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KINEMATICS OF THE GAIT OF AN INDIVIDUAL RUNNING WITH A BELOW THE KNEE AMPUTATION WEARING THE FLEX-FOOT™ AND THE SACH FOOT

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[signature]
Major professor

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KINEMATICS OF THE GAIT OF AN INDIVIDUAL RUNNING WITH A BELOW THE KNEE AMPUTATION WEARING THE FLEX-FOOT™ AND THE SACH FOOT

By

Doreen Marie Espinoza

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ABSTRACT

KINEMATICS OF THE RUNNING GAIT OF AN INDIVIDUAL WITH A BELOW THE KNEE AMPUTATION WEARING THE FLEX-FOOT™ AND THE SACH FOOT

By

Doreen M. Espinoza

The purpose of this study was to analyze the gait patterns of running of an adult with a below the knee amputation and compare kinematic variables of the lower extremity limbs while the participant wore the SACH foot and Flex-Foot™. The subject was an active adult male with a traumatic below the knee amputation on his left side, which occurred 1.4 years before this study was conducted.

Data were collected of activity history, anthropometric measurements, and kinematic variables, collected on two separate occasions to film both prosthetic appliances separately. The kinematic data collection consisted of video taping three running strides for each self selected velocity of slow, medium, and fast, for each lower extremity limb. Comparisons were made between the participant of this study and able bodied individuals, between the anatomical and prosthetic limbs, and between the prosthetic appliances.

The participant's pattern of running for the anatomical limb was of similar pattern to that found with able bodied individuals. The participant increased his velocity of running in a manner similar to that of able bodied individuals. Also, when the participant wore the Flex-Foot™, the individual was able to achieve gait patterns more similar to what has been found with able bodied individuals, than when he wore the SACH foot. And finally, there was excessive prosthetic limb knee joint hyperextension during the stance phase when either the SACH foot or the Flex-Foot™ were worn.

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Chapter I

Introduction

Sports participation by individuals with a below the knee amputation (BKA) can provide the same physiological, psychological, and sociological benefits as does sports participation for the able bodied population. Yet, Kegel, Webster, and Burgess (1980) found that 40% of the surveyed individuals with a BKA did not participate in exercise activities. Some of the stated reasons were a lack of information provided by prosthetists and therapists regarding recreational prosthetic feet and a lack of recreational organizations for amputees.

Overview of the Problem

Running is the basis of many sports and provides the foundation for velocity, power, and agility (Williams, 1985). However, running can be the most difficult one to acquire due to discomfort (Kegel, Webster, & Burgess, 1980; Michael, 1990) and gait asymmetry. Causes of the discomfort and/or asymmetry may include poor prosthetic foot alignment (Hannah & Morrison, 1984), the type of prosthetic foot, stump-socket friction, excessive weight of either the prosthesis or the individual, perspiration, fear of falling, an inability to achieve sufficient velocity, and the individual's familiarity with running (Enoka, Miller, & Burgess, 1982).

Several of the causes outlined above may be overcome by the use of advanced prostheses. An energy storing prosthetic foot may help compensate for the loss of motor functioning of the lower limb, more specifically the foot limb and the ankle joint (Czerniecki, Gitter, & Munro, 1991a). Also, many of the energy storing prosthetic feet have been found to be lighter in weight, better in shock absorption, greater in range of motion (Menard, McBride, Sanderson, & Murray, 1992; Menard & Murray, 1989) , and more efficient (Ehara, Beppu, Nomura, Kunimi, & Takahashi, 1993) than conventional prosthetic feet.

Need for the Study

Therapists, educators, and recreational personnel who work with individuals with a BKA need more information about patterns of running movement and how such patterns may change with different prosthetic feet. Such information may provide insight into factors that affect the comfort level amputees experience while running and may provide information about both prosthetic capabilities and rehabilitation practices.

Limited research has been conducted on the running gait patterns of individuals with a BKA. While some researchers included energy storing prosthetic feet (Czerniecki, et al., 1991a; Lehmann, Price, Boswell-Bessette, Dralle, Questad, & deLateur, 1993; Prince, Allard, Therrien, & McFadyen, 1992; Smith, 1990) only two included the popular Flex-Foot™, but neither reported the kinematic data (Czerniecki, et al., 1991a; Lehmann, et al., 1993). Given the fundamental sport component of running, there was a need to further understand the adaptations that are made by individuals with a BKA, relative to able bodied gait and relative to different prosthetic feet. Such information may provide therapists with information regarding the kinematic patterns of running gait and may alter therapeutic practices. Although the Flex-Foot™ is popular among several active amputees (Michael, 1987), it has not been extensively studied in active settings. Technical aspects of running could be improved by knowledge of the movement patterns of individuals with a BKA. Additionally, such knowledge may enable recreational personnel and physical educators to design appropriate programs, have realistic expectations, and provide appropriate instruction. In this way, the likelihood of beginning and continuing participation in vigorous physical activity might be enhanced.

Purpose

The primary purpose of this investigation was to study the gait patterns of the run of an adult with a BKA. Specifically, the purpose was to quantify kinematic variables of the lower extremity during running, while the participant wore each of the prosthetic feet, the SACH foot and Flex-Foot™. The movement patterns were quantitatively compared for stride characteristics, gait cycle characteristics, and greater trochanter vertical displacement. Comparisons were made between the SACH foot and the Flex-Foot™, for both the anatomical and prosthetic limbs, and between the anatomical limb and the prosthetic limb, for both the SACH foot and the Flex-Foot™. Phases of the gait cycle discussed in the hypotheses were illustrated in Figure 1. The angle conventions used in this study were relative to the angle measurements available within the Ariel Performance Analysis System (APAS) and are illustrated in Figure 2.

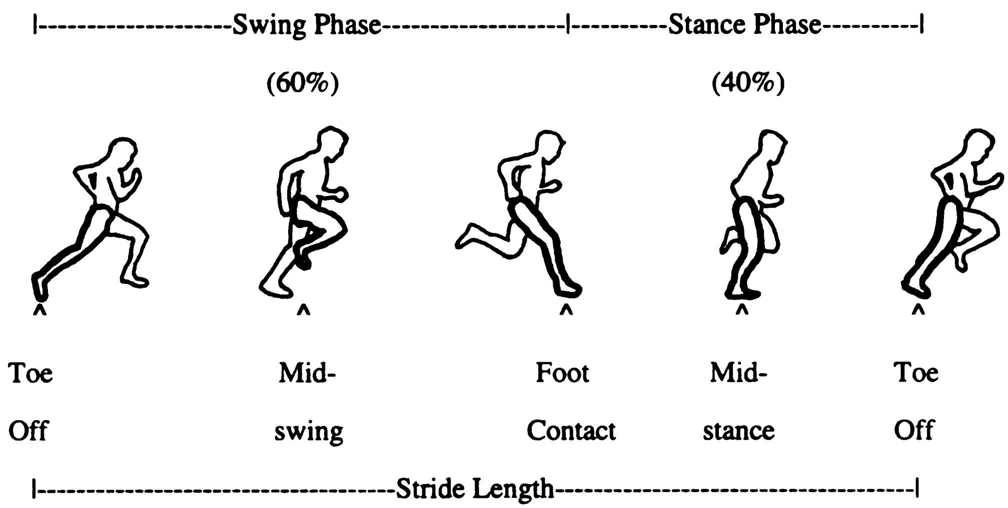

Figure 1. Phases of the running cycle.

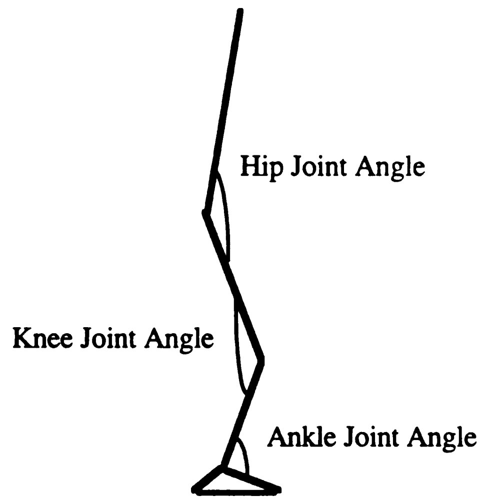

Figure 2. Angle conventions for the hip, knee, and ankle joints from the sagittal plane.

Hypotheses

Directional hypotheses were stated based on data from the literature of previous studies. The first ten of the eleven hypotheses were five pairs of comparisons of kinematic variables. Comparisons were made between the prosthetic feet and between the lower extremity limbs while wearing the different prosthetic feet.

The following hypotheses were tested in this study:

1. Stride length and stride rate will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.
2. Stride length and stride rate will be less for the prosthetic limb than the anatomical limb while wearing either the Flex-Foot™ or the SACH foot.
3. Stance phase will be less and swing phase will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.

4. Stance phase will be less and swing phase will be greater for the prosthetic limb than the anatomical limb while wearing either the Flex-Foot™ or the SACH foot.
5. Joint angular displacements of the hip, knee, and ankle will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs for their respective joints.
6. Joint angular displacements of the hip will be greater and the knee and ankle will be less for the prosthetic limb than for the anatomical limb, for their respective joints, while wearing either the Flex-Foot™ or the SACH foot.
7. Ranges of motion of the hip, knee, and ankle joints will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.
8. Ranges of motion of the hip, knee, and ankle joints will be less for the prosthetic limb than the anatomical limb, while wearing either the Flex-Foot™ or the SACH foot.
9. Angular velocities of the hip, knee, and ankle joints will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.
10. Angular velocities of the hip, knee, and ankle joints will be less for the prosthetic limb than the anatomical limb, while wearing either the Flex-Foot™ or the SACH foot.
11. The greater trochanter vertical displacement will be less while wearing the Flex-Foot™ than the SACH foot, for the prosthetic limb.

Limitations and Delimitations

The limitations to the study were:

1. As this was a case study, only one participant was included. Generalizability to any population was limited.

2. The participant was an adult. Children and youth may exhibit different gait patterns due to developmental differences.
3. The participant had a traumatic amputation and may have performed differently than someone with a congenital amputation or an amputation due to disease or tumor.
4. The endoskeletal shank of the SACH foot did not have an external covering (prosthetic skin) whereas the Flex-Foot™ had a foam covering. The addition of the prosthetic skin may have an affect on weight distribution and structural stability.
5. The runway length may not have provided sufficient space for the participant to achieve his/her normal running pattern.

This study was delimited by:

1. Only running gait was examined as the activity to identify the effect of different prosthetic feet on that pattern.
2. The study was a three-dimensional analysis in the sagittal plane.
3. The study was conducted in a laboratory setting providing a level surface.
4. A three-dimensional sagittal plane motion analysis of gait was performed in this study utilizing the APAS system. Three dimensional information obtained from this system for the primary plane is comparable to other three-dimensional systems.

Operational Definitions

Anatomical limb: The non-amputated/intact limb of an individual with a below the knee amputation.

Anatomical Flex (AF): The anatomical limb when the Flex-Foot™ was worn as the appliance.

Anatomical SACH (AS): The anatomical limb when the SACH foot was worn as the appliance.

Body center of mass: A point in the body which represent the balance point of that body. The point does not have to lie within the body.

Endoskeletal shank: The central tube, pylon, construction of the prosthesis between the prosthetic foot and the socket that makes up the shank component of the prosthesis.

Flex-Foot™: An energy storing prosthetic foot that is made according to client anthropometric data and activity level. The metal component extends from the socket and curves to the "foot" creating a backward "J" shape.

Foot contact (FC): The point in the gait cycle at which the foot of the swinging leg comes in contact with the ground. Foot contact marks the beginning of the stance phase (see Figure 1).

Joint angular displacement: The directional difference between initial and final angles of the joint.

Joint angular velocity: The rate of change of joint angular displacement.

Joint range of motion: The difference between the largest values of joint angle flexion and extension in the gait cycle.

Kinematic variables: Variables that describe motion. These variables include the linear and angular displacements, velocities , and accelerations of joint angles and body segments.

Midstance (MSt): The point in the stance phase when the shank is 90 degrees with the foot. Midstance divides the stance phase into deceleration and acceleration phases (see Figure 1).

Midswing (MSw): The midpoint of the swing phase.

Percent of height: Conversion of a measure in absolute units to that of a measure in relative units, percentage of body height.

Prosthetic Flex (PF): The prosthetic limb when the Flex-Foot™ was worn.

Prosthetic SACH (PS): The prosthetic limb when the SACH foot was worn

SACH: Solid Ankle-Cushion Heel. The foot has no moving parts except a heel wedge that compresses at heel strike. The foot is attached to a metal pylon that extends to the socket.

Stance phase: The period of limb support from initial foot contact to toe off (see Figure 1).

Stride length: The distance between contact of one foot and that foot's second contact, measured from the same anatomical point on the foot (see Figure 1). Units of measurement were in percent of body height.

Stride rate: The number of strides taken in a given period of time. In this study, the unit of time was one second.

Suspension device: A component that holds a prosthesis in place while the individual ambulates. For may suspension devices, the femoral condyles serve as the attachment site.

Swing phase: The period of time a foot is off the ground. Swing phase is from toe off to foot contact of the same leg (see Figure 1).

Toe off (TO): The point in the gait cycle at which the toe of the supporting foot leaves the ground. It marks the end of the stance phase.

Chapter II

Literature Review

Many researchers including biomechanists, physical therapists, and physicians (Czerniecki & Gitter, 1992; Czerniecki, Gitter, & Munro, 1987a; Czerniecki, Gitter, & Munro, 1991b; Czerniecki, Munro, & Gitter, 1987b; Engsberg, Lee, Patterson, & Harder, 1991; Engsberg, Tedford, & Harder, 1992; Lewallen, Dyck, Quanbury, Ross, & Letts, 1986; Menard, et al., 1992; Waters, Perry, Antonelli, & Hislop, 1976) have studied gait patterns of individuals with a below the knee amputation (BKA) by comparing gait parameters of that population with gait parameters of able bodied individuals. Understanding the basic biomechanics of able bodied running gait is necessary before attempting to analyze the running gait pattern of an individual with a BKA. Thus, this literature review is divided into three sections. The first section contains a review of the gait kinematics of able bodied runners, the second section includes a discussion of the gait kinematics of runners with a BKA, and the final section reviews the prosthetic feet included in this study.

Kinematics of Able Bodied Running Gait

Body segment motions are described by the kinematic variables of linear and angular displacements, velocities, and accelerations (Winter, 1990). This section will include a review of stride characteristics, gait cycle, and center of mass vertical displacement of able bodied adults.

Stride Characteristics

Running velocity is the result of the interaction of two variables, stride length, and stride rate (Enoka, 1988; Hay, 1985). To increase velocity, an individual must increase one parameter without negatively affecting the other (Hay, 1985), or alter both stride rate and stride length (Saito, Kobayashi, Miyashita, & Hoshikawa, 1974). However, the degree of contribution from each parameter is related to the velocity of motion. That is, stride length assumes a greater role at lower velocities, while stride rate is the more dominant variable at higher velocities (Dillman, 1975; Hoshikawa, Matsui, & Miyashita, 1973; Luhtanen & Komi, 1978).

Several researchers have found a relationship between velocity of running and the support and nonsupport phases. As velocity of running increased, the time spent in the support phase decreased. The decrease in support phase was in both the relative time, as a percentage of the total stride time (Bates, Osternig, & Mason, 1978; Mann, 1986; Mann & Hagy, 1980), and the absolute time (Hoshikawa, et al., 1973; Luhtanen & Komi, 1978). The changes in the nonsupport phase, with increased velocity, have not been as conclusive. Elliott and Blanksby (1976) found that nonsupport time increased with increased running velocity, while Luhtanen and Komi (1978) reported only slight decreases in nonsupport time when velocity increased.

Gait Cycle

The running cycle consists of four phases: stance, swing, and two flight phases (Adelaar, 1986; Mann, 1982). These phases were discussed in separate sections although this author recognizes that running is a continuous movement .

Stance phase.

The stance phase consists of approximately 30% to 40% of the gait cycle (Adelaar, 1986; Mann & Hagy, 1980). During this phase, the lower limb has been found to be involved in shock absorption, joint stabilization, and propulsion (Mann, 1982; Winter, 1980). The shock absorption occurs through flexion of the hip and knee joints, and ankle joint dorsiflexion. Joint stability is achieved by the activity of the muscles, ligaments, and tendons crossing the joints (Mann, 1982). During late stance, extension at the knee and hip joints, and plantar flexion at the ankle joint help achieve push off (Winter, 1980). The lower extremity joints ranges of motion reported during the stance phase were 55 degrees for the hip, 30 degrees for the knee, and 53 degrees for the ankle (Mann, Moran, & Dougherty, 1986).

At foot contact, lower extremity joint motions have been found to be extension at the hip, flexion at the knee, and dorsiflexion at the ankle (Elliott & Blanksby, 1979b; Mann, 1982; Mann & Hagy, 1980; Saito, et al., 1974). Body weight acceptance is achieved through these lower extremity motions during the deceleration phase (Elliott & Blanksby, 1979b; Mann, 1982; Saito, et al., 1974). The joint angles at foot contact have been reported to be between: 150 to 160 degrees for the hip (Elliott & Blanksby, 1979a; Frishberg, 1983); 150 to 163 degrees for the knee (Bates, et al., 1978; Dillman, 1970; Elliott & Blanksby, 1979a); and 84 to 101 degrees for the ankle (Mann, et al., 1986).

At midstance, the center of gravity has been found to travel in front of the stance foot (Mann, 1982). During the acceleration phase, when power is generated (Ounpuu, 1990), the motions of the lower extremity joints were found to be extension at the hip and knee joints, ankle joint plantar flexion, and external rotation at the pelvis (Bates, et al., 1978; Mann, 1982; Mann, et al., 1986; Montgomery, Pink, & Perry, 1994) .

At toe off, the propulsive force has been found to be generated through hip and knee joint extension, and ankle joint plantar flexion (Mann & Hagy, 1980; Saito, et al., 1974). The ankle angles at toe off have ranged from 105 to 115 degrees while running at 3.6 meters per second (Williams, 1993) .

The flight phase begins after toe off and consists of approximately 15% to 20% of the gait cycle (Adelaar, 1986; Mann, 1982; Mann, et al., 1986). Immediately after toe off, the hip joint was at maximum extension as was ankle joint dorsiflexion (Elliott & Blanksby, 1979b; Mann, et al., 1986).

Swing phase.

The swing phase consists of approximately 70% of the gait cycle (Adelaar, 1986; Mann, 1982; Mann, et al., 1986). Ranges of motion during the swing phase have been reported for the hip joint only and are 40 to 60 degrees at 3.3 and 4.8 meters per second, respectively (Mann, et al., 1986).

During the beginning of the swing phase, the swing limb knee continued to flex and the hip joint remained in extension (Mann, 1982; Mann & Hagy, 1980; Montgomery, et al., 1994). During the middle of the swing phase, the hip joint went into flexion and the knee continued to flex (Montgomery, et al., 1994). Maximum hip flexion of the swing leg took place when the stance limb toe off occurred (Mann, et al., 1986). During the maximum hip flexion, knee joint extension occurred and was caused by the forward thigh motion reversal (Brandell, 1973). This proximal-to-distal sequence of thigh and leg angular motion has been explained by Bunn (1972) as the summation of velocity principle, a principle supported by the recent work of Putnam (1991). The principle states that the distal segment velocity is due to the angular velocity of the proximal segment. The maximum distal segment velocity occurs after and is greater than the maximum proximal segment velocity. The explanation of distal segment velocity does not appear to be solely dependent on the muscle groups of the lower extremity (Putnam, 1991). In the late swing phase, prior to foot contact, the hip and knee joints began to extend (Mann, et al., 1986; Montgomery, et al., 1994), and the ankle joint continued dorsiflexion (Mann, 1982; Mann & Hagy, 1980) in preparation for foot contact.

Body Center of Mass Vertical Displacement

During running, the vertical displacement of the body center of mass oscillates with the change in limb positions. The center of mass oscillation has been found to be inversely related to velocity. For example, at slower velocities the vertical displacement of the center of mass has been found to be greater than at higher velocities (Luhtanen & Komi, 1978). The minimum vertical displacement of the body center of mass was during midstance

(Mann, 1982) when the hip and knee joints were flexed, and the ankle joint was in dorsiflexion (Mann & Hagy, 1980). The maximum vertical displacement of the body center of mass has been found to occur during the flight phase (Mann, 1982).

Summary

The following summary is a description of the sequence of movements that occur during one complete cycle of running and has been adapted from Mann (Mann, 1982) and Adelaar (Adelaar, 1986). The description begins at foot contact.

At foot contact, there was rapid extension of the hip joint, rapid flexion of the knee joint, and ankle joint dorsiflexion. There was progressive ankle dorsiflexion and knee flexion through midstance while the hip joint rapidly extended. During the second half of stance, there were hip and knee joint extensions, and rapid ankle plantar flexion which assisted in the propulsion of the body into the flight phase.

At the beginning of the flight phase, the leg, during the swing phase, flexed at the hip, exhibited passive knee flexion, and active ankle dorsiflexion of the swing limb. From the middle to the latter part of the swing phase, the active hip flexion and passive knee flexion peaked, followed by active knee extension, and rapid progressive dorsiflexion at the ankle joint continued. In late swing, just prior to foot contact, there was hip and knee joint extension, and ankle joint dorsiflexion in preparation for foot contact.

Lower body kinematics or running and motion of the body's center of mas have been presented. For the adult, there appeared to be a general agreement among many researchers that study these lower extremity movement patterns. Some of the uniform understanding may be explained by the amount of research that has been devoted to the able bodied population. Unfortunately, the same amount of research has not been devoted to the population of active individuals with a BKA.

