(i) Understanding the gait cycle, as it relates to the foot

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Abstract
The gait cycle is outwardly something complex, which seems difficult to grasp. This really isn’t the case and with a few relatively simple facts to understand it can be easily understood. The purpose of this article is to try and break this complex process into a series of comprehensible steps. The gait cycle is defined and its major components are then described.

The key is understanding how the foot can be both a flexible and then a rigid structure in different parts of the gait cycle. This is a function of the subtalar and especially the midtarsal joints. We also look at how the plantar fascia plays a part too.

Finally we look at how the cycle may be altered in various clinical scenarios. Which we hope will be of general use but especially to trainees taking final professional examinations.

Keywords gait cycle; midtarsal joints; plantar fascia

Introduction
Gait and topics related to it are clearly important in understanding orthopaedic conditions in the lower limb and their treatment. It is therefore no surprise that this remains an important topic in final professional examinations, such as the UK FRCS(Tr&Orth) examination.

The authors are a candidate currently sitting the FRCS(Tr&Orth) examination and a senior FRCS(Tr&Orth) examiner. They have teamed up to explain what they feel are the important aspects of this subject.

We both hope that it will be of interest to candidates taking the FRCS(Tr&Orth) examination as well as consultants and other practitioners with an interest in the lower limb, especially foot and ankle conditions.

Anatomy and kinematics
We are all familiar with the anatomy of the foot and lower limb, which in the most basic concept is a bony arch. It is quite clearly not a static arch as it can be either flexible or rigid and it can readily adapt to the surface of the ground underneath.

When one stands on tiptoe, the hindfoot inverts, the midfoot is plantar-flexed and the forefoot pronates slightly so there is an arch visible medially. Similarly, if one stands with one’s foot flat on the ground and the leg externally rotated, one will see the medial arch rise and rotating the leg internally reverses this effect. This simple process of going up and down on tiptoes involves a number of concepts that need to be understood, which are key to understanding the gait cycle and its clinical applications.

There are passive and active mechanisms at work in standing up and down on tiptoe. The active ones are easy to understand; arising from the action of muscles. The passive ones are perhaps more obscure and are a largely a function of four structures:

1. the subtalar joint,
2. the transverse tarsal joint,
3. the midtarsal joints, and
4. the plantar fascia.

Subtalar joint motion
The talus is a bone without any muscle attachments — rather like the scaphoid in the wrist. It lies on top of the calcaneus and is stabilized by ligaments and surrounded by tendons. Inversion and eversion occur at this joint and one way to consider how this may occur is by viewing the facets of this joint as being like an Archimedes screw or spiral (Figure 1a and b). This is a right-handed screw on the right side, and vice versa on the left. On the right hand side with clockwise rotation of the screw one sees hindfoot inversion distally and...
tibial external rotation proximally. This mechanism begins to explain how the arch changes shape but not how the foot changes from being compliant to rigid and load bearing. In understanding this we have to look to the midtarsal joints.

**Midtarsal joints**
The calcaneocuboid and talonavicular joints make up the transverse tarsal joint, which is also known sometimes as Chopart’s joint. Mann and Inman in 1964 looked at these joints and described parallel axes through the talus and calcaneus (Figure 2). These axes, called the talonavicular and calcaneocuboid axes, are in the frontal plane. When the foot is in eversion the axes are parallel, motion within the midtarsal joint can occur, and the midfoot is mobile. When the heel is inverted these axes are no longer parallel and motion at these joints is blocked. Inversion and eversion of the hindfoot occurs at the immediately proximal subtalar joint via muscle action and the shape of the subtalar joint facets.

These mechanisms within the subtalar and midtarsal joints help us understand at a basic level how the foot manages to be both rigid and flexible during gait. It also begins to explain some clinical aspects, for instance why patients tolerate a pronated or flat foot better than one that is supinated or varus, as in the cavus foot.

**Tarso-metatarsal joints**
The tarso-metatarsal joints are also known as the Lisfranc joint. In cross-section these joints are shaped somewhat like a Roman arch (Figure 3), with the second metatarsal deeply recessed into the midfoot. This renders the second metatarsal rigid compared to the others.

