Normal human locomotion*
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Abstract
A study of normal locomotion requires an understanding of both the movements and the force actions involved. This is equally true in appreciating the problems of pathological gait.

The gait cycle is described in terms of the significant events which occur during both the stance and swing phases.

The basic principles underlying the analysis of force actions in walking are briefly described. A simple example of force actions in the elbow joint is considered and the analysis extrapolated to provide a general statement regarding locomotion. This relates to the muscle actions required to resist turning actions at joints due to the force effects in walking and the corresponding forces in the joints themselves.

The conventional display of information relating to joint actions is considered and compared with the actual situation. "Stick diagrams" of motion in the sagittal plane are used to identify and discuss the actions at the joints of the leg in walking. Comparisons are made between this and pathological gait—in particular that of the above-knee amputee.

Introduction
Normal human locomotion is the rather grand term given to the description of walking by individuals who fall within the range considered as "normal". It is a highly individual and variable activity influenced by age, sex, body build, physical condition, temperament, fatigue and many other less obvious factors. Despite this enormous variability there are characteristic actions which are common to all forms of "normal human locomotion". An understanding of these will facilitate not only a study of normal locomotion itself, but also the analysis of the problems of pathological gait.

As this paper is one of a series concerned with the problems of the above-knee amputee, it will be appropriate to identify any factors which are particularly useful in improving our understanding of above-knee amputee gait. It will also be the intention to consider the interpretation of information which is conventionally displayed in describing locomotion.

The gait cycle
The act of locomotion is typified by a number of events which occur in a rhythmic, repetitive pattern. Figure 1 provides a visual display of the events in the "gait cycle", i.e. the period which starts the instant one foot contacts the ground and proceeds through the process of walking until the instant the same foot again contacts the ground. The gait cycle is composed

of two separate sections—the stance phase, when the foot is in contact with the ground and the swing phase, when the foot and leg are swinging forward to be placed in front of the body to begin another cycle. The stance phase accounts for about 60% of the cycle at normal walking speed, reducing as the walking speed is increased.

The stance phase is itself subdivided by a number of events—heel strike, when the heel contacts the floor; foot flat as the sole of the foot comes into contact with the ground; mid-stance when both ankles are in apposition; heel-off, when the heel leaves the ground; toe-off when the foot loses ground contact. The period between heel-off and toe-off is known as push-off, when the ankle is very actively plantar flexed.

The swing phase is typified by three events—acceleration, which is the period of acceleration of the foot forward in space; mid-swing, when both ankles are in apposition and coinciding with mid-stance on the other foot; deceleration, when the foot is being slowed down preparatory to placing on the ground to begin another stance phase.

Double support periods occur when two feet are in contact with the ground at the same time. There are two such periods in every gait cycle—between heel-off and toe-off on one side and heel strike and foot flat on the other. The faster the speed of walking, the less time is spent in double support. Indeed, in athletic terms, the definition of walking is that double support is maintained, otherwise the subject is running.

**Force effects**

Some basic understanding of force effects is essential to the study of locomotion. Force can have two effects—translation and rotation. If a force system is in equilibrium, all of the translational and rotational effects must balance.

In human body terms, the significance of this may be appreciated with reference to Figure 2, which shows a static situation in which a subject holds a 10 kg mass in his hand. It is of interest to identify the force actions produced at the elbow joint.

The rotational effect of a force is known as the moment of the force and is equal to the magnitude of the force multiplied by the perpendicular distance from the line of action of the force to the point of rotation. In the example, if rotational effects about the elbow joint are considered, the mass of the forearm and hand (which is assumed to be 1.4 kg) and the mass held in the hand (10 kg) are producing moments tending to extend the elbow. If the arm is in equilibrium, the bicep must produce a flexion moment which is equal to this. Noting that:

\[ F_b = \text{Force in the biceps} \]
\[ F_J = \text{Force in elbow joint} \]

A mass of 1 kg exerts a force of 9.81 Newtons due to gravity.

