BIOMECHANICS OF HUMAN GAIT CONCEPT IN A PROSTHETIC FOOT

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ABSTRACT

This paper describe the primary purpose of lower extremity prosthetic devices is to facilitate ambulation. The attributes of how a person ambulates through the assessment of gait is one of the most studied of all human movements. Although standardized terminology to describe events of the gait cycle do not exist, a widely used nomenclature for describing gait was developed, to understand the characteristics of a prosthetic foot/ankle mechanism, it is important to relate them to a normal foot. To do this, it is also important to understand clinically oriented anatomical terminology also major joints of the human foot include.

INTRODUCTION :

Inhabitants of developing countries suffer from amputations arising from tragic accidents or illnesses at relatively high rates; civil wars, poor health care, and a high frequency of traffic accidents result in a large number of amputees. In an economy where most occupations require physical labor, the loss of a leg can have catastrophic effects on a person's life (Ellis et al 2010).The acquisition and maintenance of prosthetics takes a tremendous amount of resources not available to most people in such countries.

To accurately communicate information regarding the prescription, fabrication, and evaluation of prosthetic devices, one must appreciate the disparities that can arise because of differences in adopted terminology. This section of the course highlights potential areas for confusion in the terminology related to gait that warrant consideration, specifically clinical terminology, gait analysis, and the terminology of clinical biomechanics.

CLINICAL TERMINOLOGY

To understand the characteristics of a prosthetic foot/ankle mechanism, it is important to relate them to a normal foot. To do this, it is also important to understand clinically oriented anatomical terminology. Major joints of the human foot include:

- ankle joint (composed of the dome of the talus and distal aspect of the tibia and fibula),
- subtler joint
- transverse tarsal joint
- metatarsalphalangeal joints

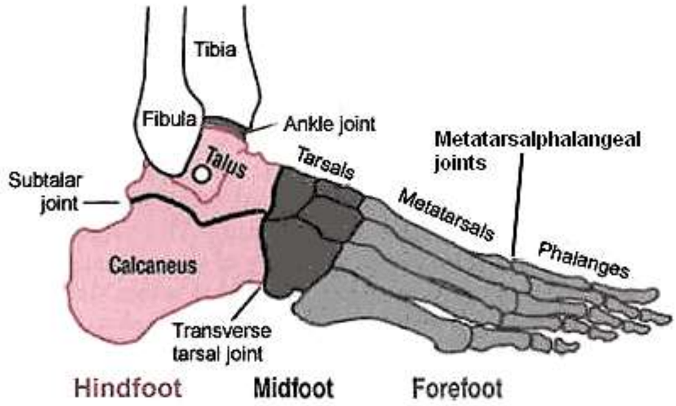

Figure : Schematic view of Human Toe part

Accordingly, movement of the foot generally is described by motion of the

- ankle
- hindfoot
- midfoot
- forefoot

In addition to motion through major joints, the foot has a strong aponeurosis that connects the calcaneus to the forefoot and upholds an arch.

Ankle Joint
Sagittal plane plantar/dorsi flexion occurs through the ankle joint.

Hindfoot
The hindfoot generally is considered responsible for transverse and coronal plane rotations. When the hindfoot inverts, the rest of the foot rolls onto the outer border of the foot as it supinates. When the hindfoot everts into valgus, the forefoot pronates, increasing weight bearing on the first ray.

Midfoot
The midfoot contains the transverse tarsal joint. This group of articulations translates motion between the hindfoot and the forefoot.

Forefoot
The forefoot contributes to these motions by rotating along the longitudinal axis of the foot. Forefoot motion in the transverse plane has been described as inversion or eversion.

Prosthetic foot designs do not replicate exact characteristics of a normal human foot. Current prosthetic feet demonstrate some of the desired characteristics effectively but remain lacking in others.

THE GAIT CYCLE:

The periodic motion of walking is referred to as the \gait cycle." It is of great importance that the act of walking must be thoroughly studied in order of get complete understanding of the human lower limb prosthetics. Walking is basically series of repeating events in which weight is being transferred between the two legs. Cycle of events happening on one leg during walking is termed as the gait cycle. The gait cycle is further divided into the following events of the limb. The stance period shown above is basically the period of time that the foot is on the ground where as the swing period is the period of time in which the foot is in the air for limb advancement. These periods are further divided as shown in the diagram