Kinematics of Below the Knee Amputee Running Gait

Much of the biomechanical research on individuals with a BKA has focused on walking gait of adults (Culham, Peat, & Newell, 1984; Doane & Holt, 1983; Goh, Solomonidis, Spence, & Paul, 1984; Hannah & Morrison, 1984; Menard, et al., 1992; Murray, Hartvikson, Anton, Hommonay, & Russell, 1988; Powers, Torburn, Perry, & Ayyappa, 1994; Robinson, Smidt, & Arora, 1977; Seliktar & Mizrahi, 1986; Torburn, Perry, Ayyappa, & Shanfield, 1990; Wagner, Sienko, Supan, & Barth, 1987; Winter, 1988) and children (Colborne, Naumann, Longmuir, & Berbrayer, 1992; Engsberg, et al., 1992; Lewallen, et al., 1986; Schneider, Hart, Zernicke, Setoguchi, & Oppenheim, 1993; Zernicke, Hoy, & Whiting, 1985). Fewer studies have been published on running patterns of adults with a BKA (Czerniecki & Gitter, 1992; Czerniecki, et al., 1991a; Enoka, et al., 1982; Lehmann, et al., 1993; Miller, 1981; Miller, 1987; Smith, 1990) and children with a BKA (Brouwer, Allard, & Labelle, 1989; Engsberg, Lee, & Harder, 1993). Some of the research on individuals with a BKA have included the dynamic elastic response (DER) terminal feet in their analyses. Such feet are so named because of their ability to store and release energy, defined as the integration of power in the ankle joint during the stance phase (Ehara, et al., 1993). One prosthetic foot in particular, the Flex-Foot™ , has been reported to be perceived by users as being easier for walking (Macfarlane, Nielsen, Shurr, & Meier, 1992; Menard & Murray, 1989), jogging, and dancing (Menard & Murray, 1989) than the conventional SACH, or two other DER feet; the Seattle and the Uniaxial prostheses.

The Flex-Foot™ has been shown to have a higher efficiency ratio, which is the ratio of released energy to stored energy, and higher total energy, the sum of the released and stored energy, relative to the SACH (Ehara, et al., 1993). Although the Flex-Foot™ had the highest energy values, Ehara et al. (1993) indicated that for walking participants preferred a foot that absorbed a large amount of energy. Such findings possibly indicated that low energy storing appliances are preferred for daily living activities, while higher energy storing prosthetic feet are preferred for sports activities. Yet, given its preference and energy storing capabilities, few researchers (Czerniecki, et al., 1991a; Czerniecki, et al., 1987b; Lehmann, et al., 1993) have investigated the Flex-Foot™ during running gait.

Due to the limited literature on the kinematic gait patterns of running while wearing the Flex-Foot™, the focus of this review shall be on the SACH foot and two other DER feet, the Energy Storing Carbon Fiber (ESCF) and the Greissinger. The ESCF, like the Flex-Foot™, is an energy storing foot. Both feet provide stability in medial and lateral motion and neither foot allows for pronation, supination, eversion or inversion of the foot. But, the ESCF has a fixed ankle mechanism, whereas the Flex-Foot™ has a flexible ankle mechanism. The Greissinger foot is heavier than the Flex-Foot™, but both are used for recreational activities. The greatest difference between these two appliances is that the Greissinger foot allows for pronation, supination, eversion, inversion and transverse rotation of the foot (Michael, 1987).

The following review section focuses on the kinematics of running for adults with a unilateral BKA. Unless indicated otherwise, the researcher(s) of each cited study found that participants were able to attain a running cycle, but the gait pattern was found to be asymmetrical.

Stride Characteristics

Miller (1981) conducted one of the first biomechanical investigations of running patterns of adults with a BKA. Although many of the participants had limited running experience prior to the study, almost 70% attained a running cycle. Enoka et al. (1982) had similar results with 60% of the adult participants attaining a running pattern. Both Miller (1981) and Enoka et al. (1982) noted that participants increased their running velocity through an increase in stride rate only, which differed from individuals without amputations who increased running velocity through changes in both stride rate and stride length (Enoka, et al., 1982; Saito, et al., 1974).

Enoka et al. (1982) proposed that the increase in stride rate reflected an unwillingness of an individual with a BKA to alter stride length beyond what was perceived as reasonable and within safe limits. Lehmann et al. (1993) found that when compared with the SACH, participants who wore DER feet had a longer prosthetic midstance phase and a shorter prosthetic push off but were not able to increase their subsequent anatomical stride length. That finding was not what Lehmann et al. (1993) expected to find, which was that better prosthetic push off would demand a longer anatomical limb stride length. They explained such findings by stating that "...the differences in construction of terminal feet are not great enough to increase the stride length on the sound side" (Lehmann, et al., 1993, p. 1230).

Enoka et al. (1982) further elaborated on the increased stride rate with increased velocity. The time of non-support remained essentially constant across velocity for the anatomical stride but the non-support time increased with velocity for the prosthetic stride. Smith (1990) also found that the single support phase of the prosthetic limb decreased when participants wore a DER foot, as compared with the SACH foot. Thus, with increased velocity (up to 8.2 meters per second) the amputated side became progressively more active than at the slower velocities (Enoka, et al., 1982). Such finding may indicate that running activities may be better suited to the frequency response of the DER prostheses (Smith, 1990).

Gait Cycle

The following discussion of the lower extremity movement patterns has been divided into stance and swing phases. Within each division, the order of discussion is of the anatomical limb followed by the prosthetic limb patterns.

Stance phase.

Knee and ankle movements of the anatomical limb are similar to those of a non-amputee, indicating that ankle dorsi- and plantar flexion, and knee flexion and extension, interact in a coordinated manner (Enoka, et al., 1982). Immediately following heel strike, the anatomical ankle was dorsiflexed followed by plantar flexion and knee flexion through midstance. At approximately 35% of the gait cycle, the ankle movement reversed to plantar flexion in preparation for push off (Enoka, et al., 1982; Smith, 1990).

Anatomical knee flexion occurred during the deceleration phase, indicating a controlled lowering of the body. At midstance, the knee joint reversed direction to extension in preparation for push off (Enoka, et al., 1982; Miller, 1981; Miller, 1987; Smith, 1990). Participants with little or no running experience did not initiate toe off on the anatomical side until after initiation of knee flexion on the same side (Enoka, et al., 1982). At the anatomical hip, there was an initial flexion pattern through early stance and then direction reversed to extension and continued to toe off (Smith, 1990).

Ankle motion of the SACH foot is limited to the deformation of the heel and toe bumpers and therefore has limited dorsi- and plantar flexion abilities (Enoka, et al., 1982; Smith, 1990) (see Figure 3). Lehmann et al. (1993) found the SACH ankle range of motion was less than either the Seattle foot , the Flex-Foot™ or the anatomical limb. However, all the prosthetic feet had a smaller ankle range of motion than the anatomical side. The SACH and Greissinger foot had similar ankle angles at foot contact and toe off (Miller, 1987), although Enoka et al. (1982) found the Greissinger foot allowed a slightly greater degree of passive ankle joint dorsiflexion. These ankle patterns during stance reflected the passive nature of the artificial feet and the absence of plantar flexion musculature (Miller, 1987). The motion of the ankle while wearing the Energy Storing Carbon Fiber (ESCF) foot, appeared to have patterns which were similar to the anatomical limb than to the SACH foot (Smith, 1990) (see Figure 3).

Individuals with a BKA with little running experience and those wearing the SACH foot, exhibited knee extension during the initial portion of the prosthetic support phase (Czerniecki, et al., 1991a; Enoka, et al., 1982; Miller, 1981; Smith, 1990). Although the action of knee extension is regarded as a concern due to the inability of the lower extremity to act sufficiently as a shock absorber, Miller (1981) believed that through training and prosthetic modification, the knee extension tendency might be eliminated. Some individuals wearing either the Greissinger or the SACH foot, displayed similar thigh and knee angular displacement patterns to those individuals without amputations. They

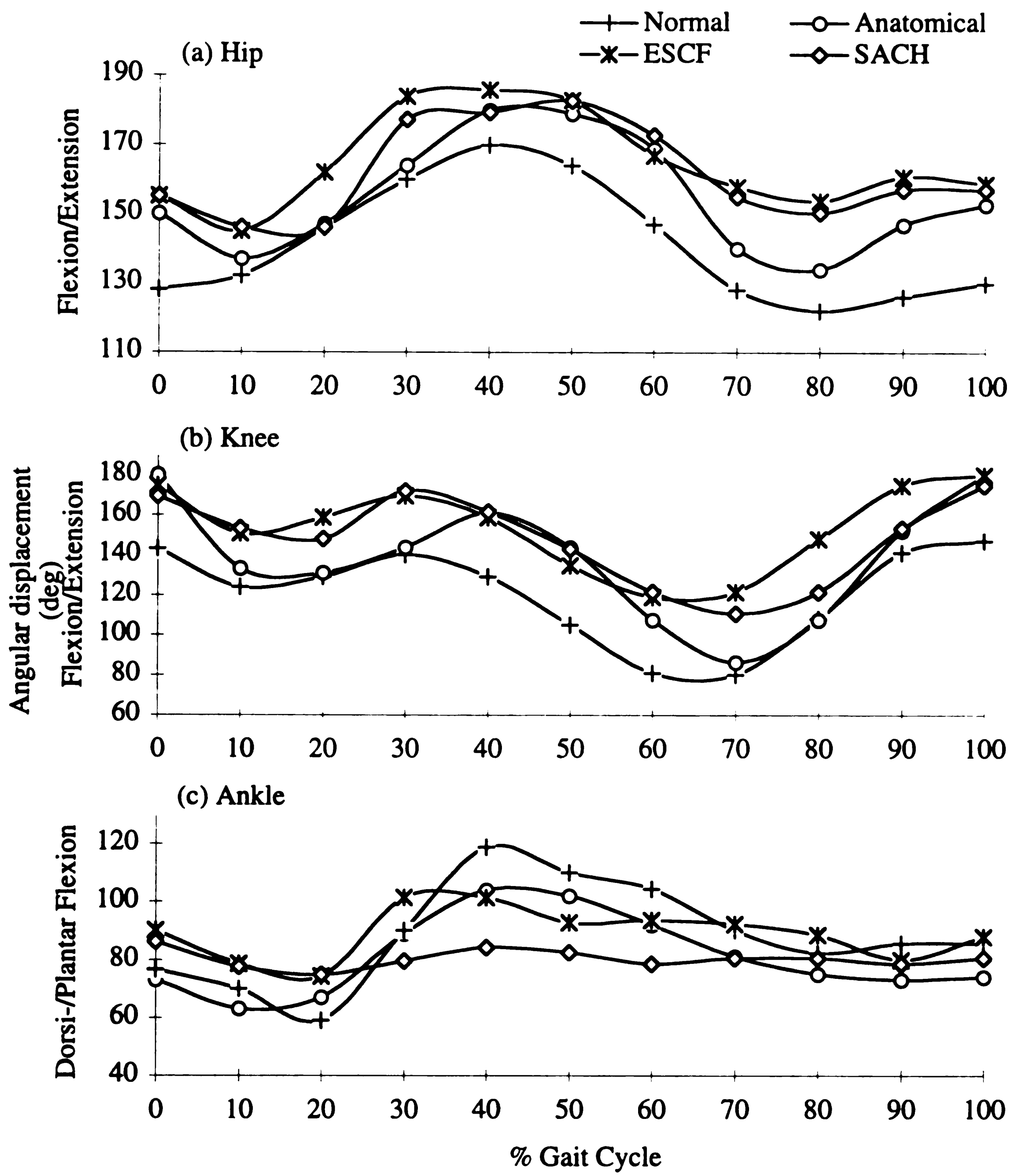

Figure 3. Angular displacements of the (a) hip, (b) knee, and (c) ankle joints at slow velocities of running.

From "Biomechanics of Running," by R. A. Mann, 1982, In The Foot and Leg in Running Sports (p. 9-11), J. E. Bateman and A. Trott (Eds.), New York: Thieme-Stratton, Adapted with permission.

From "A Biomechanical Analysis of Amputee Athlete Gait," by A. W. Smith, 1990, International Journal of Sports Biomechanics, 6, pp. 273-276. Adapted with permission.

exhibited knee flexion during the deceleration segment of the support phase, indicating a controlled lowering of the body. During midstance, the peak knee flexion for the SACH and the ESCF feet was approximately 145 degrees compared with 130 degrees for the anatomical limb (Smith, 1990) (see Figure 3).

Limited information exists regarding the hip angle displacement and prosthetic limb motion during the stance phase. The hip range of motion while wearing the SACH and ESCF had a smaller range of motion than the range of motion for the able bodied individuals (Smith, 1990) (see Figure 3). The hip extensors on the residual limb may act in a compensatory manner by assisting the quadriceps in controlling residual knee flexion immediately following foot contact and helping with knee extension during midstance. The action of the hip extensors, during the stance phase, would rotate the thigh backward relative to the hip, which would result in knee extension (Czerniecki, et al., 1991b; Miller, 1987).

Swing phase.

From early to late swing, the anatomical ankle dorsiflexed slightly as the knee flexed, followed by plantar flexion in preparation for foot contact (Enoka, et al., 1982; Smith, 1990). The anatomical limb had a smaller range of knee flexion during the forward swing phase than commonly exhibited in able bodied runners (Enoka, et al., 1982; Miller, 1981; Smith, 1990). Therefore, the anatomical foot was close to the ground during the recovery phase. In late swing, there was extension at the knee joint of the anatomical limb, in preparation for foot contact (Smith, 1990). Both Miller (1981) and Enoka et al. (1982) hypothesized that the limited anatomical knee flexion was an attempt by the runner to feel secure by maintaining the foot close to the ground and not lengthening the stride. That pattern was primarily exhibited by inexperienced amputee runners.

Immediately after toe off, the anatomical hip joint continued to extend, then flexed in conjunction with the knee. In preparation for foot contact, the hip again reversed direction to hip extension (Smith, 1990).

The prosthetic ankle was found to have smaller ranges of motion than the anatomical limb ankle. For participants wearing the SACH foot, the design of the foot limits the range of motion about the ankle region (Miller, 1981; Smith, 1990) (see Figure 3). Miller (1981) found the Greissinger foot had slightly more dorsiflexion and plantar flexion than did the SACH foot, but still did not approach the able bodied range of motion of the anatomical limb ankle joint.

The range of motion at the knee joint, while wearing the SACH or ESCF feet, also has been found to be less than the anatomical limb, but the movement patterns were similar (see Figure 3). Following toe off, the knee joint flexed and continued until it reached a maximum flexion at midswing followed by extension in preparation for foot contact. Peak knee flexion, which occurred at about midswing, was approximately 115 degrees compared with 80 degrees for the anatomical limb (Smith, 1990). Enoka et al. (1982) found that in preparation for foot contact the prosthetic limb shank had a tendency to assume a more extended angle than the anatomical limb. They hypothesized that such extension may be due to a "larger mass moment of inertia of the prosthesis with respect to the knee" (Enoka, et al., 1982 pp. 82) than in the anatomical limb.

The hip range of motion, while wearing either the SACH or the ESCF feet, was less than the range of motion of the anatomical limb, but again similar patterns of movement were seen (Smith, 1990) (see Figure 3). For the SACH and the ESCF feet, mid to late swing peak flexion was about 155 and 160 degrees, respectively, compared to about 135 degrees for the anatomical limb. Although the movement patterns about the hip joint with the ESCF foot were similar to both the anatomical limb and the SACH foot, in late swing the anatomical limb had some flexion prior to extension in preparation for foot contact (Smith, 1990).

The variation in the lower extremity joint motions of the anatomical and prosthetic limbs was greater in relation to the degree of range of motion than the pattern of movement (Enoka, et al., 1982). Smith (1990) examined the inter- and intraparticipant variability with the assumption that less variability was indicative of a more desirable motor pattern. He found that regardless of the type of limb, an increase in cadence generally resulted in a reduction in variability of joint angular displacements. However, angular displacements of the hip joint were found to be more variable with increasing cadence. Smith (1990) hypothesized that the hip joint variability may reflect an increased difficulty to balance the trunk over the supporting limb as the trunk's momentum increased from walking to jogging. Although the SACH, ESCF, and the anatomical limb have unique amounts of individual variability, the amount of variation has been found to be less for kinematic variables at slow velocity than fast velocity.

Review of Prosthetic Feet

The basic configuration in a below the knee prosthesis includes a socket, a spacer, a prosthesis, and some form of suspension necessary to keep the prosthesis in place on the residual limb. The socket serves to hold the residual limb. The spacer lies between the socket and the foot, and may be made of either wood, plastic, foam or a metal pylon depending on the system. Finally, the suspension system holds the prosthesis in place (Shurr & Cook, 1990).

The specific configuration for an individual is dependent upon their residual limb length, the health and condition of the residual limb, and the prosthesis. The surgical practice regarding the level of amputation on the shank is to maximize the length of the limb below the knee given adequate circulation and soft tissue of the limb. By maximizing the limb length, the individual has better prosthetic control and reduces the likelihood of having the residual limb come out of the socket while sitting (Sanders, 1986). The conventional prosthesis prescription is often fitted according to the preference, skills and/or geographic area of the prosthetist and often does not consider and include the needs or thoughts of the individual (Shurr & Cook, 1990). The ideal prosthetic foot prescription is a process of the prosthetist continually molding the socket, and adjusting the prosthetic foot(s) such that the individual can function comfortably is his/her daily life (Y. Stokosa, personal communication, June 1996). A universally accepted prosthetic prescription does not exist (Shurr & Cook, 1990) and the prescription can range from the conventional to the ideal.

The most commonly prescribed prosthetic foot used today in the United States is the solid ankle-cushion heel (SACH) foot (see Figure 4) (Michael, 1987; Shurr & Cook, 1990). The SACH foot has a wooden keel and a polyurethane foam heel wedge. The remainder of the foot is a poured polyurethane foam. Mechanically, the SACH foot has no moving parts but simulates plantar flexion as the heel wedge compresses at heel strike and into early foot flat. The prosthetist selects the heel wedge density based on the weight of the patient (Shurr & Cook, 1990). If the heel wedge is too stiff the foot flat position is delayed and knee instability may ensue. Although several types of sockets exist to attach the SACH foot and spacer to the residual limb, the most common prescribed socket is the patellar tendon-bearing (PTB) socket (Picken, 1985).

The PTB socket envelopes the residual limb stump and thereby has total contact over the residual limb. Weight bearing is distributed to specific areas of the stump and the pressure sensitive areas of the stump would not bear weight. The proper fit is a process of adjusting the mold and fit of the socket (Shurr & Cook, 1990).

In addition to the SACH, a multiaxis foot is also common. The Greissinger foot is one example of the multiaxis foot that allows dorsiflexion and plantar flexion, inversion and eversion, and transverse rotation (Picken, 1985). All motions are controlled by a system of bumpers made of rubber or hard plastic (Shurr & Cook, 1990). As the amputee places weight on the prosthetic foot at heel strike, the bumper allows plantar flexion of the foot. Plantar flexion stops at the end of the bumper's allowable range.

A more recently developed prosthetic foot is the Flex-Foot™ (see Figure 5). The Flex-Foot™ is hand made from a computer design that incorporates client data such as weight, activity level, and residual limb characteristics (Michael, 1987). The material is a lightweight graphite composite making the foot flexible, yet strong. A large main lead extends from the base of the prosthetic socket through the ankle and into the toe region of

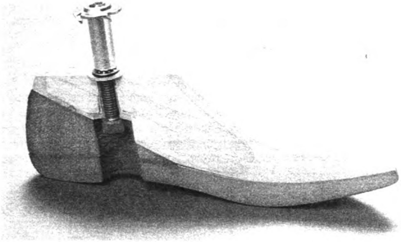

Figure 4. SACH (Solid Ankle-Cushion Heel) prosthetic foot.

Note. From Lower Limb Amputations: A Guide to Rehabilitation (p. 149), by G. T. Sanders, 1986, Philadelphia: F.A. Davis Company. Reprinted with permission.

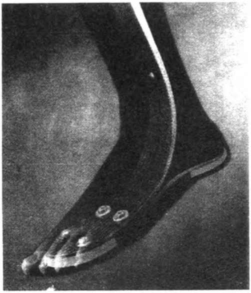

Figure 5. Flex-Foot™ prosthesis.

Note. Photograph from Flex-Foot™ Inc. Reprinted with permission.

the foot. The smaller leaf is attached to the larger lead at the level of the mid-foot and extends posteriorly, forming a heel component. The smaller posterior lead is designed to attenuate the shock of heel strike and force the prosthesis forward. The main leaf is designed to dorsiflex under stress during stance phase and to plantar flex forcibly during push off. The entire prosthesis bends as downward force is applied (Michael, 1987; Wing & Hittenberger, 1989). The Flex-Foot™ prosthesis attaches to the residual limb length by a socket, usually the PTB socket. The Flex-Foot™ structure has a foam cover that extends to form the shank where the socket rests (Shurr & Cook, 1990).

Ehara et al. (1993) evaluated the energy characteristics of 14 different prosthetic feet in a comprehensive study that included the Flex-Foot™, Greissinger foot, and SACH foot. Released energy was defined as the integration of the positive power present from maximum ankle dorsiflexion to toe off. Stored energy was defined as the integration of the negative power present during midstance between the neutral ankle angle to maximum ankle dorsiflexion. Efficiency was defined as the ratio of released to stored energy, and total energy was the sum of released and stored energy.

Ehara et al. (1993) found the Flex-Foot™ to have the highest value in both efficiency and total energy. The Greissinger foot had higher efficiency and total energy than the SACH foot. However, the participant used in the study did not prefer a high energy release foot, but instead preferred a high energy absorbing foot. Ehara et al. (1993) speculated that individuals with amputations might prefer higher energy absorbing feet in daily living activities and higher total energy feet in sports activities.

