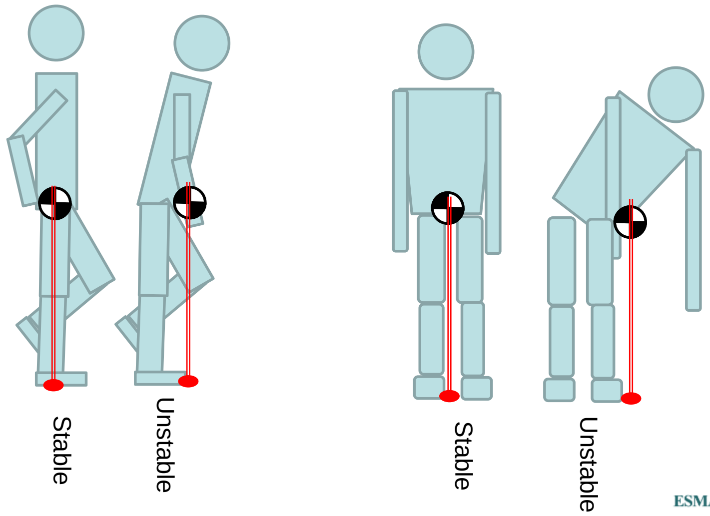
Rotational Kinetic Energy

$$KE_{rot,seg} = \tfrac{1}{2} I_{COM,seg} . \omega_{COM,seg}$$

Total Energy

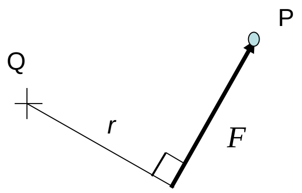
$$E_{TOT} = PE + KE_{body,trans} + \sum KE_{seg,trans} + \sum KE_{seg,rot}$$

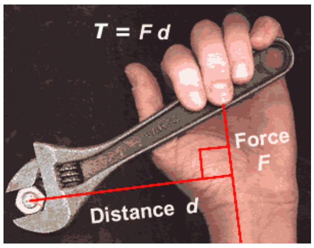
CoM and Base of Support



Rotational Forces or Moments

Moment of Force





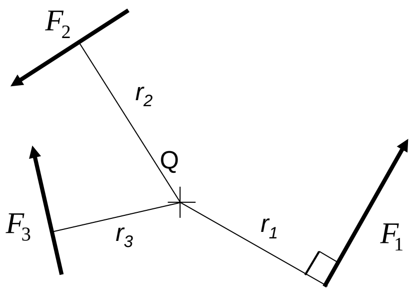
The moment of the Force, *F*, about Q is given as the product of the magnitude of *F* and the perpendicular distance between *F* and Q, *r.*

$$M_Q = rF$$

In vector terms:

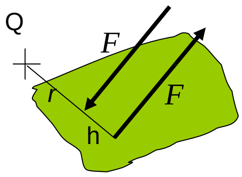
$$\mathbf{M}_Q = \mathbf{r} \otimes \mathbf{F}$$

Adding Moments



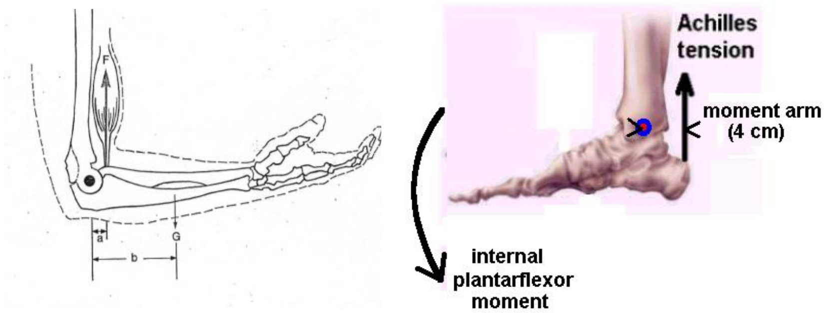
$$M_Q = r_1F_1 + r_2F_2 - r_3F_3$$

Note: Moments are vector quantities and add. There is a sign convention - anticlockwise forces are positive



?