Then:
\[ F_b \times 50 = 9.81 \times 1.4 \times 120 + 9.81 \times 10 \times 360 \]
\[ : F_b = 739 \text{ Newtons} \]

Considering then the translational effects, it is seen that the forearm and hand and the mass held in the hand exert downward forces of (1.4 + 10) 9.81 Newtons. Bicep exerts a force upward of 739 Newtons. For equilibrium there must be a force in the joint acting downward on the radius and ulna,

\[ F_J = 739 - (11.4 \times 9.81) = 627 \text{ Newtons} \]

In general when force actions are exerted on the body, they tend to produce turning effects or moments at joints. These turning effects are counterbalanced by turning effects produced by pull in appropriately placed muscles. The muscle forces are often much larger than the externally applied forces because lines of action
The joints of the lower limbs are subjected to external force actions in the process of walking. These force actions tend to cause moments at the joints which are resisted or controlled by muscle action. Normal walking is characterized by an ability to exert and control the appropriate muscle groups in accordance with the external force actions. Pathological gait arises from an inability to exert or control the muscle forces or the resulting joint forces.

In the lower limb the relevant external forces are due to the force between the foot and the ground; the force due to the mass of the segments of the limb; the forces due to inertia effects, i.e. due to the accelerations and decelerations of the limb segments. For most of the stance phase, by far the largest contribution is by the external force action between the foot and the ground.

Analysis of motion in the sagittal plane

Conventionally information on locomotion has been presented in the form of graphs of variation with time of angle and moment at the joints of the leg, such as in Figure 3, which displays this information for the knee joint. It is interesting to compare this clearly defined presentation with a composite graph of knee moments (Fig. 4) measured by Bresler, Frankel and Morrison (Paul, 1974). This demonstrates that although Figure 3 displays a characteristic pattern, wide variations do exist as might be expected. Conventional locomotion data is useful, but must be treated with an understanding that it presents a distillate of a widely varying reality.

A useful approach to presenting a composite picture of the force actions and muscle activities at the joints of the leg utilizes "stick diagrams" and identifies the situation at significant points throughout the gait cycle as shown in Figures 5 to 13, inclusive. Only the force action between ground and foot is considered during stance as this is the major action—the mass of the leg and inertia effects are neglected.
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Fig 5. Heel strike

Reaction:
Anterior to hip causing flexion moment. Anterior to knee causing extension moment. Posterior to ankle causing plantarflexion moment.

*Hip* is flexed to 25°. The gluteus maximus and hamstrings are active in preventing further flexion.

*Knee* is in full extension at heel strike. The extension moment is overcome by action of the hamstrings which controls knee extension and initiates flexion.

*Ankle* is in neutral position then begins to plantarflex. This plantarflexion is controlled by action of the pretibial muscles.

Fig. 6. Shortly after heel strike

Reaction:
Anterior to hip causing flexion moment. Posterior to knee causing flexion moment. Posterior to ankle causing plantarflexion moment.

*Hip* is held in 25° of flexion by action of gluteus maximus and the hamstrings.

*Knee* is in 5° of flexion and continues to flex. The rate of flexion is controlled by action of the quadriceps.

*Ankle* is in 5° of plantarflexion and continues to plantarflex under the control of the pretibial muscles.
Fig. 7. Foot flat

Reaction:
Anterior to hip causing flexion moment.
Posterior to knee causing flexion moment.
Posterior to ankle causing plantarflexion moment.

Hip is in 25° of flexion then begins to extend
by action of gluteus maximus and the hamstrings.

Knee reaches 15° of flexion and continues to flex until it reaches 20° shortly after foot flat.
It then begins to extend. The quadriceps are active in controlling the angle of flexion.

Ankle is in 10° of plantarflexion. The plantarflexion moments reduce as the reaction moves
along the foot and the pretibial muscle activity falls off. As the ground reaction passes anterior
to the ankle joint the segments of the supporting limb begin to rotate over the fixed foot.

Fig. 8. Mid stance

Reaction:
Passes through hip joint, no moment.
Posterior to knee causing a flexion moment.
Anterior to ankle causing dorsiflexion moment.

Hip is in 10° of flexion and continues to extend as the ground reaction moves posterior
to the hip joint shortly after mid stance.