The research devoted to prosthetic design and the responses individuals have while using these devices for activity have been reviewed. While the lack of kinematic data for the Flex-Foot™ make comparisons of the kinematic variables between appliances difficult, it also exemplifies the need for such analysis. This author proposes to evaluate kinematic parameters of the Flex-Foot™, SACH foot, and the anatomical limb during running.

Chapter III

Methodology

The primary purpose of this study was to investigate selected kinematic variables in the running patterns of an individual with a below the knee amputation (BKA). Several individuals with a BKA use the Flex-Foot™ for recreational activity (Menard & Murray, 1989). Also, the SACH foot is the most commonly prescribed foot (Michael, 1987; Shurr & Cook, 1990). In this study, the Flex-Foot™ and the SACH foot were used to analyze the running pattern of an individual with a BKA. Kinematic variables of the running gait pattern, anthropometric data, prosthetic usage, and exercise history were the measurements and information utilized in this study.

Design

The case study design is a form of descriptive research that provides an in-depth analysis of a single case. An advantage of the case study is that it provides a basis for new ideas and hypotheses about problem areas. When using this design, there is an assumption that the single participant is an example of and will provide an understanding about other similar participants. However, generalizations cannot be made from a single case study.

The independent variables included two types of prosthetic feet and three levels of running velocity. The two prosthetic feet were the SACH foot and the Flex-Foot™. The running velocities were self selected slow, medium, and fast.

The dependent variables were the kinematic variables of the running gait. Those components included stride length and stride rate; stance and swing phases; greater trochanter vertical displacement; hip, knee, and ankle joint angular displacements; hip, knee, and ankle joint ranges of motion; and hip, knee, and ankle joint angular velocities.

Anthropometric measurements and activity level were other sources of participant information obtained. Reporting of such measurements allow for this investigator and future investigators to compare results based on participant size and exercise history.

Although there are several strengths to the case study design, efforts must be made to control for threats to internal and external validity. Internal validity refers to the control component of a study. In this study, potential threats to internal validity included history, testing, instrumentation, and participant selection bias. History referred to the time, approximately one week, between testing the two prosthetic feet. That time lag may have introduced confounding variables, such as a change in exercise habits, that may have affected the dependent variable. The effect of subsequent testing dates may have also affected results. From the first to the second data collection session, the participant may have felt more comfortable and performed differently, regardless of the type of prosthetic foot. Another potential problem source was the degree of reliability of the anthropometric measurements. Although the anthropometrist was experienced, the nonstandard below knee residual limb length measurement may be imprecise. A final threat to validity was the inability to have a control. One might consider the anatomical limb patterns to be the control, but that limb pattern may be altered by the prosthetic foot.

External validity pertains to the generalizability of the results and it was this factor that was the greatest limitation to the case study design. The single set of data regarding the participant's age, gender, anthropometric measurements, and activity level were sources of limitations to the study. Also, the prosthetic foot choice may have been a factor of personal choice and/or economic resources, more than technological advantages. Two other potential threats to external validity have been termed the Hawthorne and Rosenthal effect. The Hawthorne effect refers to the participant's knowledge that he/she is participating in an experiment, thereby altering anxiety and motivation levels. The Rosenthal effect refers to the possibility that the investigator modified the participant's behavior through cues and/or appearance.

Participant

For this study, the participant was a physically active adult male volunteer, 24.8 years of age, with a traumatic unilateral below the knee amputation, 1.4 years post amputation. The participant had access to both the SACH foot and the Flex-Foot™ and was free of lower extremity joint dysfunctions, or a concurrent painful condition that might have affected the gait pattern. An individual with a traumatic amputation was included to eliminate the potential confounding effect on health status of a disease or tumor amputation.

The "Amputee" Listserve and two certified prosthetists/orthotists from the mid-Michigan area were contacted to provide names of individuals who met the selection criteria. Following human subjects approval, the primary investigator notified the participants to determine if they met the selection criteria, provided additional information about the study, and informed the participants that only one individual would be randomly selected.

From the list of interested participants, one was selected. An information letter and informed consent form (see Appendix A) was mailed to that individual. Approximately five days after the mailing, the primary investigator telephoned the participant to answer additional questions and to confirm the participant's willingness to participate. If confirmation had not been established, the selection process would have continued until an individual gave consent to participate in this study.

Dates for testing were determined in consultation with the participant. The participant was requested to bring his/her signed informed consent form and running attire. The running attire included a low neck sleeveless shirt; and high cut running shorts, and running shoes (no socks) to allow for markers to be placed on the greater trochanter and lateral malleolus (the lateral malleolus position for the prophetic limb), respectively.

Instrumentation

All data collection occurred at the Intramural (IM) Sports Circle facility at Michigan State University. A small conference room was used for participant introduction to the research process and was the site of questionnaire and anthropometric data collection. Kinematic data collection occurred in a dance studio.

Demographic Information

A questionnaire, administered by the primary investigator during the first visit, served to obtain information about the participant's prosthetic feet, suspension devices, and the usage history of the prosthetic feet. The participant was also asked to provide information regarding his activity history before and after amputation (see Appendix D).

Anthropometric Measurements

Long and short anthropometers were used to collect the anthropometric data and were recorded on a participant information sheet (see Appendix C). Stature and sitting height were measured using the long anthropometer and were used to estimate leg length (Malina & Bouchard, 1991). Stature minus sitting height provided an estimate of the anatomical lower limb length (anatomical leg length). The short anthropometer was used to measure anatomical and prosthetic foot lengths and below knee residual limb length (Radcliffe & Foort, 1961) (see Appendix B). A Detecto-Medic beam balance scale was used to measure body weight both with and without each prosthetic foot. The anthropometric measurements were performed by an experienced professional of growth and development at Michigan State University, Dr. John Haubenstricker.

Kinematic Data

Two Panasonic S-VHS video camcorders operating at 60 Hz were used to record kinematic data. One complete running cycle was filmed with both cameras positioned along the same sagittal plane of the body's motion. One timing light box, accurate to 1/1000 of a second, was used to synchronize the film data. The layout of the testing environment included two cameras positioned along a 20 meter pathway, two halogen lamps next to each camera in line with the view lens, and one timing light box (see Figure 6). Data boards were placed directly in front of the camera lens, prior to each trial, to designate the prosthetic foot, velocity of running, and trial number.

Reflective markers were placed on anatomical landmarks to obtain position data during the digitizing process. The following eleven landmarks were used: one at the neck at the spinous process of C7; and one each on the right and left side of the body at the greater trochanter, lateral femoral condyle, lateral malleolus, heel, and head of the fifth metatarsal. The placement of the fifth metatarsal marker on the prosthetic limb was determined by measuring the anatomical limb distance from the heel marker to the fifth metatarsal marker. The placement of the lateral malleolus marker on the prosthetic limb was determined by measuring the anatomical limb distance from the floor to the lateral malleolus marker (Czerniecki, et al., 1991b).

A calibration structure was used to define a volume of space. Once the space was calibrated, position was defined relative to the lab coordinate system. Displacements of relative points were then converted to actual displacements. The calibration structure consisted of four tripods whose plumb lines were placed on each of four corners of a rectangle. Each tripod, with suspended plum bob line, had four targets of known positions. Each target was covered with reflective tape. The structure was placed in the field of view of both cameras and filmed prior to participant data collection. After filming of the calibration structure, the structure was removed from the filming area.

The primary investigator, one biomechanist, and two aides assisted with the kinematic data collection. The primary investigator and the biomechanist set up the filming area for kinematic data collection and tested the equipment for proper functioning. The primary investigator introduced the participant to the testing environment, placed the reflective joint markers on the participant, and informed the participant of each trial's criteria. Throughout data collection, the primary investigator and the biomechanist ensured proper equipment functioning and proper data collecting. Each of the two aides

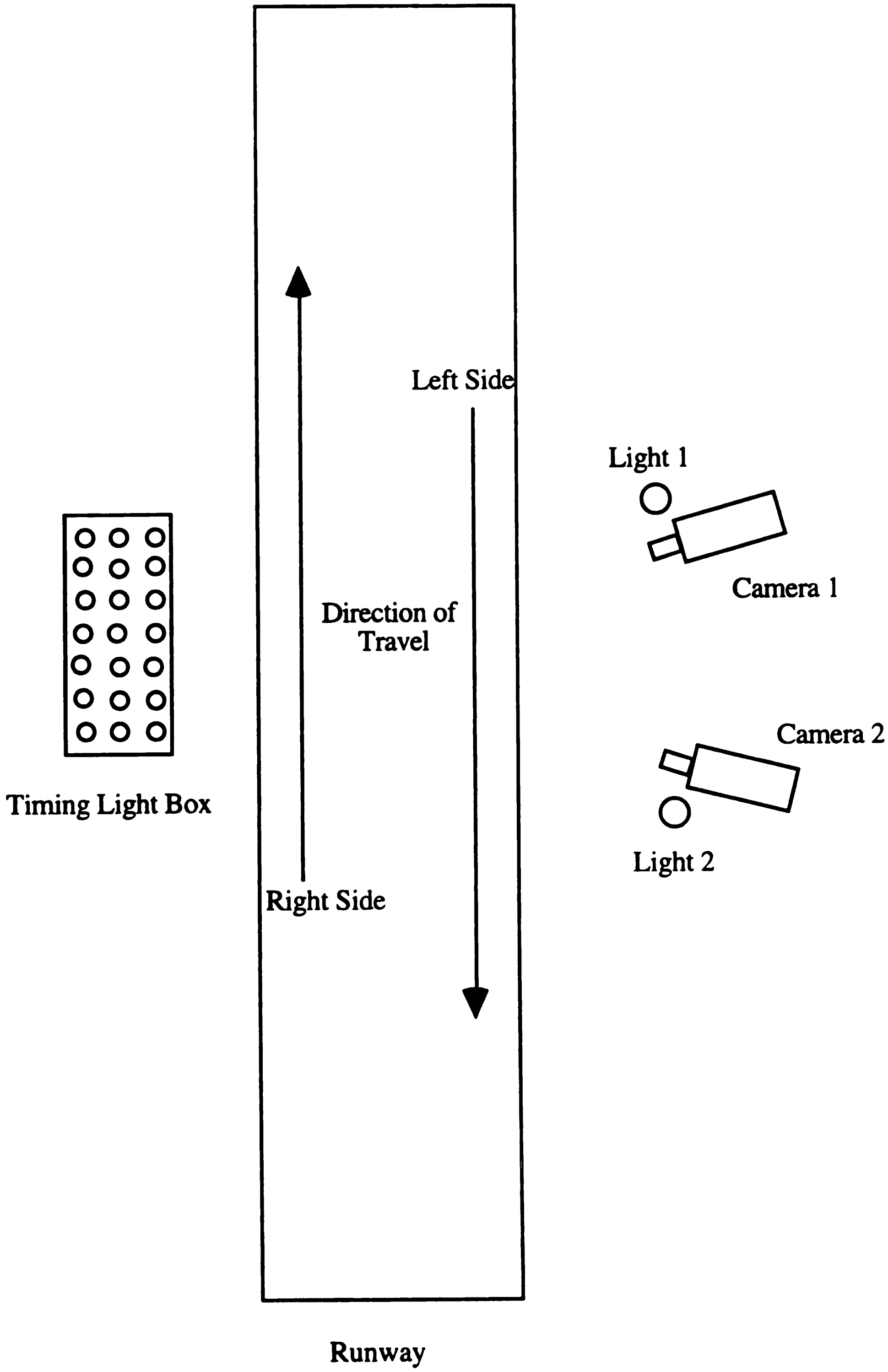

Figure 6. Layout of the filming area.

were posted at one of the two cameras to monitor proper camera functioning and to update the data boards.

Data Collection Procedures

One week before data collection, the primary investigator sent the participant directions to the site, a confirmation note of the date and time of data collection, and a reminder to bring appropriate running attire for the filming session. Two days before the date, the participant was called by the primary investigator to remind him of the site location, date, attire, informed consent form, and answered questions.

When the participant arrived at the testing site, he was greeted at the door by the primary investigator and was escorted to the conference room. The participant was informed again of the confidentiality of the data, and the purpose and procedures of the study. The consent form was completed and was in accordance with the policies established by the Michigan State University Committee for the Research Involving Human Subjects.

The participant was then asked to complete the questionnaire. All questions the participant had regarding the questionnaire were answered by the primary investigator. When the questionnaire was completed, the anthropometrist was contacted to meet in the conference room and was introduced to the participant. The anthropometrist collected the anthropometric data according to established protocol (Gordon, Cameron, & Roche, 1988; Radcliffe & Foort, 1961). The primary investigator recorded each of the measurements on the participant information sheet.

When the collection of anthropometric data was completed, the participant was escorted by the primary investigator to the filming site for kinematic data collection. The testing environment and the process of data collection were explained to the participant. Questions were answered during that time and the participant was asked if he was willing to continue with the remainder of the investigation.

Kinematic data were recorded on two days, separated by one week, to film both the Flex-Foot™ and the SACH foot in random order. The participant was asked to maintain his normal activity level between the testing dates.

The following steps took place at each data collection session. The primary investigator placed seventeen reflective markers on the anatomical landmarks. The participant then warmed up for approximately five minutes, or longer when desired. Next, the participants was directed to run at one of three randomly ordered self selected running velocities of slow, medium, or fast. Self selected velocities were chosen to enable the participant to assume the gait patterns he might have while participating in activities that involve running. In order to film both the anatomical and the prosthetic limbs, the participant was asked to run down the pathway in both directions. One limb was filmed when the participant ran in one direction. The participant remained at the end of the runway, then ran down the runway in the other direction in order to film the other limb. Trials alternated sides of the body. Three trials of one complete running cycle per limb side at each of the three velocities was filmed (3 x 2 x 3). Data collection concluded after all trials were completed and filmed for that appliance.

The second visit involved only the kinematic data collection. Upon arrival to IM Sports Circle, the participant was greeted at the door and escorted by the primary investigator to the dance studio for the filming session.

<u>Data Analyses</u>

The first step was to transfer the video image to the video motion analysis system, the Ariel Performance Analysis System (APAS), for digitizing. Frame grabbing provided the method of transferring each video image to a digital graphic image in APAS. The calibration structure, ten frames before foot contact, the running cycle, and ten frames after the subsequent foot contact were frame grabbed. The markers within each frame were then manually digitized.

Several of the independent variables were analyzed using four different contrasts. The independent variables examined in this manner were stride length and stride rate; stance and swing phases; hip, knee, and ankle joint angular displacements; hip, knee, and ankle joint ranges of motion; and hip, knee, and ankle joint angular velocities. The four different contrasts were paired as follows: two among prosthetic feet, and two within prosthetic foot comparisons. For the two among prosthetic feet comparisons, the anatomical SACH was compared to the anatomical Flex, and the prosthetic SACH was compared to the prosthetic Flex. For the two within prosthetic foot comparisons, the anatomical SACH was compared to the prosthetic SACH, and the anatomical Flex was compared to the prosthetic Flex.

To test the hypothesis regarding the greater trochanter vertical displacement, comparisons were made between the two prosthetic feet, for each of the three velocities. Although the literature on walking and running gait patterns of individuals with a BKA has not reported vertical displacement of the greater trochanter, this variable may provide insight into the level of synchronous actions of the knee, ankle, and foot. That is, vertical oscillation of the greater trochanter display a smooth sinusoidal path, when the joints of the lower extremity move in a simultaneous and precise fashion (Mann, 1986).

Specific parameters were placed on and assumptions were made about selected independent variables under investigation. The following parameters were set in order to normalize the data: stride length was measured as a percentage of height, stride rate was measured in units of strides per second, and the phases of the gait cycle were measured as a percentage of the total gait cycle. This investigator assumed the velocity of running to be the same within each self selected velocity, whether the trial was with the anatomical limb or with the prosthetic limb. Joint centers were assumed to be fixed, relative to rigid bodies, designated by joint markers. For the greater trochanter vertical displacement calculation, the hip joint was used as a substitute for center of mass vertical displacement. This investi

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investigator assumed the path of the hip joint would follow the same path, but different location, as the body center of mass (Larkins, 1987).

The information of the activity history provided descriptive participant information and provided insight into the gait patterns seen in this single participant. Often, investigators do not provide information on participant fitness levels, thereby leaving the reader without a means to interpret the data as representative of active or inactive individuals.

Chapter IV

Results and Discussion

The results of each parameter studied and a discussion of the findings as they pertain to related literature are found in the sections that follow. For each parameter there were four conditions analyzed at the slow, medium, and fast velocities. The four conditions were (a) the anatomical SACH, the anatomical limb when the SACH foot was worn as the appliance; (b) the anatomical Flex, the anatomical limb when the Flex-Foot™ was worn as the appliance; (c) the prosthetic SACH, the prosthetic limb when the SACH foot was worn; and (d) the prosthetic Flex, the prosthetic limb when the Flex-Foot™ was worn.

This chapter was divided into five sections. The participant's anthropometric data, and activity history before and after amputation were presented in the first section. The second section contained the results of the temporal data analyses. In the third and fourth sections are reported the findings of the angular displacements and velocities of the hip, knee, and ankle joints, respectively. And finally, the results of the center of mass vertical displacement were presented in the fifth section.

In sections two through five of this chapter, four separate pairs of comparisons, at the slow, medium, and fast velocities, were made between the (a) anatomical SACH and anatomical Flex, (b) prosthetic SACH and prosthetic Flex, (c) anatomical SACH and prosthetic SACH, and (d) anatomical Flex and prosthetic Flex. The comparisons were made between the mean values based on three trials. In the last three sections, numeric, and graphical representations of the means, again based on three trials, standard deviations, and medians were reported. Within each graph, the following acronyms and markers were used for the four conditions: AS referred to anatomical SACH, marked with circles; AF referred to anatomical Flex, marked with triangles; PS referred to prosthetic SACH, marked with squares; and PF referred to prosthetic Flex, marked with crosses. Four additional terms were used to describe points within the gait cycle, specifically TO referred to toe off when the foot left the floor, MSw referred to midswing at the middle of the swing phase, FC referred to foot contact when the foot first touched the floor, and MSt referred to midstance which occurred when the shank was perpendicular to the floor. For all the graphs, the solid line represented the mean, derived from three trials, of the variable and the dotted lines represented plus and minus one standard deviation of the mean.

Participant Profile

The participant's profile and selected anthropometric measurements were provided in Table 1. The participant was a 24.8 year old male, 71.2 kilograms in weight, and 184 centimeters in height. The participant's left shank and foot were amputated following a traffic accident in June, 1995. He was filmed 1.4 years post amputation. The participant was fitted for the Flex-Foot™ in February, 1996, and had used that appliance for 9 months

Table 1.

Demographic and Anthropometric Measurements.

Descriptive	
Gender	male
Age	24.8 years
Weight (without prosthesis)	71.2 kg
Height	184 cm
Anatomical leg length	86.5 cm
Residual limb length below the knee	12.9 cm

at the time of filming. The participant used the Flex-Foot™ for daily, recreational and competitive activities and wore it for approximately 16 hours per day. Three weeks prior to filming, the participant was fitted for the SACH foot. During those three weeks, the participant wore the SACH foot for work, recreational and competitive activities.

In Table 2, the participant's activity history both before and after the amputation were presented. In the years prior to the amputation, and subsequent to the amputation, the participant participated in several sport activities both recreationally and competitively. At the time of data collection, the participant was training for try-outs for the paralympic track and field team and Tae Kwon Do team, and was also competing in kick boxing. The participant trained five days per week for approximately three hours in either or both, kick boxing, and track and field.

Table 2.

Recreational and Competitive Activities in which the Participant Participated and the Length of Time of Involvement.

Activity	Pre amputation	Post amputation
Kickboxing	3 years	1 year
Rock climbing	2 years	
Roller blading	5 years	6 months
Rugby	6 years	
Snow boarding	1 year	
Soccer	3 years	
Track and field		2 months

Gait Characteristics

Velocity

The results of horizontal velocity of running were examined to determine if there were differences, within the three velocity categories, among the four separate pairs of comparisons. The means, standard deviations, and medians (in parentheses) of the horizontal velocity of running, in meters per second (mps), of each of the three self selected velocities of slow, medium, and fast for each prosthetic foot, SACH and Flex, and lower extremity limb, anatomic and prosthetic, were given in Table 3.

Table 3.

Means, Standard Deviations, and Medians for Velocity of Running at Three Velocities With Both Prosthetic Feet.

	SACH Foot			Flex-Foot™		
	Slow	Medium	Fast	Slow	Medium	Fast
Anatomical Limb	3.2 ± 0.10	3.9 ± 0.10	5.0 ± 0.14	3.9 ± 0.01	4.2 ± 0.11	6.7 ± 0.04
	(3.2)	(4.0)	(5.0)	(3.9)	(4.2)	(6.7)
Prosthetic Limb	3.2 ± 0.06	4.0 ± 0.14	4.7 ± 0.10	3.5 ± 0.09	4.5 ± 0.16	5.4 ± 0.02
	(3.3)	(4.0)	(4.7)	(3.5)	(4.5)	(5.3)

Note. The unit of measurement for velocity was meters per second.

The mean velocities for slow running were within 0.7 mps of each other. The largest mean velocity difference, 0.7 mps, was between the anatomical SACH (3.2 mps), and the anatomical Flex (3.9 mps). No difference in mean velocities was found between the anatomical SACH and the prosthetic SACH.

At the medium velocity, the average velocities of the four pairs of comparisons were within 0.5 seconds of each other. The largest mean difference, 0.5 mps, was between the prosthetic SACH (4.0 mps) and the prosthetic Flex (4.5 mps). The difference in mean velocities for the remaining pairs were equal to, or below, 0.3 mps.