Muscles produce moments



In static equilibrium, the internal moment generated by the muscles must be equal and opposite to the moments produced by the external loads.

Rotational Motion

- We have seen the forces that act on a body when the body is static (gravity) and we have seen the forces that act on a body due to movement inertia.
- What we have considered thus far is linear movement but what about rotational movement? – are there equivalent terms/quantities?

Mass Moment of Inertia

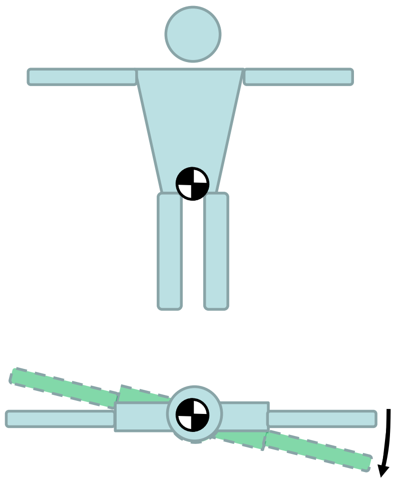
- Is their a rotational equivalent to mass?

$$F = ma$$

$$M = I\alpha$$

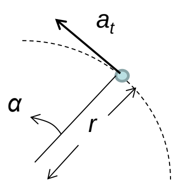
Where *M* is the moment, α is the angular acceleration, and *I* is a constant. Can we find *I* in terms of *m* the mass of the point/object?

Whirly skating man



- Imagine our little man now with a pair of skates on.
- He is turning on the spot and his centre of mass isn't moving.
- Are there any forces involved?

Acceleration of a single particle in an arc



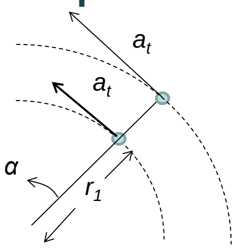
Imagine a particle of mass *m* that was attached to thin massless rod that had a tangential acceleration of a_t.
We now have an expression for the mass moment of inertia *I* of a single particle.

$$a_t = r\alpha$$

$$F_t = mr\alpha$$

$$M = F_t r = mr^2\alpha$$

Acceleration of multiple particles in an arc



Imagine 2 particles of mass *m* attached to thin massless rod that had an angular acceleration of *α*.

$$a_t = r\alpha$$

$$F_t = mr_1\alpha + mr_2\alpha$$

$$M = F_t r = mr_1^2\alpha + mr_2^2\alpha$$

Or more generally,

$$M = \sum mr^2.\alpha$$

$$I = \sum m_i r_i^2$$

Radius of gyration

Mass tells us about the amount of material in a body and Moment of inertia tells us something about how that mass is distributed. Sometimes it is convenient to imagine a point mass equivalent to the total mass of the body at a certain distance from the centre of rotation that gives rise to an equivalent moment of inertia. This distance is the radius of gyration. The mathematical equivalent to this statement is given below:

$$I_0 = \sum m_i r_i^2 = mk^2$$

where m_i is the point masses,

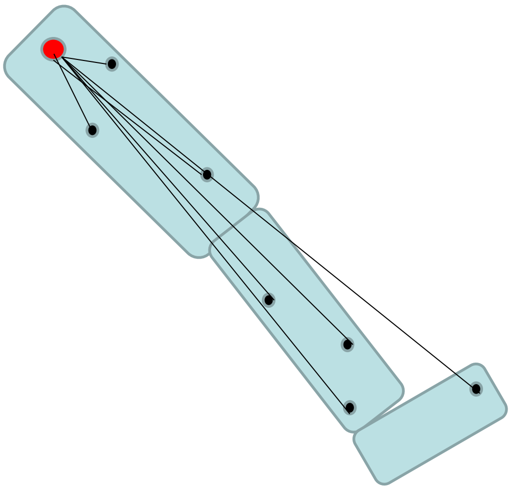
m is the total mass and k is the radius of gyration

Moment of Inertia (a rotational equivalent to mass)

The moment of inertia of a body is a measure of the rotational inertia of the body. It reflects how hard it is to start a body rotating about a given axis or how hard it is to stop an object when it is rotating.