In 1953, Hicks demonstrated that when the first ray is either plantar-flexed or dorsiflexed, the other lesser metatarsocuneiform joints move less. Thus, when standing on tiptoe the intrinsic structure of the tarso-metatarsal joint and the plantar-flexion of the first ray give further stability to the foot. This is reversed when the foot is not loaded and is in neutral alignment.

**Plantar fascia**
The plantar fascia attaches to the calcaneum and extends forward as a band-like structure to attach to the plantar aspect of the proximal phalanges of the toes. This results in a structure resembling a bow (as in bow and arrow), where the bones are represented by the bow itself and the fascial band is the bowstring. This in some texts is called a truss, with the fascial band being a tether.

One can immediately see that this bow-like structure forms an ideal shock absorber. However, the plantar fascia can function in another way and for this we can consider the model of the so-called Spanish windlass (Figure 4). As the metatarsophalangeal joints extend, the plantar fascia is tightened and the distance between the calcaneus and metatarsal heads shortens. This, via the mechanism described by Hicks, locks the midtarsal joints and also brings the heel into slight varus, which, via the subtalar joints, locks the transverse tarsal joint.

The metatarsophalangeal joints are arranged in a cascade, with the second metatarsal usually being the longest and the fifth the shortest. The so-called ‘metatarsal break’ is the line joining
the individual articulations. One can see as one moves higher on tiptoe that the plantar fascia will steadily tighten as one rolls from the medial to the lateral part of the foot. This is due to the orientation of the metatarsal break. Therefore, one can see clearly that surgery on the metatarsals or plantar fascia can potentially have a negative effect on foot function.

In summary, these largely passive mechanisms control the shape and thereby the function of the foot and we have some explanation as to how the foot can be both rigid and flexible.

**The gait cycle**

By convention we think of a ‘single cycle’ as the motion between heel strike of one foot to the heel strike of the same foot on the subsequent step. Thus, during this one cycle the foot can either be off the ground (otherwise known as swing phase) or on the ground (the so-called stance phase). The stance phase makes up approximately 60% of the gait cycle, with swing phase occupying 40%.

In the normal individual this cycle is a fluid motion, but again by convention we divide the stance part of the cycle into three phases; otherwise referred to as ‘intervals’ or ‘rockers’:

1. **First interval**
   - From heel strike to foot flat
2. **Second interval**
   - With foot flat — the body is passing over the foot
3. **Third interval**
   - From the heel lifting off the ground to toe-off

**First interval**

As the heel makes contact with the ground the ankle rapidly flexes so the foot is flat. This ankle motion is controlled by the anterior muscles, which contract eccentrically. The posterior muscles are electrically quiet at this time.

The foot is loaded and the heel goes into eversion, which is a passive process, and this in turn (via the subtalar joint and transverse tarsal joints) allows the foot to go flat. This phase is mostly centred around the absorption of the forces generated by the heel strike.

**Second interval**

During this time the body’s centre of gravity is passing over the foot. The ankle joint dorsiflexes and the heel rises. It is in this phase that the changes within the foot from a flexible to a rigid structure occur.

The subtalar joint is at the centre of this change and there are several factors that come into play. Which of these might be the most important is not known but they include the external rotation of the tibia proximally, which is brought about by the contralateral swinging limb. This external rotation, as we have previously discussed, brings the subtalar joint into inversion, which in turn locks the transverse tarsal joints.

As the forefoot is planted on the ground, the subtalar inversion is passed distally in the foot and serves to make the mid-tarsal joints more stable via the mechanism that Hicks described.

Various muscles have shown to be active during this phase including the triceps surae, tibialis posterior, flexor hallucis longus, flexor digitorum longus and the intrinsic muscles within the foot.

**Third interval**

The ankle begins rapid plantarflexion, which is brought about by the posterior muscles, primarily the triceps surae. As the foot bears the weight, the intrinsic foot muscles remain active so as to stabilize the longitudinal arch. The main stabilizer at this point is in fact the plantar fascia. The Spanish windlass effect comes into play, with the toes dorsiflexing at the metatarsophalangeal joints and so tightening the plantar fascia.