The greatest range in the average velocities of running was found at the fast velocity. The comparison that had the largest difference, 1.7 mps, was between the anatomical SACH (5.0 mps), and the anatomical Flex (6.7 mps). The difference between the mean velocities of the anatomical Flex (6.7 mps), and the prosthetic Flex (5.4 mps) was 1.3 mps. The remaining comparisons had a difference in average running velocity that was less than, or equal to, 0.7 mps.

The differences in velocity for each self-selected running velocity, were a function of the variation within the participant when performing at each velocity and the difference in prosthetic feet. For each self-selected velocity, the velocity was greater for both lower extremity limbs with the Flex-Foot™, than with the SACH foot. Across the three velocities, the difference in mean velocity of running was largest between the anatomical SACH and Flex (0.3 - 1.7 mps) and smallest between the anatomical and prosthetic SACH (0.0 - 0.3 mps). Although the participant was able to attain higher velocities while wearing the Flex-Foot™, his ability to repeat the self selected velocities was better while wearing the SACH foot.

Stride Length and Stride Rate

Stride length.

The relative means, standard deviations, and medians (in parentheses) of stride length, as a percentage of standing height, were presented in Table 4. Results for each of the four comparisons at each of the running velocities were listed.

The stride length for all velocities was longer with the anatomical Flex, than with the anatomical SACH, and with the prosthetic Flex than with the prosthetic SACH. These findings corresponded with the higher velocities of the Flex-Foot™ when compared to the SACH foot. Also, the largest difference in stride length (46%) was at the fast velocity between the anatomical SACH and the anatomical Flex. The Flex-Foot™ has been found

Table 4.

Means, Standard Deviations, and Medians for Stride Length, as a Percentage of Standing Height, at Three Velocities With Both Prosthetic Feet.

	SACH Foot			Flex-Foot™		
	Slow	Medium	Fast	Slow	Medium	Fast
Anatomical Limb	118 ± 3.05	135 ± 6.01	158 ± 0.97	139 ± 4.20	151 ± 1.56	204 ± 2.41
	(119)	(138)	(158)	(141)	(151)	(204)
Prosthetic Limb	120 ± 2.22	138 ± 0.83	156 ± 0.96	132 ± 6.34	150 ± 8.70	163 ± 1.91
	(122)	(138)	(156)	(129)	(146)	(164)

to absorb more energy than the SACH foot (Ehara, et al., 1993). During the longer stride length with the Flex-Foot™, the participant may have experienced a higher impact force than with the SACH foot (Nigg, Bahlsen, Luethi, & Stokes, 1987), yet felt more comfortable with the Flex-Foot™ at the longer stride lengths, due to the design of the Flex-Foot™ and due to prior experience with the Flex-Foot™. Since stride length is one of two factors that determine velocity (Hay, 1985), the participant's increase in stride length, without a comparable decrease in stride rate, assisted his ability to attain higher velocities with the Flex-Foot™ than with the SACH foot.

The stride lengths of the prosthetic SACH and the anatomical SACH were similar for all velocities. At the slow and medium velocities, the stride length of the prosthetic SACH was slightly longer than for the anatomical SACH. At the fast velocity, the opposite was true, with the stride length of the anatomical SACH being slightly longer than the stride length of the prosthetic SACH. Those patterns were similar for the variable, velocity of running. The velocity for the prosthetic SACH was higher than for the anatomical SACH at the slow and medium velocities, but the opposite was true at the fast velocity.

Those results indicate that as the velocity of running increased so to did the stride length and therefore increased velocity of running was a function of increased stride length.

The stride length of the anatomical Flex was greater than the stride length of the prosthetic Flex at all velocities, although the range of stride length was different at each velocity. At the slow and medium velocities, the differences in mean stride lengths between the anatomical Flex and the prosthetic Flex were minimal, 7% at the slow velocity and 1% at the medium velocity. But at the fast velocity, there was a greater difference in stride length, 41%, which corresponded to the large difference in velocity (1.3 m/s). The larger stride length and velocity found with the anatomical Flex than with the prosthetic Flex, may be a result of the participant having run faster during the fast velocity trials when the anatomical limb was filmed. Therefore, bilateral symmetry in velocity did not exist between the anatomical and prosthetic limbs.

Stride rate.

The means, standard deviations, and medians (in parentheses) of stride rate, measured in strides per second (sps), were presented in Table 5. Results were presented for each of the four comparisons at each of the velocities.

At the slow velocity, the stride rate was higher for the anatomical Flex at 1.5 sps, than the anatomical SACH at 1.4 sps. There was no difference in mean stride rate values between the prosthetic SACH and the prosthetic Flex, nor with the anatomical SACH and the prosthetic SACH. The anatomical Flex had a higher mean stride rate at 1.5 sps, than the prosthetic Flex at 1.4 sps.

At the medium velocity, the difference between the stride rate values at each of the four comparisons was 0.1 sps. The mean stride rate value was greater for the anatomical SACH (1.6 sps) than for either the anatomical Flex (1.5 sps), or the prosthetic SACH (1.5 sps). However, the mean stride rate was greater for the prosthetic Flex than for either the prosthetic SACH, or for the anatomical Flex.

Table 5.

Means, Standard Deviations, and Medians for Stride Rate at Three Velocities With Both Prosthetic Feet.

	SACH Foot			Flex-Foot™		
	Slow	Medium	Fast	Slow	Medium	Fast
Anatomical Limb	1.4 ± 0.02	1.6 ± 0.02	1.7 ± 0.01	1.5 ± 0.04	1.5 ± 0.02	1.7 ± 0.03
	(1.4)	(1.5)	(1.7)	(1.4)	(1.5)	(1.7)
Prosthetic Limb	1.4 ± 0.02	1.5 ± 0.04	1.6 ± 0.02	1.4 ± 0.02	1.6 ± 0.05	1.8 ± 0.01
	(1.4)	(1.5)	(1.6)	(1.4)	(1.6)	(1.8)

At the fast velocity, the stride rate of the prosthetic Flex was higher (1.8 sps) than the prosthetic SACH (1.6 sps). There was no difference in mean stride rate values of the anatomical Flex and the anatomical SACH at 1.7 sps. For the comparisons among prosthetic feet, the differences among the mean stride rate values was 0.1 sps, with the anatomical SACH higher than the prosthetic SACH, and the prosthetic Flex higher than the anatomical Flex.

Two graphs are presented in Figure 7. The top graph illustrated stride length in percent standing height and one standard deviation about the mean. Each of the four conditions were shown for each velocity. The velocities are separated by vertical dotted lines. A similar format was used for the second graph of stride rate measured in strides per second.

When comparing stride lengths between types of prosthetic feet, it became apparent that the stride lengths for the anatomical SACH at the medium and fast velocities were similar to the anatomical Flex at the slow and medium velocities, respectively. From these comparative findings the investigator determined that the SACH foot enabled the participant

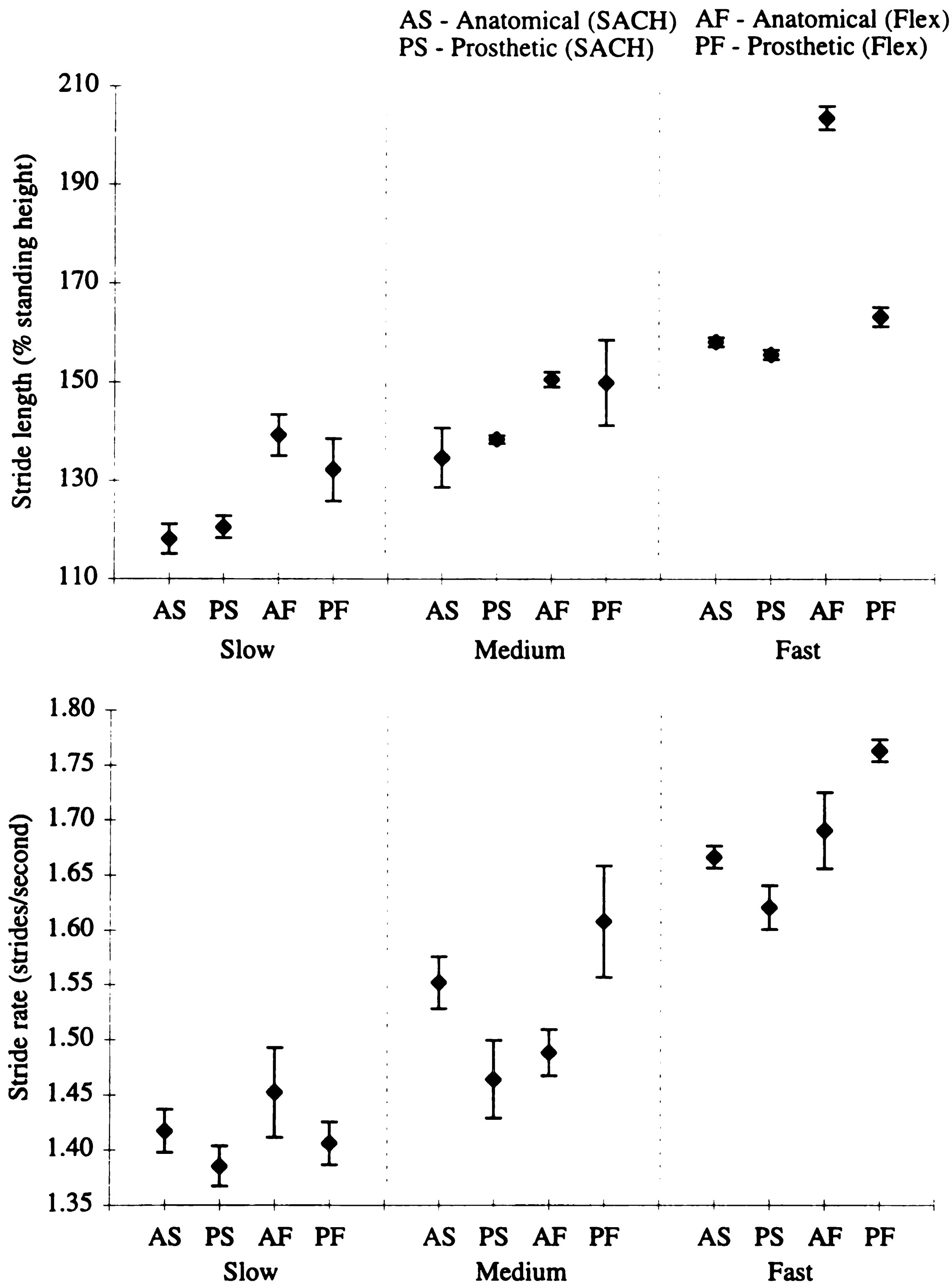
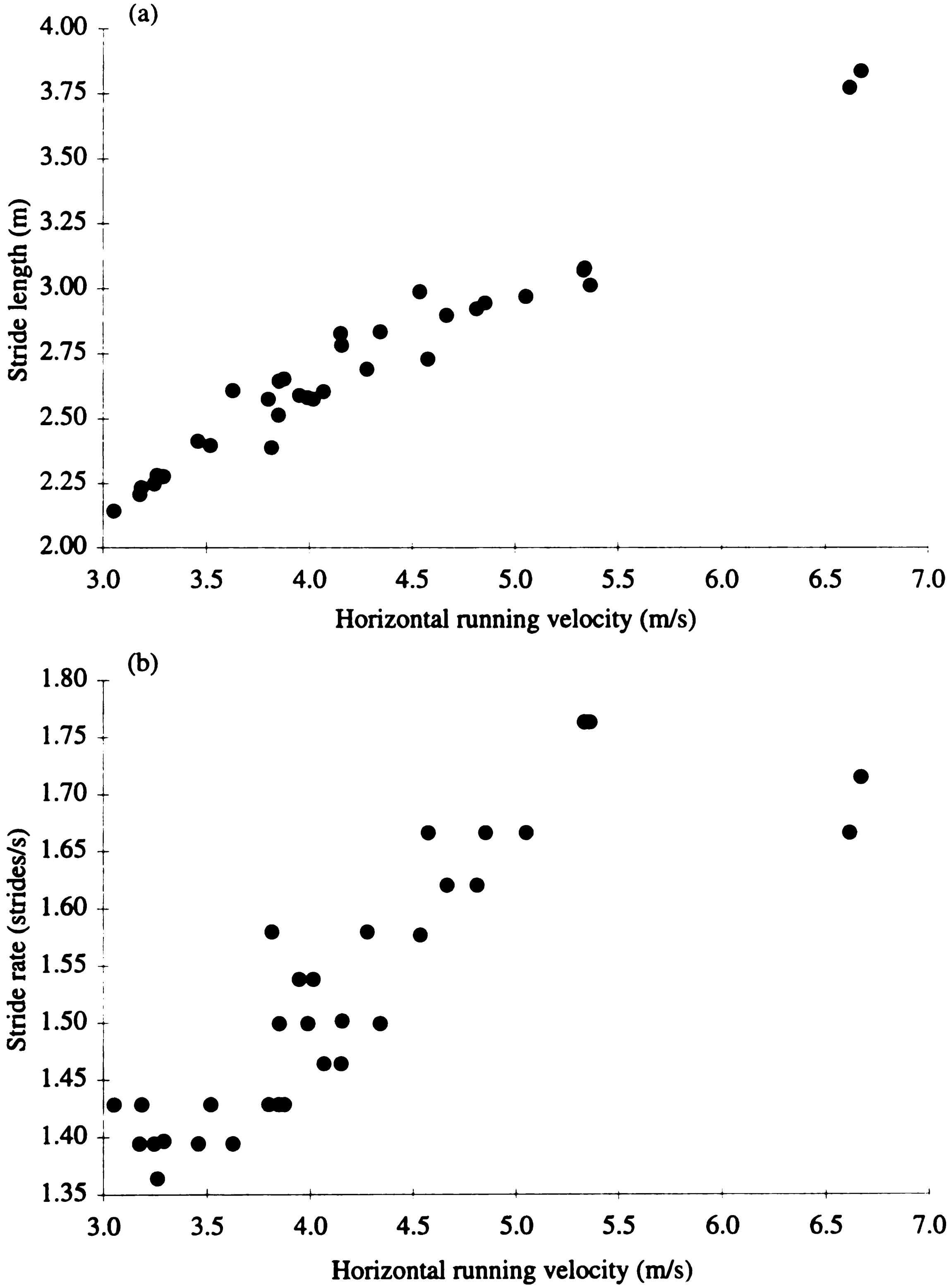


Figure 7. Stride length and stride rate means (±1SD) for all four conditions at slow, medium, and fast velocities.

to attain stride lengths similar to those attained when the Flex-Foot™ was worn, but at higher velocities for the SACH foot.

The trends and patterns of stride rate were less consistent than were those found with stride length. The mean stride rates at the slow, medium, and fast velocities were less with the prosthetic SACH than with the anatomical SACH. The mean stride rate at the slow velocity was less with the prosthetic Flex than with the anatomical Flex, but at the medium and fast velocities the mean stride rates were higher with the prosthetic Flex than with the anatomical Flex. Among prosthetic feet, the anatomical SACH had lower mean stride rates than the anatomical Flex at the slow and fast velocities, but at the medium velocity the anatomical SACH stride rate was greater than that of the anatomical Flex. At each velocity, the prosthetic Flex had higher mean stride rates than the prosthetic SACH. Although stride rate increased with increased velocity, the participant was not able to repeat similar patterns of stride rate both within and among prosthetic feet. The participant's lack of prosthetic shank musculature may explain the inconsistencies found. That lack of prosthetic limb musculature would affect the ability to produce force during the end of the prosthetic limb stance phase, which would decrease the stride length. As has been found with able bodied individuals (Hoshikawa, et al., 1973; Ito, Komi, Sjodin, Bosco, & Karlsson, 1983; Luhtanen & Komi, 1978), the participant's stride length and stride rate increased with increased velocity.

To examine the contribution of each parameter to velocity of running, stride length and stride rate were graphed against horizontal running velocity, in Figure 8. Both graphs were formatted in a similar fashion, with horizontal running velocity, in meters per second (m/s), along the X-axis. Along the Y-axis, the top graph was stride length, values in meters, and the bottom graph was stride rate, values in stride per second (sps). The Y-axis scale was different for each graph. The stride length Y-axis scale was in increments of 0.25 m and the stride rate Y-axis scale was in increments of 0.05 sps. The dots represent



<u>Figure 8.</u> Relationship between (a) stride length, and (b) stride rate and horizontal running velocity for all trials.

each trial analyzed for this study and the slope of the line of best fit through the data determined the rate of change for the respective variables, stride length and stride rate.

At the slower velocities, 3.0-3.7 m/s, it appeared that increments in velocity were attained by increasing the stride length. Whereas at higher velocities, 4.0-5.5 m/s, increases in velocity were primarily gained by increasing the frequency of strides. These results were the same as the findings of Frishberg (1983), Luhtanen and Komi (1978), and Dillman (1975) on able bodied individuals but inconsistent with the work of Miller (1981), Enoka et al. (1982), and Czerniecki et al. (1991) on individuals with below the knee amputations. The authors in those studies found individuals with amputations increase their running velocity by increasing their step rate at slow and fast velocities. Miller (1981) and Enoka et al. (1982) hypothesized that the runners in their studies were reluctant to increase stride length beyond a secure and comfortable limit, and therefore attained higher velocities by increasing stride rate.

However, at the two trials of the highest running velocity, approximately 6.7 m/s, the velocity was attained by increasing stride length, not stride rate. Those results were opposite to what was expected from the pattern discussed above but consistent with one study by Chapman and Caldwell (1983) who studied one world-class female sprinter. Since the two trials at the high velocity were of the participant wearing the Flex-Foot™, it was possible that the participant reached a limit in the swing rate of the prosthetic limb, but felt comfortable with increased flight time and increased ground contact impact.

Stance and Swing Phases

In Table 6, the stance phase means, standard deviations, and medians (in parentheses), as a percent of the gait cycle, were presented. Results were presented for each of the four comparisons at each of the velocities.

Among prosthetic feet, the stance phase was greater when the SACH foot was worn than when the Flex-Foot™ was worn for each velocity, for both the anatomical and prosthetic limbs. Relative to the prosthetic SACH, the anatomical SACH had a longer

Table 6.

Means, Standard Deviations, and Medians for Stance Phase, as a Percent of the Gait Cycle, at Three Velocities With Both Prosthetic Feet.

	SACH Foot			Flex-Foot™		
	Slow	Medium	Fast	Slow	Medium	Fast
Anatomical Limb	39 ± 1.2 (40)	33 ± 1.0 (33)	32 ± 2.0 (32)	31 ± 1.7 (31)	28 ± 2.7 (29)	25 ± 0.5 (25)
Prosthetic Limb	34 ± 1.2 (34)	32 ± 0.8 (33)	35 ± 0.7 (35)	29 ± 2.9 (30)	30 ± 1.8 (32)	28 ± 1.7 (29)

mean stance phase at the slow velocity, a similar mean stance phase at the medium velocity and a shorter mean stance phase at the fast velocity. The anatomical Flex had a longer mean stance phase at the slow velocity and shorter mean stance phases at the medium and fast velocities than the prosthetic Flex. With one exception, there was an indirect relationship between stride length and stance phase. A shorter stride length was accompanied by a longer stance phase. Since stride length is a function of flight time (Hay, 1985), a shorter flight time and hence shorter stride length results in a long stance phase. The one exception was at the slow velocity, in which the anatomical Flex had a longer mean stride length (139%) than the prosthetic Flex (132%) (see Table 4).

In Table 7, the swing phase means, standard deviations, and medians (in parentheses), as a percent of the gait cycle, were presented. Results were presented for each of the four comparisons at each of the velocities.

At each velocity, the swing phase was greater for both limbs when the Flex-Foot™ was worn than when the SACH foot was worn. The longer swing time of the Flex-Foot™ was probably related to the ability of the appliance to assist in propelling the body forward into the swing phase through released energy (Ehara, et al., 1993) at toe off.

Table 7.

Means, Standard Deviations, and Medians for Swing Phase, as a Percent of the Gait Cycle, at Three Velocities With Both Prosthetic Feet.

	SACH Foot			Flex-Foot™		
	Slow	Medium	Fast	Slow	Medium	Fast
Anatomical Limb	61 ± 1.2 (60)	67 ± 1.0 (67)	68 ± 2.0 (68)	69 ± 1.7 (69)	72 ± 2.7 (71)	75 ± 0.5 (75)
Prosthetic Limb	66 ± 1.2 (66)	68 ± 0.8 (68)	65 ± 0.9 (65)	71 ± 2.9 (70)	70 ± 1.8 (69)	72 ± 1.7 (71)

The results of the within prosthetic foot comparisons of the swing phase were opposite to those found for the stance phase. The anatomical SACH mean swing phases were shorter at the slow and medium velocities, and longer at the fast velocity, than the prosthetic SACH. The anatomical Flex had a shorter swing phase at the slow velocity, and longer swing phases at the medium and fast velocities than the prosthetic Flex. The time spent in the swing phase was directly related to stride length. The swing phase is one of the factors that determined the stride length, and therefore a shorter swing phase contributed to a shorter stride length. However, the anatomical Flex had a longer stride length, as well as a higher velocity and greater stride rate, at the slow velocity than the prosthetic Flex. Those results may indicate that the participant had a long, yet quick, anatomical stride relative to the prosthetic stride.

Illustrated in Figure 9 are the means, plus and minus one standard deviation, of the swing phase (top graph), and the stance phase (bottom graph), measured as a percentage of the gait cycle, of the four conditions at each velocity. For each condition, the two graphs were used to present the patterns and trends of the stance and swing phases.