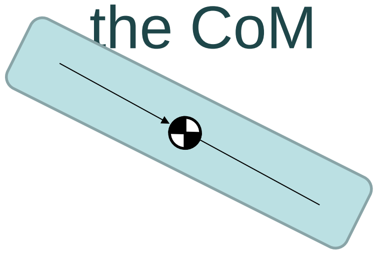
Bodies can be considered to be made up of tiny masses (m_1, m_2, etc) each at a distance r_1, r_2, etc from the given axis of rotation.

Mass moment of inertia



Study the figure – what does the mass moment of inertia depend upon

Mass moment of Inertia and the CoM



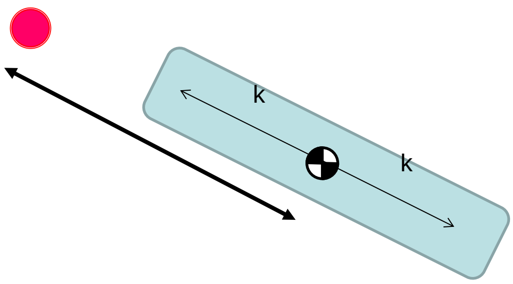
The minimum mass moment of inertia of a rotating object is when the axis of rotation passes through the CoM. Under these circumstances and for convenience we sometimes describe the segment as having an equivalent radius, *k*, the radius of gyration

$$I_0 = \sum m_i r_i^2 = mk^2$$

where m_i is the point masses,

m is the total mass and k is the radius of gyration

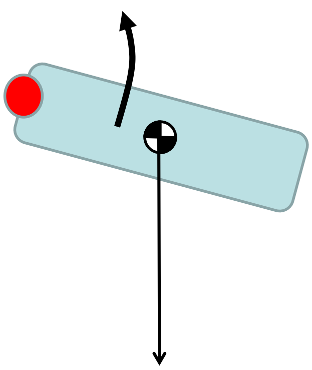
Parallel Axis Theorem



$$I = I_0 + mc^2$$

$$I = mk^2 + mc^2$$

How do I calculate a moment in a moving limb

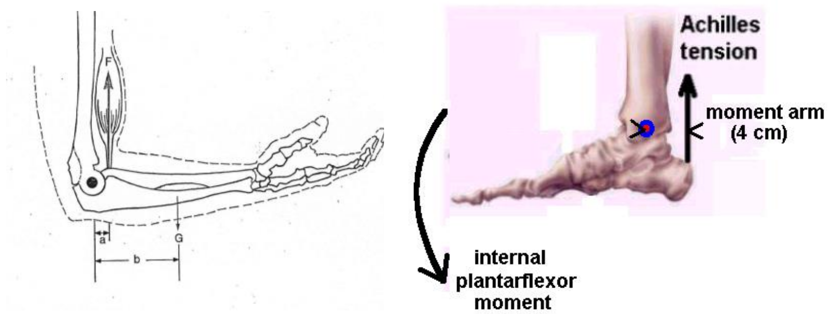


What are joint moments?