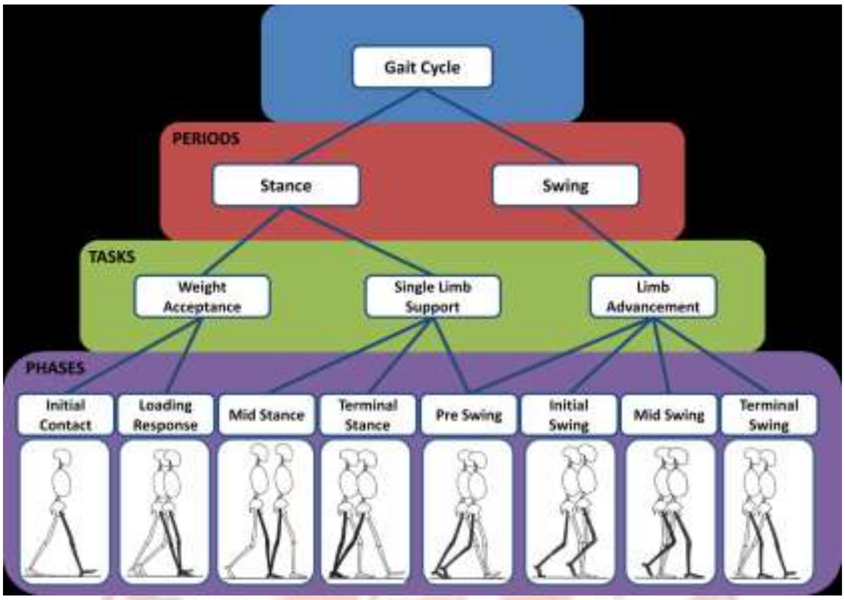

Figure : Gait Cycle

The gait cycle can be broken down into eight phases:

- Initial contact
- Loading response
- Midstance
- Terminal stance
- Pre swing
- Initial swing
- Mid swing
- Terminal swing

Initial contact

- Represents the beginning of the stance phase

Loading response

- Occupies the first 10% of the gait cycle which is also the period of initial double-limb support.
- The foot comes in full contact with the floor, and body weight is fully transferred onto the stance limb.

Midstance

- Represents the first half of single support, 10% to 30% of the gait cycle.
- Begins when the contralateral foot leaves the ground (opposite toe-off)
- The body weight travels along the length of the foot until it is aligned over the forefoot.

Terminal stance

- Represents the second half of single-limb support, 30% to 50% of the gait cycle,
- Beginning with heel rise and ending when the contralateral foot contacts the ground.
- During this phase the body weight moves ahead of the forefoot.

Preswing

- The terminal double-limb support period occupying the last 12% of stance phase (50% to 62% of the gait cycle).
- This phase begins when the contralateral foot contacts the ground and ends with ipsilateral toe-off.
- The stance limb is unloaded and body weight is transferred onto the contralateral limb.

Initial swing

- Represents one-third of the swing period, from 62% to 75% of the gait cycle.
- It begins the moment the foot leaves the ground (toe-off or terminal contact) and continues until maximum knee flexion occurs, when the swinging extremity is directly under the body and directly opposite the stance limb.

Midswing

- Occurs in the second third of the swing period, from 75% to 85% of the gait cycle.
- This phase begins after maximum knee flexion and ends when the tibia is in a vertical position.

Terminal swing

- Represents the final phase, from 85% to 100% of the gait cycle,

Occurs when the tibia passes beyond perpendicular and the knee fully extends in preparation for foot contact.

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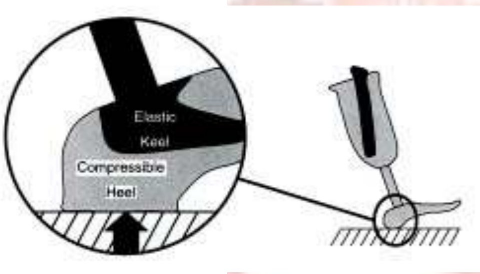
-Kinematic parameters of gait represent the linear and angular displacements, velocities, and accelerations that a subject produces when they walk.

-Kinetic studies can be conducted when external forces applied to the body are measured and limb segment properties such as mass, mass moments of inertia, and center of mass locations are estimated. External forces (such as the ground reaction forces), typically are measured using force plates. Net joint moments are calculated via an inverse dynamics solution of the link segment model.

APPLICATION OF GAIT CONCEPT IN A PROSTHETIC FOOT:

For lower limb amputees, prosthetic foot-ankle complex is very critical in order to complete the lower limb mechanics. The two main components of this complex are the heel and the keel. These two components play a key role for energy storage and energy return in a prosthetic foot. Generally, the heel functions as an energy-absorbing component, when the limb strikes the ground at initial contact whereas the Keel functions as a stable surface for position and, in some prostheses, as a propelling mechanism to push the amputee into the next step of gait.

(a)



(b)

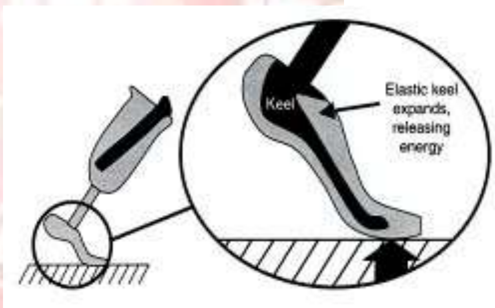
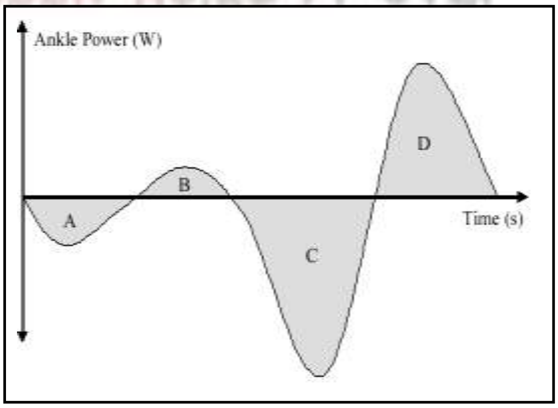