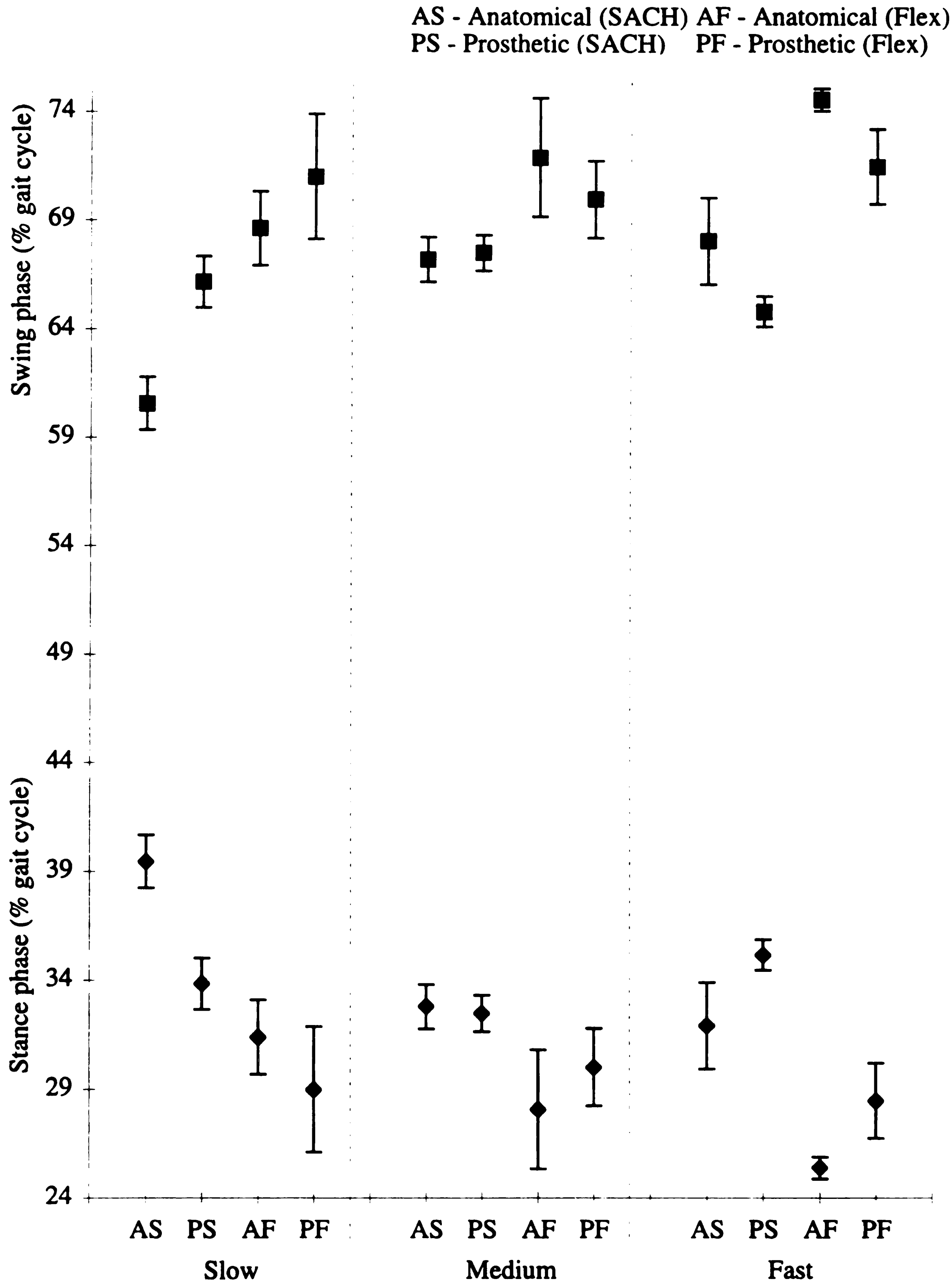


Figure 9. Swing phase and stance phase mean durations (±1SD) for all four conditions at slow, medium, and fast velocities.

Results of the comparisons between the stance phase and the swing phase within each velocity category follow. At the slow, medium, and fast velocities, the mean stance phases were longer and the mean swing phases were shorter when the SACH foot was worn than when the Flex-Foot™ was worn. Of all four conditions at the slow velocity, the anatomical SACH had the longest stance phase, at 39%, and the shortest swing phase, at 61%. Also, the prosthetic Flex had the shortest stance phase, at 29%, and the longest swing phase, at 71%, than the other three conditions at the slow velocity. At the medium velocity, the stance phases of the anatomical SACH and the prosthetic SACH were similar (33% and 32%, respectively) as were their complimentary swing phases (67% and 68%, respectively). Of all four conditions at the fast velocity, the prosthetic SACH had the longest stance phase, at 35%, and the shortest swing phase, at 65%. The anatomical Flex had the shortest stance phase, at 25%, and the longest swing phase, at 75%, than the other three conditions at the fast velocity.

One trend was suggested when these data were evaluated within each velocity category. At the slow, medium, and fast velocities the stance phases were longer and the swing phases were shorter with the anatomical SACH, compared to the anatomical Flex, and with the prosthetic SACH compared to the prosthetic Flex. Although not a trend, a change in pattern occurred between the anatomical and prosthetic limbs from the slow velocity to the fast velocity. At the slow velocity, the anatomical SACH and the anatomical Flex had longer stance phases and shorter swing phases than the prosthetic SACH and the prosthetic Flex, respectively. However, at the fast velocity the anatomical SACH and the anatomical Flex had shorter stance phases, and longer swing phases than the prosthetic SACH and the prosthetic Flex, respectively. The mechanical components of the prosthetic foot may explain the change from prosthetic dominant swing phase to anatomical dominant swing phase from the slow to the fast velocity, respectively. At the slow velocity, the participant had sufficient time to rotate the prosthetic limb through the swing phase.

However, at the fast velocity, the shorter time period needed to rotate the prosthetic limb through the swing phase may not have been sufficient.

At the medium velocity, the findings between the anatomical and prosthetic limbs were mixed. The anatomical SACH and prosthetic SACH had similar stance and swing phases, and the anatomical Flex had a shorter stance phase and longer swing phase than the prosthetic Flex. Those results may indicate that the participant had difficulty replicating that particular velocity of running which would have altered the stride characteristics.

To understand the interchange between the stance and swing phases with changes in velocity, trends across velocity were examined. One trend was a decrease in the stance phase and a subsequent increase in the swing phase with the anatomical SACH and the anatomical Flex as the velocity of gait increased. Consequently, for the anatomical SACH and the anatomical Flex, less time was spent in contact with the ground as the velocity increased. However, the trend was not as evident for the prosthetic limb. From the slow to medium velocity, the prosthetic SACH stance phase decreased and the swing phase increased, but the prosthetic Flex stance phase increased and the swing phase decreased. From the medium to the fast velocity, the prosthetic SACH stance phase increased and the swing phase decreased, but the prosthetic Flex stance phase decreased and its corresponding swing phase increased. The mixed results may indicate a lack of consistency in the participant's ability to reproduce similar gait patterns on the prosthetic limb, regardless of the prosthetic foot worn.

Although there appeared to be much discrepancy across velocities, all but one of the comparisons was explained by the stride length. Between the anatomical and prosthetic limbs, the limb with the longer swing phase (see Table 7) also had the longer stride length (see Table 4), indicating a functional relationship between swing phase and stride length. That is, the longer swing phase resulted in a longer stride length due to the limb spending a higher proportion of the gait cycle in the flight and opposing limb single support phases. For example, at the fast velocity, the swing phase and the stride lengths were longer for the anatomical SACH (68% and 158%) than for the prosthetic SACH (65% and 156%), and for the anatomical Flex (75% and 204%) than for the prosthetic Flex (72% and 163%), respectively. Except at the slow velocity, the swing phase was longer but the stride length was shorter for the prosthetic Flex (71% and 132%) than the anatomical Flex (69% and 139%), respectively.

Summary of Gait Characteristics

Taken together, the results of the gait characteristics indicated that the Flex-Foot™ was superior to the SACH foot for activities of running. Previous research (Ehara, et al., 1993) has shown that the Flex-Foot™ was capable of absorbing and thereby returning more energy than the SACH foot. At the longer stride lengths attained by the participant of this study, more energy may have been stored and returned by the Flex-Foot™ due to a higher ground impact at the longer stride lengths. The higher energy return then assisted in the longer swing phase and thereby longer stride lengths, a kind of positive feedback, and thus the participant was able to attain a faster speed of running.

Also, the results may indicate that the Flex-Foot™ requires less energy output by the participant than the SACH foot. If the Flex-Foot™ allows the user to store and release more energy in the prosthetic foot, then is less energy required of the participant to swing the prosthetic limb through the swing phase to maintain a long stride length and high stride rate? Further research that includes participant energy output measures are necessary to begin to answer the question of energy efficiency between the prosthetic foot and the user of the foot.

Angular Displacements

Analysis of the angular displacement curves for the lower extremity joints provided detailed information about the patterns of movement during the gait cycle, thereby enabling this investigator to make comparisons between the prosthetic feet, and between the anatomical and the prosthetic limbs. In this section, angular displacements of the three lower extremity joints, for each of the four conditions at each of the three velocities, were presented and discussed. For each lower extremity joint, the range of motion, expressed in maximum and minimum values, and the angular displacements throughout the gait cycle were illustrated. In Figure 10 are two stick figure sequences through one gait cycle at the medium velocity. The sequences are representative samples of the participant's hip, knee and ankle joint angular displacements while wearing the (a) SACH foot and the (b) Flex-Foot™.

In the tables of the hip, knee, and ankle joints range of motion for the four conditions, the maximum hip and knee joint flexion and ankle joint dorsiflexion values were the smaller numbers, and the maximum hip and knee joint extension and ankle joint plantar flexion were the larger numbers. The difference between the maximum flexion and the maximum extension values for the hip and knee joints, and between the maximum dorsiflexion and maximum plantar flexion values for the ankle joint, represented the absolute range of motion and was the value in parentheses.

Hip Joint

Comparisons were made of the hip joint angular displacements between the participant in this study and the values reported for able bodied participants in the literature. Table 8 is a summary of the maximum hip joint flexion and maximum hip joint extension angular displacement values reported in literature for able bodied participants. The contents of Table 8 were discussed in the next section when comparisons were made between able bodied individuals and the participant of this study.

The hip joint range of motion for both the SACH foot and the Flex-Foot™ at the slow, medium, and fast velocities were presented in Table 9. Maximum hip joint flexion angles at the slow velocity ranged from 135 to 142 degrees, compared to 145 degrees at a similar velocity for able bodied individuals (see Table 8). Thus, at slow velocities the anatomical Flex had similar maximum hip flexion values and the other three conditions had lower maximum hip flexion values relative to the able bodied population. At the medium

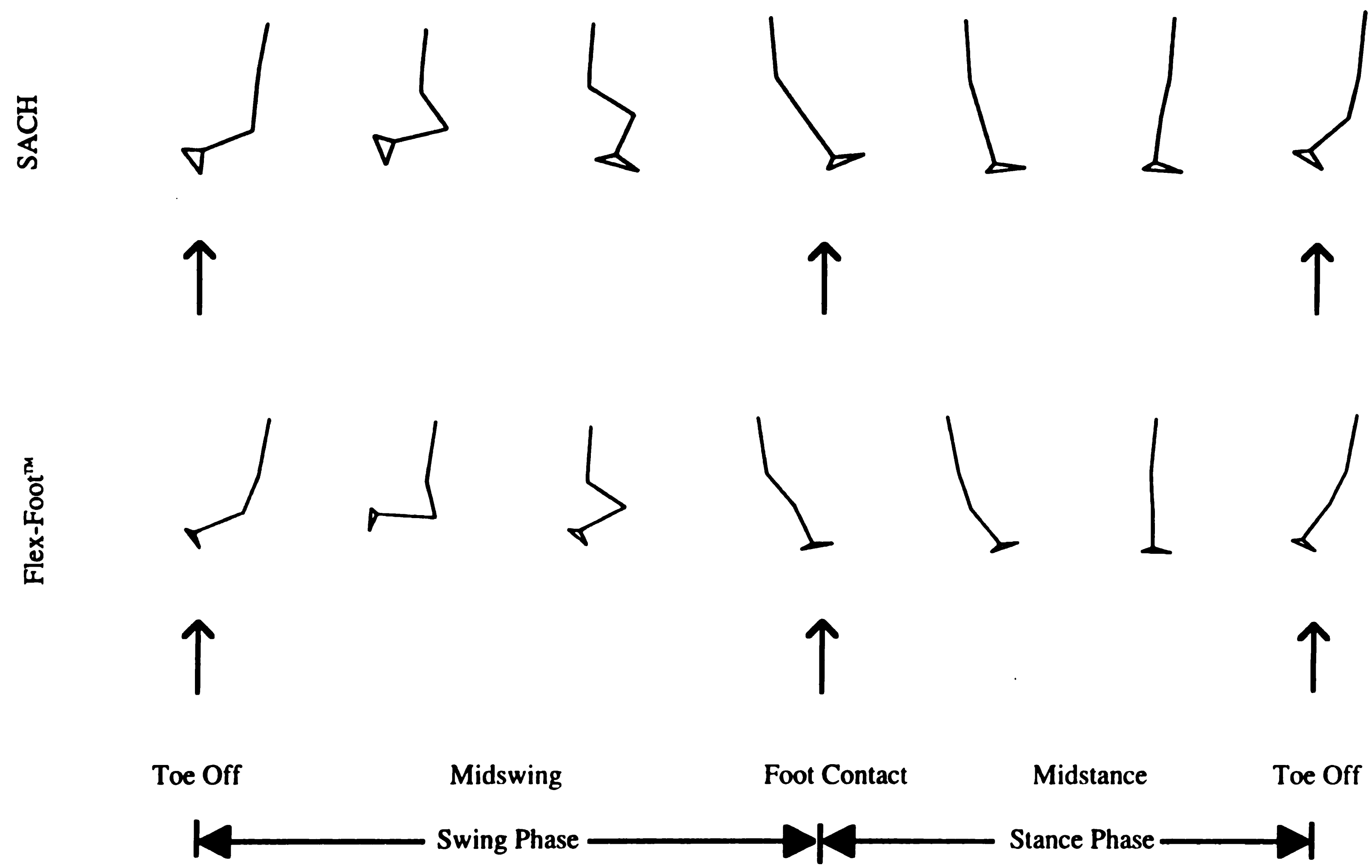


Figure 10. Stick figure representations of the motion of the trunk and prosthetic limb while wearing the SACH foot and the Flex-FootTM running at the medium velocity.

Table 8.

Literature Summary: Hip Joint Range of Motion for the Adult Able Bodied Population.

Investigators	Velocity of running (m/s)	Maximum flexion (degrees)	Maximum extension (degrees)
Elliott and Blanksby (1979)	3.5	145	191
Williams (1993)	3.6		194
Williams (1985)	4.5	123 to 128	
Mann (1982)	5.4	125	190
Mann and Hagy (1980)	7.7	95	
Dillman (1970)	8.0	109 to 114	199 to 202

Table 9.

Maximum Flexion and Maximum Extension Angular Displacement Values and Their Difference for the Hip Joint at Three Velocities With Both Prosthetic Feet.

	SACH Foot			Flex-Foot™		
	Slow	Medium	Fast	Slow	Medium	Fast
Anatomical Limb	139-196	134-201	124-208	142-194	135-206	116-207
	(57)	(66)	(84)	(52)	(71)	(91)
Prosthetic Limb	138-189	131-190	134-195	135-189	128-191	124-199
	(51)	(58)	(61)	(54)	(62)	(74)

velocity, the peak hip flexion values for each condition, was less than each respective value at the slow velocity, and ranged from 128 to 135 degrees, compared to a range in the literature of 123 to 128 degrees at similar velocities for able bodied individuals. Thus, at the medium velocity, the prosthetic Flex had similar maximum hip flexion values, and the other three conditions had higher maximum hip flexion values relative to the able bodied population. At the fast velocity, the peak hip flexion values ranged from 116 to 134 degrees compared to a range in the literature of able bodied individuals of 95 to 114 degrees at velocities higher than 7.5 m/s. Thus, at the fast velocity, all four conditions had larger maximum hip flexion values than able bodied individuals. Less hip flexion may indicate that the participant did not want to raise the lower extremity high above the ground for fear of falling.

The maximum hip joint angles, representing extension, at the slow velocity ranged from 189 to 196 degrees, and were similar to the maximum hip joint extension values reported for able bodied individuals, 191 to 194 degrees, at similar velocities. At the medium velocity, the range in maximum hip extension values ranged from 190 to 206 degrees. Reported maximum hip extension values at similar velocities for able bodied populations were not found by this investigator. At the fast velocity, maximum hip extension values ranged from 195 to 208 degrees, and were similar to able bodied participants, with a range in the literature of 190 to 202 degrees but at higher velocities.

To examine the similarities and differences of the absolute hip joint ranges of motion, comparisons of the values in Table 9 were made across the four condition. At the slow velocity, the difference in hip joint range of motion between the SACH foot and the Flex-Foot™ for both the anatomical and the prosthetic limbs were minimal. The anatomical SACH hip joint range of motion was 5 degrees greater than for the anatomical Flex. There was a smaller difference in hip joint range of motion, 3 degrees, between the prosthetic SACH and the prosthetic Flex, with the prosthetic Flex having the greater range of motion than the prosthetic SACH. The anatomical SACH had a larger range of motion than the prosthetic SACH which primarily was due to the greater hip extension, of the anatomical limb. There was only a 2 degree difference between the anatomical Flex (52 degrees) and prosthetic Flex (54 degrees).

For the medium and fast velocities, the range of motion was greater for the anatomical Flex (71 and 91 degrees) and prosthetic Flex (62 and 74 degrees) than for the anatomical SACH (66 and 84 degrees) and prosthetic SACH (58 and 61 degrees), respectively. That difference in range of motion was due primarily to greater hip flexion with the Flex-Foot™ than with the SACH foot. But, for the anatomical Flex at the medium speed the hip flexion was smaller than the anatomical SACH, by 1 degree.

At the medium and fast velocities, the anatomical SACH (66 and 84 degrees) and anatomical Flex (71 and 91 degrees) had a greater range of motion than either the prosthetic SACH (58 and 61 degrees) or the prosthetic Flex (62 and 74 degrees), respectively. The range of motion of the anatomical limb was greater than the prosthetic limb due to a larger hip extension of the anatomical limb.

The angular displacement of the anatomical SACH and anatomical Flex hip joints at the (a) slow, (b) medium, and (c) fast velocities were illustrated in Figure 11. The peak hip extension at each velocity and the peak hip flexion at the slow and fast velocities occurred earlier in the gait cycle with the anatomical SACH, than with the anatomical Flex. At the medium velocity, the peak hip flexion occurred at approximately 46% of the gait cycle for both the anatomical SACH and the anatomical Flex. For both prosthetic feet, the peak hip flexion occurred later in the gait cycle as the velocity increased, which corresponded to the increased swing phase with increased velocity. Hip flexion during initial stance became less pronounced as the velocity of gait increased for both the anatomical SACH and the anatomical Flex.

Hip joint angular displacements of the prosthetic SACH and prosthetic Flex at the (a) slow, (b) medium, and (c) fast velocities were illustrated in Figure 12. Differences in peak hip extension between the prosthetic SACH and prosthetic Flex were minimal. At the slow and medium velocities, the difference was one degree, and at the fast velocity the difference was four degrees in peak hip extension values between the prosthetic SACH and prosthetic Flex, with the prosthetic Flex being greater at all velocities than the prosthetic

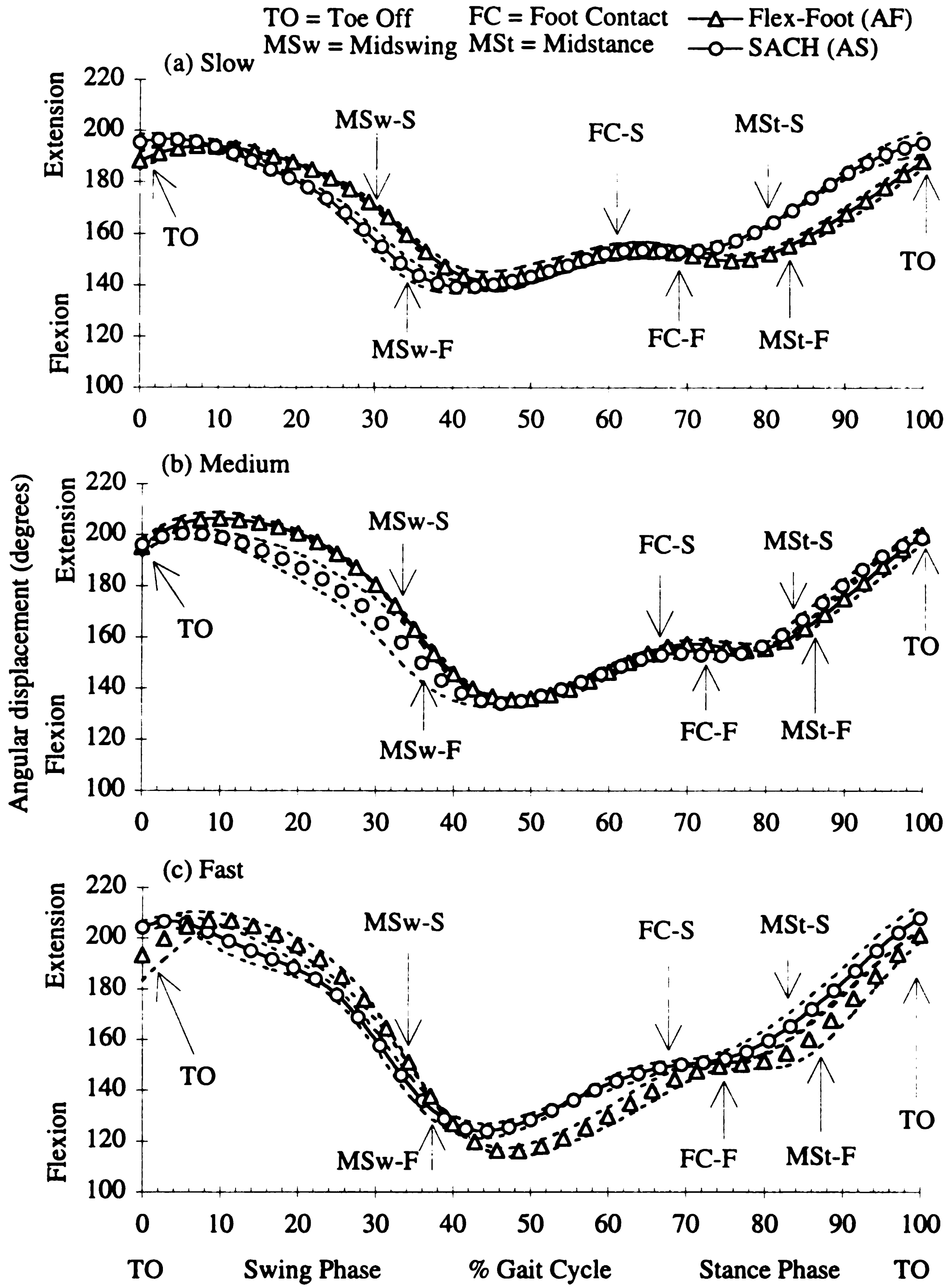


Figure 11. Hip joint angular displacements (mean ± 1SD), from toe off to toe off, of the anatomical SACH and anatomical Flex at (a) slow, (b) medium, and (c) fast velocities.