- What muscles generate around joints.
- What causes the body to move but…

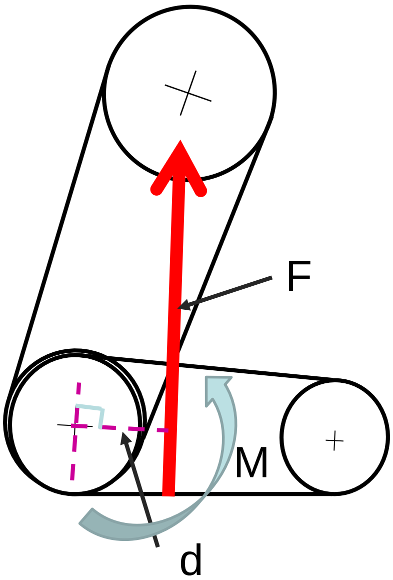
  …the movement of all the segments is determined by all the joint moments.
- Very difficult to relate the moment to any particular joint angle without a computer model to do it for you.
- They can help us to understand a patients movement difficulties.

Muscles produce moments



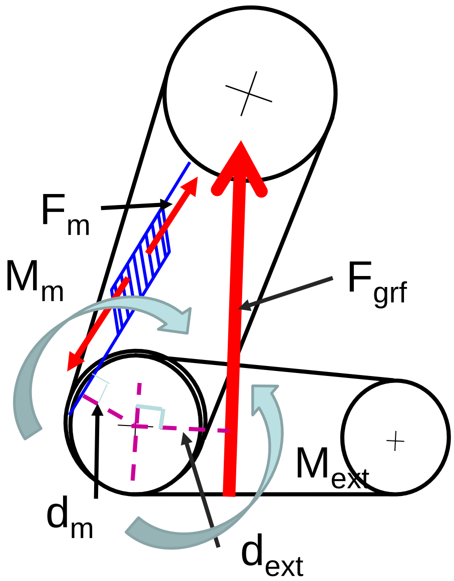
In static equilibrium, the internal moment generated by the muscles must be equal and opposite to the moments produced by the external loads.

Moment (M) = Force (F) x Distance (d)



- The moment (or torque) around a joint = The ground reaction force x the perpendicular distance between the joint centre and the force vector.

Muscles generate moments

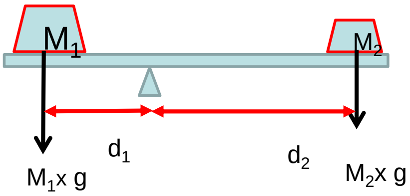


- Muscles oppose the action of the ground reaction force and overcome inertia to move our body segments.
- But how do muscles create moments (torques) at joints?
- $F_{grf} \times d_{ext} = F_m \times d_m$

Balance of moments in static equilibrium

- In static equilibrium around a joint the sum of the moments equal zero otherwise there would be inertial accelerations of the body segments around the joint.

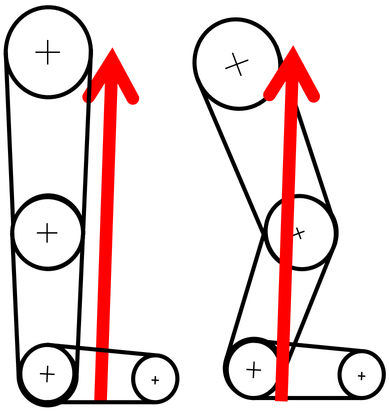
$F_{grf} \times d_{ext} = F_m \times d_m$



$M_1 x\ g\ x\ d_1 = M_2\ x\ g\ x\ d_2$

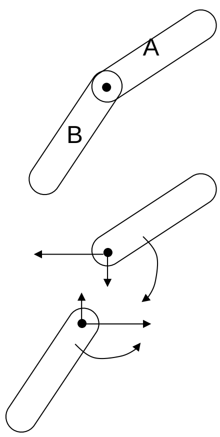
You do the analysis!

- What positions are the joints in?
- What is the ground reaction force doing at each joint (is it trying to flex or extend the joint)?
- How could I work out the size of the torque (moment) at each joint?
- Which muscle groups are opposing its action?