The subtalar joint will continue to invert during this interval too, reaching maximal inversion at toe-off. The inversion at this joint is again largely driven by the limb above continuing to externally rotate, but this is enhanced by the plantar fascia’s role as well as other factors such as the obliquity of the axis of the ankle joint and the orientation of the lesser metatarsophalangeal joints. The inversion holds the transverse tarsal joints in a stable position, keeping the foot rigid until toe-off.

When a series of cycles is observed, as for example when observing a patient walk, there are various other displacements of the body as a whole. For instance, as one goes through a single gait cycle the trunk will rise at toe-off at the end of the third interval and lower at the point of heel strike at the beginning of the first interval. The pelvis, hip and knee as well as the foot modulate vertical displacement.

Similarly, with gait there are not only vertical displacements but also rotatory movements too. The shoulders and pelvis rotate as well as the femur and tibiae. The tibiae rotate about their long axes: in the swing phase and early part of stance phase they rotate internally, and in the later part of stance they rotate externally (during the third interval of stance phase).

Finally, when walking the body oscillates from side to side; this is thought to be to try and keep the centre of gravity over the weight bearing foot. This can be noticed by walking with a broad based stance and conversely reduced by walking with the feet close together.

When running, there is no period in the gait cycle when both feet are on the ground at the same time. As the pace quickens the time the foot spends on the ground gets less both in time and as a percentage of the overall gait cycle.

**Clinical application of the gait cycle**

As we have mentioned, the gait cycle is from heel strike of one foot to heel strike of the same foot and happens in a little over one second. Clinical evaluation of gait requires a systematic approach and the following aspects need to be considered.

1. **Presence of pain — localization of pain and identification of the phase of painful gait.**
2. **Look for the base i.e. how wide or narrow the stance is.**
3. **Look for changes in the stride — is it even or uneven and cadence i.e. asymmetry.**
4. **Observe the shoulder levels for either dipping or elevation.**
5. **Observe the trunk for lurch, or a fixed tilt.**
6. **Observe the pelvis for any obliquity or raise or drop.**
7. **Look at the attitude of the hip, knee and foot in the various phases of gait. Are any of these exhibiting a fixed position?**
8. **Observe the foot for altered heel strike and toe-off.**

This is quite difficult to do in the context of examinations but the first two points one can gather before the patient starts moving by asking where the pain is and observing how far the feet are spaced apart. Thereafter is a matter of observing the whole patient, from the shoulder to the foot.
The painful hip
The commonest abnormal gait pattern seen is from a painful hip, referred to as an antalgic gait. The main changes seen include a decreased time in stance phase, to offload the painful hip. One observes the following:
- Lurching of trunk to affected side in stance phase,
- Dipping of shoulder on the affected side,
- Elevation of the shoulder on the opposite side and
- Shifting of the pelvis on affected side.

The effect of these actions is to move the body's centre of gravity closer to the affected hip, which reduces the stresses across the joint. In swing phase the hip is often held in flexion, abduction and external rotation. The heel strike is 'soft', again to prevent excess loading of the joint.

The painful knee
Painful conditions of the knee usually lead to it being held in a flexed attitude during swing and stance phase and leads to compensatory avoidance of heel strike and toe walking.

Flexion contractures of more than 30° are usually apparent with normal walking whereas contractures of less than 30° become pronounced with faster walking.

In posterolateral instabilities one can see a varus thrust gait occurring in the stance phase. Similarly, in varus osteoarthritis of the knee one can see a valgus thrust, this is thought to arise from a concomitant weakness of the lateral structures including the iliobibial band.

The so-called 'quadriceps avoidance gait' is seen in ACL injuries because the quadriceps provides an anterior force to the tibia that could lead to anterior subluxation of the tibia. This gait is characterized by avoidance of loading the limb by decreasing the stride length and avoiding knee flexion during the second interval of stance.