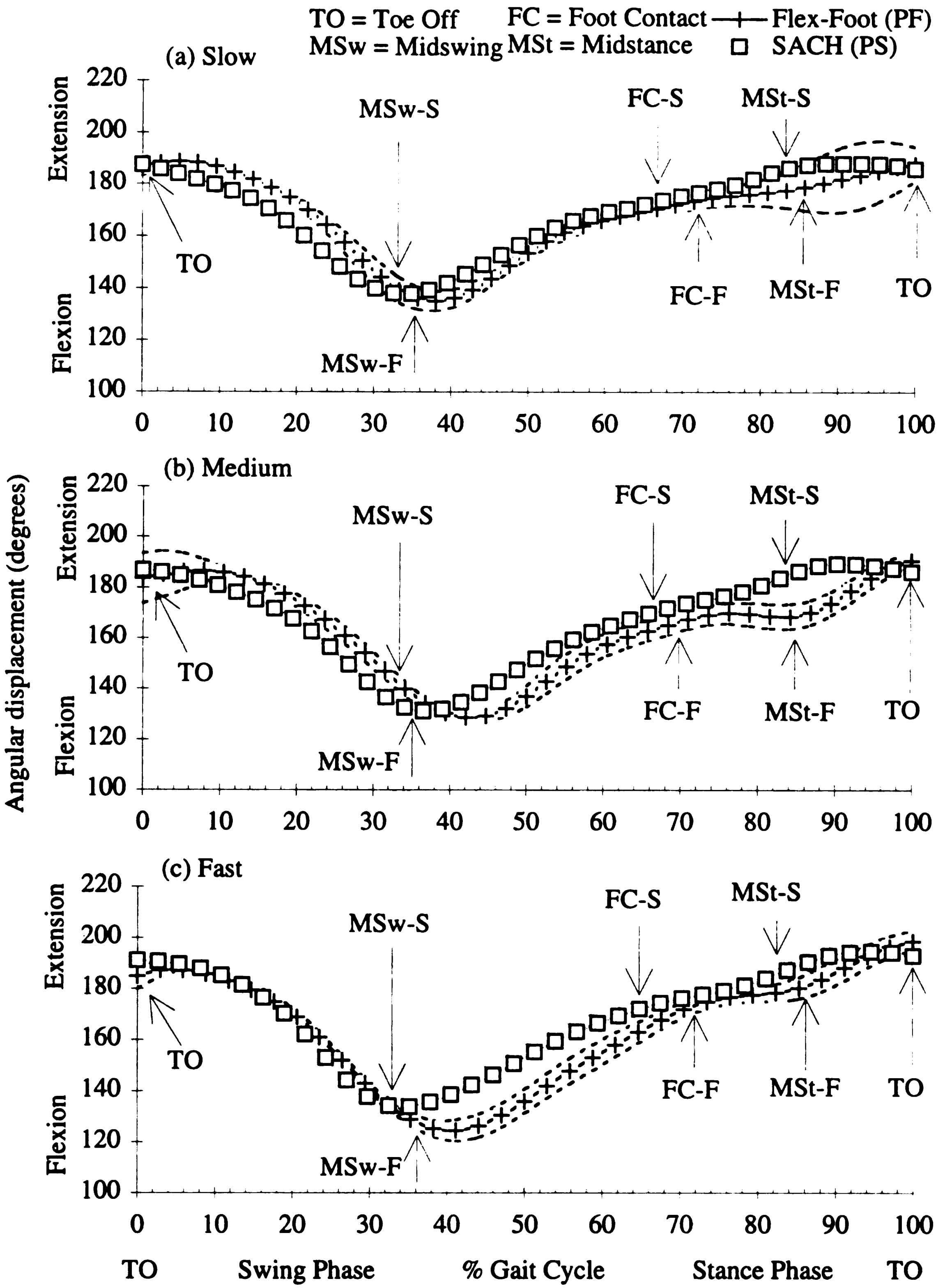


Figure 12. Hip joint angular displacements (mean ± 1SD), from toe off to toe off, of the prosthetic SACH and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

SACH. The peak hip flexion of the prosthetic SACH occurred before the prosthetic Flex at all velocities, but the magnitude of hip flexion was greater with the prosthetic Flex, than with the prosthetic SACH. Hip flexion did not occur upon foot contact with either the SACH foot or the Flex-Foot™, instead there was continued hip extension from the end of the swing phase.

The hip joint angular displacements of the anatomical SACH and prosthetic SACH were illustrated in Figure 13 for the (a) slow, (b) medium, and (c) fast velocities. At all velocities, the anatomical SACH had a larger hip extension at toe off than did the prosthetic SACH. The peak hip flexion occurred earlier with the prosthetic SACH, than for the anatomical SACH at all velocities. After prosthetic SACH peak hip flexion, the participant progressively extended the hip throughout the remainder of the swing phase and through midstance at all velocities. Therefore, the foot was close to the ground during the swing phase, a position that may have been desired by the participant in case of falling or tripping.

Hip joint angular displacements of the anatomical Flex and prosthetic Flex were illustrated in Figure 14 for the (a) slow, (b) medium, and (c) fast velocities. As was found with the SACH foot, the anatomical Flex hip extension peak at toe off was larger than the peak extension for the prosthetic Flex, at all velocities. Also, the peak hip flexion of the prosthetic Flex occurred before the anatomical Flex, at each velocity. After peak hip flexion for the prosthetic Flex at each velocity, there was progressive hip extension through foot contact followed by a maintained hip extension position through midstance. From midstance to toe off, at each velocity, anatomical Flex and prosthetic Flex hip joint extension occurred, except that the prosthetic Flex at the slow velocity maintained an extension position but did not increase the extension angle.

Knee Joint

Comparisons were made of the knee joint angular displacements between the participant in this study and the values reported for able bodied participants in the literature. Table 10 is a summary of the maximum knee joint flexion and maximum knee joint

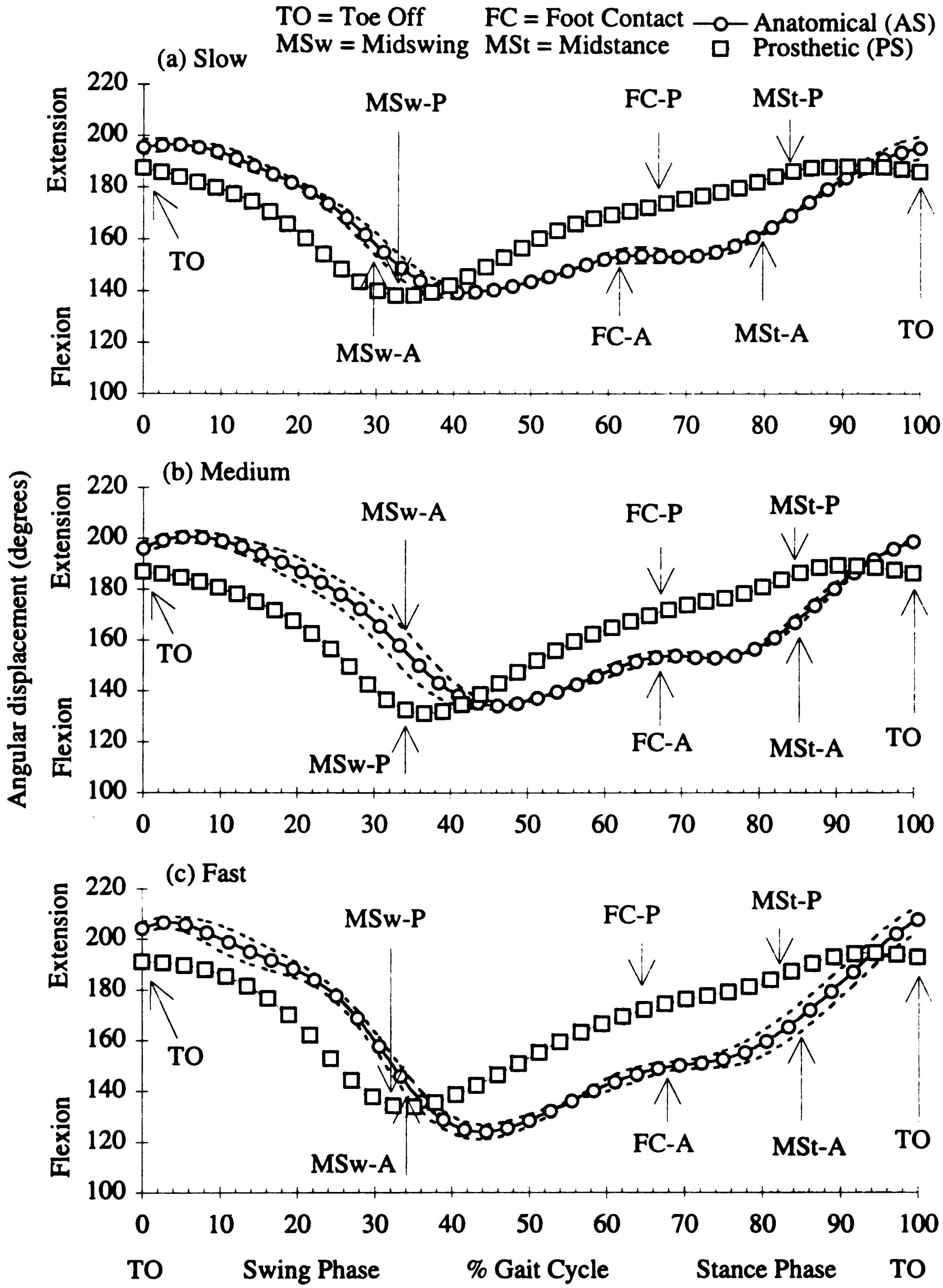


Figure 13. Hip joint angular displacements (mean ± 1SD), from toe off to toe off, of the anatomical SACH and prosthetic SACH at (a) slow, (b) medium, and (c) fast velocities.

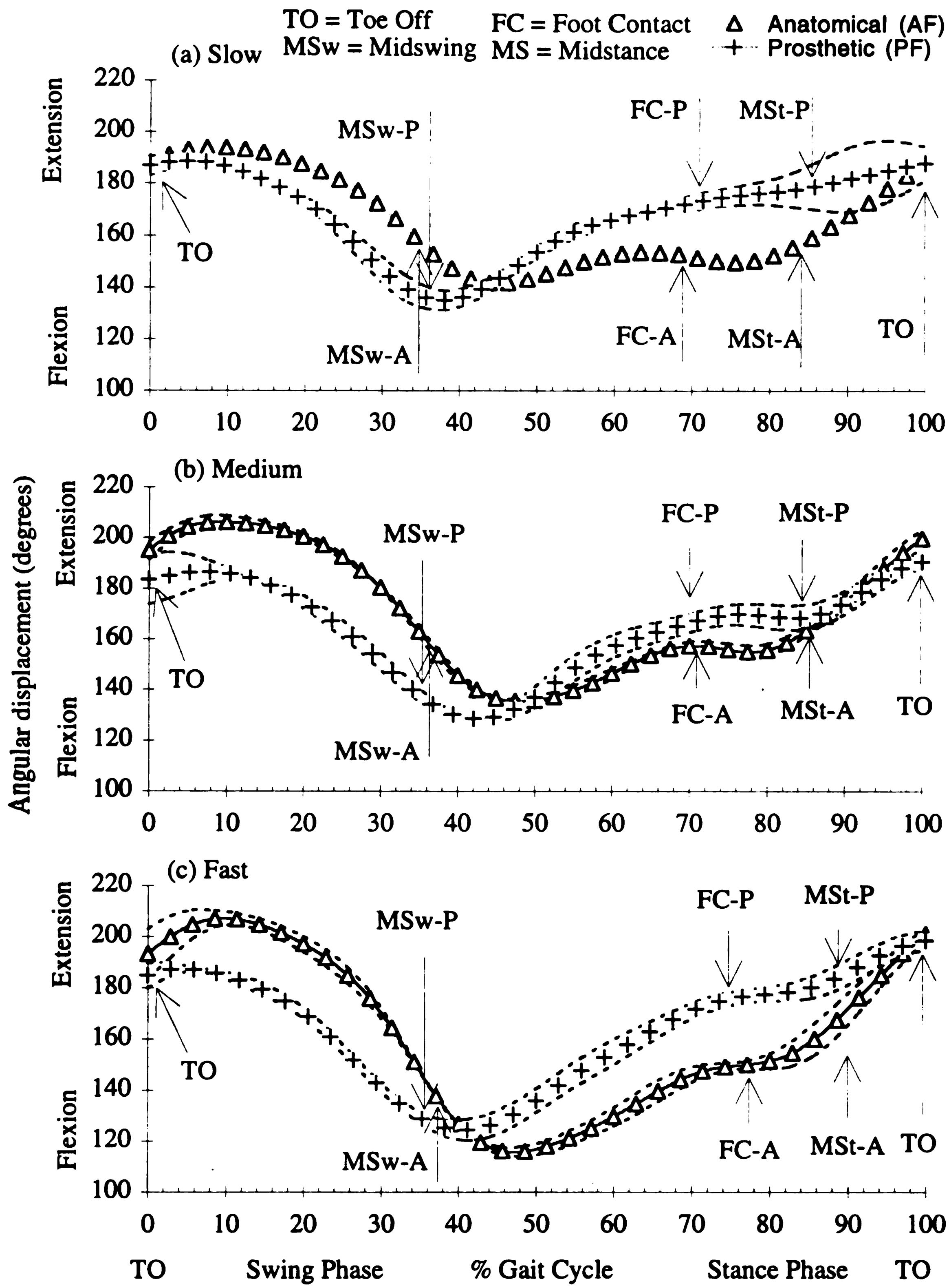


Figure 14. Hip joint angular displacements (mean ± 1SD), from toe off to toe off, of the anatomical Flex and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

extension angular displacement values reported for able bodied participants from the literature. The contents of Table 10 were discussed when comparisons were made between able bodied individuals and the participant of this study.

Table 10.

Literature Summary: Knee Joint Range of Motion for the Adult Able Bodied Population.

Investigators	Velocity of running (m/s)	Maximum flexion (degrees)	Maximum extension (degrees)
Bates, Osternig, and Mason (1978)	3.4		163
	4.5		163
Buczek and Cavanagh (1990)	4.5		155
Dillman (1970)	7.5	49	154
Elliott and Blanksby (1979)	3.5	74	156
Mann and Hagy (1980)	5.4	50	160
	7.7	40	150
Mann, Moran, and Dougherty (1986)	3.3	73	147
	5.4	52	137
Nilsson, Thorstensson, and Halbertsma (1985)	5.0	70	170
	7.0	50	

The knee joint ranges of motion for both the SACH foot and the Flex-Foot™ at the slow, medium, and fast velocities were presented in Table 11. Maximum knee joint flexion angles at the slow velocity ranged from 69 to 84 degrees, compared to a range in the literature of 73 to 74 degrees at similar velocities with able bodied participants. The participant's maximum knee joint flexion was most similar to able bodied individuals when

Table 11.

Maximum Flexion and Maximum Extension Angular Displacement Values and their Difference for the Knee Joint at Three Velocities With Both Prosthetic Feet.

	SACH Foot			Flex-Foot™		
	Slow	Medium	Fast	Slow	Medium	Fast
Anatomical Limb	84-160	73-162	63-164	79-168	64-165	40-161
	(76)	(89)	(101)	(89)	(101)	(121)
Prosthetic Limb	81-184	75-185	67-187	69-193	67-189	57-189
	(103)	(110)	(120)	(124)	(122)	(132)

the SACH foot was worn at the medium velocity. At the medium velocity, the peak knee flexion values ranged from 64 to 75 degrees. At the fast velocity, the peak knee flexion angles ranged from 40 to 67 degrees, and were similar to a range in the literature of 50 to 70 degrees for able bodied participants running at similar velocities. At velocity greater than 7.0 m/s, reported knee joint maximum flexion values for able bodied participants ranged from 40 to 50 degrees, which were similar to the maximum knee flexion of the anatomical Flex, but at a slower velocity. The peak knee flexion angles with the SACH foot at the fast velocity were similar to those values found with the Flex-Foot™ at the medium velocity. When the participant wore the SACH foot, he had to run at a faster velocity in order to obtain knee joint angular displacements similar to those found with the Flex-Foot™.

The maximum knee joint extension angles at the slow velocity ranged from 160 to 193 degrees, compared to a range in the literature of 147 to 163 degrees for the able bodied population at similar velocities. At the slow velocity, maximum knee extension values of able bodied individuals were similar to the anatomical limb, but lower in magnitude than the prosthetic limb values. At the medium velocity, peak knee extension angles ranged from

162 to 189 degrees, compared to a range in the literature of 155 to 163 degrees for able bodied individuals. Again, the values for the able bodied individuals were similar to what was found with the anatomical limb, but lower than the prosthetic limb values. The peak knee extension values at the fast velocity for the anatomical limb occurred during toe off, as opposed to prior to foot contact, as was the case for all the other conditions. To maintain consistency in comparing angular displacement at a particular point in the gait cycle, just before foot contact, for both the participant in this study and for the findings of the able bodied participants, this investigator used the peak knee extension values prior to foot contact for the anatomical SACH, at 159 degrees, and for the anatomical Flex, at 155 degrees. The maximum knee joint extension angles at the fast velocity ranged from 155 to 189 degrees, compared to the range of 137 to 160 degrees for able bodied participants at similar velocities. The anatomical limb had similar maximum knee joint extension angular displacement values as the able bodied participants. Again the prosthetic limb had larger peak knee extension values than those of the able bodied individuals. The primary difference between the participant of this study and able bodied individuals was the prosthetic limb knee joint hyperextension prior to foot contact. Discussion of knee joint hyperextension occurs later in this section.

To examine the similarities and differences of the absolute knee joint ranges of motion, comparisons across the four conditions were made from the values in Table 11. At all velocities, the absolute knee joint range of motion was greater for the anatomical Flex and the prosthetic Flex, than for the anatomical SACH and prosthetic SACH, respectively. Except for the anatomical Flex at the fast velocity, the greater range of motion of the Flex-Foot™ was due to a greater magnitude of both knee flexion and knee extension. The anatomical Flex had a greater magnitude of knee flexion at the fast velocity than the anatomical SACH, which was the single reason for the difference in absolute range of motion. At all velocities, the prosthetic limb had a greater range of motion than its corresponding anatomical limb. The primarily reason for the difference was in the range of motion at the knee joint, the prosthetic limb knee joint was hyperextended.

The angular displacement of the anatomical SACH and anatomical Flex knee joints at the (a) slow, (b) medium, and (c) fast velocities were illustrated in Figure 15. Anatomical limb peak knee joint extension angles occurred prior to foot contact at the slow and medium velocities. At the fast velocity, anatomical limb peak knee joint extension occurred at toe off. As stated in the discussion of Table 11, the anatomical limb peak knee extension angles at all velocities, were similar to those found with able bodied individuals. During the stance phase, there was a period of maximum anatomical limb knee flexion prior to midstance between 75% and 85% of the gait cycle. The stance phase knee joint peak flexion angles, 130 to 136 degrees, were slightly smaller in magnitude than those reported for able bodied individuals at 136 to 141 degrees (Bates, et al., 1978; Bates, Osternig, Mason, & James, 1979; Buczek & Cavanagh, 1990). The knee joint angles at toe off for the anatomical SACH and the anatomical Flex were similar at all velocities and ranged from 159 to 164 degrees. Those values were within the range of reported knee joint angles at toe off, 140 to 173 degrees, for able bodied individuals (Bates, et al., 1978; Dillman, 1970; Elliott & Blanksby, 1979a; Mann, et al., 1986). The peak knee flexion occurred between 30% and 40% of the gait cycle during the swing phase. As stated earlier, the knee flexion angles were greater in magnitude for the anatomical Flex than for the anatomical SACH, and the magnitude of flexion increased for both the anatomical SACH and the anatomical Flex as velocity increased. These results indicate that the anatomical limb knee joint angular motion for the participant of this study was similar to that of an able bodied individual except during the stance phase when the peak flexion angles were smaller for the participant of this study.