Figure : Heel strike during Walking phase



(c)

Figure : Energy Stored and Return during Walking phase

Figure 1.3(a) shows the compression of the heel when a load is applied on the prosthesis. As the amputee moves forward the heel starts to unload and the keel loading begins, Figure 1.3(b). This entire process can be studied more efficiently using an ankle-power graph in Figure 1.3(c):

Ankle Power; A = energy stored in heel, B = energy returned by heel, C = energy stored in keel, D = energy returned by keel, $\sum_A^D$ = total energy (Hafner et al. 2002)

The area shown under each curve corresponds to energy stored and energy returned. Ankle Power graphs is generated using a complex set up that consists of several cameras and a force plate (White et al., 2000). This equipment records a person walking at a normal speed with a natural gait and measures the velocity the person, and the forces applied to the force plate. Power can be calculated for different points in time in the following manner:

1) $Energy = F * \Delta d$ 2) $Energy = P * \Delta t$ 3) $P * \Delta t = F * \Delta d$ 4) $P = F * \frac{\Delta d}{\Delta t}$

$\frac{\Delta d}{\Delta t} = v$ (Definition of velocity)

Therefore

$$P = F * v$$

In order to accomplish this, five different properties need to be studied: energy storage, energy return, dissipated energy, efficiency, and total energy. Current analysis methods commonly consider only one of these properties and these methods do not work well. Below are several types of foot that score highly for one property, but are still inadequate (Hafner et al., 2002).

- ‘High Efficiency’ Foot- A high efficiency prosthesis has low energy storage and therefore low energy return. Such prosthesis would be considered stiff and uncomfortable as it will not have a shock absorbing capacity.
- ‘High Energy Storage’ Foot- With good energy storage, but low efficiency prosthesis would have low energy return and high energy loss. This prosthesis would be difficult to use, as it would require a large energy input from the amputee to make up for the energy lost.
- ‘High Energy Return’ Foot- A prosthesis with good energy return and a low efficiency, will have extremely high energy storage and energy loss. Such prosthesis would have too much deflection and would not be practical.
- ‘High Total Energy’ Foot- A prosthesis with high total energy due to energy storage, and low energy return, would have low efficiency, and therefore high energy loss.This prosthesis would require a large energy input from the amputee to make up for the lost energy.

CONCLUSIONS DRAWN FROM ENERGY RETURN AND GAIT ANALYSIS:

Both the heel and the keel of the prosthesis must be considered separately since each has different optimal properties. The heel is responsible for the majority of the shock absorption during initial impact, a high level of energy storage is important. Unfortunately, the energy return from the heel is only useful if it can be transmitted to the keel. Most of the energy returned by the keel is used to propel the patient's leg forward during the swing phase of gate, making keel energy storage and energy efficiency important factors (Hafner et al., 2002).

Hafner et al. (2002) proposed a new analysis system. Their method reports energy storage and energy return for both the heel and the keel. With these four properties, any of the other three properties can be calculated using the equations below:

Energy Return = (Energy Storage)*(Efficiency)

Energy Loss = (Energy Storage)*(1 - Efficiency)

Total Energy = (Energy Storage)*(1 + Efficiency)

Table : Prosthesis Analysis and Activity Level from Hafner et al. (2002)

Heel Energy Storage	Heel Efficiency	Keel Energy Storage	Keel Efficiency	Walking Speed			Sports Activities		Other Properties	
				Slow	Moderate	High	Running	Uneven Terrain	Shock Absorption	Increased Simulated ROM
High	High	High	High		X	X	X			X
High	Low	High	High		X	X	X		X	X
High	Low	Low	High	X	X				X	
High	Low	High	Low	X	X			X	X	X
High	Low	Low	Low	X	X				X	
High	High	High	Low							
High	High	Low	High							
High	High	Low	Low							

■ = Not suitable prosthesis' ; ROM = Range of Motion; X = Well Suited

Using these four properties, Hafner et al. (2002) created an analysis chart (see Table 1. 2) that can be used to rank different types of prosthetic feet and to select an appropriate prosthesis to accommodate the activity level of the patient. In addition, Hafner et al. (2002) claimed that the final three combinations of heel-keel energy storage and efficiency listed on the table were not suitable for a working prosthesis.

This analysis method will be used to compare our final design to currently available prosthesis. Energy storage and energy efficiency will be calculated from data obtained from the Instron.The table above only provides relative measurements for energy storage and efficiency (i.e. High and Low). It does not provide information on what optimal energy storage and efficiency are, or what values of energy storage and efficiency are considered "high" or "low".

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