Knee contractures can cause a short leg gait, with toe walking on the affected side and a 'stepping gait' or 'hip hiking gait' on the opposite side.

Leg length discrepancy
With shortening less than 1.25 cm, the stance phase of the gait is characterized by dipping of the shoulder and pelvic drop onto the affected side, with elevation of the shoulder on the opposite side. With shortening of more than 3.5 cm, tiptoeing on the affected side with full knee extension during stance phase is observed. To clear the contralateral leg that is comparatively longer, the patient usually compensates by circumduction, hip hitching or a hip stepping gait.

Neurological problems and gait
There is a wide array of neurological conditions that may affect gait, and the commonest are discussed below.

Gluteus medius weakness (Trendelenburg) gait: in this gait there is a pelvic drop on the affected side, along with a lateral bend of the trunk over the affected hip and a dropping of the shoulder on the affected side. This effectively moves the centre of gravity nearer to the affected hip and hence decreases the muscle force required to stabilize the pelvis. The affected leg can also be functionally longer and to compensate for this there might be an increase in hip flexion, knee flexion and ankle dorsiflexion (so-called high stepping gait) to aid toe clearance.

Gluteus maximus weakness: this leads to a backward lurch of the trunk, with the shoulders held backwards just after heel strike on the affected side. This keeps the centre of gravity posterior to the hip joint, locking the hip in extension and compensating for the hip extensor weakness.

Quadriceps weakness: this leads to loss of extension of the knee at heel strike. This is compensated for by trunk flexion, creating an extension moment at the knee. Some patients use their hand to support the upper thigh and to extend it e.g. post-polio weakness (hand to knee gait).

Ankle dorsiflexor weakness: this leads to a drop foot or high steppage gait. In mild or moderate weakness the heel strike to foot flat phase is quite rapid. In severe weakness the foot will fall into plantarflexion and heel strike is lost and instead the foot lands onto the toes. This causes relative lengthening and is compensated for by a high steppage gait on the affected side.

Ankle plantar flexor weakness (ruptured tendo-Achilles): heel lift-off is delayed and toe push-off is decreased, leading to shortening of the stride on the contralateral side to accommodate the delay of the forward movement of the ipsilateral hip.

A flexion moment is created posterior to the knee that might lead to buckling of the knee due to altered ground reaction forces.

Spastic gait: this can be seen in cerebral palsy, leading to a crossed limb or scissoring of the lower limbs due to over-activity of the hip adductors. The base is narrow or even crossed. The actual gait depends on the specific muscle group involvement in this condition.

Foot and ankle pathology
In general, in painful foot conditions the stride length is shortened and normal heel-to-toe motion is lost. With painful pathology affecting the ankle joint and hindfoot, heel strike is avoided, leading to a tiptoeing gait on the affected side. In conditions affecting the forefoot, plantarflexion and toe-off will be avoided.

A very tight tendo-Achilles will result in loss of heel contact and heel-to-toe motion. There will be compensatory exaggerated hip and knee flexion in swing phase, to clear the foot off the ground. A tight tendo-Achilles might lead to hyperextension of the ipsilateral knee in stance phase due to an extension moment caused at the knee by the plantarflexion of the ankle.

Generally, a flat foot is better tolerated than a cavus foot because with a cavus foot there is heel varus, leading to locking of the transverse tarsal joints, resulting in decreased flexibility of the foot.

The cavus foot: this deformity has several aetiologies, the commonest being Hereditary Motor Sensory Neuropathy (HMSN) or Charcot Marie Tooth Disease. The latter is not to be confused with Charcot Disease, seen in neuropathic (including diabetic) feet.

The deformity is usually very obvious and a key question to ask is whether or not the subtalar complex is mobile; the relevance being that if a deformity is fixed then most likely a corrective osteotomy or fusion will have to be considered, whereas if a deformity is mobile then conservative treatment or lesser soft tissue surgery along with joint preserving surgery may
be possible. The key to this question is answered using the Coleman block test. This is performed by observing the heel from behind and noting its position. One then places a (wooden) block of about 2.5 cm thickness under the lateral part of the foot, leaving the first ray free. If the subtalar complex remains mobile then the hindfoot will adopt a neutral or even valgus position.