Knee joint angular displacements of the prosthetic SACH and the prosthetic Flex at the (a) slow, (b) medium, and (c) fast velocities were illustrated in Figure 16. Prosthetic limb maximum knee joint extension angles occurred prior to foot contact at approximately

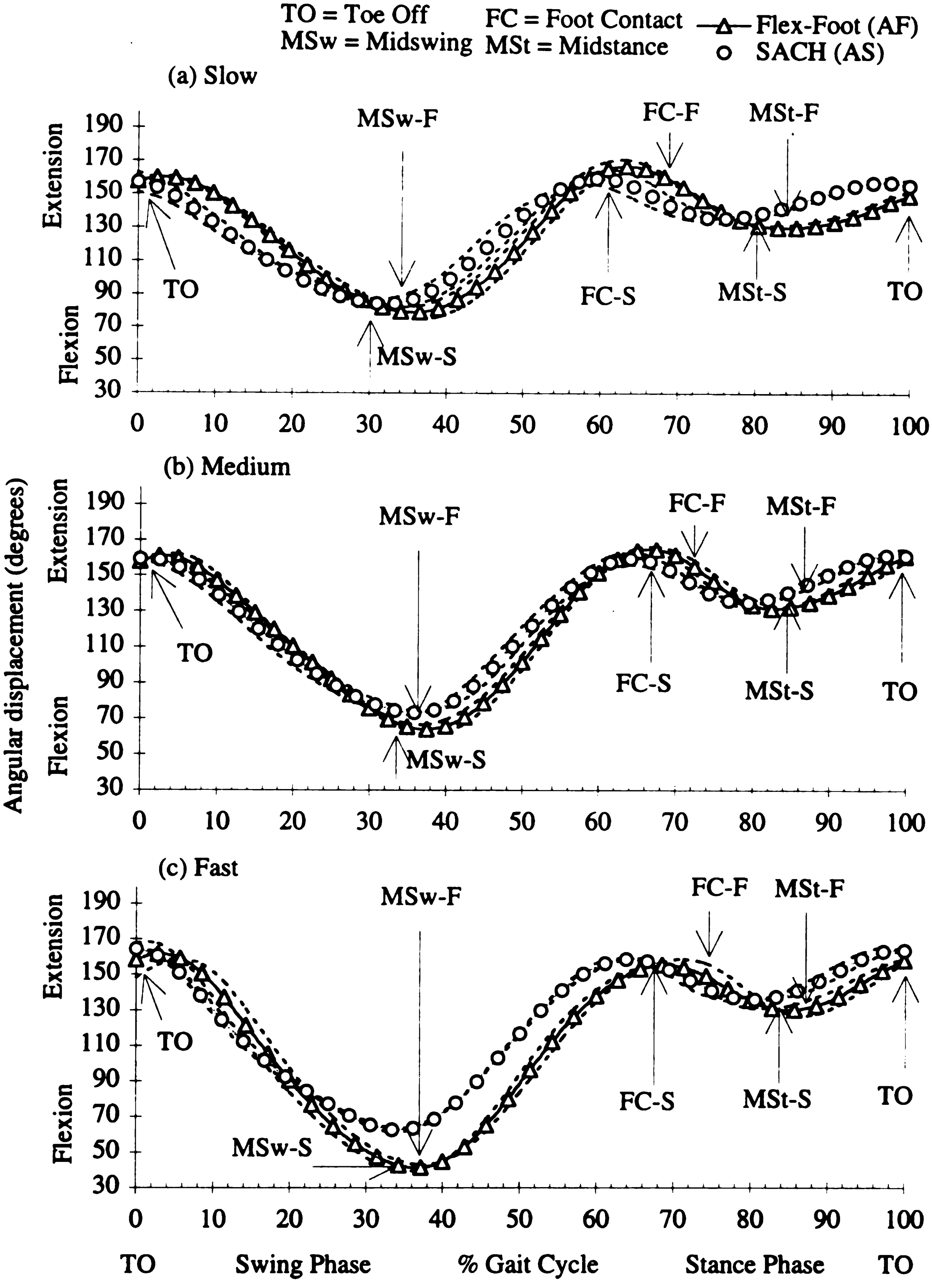


Figure 15. Knee joint angular displacements (mean ± 1SD), from toe off to toe off, of the anatomical SACH and anatomical Flex at (a) slow, (b) medium, and (c) fast velocities.

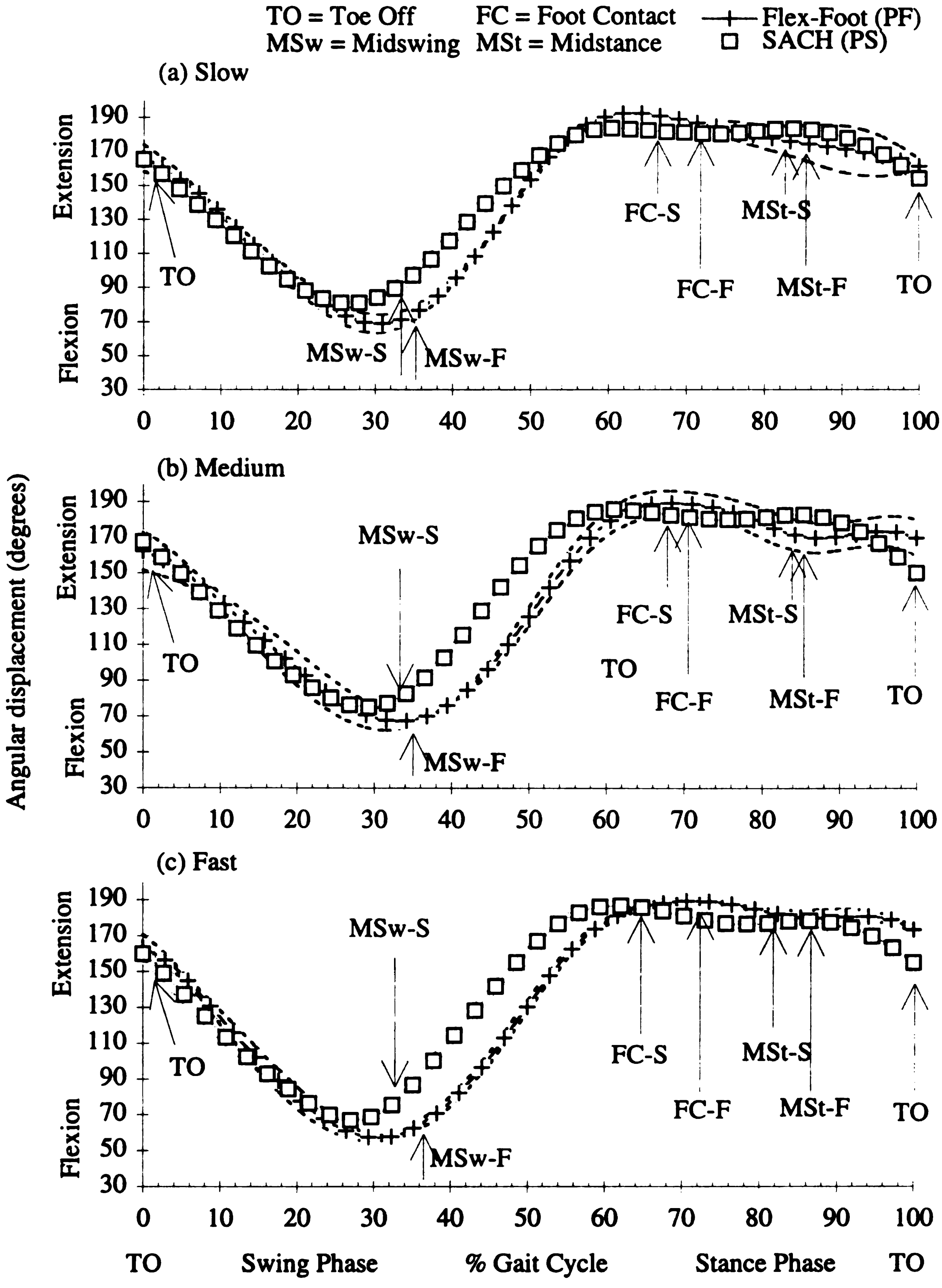


Figure 16. Knee joint angular displacements (mean ± 1SD), from toe off to toe off, of the prosthetic SACH and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

65% to 75% of the gait cycle. As previously discussed, the prosthetic limb knee joint was in a position of hyperextension at foot contact. Unlike the anatomical limb knee joint which flexed during the initial stance phase, the prosthetic limb maintained or slightly deviated from an extended knee joint position of 180 degrees. During the end of the stance phase, the prosthetic Flex continued to maintain knee joint extension followed by slight flexion just before toe off. However, with the prosthetic SACH, there was a greater magnitude of knee joint flexion that occurred prior to toe off, which was opposite to the extension found during terminal stance with the anatomical limb. Prosthetic limb knee joint angle at toe off ranged from 159 to 167 degrees and, as was found with the anatomical limb, those range of motion values were within the range of able bodied individuals, at 140 to 173 degrees (Bates, et al., 1978; Dillman, 1970; Elliott & Blanksby, 1979a; Mann, et al., 1986).

Peak knee flexion occurred between 25% and 35% of the gait cycle and occurred later in the gait cycle, by approximately 5%, with the prosthetic Flex, than with the prosthetic SACH. The peak knee flexion was greater in magnitude for the prosthetic Flex, than for the prosthetic SACH. As stated during the discussion of Table 11, the peak knee flexion values for the prosthetic Flex were similar to those values of able bodied individuals.

The knee joint angular displacements of the anatomical SACH and prosthetic SACH were illustrated in Figure 17 for the (a) slow, (b) medium, and (c) fast velocities. The actual values for the specific gait cycle events will not be presented during the discussion of Figure 17 due to previous presentation of those values during the discussions of Table 9 and Figures 17 and 18. The discussion that follows focused on patterns of similarities and differences between the lower extremity limbs.

In Figure 17, at foot contact, the prosthetic SACH knee joint was hyperextended and that position was maintained throughout initial stance, whereas with the anatomical SACH knee joint flexion following foot contact was seen. During terminal stance at all velocities, knee joint flexion of the prosthetic SACH occurred, a motion that was opposite

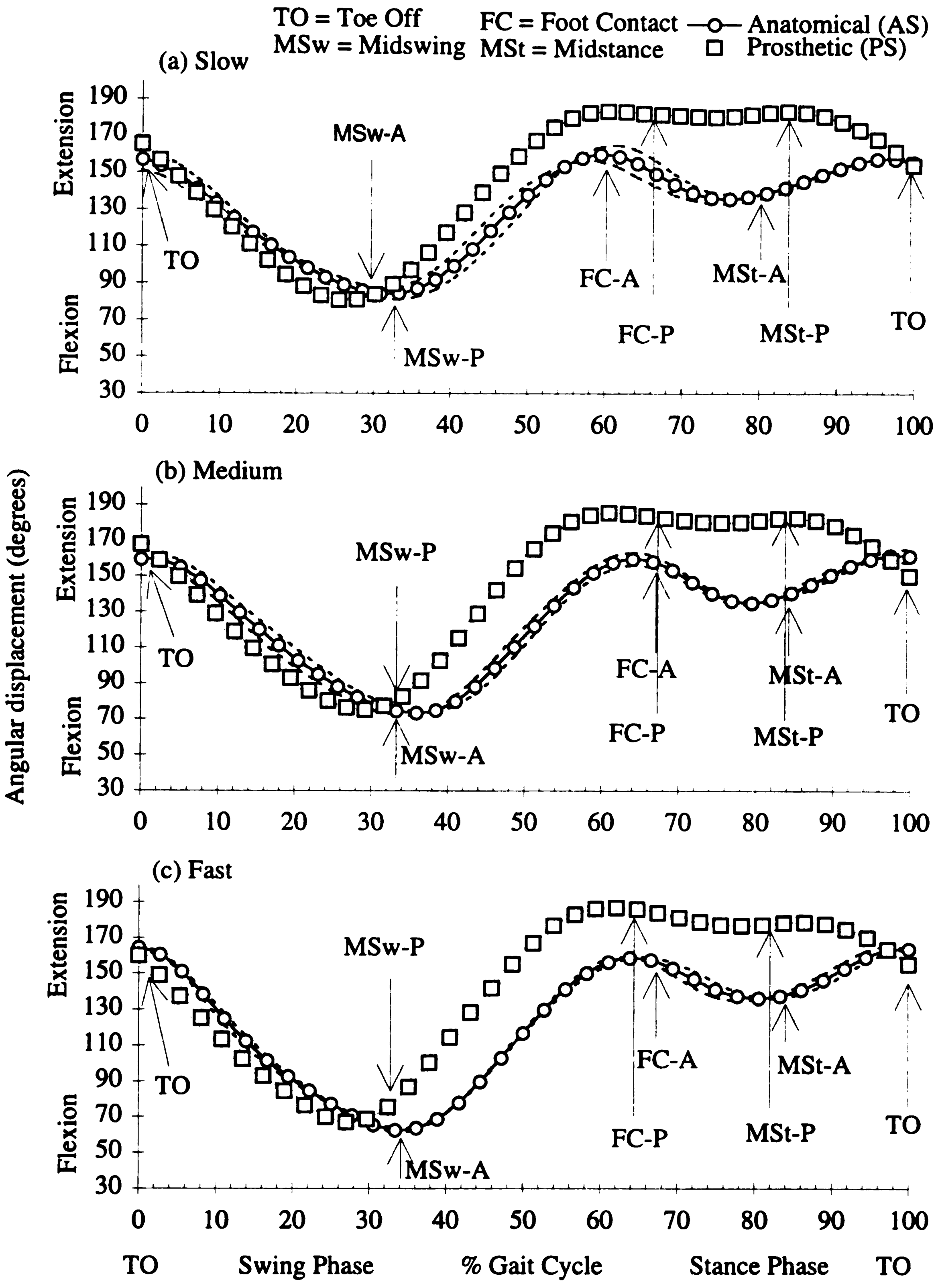


Figure 17. Knee joint angular displacements (mean±1SD), from toe off to toe off, of the anatomical SACH and prosthetic SACH at (a) slow, (b) medium, and (c) fast velocities.

to the knee joint extension of the anatomical SACH. At toe off, there was progressive knee joint flexion of the prosthetic SACH until peak knee flexion in the swing phase at approximately 25% to 30% of the gait cycle. The anatomical SACH had a small amount of knee joint extension at toe off followed by flexion in the swing phase. At all three velocities, the peak knee flexion of the prosthetic SACH occurred prior to that of the anatomical SACH, by approximately 6% of the gait cycle.

The knee joint angular displacements of the anatomical Flex and the prosthetic Flex were illustrated in Figure 18 for the (a) slow, (b) medium, and (c) fast velocities. Again, the actual values for specific gait cycle events were not given due to the previous presentation of those values. In Figure 18, the peak knee extension angle occurred prior to foot contact at approximately 60% to 65% of the gait cycle for all velocities. Under each condition, the knee joint of the prosthetic Flex was hyperextended prior to and during foot contact. This hyperextended position was maintained through midstance but with a decrease in the magnitude of hyperextension. Unlike the prosthetic limb, knee flexion occurred prior to foot contact through initial stance for the anatomical Flex. After midstance, the knee of the anatomical Flex reversed direction to extension in preparation for toe off. During the end of the stance phase with the prosthetic Flex, there was progressive flexion at the slow and fast velocities and a maintained extension position at the medium velocity.

Although the knee joint angles were similar for the anatomical and prosthetic limbs at toe off, their actions immediately after toe off were opposite. Immediately after toe off, knee extension occurred for the anatomical Flex in order to push off into the swing phase. However, with the prosthetic Flex, flexion was observed. During the swing phase, the peak knee joint flexion of the anatomical Flex occurred later in the gait cycle, at 36% to 38% of the gait cycle, at all velocities, than for the prosthetic Flex, at 30% to 34% of the gait cycle. However, the difference in magnitude between the anatomical Flex and the prosthetic Flex maximum knee joint flexion angles changed with speed. At the slow

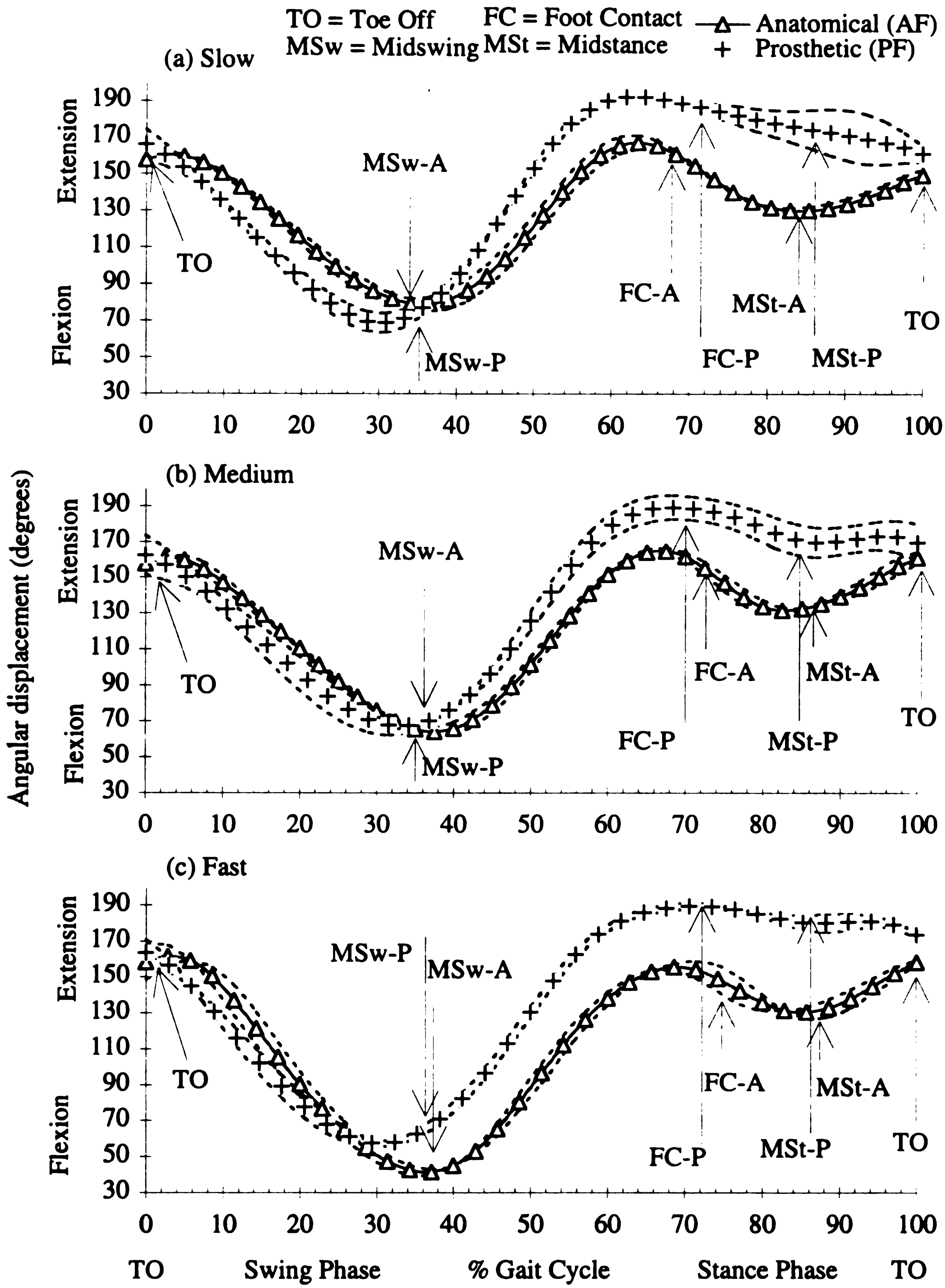


Figure 18. Knee joint angular displacements (mean ± 1SD), from toe off to toe off, of the anatomical Flex and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

velocity, the anatomical Flex had a larger angle than the prosthetic Flex, a difference of 10 degrees. At the medium velocity, the maximum knee joint angles of the anatomical Flex and prosthetic Flex were similar. However at the fast velocity, the anatomical Flex had a knee joint flexion angle 17 degrees smaller than the prosthetic Flex. At increased velocity, the peak knee flexion angles progressively got smaller, with a more dramatic decrease observed for the anatomical Flex than for the prosthetic Flex. The larger flexion angles of the prosthetic Flex were due to the resistance of the prosthetic shank to backward swing, and thereby increased the resistance of the knee joint to swing the prosthetic limb forward.

Knee joint hyperextension was seen for both the prosthetic SACH and the prosthetic Flex prior to and during initial stance, a finding consistent with Miller (1987) and Enoka et al. (1982). Miller (1987) and Enoka et al. (1982) found that the individuals who maintained a straight or hyperextended knee during prosthetic stance lacked sufficient quadriceps muscle strength, due to limited knee musculature to permit knee flexion. Enoka et al. (1982) also hypothesized that knee joint hyperextension was a means for the individual to protect against the knee buckling upon ground contact.

Ankle Joint

Comparisons of the ankle joint angular motion during running between able bodied individuals and the participant in this study were limited. First, the available data on able bodied participants describing the angles of dorsiflexion and plantar flexion at various phases of the gait cycle were few. Second, some of the previous studies defined the ankle angle as the angle between the shank and the line connecting the calcaneous and the head of the fifth metatarsal, whereas in this study the angle was defined as the angle between the shank and the line connecting the lateral malleolus and the head of the fifth metatarsal. Finally, the amount of displacement immediately following foot contact was determined by the foot position upon contact (heel, mid sole or toe) which differs across trials and across individuals. Therefore, comparative data were limited in this section.

Table 12 is a summary of the maximum ankle joint dorsiflexion and maximum ankle joint plantar flexion angular displacement values reported for able bodied participants from the literature. The contents of Table 12 were discussed in the next section when comparisons were made between able bodied individuals and the participant of this study.