- The GRF projection method is limited because it does not fully account for the moments (torques) produced by the inertial accelerations of the body segments. For a more accurate estimate of joint moments, one needs to perform *inverse dynamics.*

Reaction Forces and Moments at a Joint

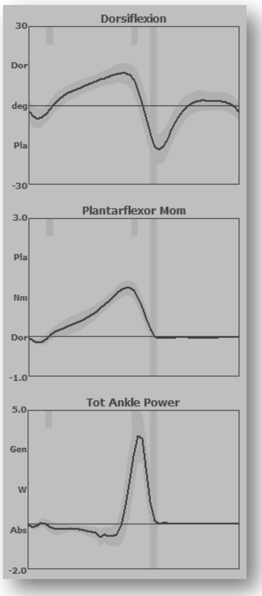


To do *inverse dynamics,* one must have an appreciation of Newton's 3rd law. For every *action*, there must be an equal and opposite *reaction*.
For a connected body, the force acting on B by A through the joint is equal and opposite to the force acting on B from A.
The moment of force produced by A around the joint is equal in magnitude and opposite in direction to the that produced by B

Agonist & Antagonist Contributions

- Joint moments tell us about the contributions of all the muscles about the joints.
- They tell us nothing about amount of co-contraction.

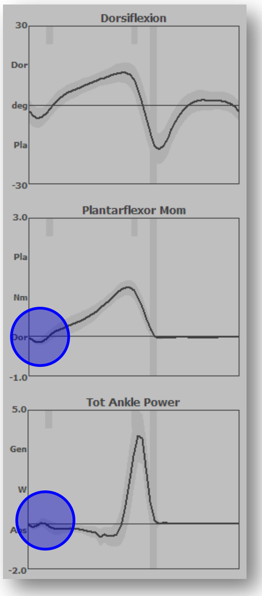
Calculating joint powers



- Find angular velocity (slope of joint angle)
- Multiply by moment

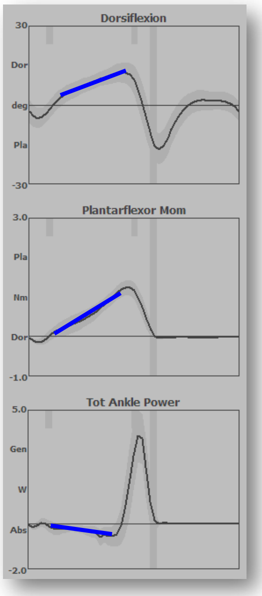
- If both are in same sense then power is generated by motor.
- If in opposite sense then power is absorbed.

Angular velocity x moment



- If moment is small then power must be small (regardless of angular velocity)

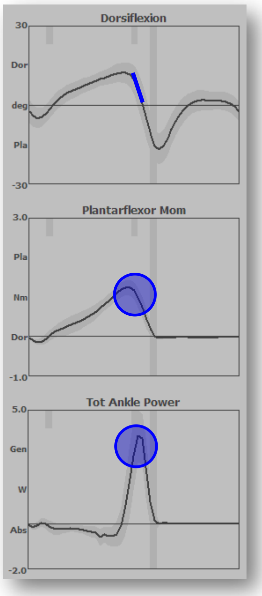
Angular velocity x moment



- Slope constant (but mild)
- Moment increasing
- Power mild but increasing in magnitude

- Because there is increasing dorsiflexion but a plantarflexion moment

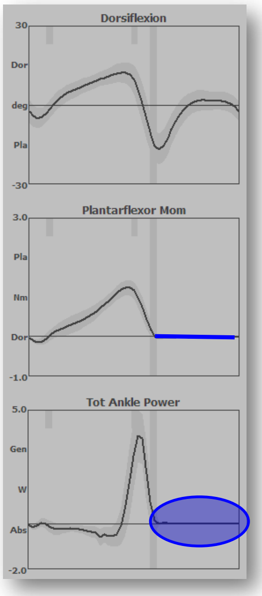
Angular velocity x moment



- Slope steep
- Moment large
- Power large

- Because there is increasing plantarflexion with a plantarflexion moment the power is generated

Angular velocity x moment



- Moment Zero
- Power zero whatever the angular velocity