Knee reaches 10° of flexion and continues to extend. Quadriceps action has fallen off and it is
suspected that the soleus is active in controlling knee flexion.

Ankle 5° of dorsiflexion and continues to dorsiflex due to ground reaction. The dorsiflexion
is controlled by the calf group of muscles which begins to display activity.
Fig. 9. Heel off

Reaction:
Posterior to hip causing extension moment. Anterior to knee causing extension moment. Anterior to ankle causing dorsiflexion moment. 

*Hip* reaches about 13° of extension then begins to flex. The iliacus and psoas major are active in controlling extension and initiating flexion.

*Knee* is flexed to about 2°, which is the maximum extension reached at this point in the gait cycle. The gastrocnemius may be active in preventing further extension.

*Ankle* reaches 15° of dorsiflexion after which it plantarflexes due to a powerful contraction of the calf muscles which counteracts the dorsiflexion moment and assists in propelling the body forward.

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Fig. 10. Toe-off

Reaction:
By toe-off the reaction has lost most of its significance as the majority of weight is borne by the other foot.

*Hip* is in 10° of extension and continues to flex due to the plantarflexion of the foot and activity of the rectus femoris.

*Knee* is flexed to about 40° and continues to flex under the small ground reaction moment and plantarflexion of the foot.

*Ankle* has reached 20° of plantarflexion due to contraction of the calf muscles. These muscles become inactive directly after toe off.
Fig. 11. Acceleration

*Hip* is in 10° of extension and flexes as the hip flexors accelerate the limb forward.

*Knee* is in 40° of flexion and continues to flex under pendulum action as the limb accelerates.

*Ankle* is in 20° of plantarflexion directly after toe off. It then begins to dorsiflex under action of the pretibial group of muscles.

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Fig. 12. Mid swing

*Hip* is flexed to about 20° and continues to flex.

*Knee* reaches about 65° of flexion then begins to extend under pendulum action.

*Ankle* has reached its neutral position and is held there by slight activity of the pretibial muscles.
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**Fig. 13. Deceleration**

The importance of combining motion and force studies may be appreciated by considering Figure 6 which displays the situation shortly after heel strike. In this situation the ankle is plantar flexing; however, the pretibial muscles are active not the plantar flexors. This is because the force action exerted on the foot in this position is tending to plantar flex the foot and consequently the pretibial group must act to produce a resisting dorsiflexion moment, thus controlling the movement. Note that absence of the ability to exert this controlling moment, as in hemiplegia would produce a pathological gait observed as “foot slap”. Similarly at the knee, although the knee is flexing, it is the knee extensors which are active because the external force is tending to produce flexion. It can be seen then that movement studies alone provide insufficient information from which to infer the required muscle actions and this is essential to an understanding of normal or pathological gait.

**Amputee gait**

Similar considerations govern all aspects of above-knee amputee gait. The moment action at prosthetic joints will determine the resisting moment which must be applied by that joint. In the example cited above at Figure 6, the plantar flexion moment at the ankle would be resisted by the plantar flexion rubber or “bumper”. The moment action at the knee, however, in the case of a single axis knee without a stance phase stability mechanism would lead to flexion of the knee with consequent collapse of the amputee as there are no knee muscles to exert an extension moment. In this situation it would be necessary to ensure that the force actions were tending to extend the knee, a force effect which could be resisted by the extension limiter. This could be achieved, for example, by placing the knee centre posteriorly behind the line of action of the external force, thus changing the moment action from that of flexion to extension. Such consideration and the other alternatives will be presented in a subsequent paper on the biomechanical considerations related to the above-knee amputee and his prosthesis.

*Hip* reaches 25° of flexion and is restrained by gluteus maximus and the hamstrings.

*Knee* is in full extension and restrained by the hamstrings.

*Ankle* is still held in the neutral position by action of the pretibial muscles.

The hip, knee and ankle are now positioned for the following heel strike. All the muscle groups that are necessary to counteract the ground reaction force are now active.
BIBLIOGRAPHY


UNIVERSITY OF CALIFORNIA. (1947). Fundamental studies of human locomotion and other information relating to design of artificial limbs. Prosthetic devices research project, Berkeley, California. 2 Vols.