The flat foot: the commonest condition to consider here, both in clinical practice and in professional examinations, is tibialis posterior tendonitis. In general, and as mentioned previously, the flat foot is more forgiving because the subtalar complex (and in particular the midtarsal joints) is maintained in an unlocked position. The heel strike will involve the lateral aspect of the calcaneum, the second interval will involve a significant collapse of the medial arch and the third interval will be near normal. This is related to the windlass mechanism of the plantar fascia. As the body moves forward the plantar fascia rolls around the extending metatarsophalangeal joints and swings the heel into a more varus or neutral position.

One can sometimes see this clinically where a patient with tibialis posterior insufficiency cannot initiate a single leg heel raise but can maintain a single leg heel raise position from a double leg stance on tiptoe.

What position should the hindfoot be fused in?

Discussion of the different elements of the gait cycle, as they apply to the foot, leads on logically to consideration of the ideal positions in which fusions in the foot/ankle should be performed if one is to maintain as good function as possible.

Ankle fusion

A number of different planes need to be considered: first, the most important point to consider is the varus/valgus position. If the ankle is fused in too much varus, the subtalar joint will remain in inversion and so lock the transverse tarsal joint. The second interval of the stance phase of the gait cycle will be adversely affected, as the body will pass over the flat foot with difficulty.

Rotation should also be considered. If, for instance, the ankle is fused in excessive internal rotation, then when the centre of gravity passes over the foot within the second interval of stance phase there will be increased stress on the subtalar joint and in the midtarsal area. If on the other hand the ankle is fused in too much external rotation, the patient will push-off during the third interval of stance phase with the medial border of the foot. This places extra stresses around the 1st MTPJ and over time this may lead to a hallux valgus type deformity.

The third plane to consider is the degree of dorsiflexion or plantarflexion that the ankle is fused in. If the ankle is fused in too much plantarflexion, this makes the fused limb functionally longer and can lead to a backward knee thrust, an uneven gait and increased stresses within the midfoot joints. Conversely if the ankle is fused in too much dorsiflexion, this makes heel strike at the beginning of the first stance interval uncomfortable and will affect the other two phases too.

Therefore, the best position in which to fuse the ankle is in neutral dorsi/plantarflexion, neutral rotation and approximately 5° of valgus, to ensure that there is mobility in the subtalar joint.

Even if an ankle is fused in an ideal position, the fusion will still affect the gait cycle. Looking at the three stance intervals, heel strike to foot flat is clearly going to be affected. This can be helped in some patients by cutting a wedge from the heel to allow a smoother contact of the foot with the ground. The second interval is also affected as the body cannot easily pass over the flat foot. However, many patients exhibit an increase in sagittal plane mobility from the un-fused joints. Thus, the first two phases of stance may be slightly shortened and the third phase should largely be unaffected if there some valgus within the hindfoot and there is increased mobility from the other joints.

Other hindfoot fusions

Triple fusion refers to fusion of the subtalar, calcaneocuboid and talonavicular joints. As we have seen, these joints function as a unit and fusion of one will inevitably affect the function of the others.

In performing a solitary subtalar fusion, one must take care to fuse in around 5° of valgus. The reason is as before, to allow the midtarsal joints to be mobile; they will unlock doing the first and second intervals and lock out later in the third interval from the action of the plantar fascia.

The same is largely true of coalitions, notably talo-calcaneal coalitions.

In the case of triple fusion, again a position of slight valgus is preferred, although if excessive this will lead to degenerative change within the ankle joint above.

Conclusions

The key messages are:

- Gait involves a swing and stance phase.
- Stance phase is made up of three intervals.
- The key to understanding how the foot goes from being a complaint to a rigid structure lies within the structure of the subtalar and midtarsal joints.
- The plantar fascia plays an important role.
- From here, most clinical situations encountered at the level of the FRCSOrth examination can be understood. One should remember that a varus or cavus foot is stiff whereas a flat or planus foot is pliable.

REFERENCES


FURTHER READING