Table 12.

Literature Summary: Ankle Joint Range of Motion for the Able Bodied Population.

Investigators	Velocity of running (m/s)	Foot contact (degrees)	Toe off (degrees)
Bates, Osternig, and Mason (1978)	3.35	115	140
	4.5	116	145
Elliott and Blanksby (1979)	3.5	99	123

The ankle joint range of motion during the stance phase for the SACH foot and the Flex-Foot™ at the slow, medium, and fast velocities were presented in Table 13. The peak stance phase ankle joint dorsiflexion angles, within each velocity category, were smaller with the ankle joint dorsiflexion angles, within each velocity category, were smaller with the anatomical limb, all angles less than 90 degrees, than the prosthetic limb angles, all greater than 100 degrees. During the stance phase, there was limited movement of the prosthetic shank over the stationary foot. The peak stance phase plantar flexion angles were greater for the anatomical limb than for the prosthetic limb, at all velocities, except for the Flex-Foot™ at the slow velocity. The anatomical Flex and the prosthetic Flex had the same maximum plantar flexion angle. The absolute range of motion during the stance phase was greater for the anatomical limb than for the prosthetic limb. The differences between the anatomical and prosthetic ankle joints ranges of motion were due to smaller

Table 13.

Stance Phase Maximum Dorsiflexion and Maximum Plantar Flexion Angular Displacement Values and their Difference for the Ankle Joint at Three Velocities With Both Prosthetic Feet.

	SACH Foot			Flex-Foot™		
	Slow	Medium	Fast	Slow	Medium	Fast
Anatomical Limb	86-131	88-128	87-136	88-118	80-127	89-127
	(45)	(40)	(49)	(30)	(47)	(38)
Prosthetic Limb	111-117	110-116	108-116	104-118	102-118	102-118
	(6)	(6)	(8)	(14)	(16)	(16)

magnitudes of dorsiflexion and plantar flexion allowed by the prosthetic ankle joint. Within the prosthetic limb, there was a greater magnitude of absolute range of motion for the Flex-Foot™ than for the SACH foot, due primarily to the greater magnitude of dorsiflexion allowed by the prosthetic Flex than allowed by the prosthetic SACH.

In the remaining discussion, reference was made to illustrations of the ankle joint motion during the gait cycle. In Figures 19 through 22, the reader will note two particular patterns of the ankle joint not seen as dramatically at the knee and hip joints. First, there was a large amount of variation in the ankle joint motion throughout the gait cycle. The lack of consistency was a direct result of the participant's lack of ankle joint musculature and neural feedback and therefore his inability to control the motion of the artificial ankle joint. Second, the standard deviation lines cross the mean line at various points. The crossing represented a point along the gait cycle where the ankle joint pattern of one trial crossed the pattern of another trial.

The angular displacements of the anatomical SACH and the anatomical Flex ankle joints at the (a) slow, (b) medium, and (c) fast velocities were illustrated in Figure 19.

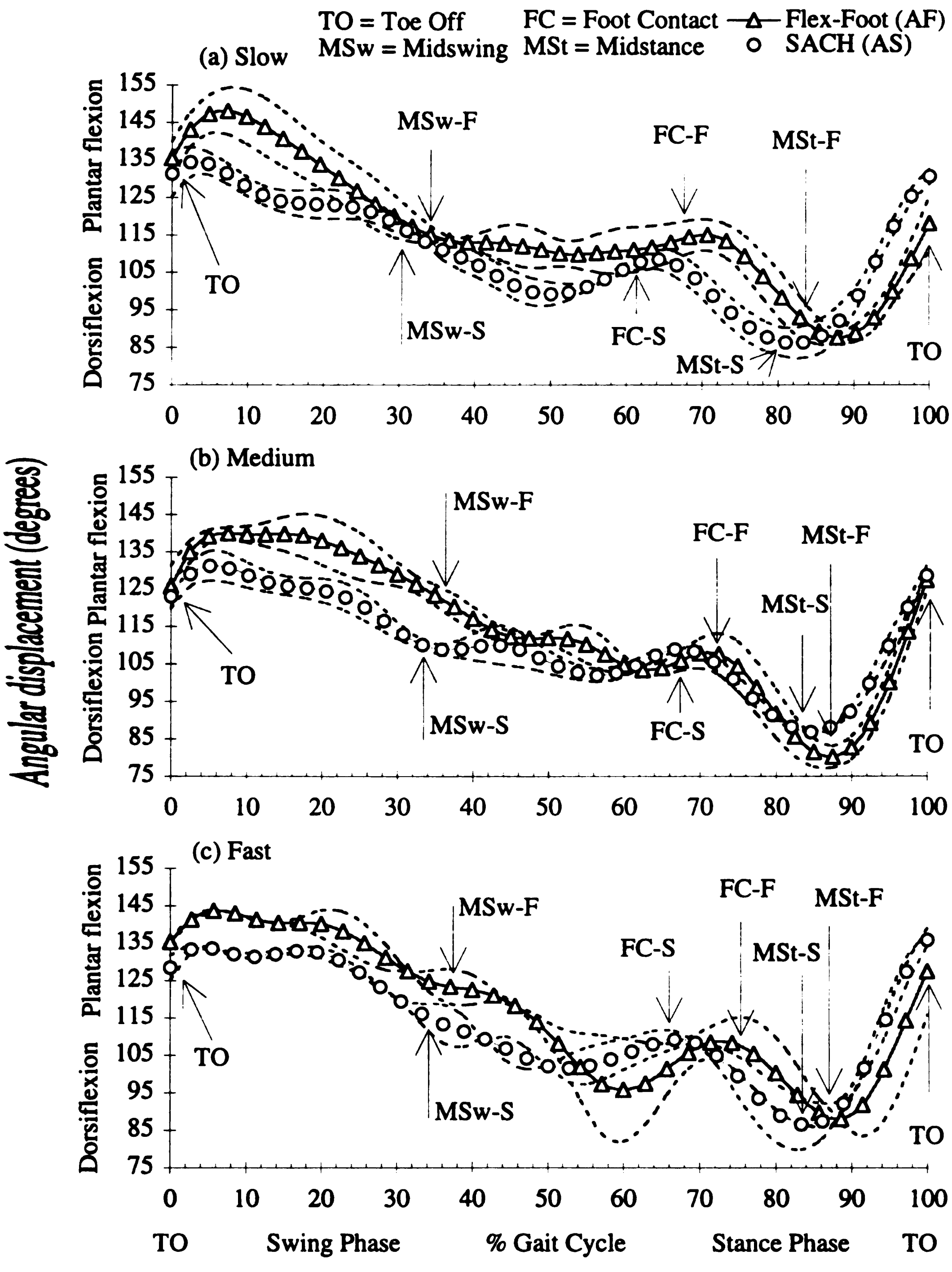


Figure 19. Ankle joint angular displacements (mean ± 1SD), from toe off to toe off, of the anatomical SACH and anatomical Flex at (a) slow, (b) medium, and (c) fast velocities.

Ankle joint angles at foot contact were larger and occurred later in the gait cycle with the anatomical Flex, 115 degrees at 68%, than with the anatomical SACH, 108 degrees at 60%, compared to a range in the literature on able bodied individuals of 99 to 115 degrees. The values at foot contact are related to the position of the foot upon ground contact thereby making comparative interpretations difficult, and the ankle angles of the prosthetic limb are predetermined with the appliance. At the medium and fast velocities, the ankle joint angles at foot contact were similar, but occurred earlier in the gait cycle for the SACH foot than for the Flex-Foot™, 109 and 108 degrees, respectively. At a velocity similar to the medium velocity of this study, able bodied participants had ankle displacement values at foot contact of 116 degrees, larger in magnitude than those of this participant.

During the stance phase, as the shank moved over the foot, maximum ankle joint dorsiflexion occurred. The maximum ankle joint dorsiflexion occurred earlier in the gait cycle with the SACH foot than with the Flex-Foot™ at the slow, 81% versus 88%, medium, 84% versus 87%, and fast velocities, 83% versus 89%, respectively. When the shank was beyond the foot and the participant prepared for the subsequent toe off, the anatomical ankle joint reversed into plantar flexion. The anatomical Flex at the slow velocity, however, had progressive ankle joint dorsiflexion until approximately 90% of the gait cycle when ankle joint plantar flexion occurred.

The ankle joint angles at toe off were larger for the anatomical Flex than for the anatomical SACH at the slow, 135 and 131 degrees, medium, 126 and 123 degrees, and fast velocities, 135 and 128 degrees, respectively. Ankle joint angles at toe off of 123 to 140 degrees have been reported for able bodied participants running at similar slow velocities, and were similar to those found for the participant of this study at all velocities. The anatomical Flex had higher peak plantar flexion angles and occurred later during the swing phase than the anatomical SACH. The peak plantar flexion angle and the position as a percentage of the gait cycle for the anatomical Flex and the anatomical SACH were as follows: (a) at the slow velocity, 148 degrees at 8% and 134 degrees at 3%; (b) at the medium velocity, 140 degrees at 8% and 131 degrees at 5%; and (c) at the fast velocity, 144 at 6% and 134 at 5%. Following the peak ankle plantar flexion, all conditions showed a general progression towards ankle dorsiflexion, a movement necessary to clear the foot from the ground during the swing phase. At approximately 50% to 65% of the gait cycle, plantar flexion began as the foot was lowered to the ground in preparation for foot contact, except with the anatomical Flex at the slow velocity where a plantar flexed position was maintained.

Ankle joint angular displacements of the prosthetic SACH and the prosthetic Flex at the (a) slow, (b) medium, and (c) fast velocities were illustrated in Figure 20. The pattern of motion for the prosthetic limb was not similar to the able bodied population as was seen with the anatomical limb. Instead, the motion was rigid and limited in the amount of dorsiflexion and plantar flexion due to the mechanical characteristics of each appliance. Ankle joint angles at foot contact were slightly larger and occurred later in the gait cycle with the prosthetic Flex than with the prosthetic SACH and were as follows: (a) at the slow velocity, 116 degrees at 71% and 114 degrees at 66%; (b) at the medium velocity 115 degrees at 70% and 113 degrees at 68 %; and (c) at the fast velocity, 114 degrees at 72% and 112 degrees at 65%. Although there were differences among prosthetic feet at each velocity, the ankle joint angles were very similar within each prosthetic foot across velocities. This similarity indicated that the prosthetic appliance motion upon foot contact was minimally affected by the velocity of gait. From foot contact to midstance for all conditions, there was minimal progressive ankle joint plantar flexion followed by ankle joint dorsiflexion which peaked past midstance. The peak dorsiflexion angle and position in the gait cycle were smaller and occurred later for the Flex-Foot™ than for the SACH foot, and the values were as follows: (a) at the slow velocity, 104 degrees at 93% and 111 degrees at 86%; (b) at the medium velocity, 102 degrees at 92% and 110 degrees at 87%; and (c) at the fast velocity, 102 degrees at 94% and 108 degrees at 89%. Again, the motion

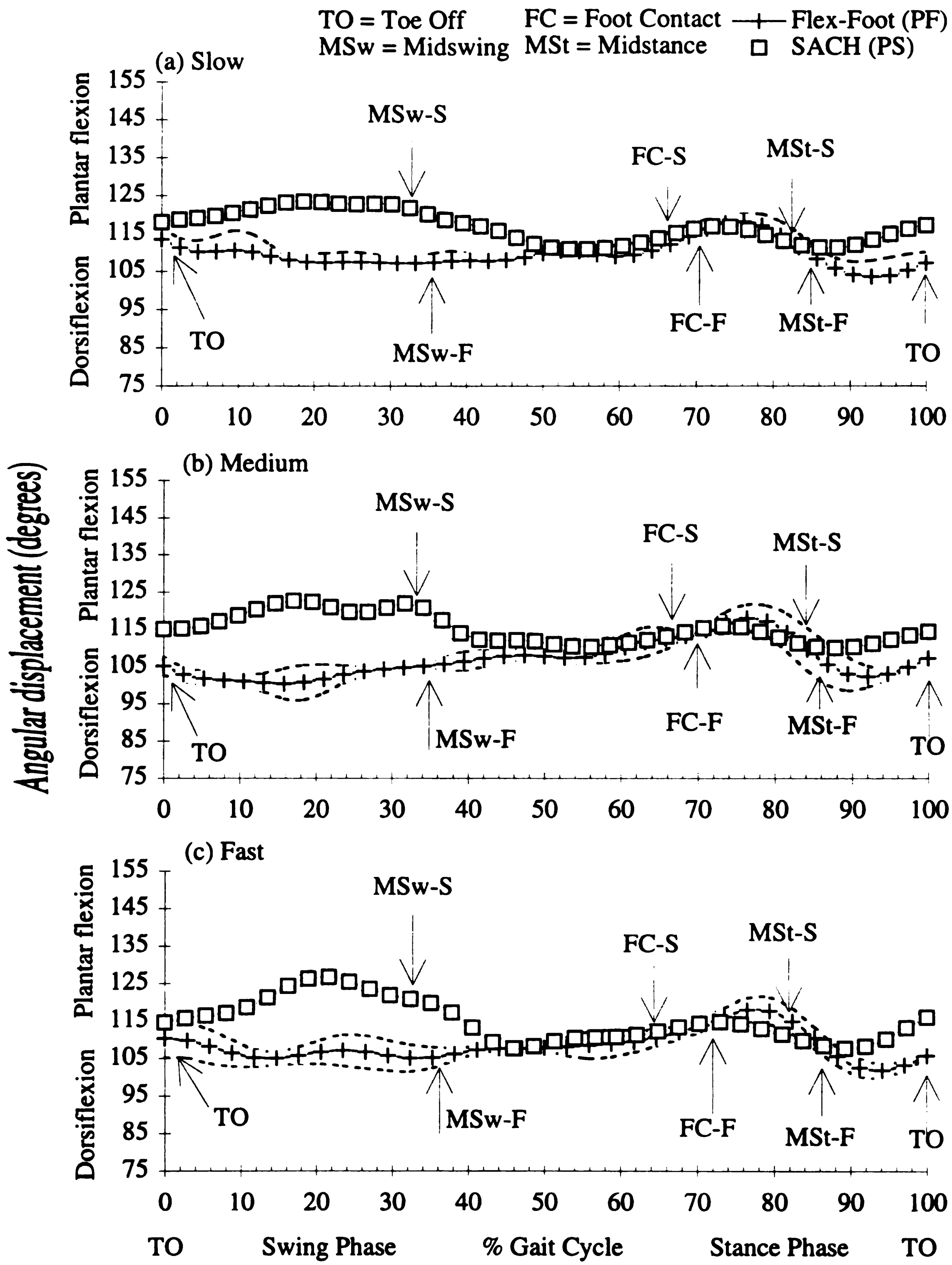


Figure 20. Ankle joint angular displacements (mean ± 1SD), from toe off to toe off, of the prosthetic SACH and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

of the prosthetic appliance during the stance phase was minimally affected by the velocity of gait.

After the peak ankle joint dorsiflexion occurred, the ankle joint reversed direction into plantar flexion that progressed through toe off. This plantar flexion motion was seen in all conditions. The pattern of motion with the prosthetic Flex during the stance phase was similar to that found in able bodied populations, although the prosthetic Flex had a shift in the range with larger dorsiflexion angles and smaller plantar flexion angles (Bates, et al., 1978; Mann, 1982). The ankle plantar flexion angles at toe off, were similar across velocities within the prosthetic feet, but the Flex-Foot™ had higher angles than the SACH foot at all velocities. With the SACH foot and the Flex-Foot™, the toe off angles were: (a) 113 and 118 degrees at the slow velocity, (b) 105 and 115 at the medium velocity, and (c) 110 and 115 degrees at the fast velocity. The Flex-Foot™ showed a greater amount of deformation throughout the stance phase than did the SACH foot due to the difference in appliance design and material.

The ankle joint angular displacements of the anatomical SACH and the prosthetic SACH were illustrated in Figure 21 for the (a) slow, (b) medium, and (c) fast velocities. The actual values for specific gait cycle events will not be presented during the discussion of Figure 21 due to previous presentation of those values during the discussions of Table 13. The next section focused on patterns of similarities and differences between the lower extremity limbs.

In Figure 21, at all three velocities, the anatomical limb had patterns of motion that were similar to the able bodied population, and the prosthetic limb was limited in motion. The ranges of motion of both limbs with the SACH foot were slightly larger at the fast velocity, than at the medium and slow velocities due to a larger plantar flexion angle during the swing phase. The two major differences between the anatomical SACH and the prosthetic SACH was during the stance phase and the dorsiflexion during the end of the swing phase. Since there was essentially no ankle joint dorsi- or plantar flexion with the

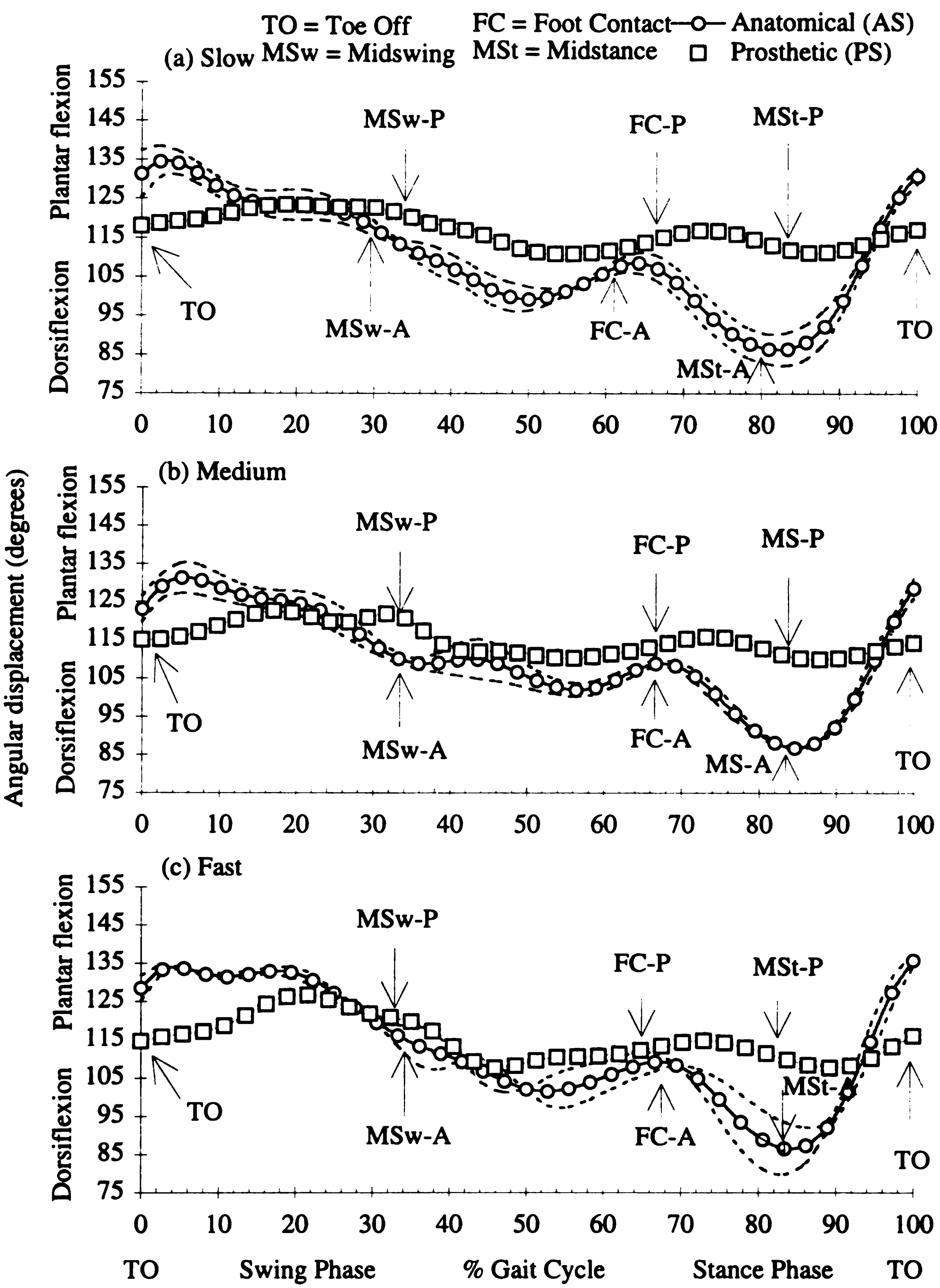


Figure 21. Ankle joint angular displacements (mean ± 1SD), from toe off to toe off, of the anatomical SACH foot and prosthetic SACH at (a) slow, (b) medium, and (c) fast velocities.

prosthetic SACH during the entire stance phase, the prosthetic ankle joint minimally contributed to the propulsion of the body forward into the flight phase at toe off. With the prosthetic ankle there was no dorsiflexion during terminal swing in preparation for foot contact.

The ankle joint angular displacements of the anatomical Flex and the prosthetic Flex were illustrated in Figure 22 for the (a) slow, (b) medium, and (c) fast velocities. Again, the actual values for specific gait cycle events will not be given due to the previous presentation of those values. In Figure 22, the patterns of motion during the stance phase were similar between the anatomical and prosthetic limbs. However with the prosthetic ankle, the magnitudes of dorsiflexion were larger and planter flexion were smaller than with the anatomical ankle. During the swing phase, the peak plantar flexion and progressive dorsiflexion was absent with the Flex-Foot™. Instead, a slight plantar flexion position was maintained with the Flex-Foot™ throughout most of the swing phase.

Summary of Angular Displacement

The greater range of motion attained with the anatomical limb relative to the prosthetic limb was primarily due to an increased magnitude of hip joint extension that occurred at or near toe off. The participant may not have extended the hip joint of the prosthetic limb at toe off for reasons of comfort, fear of loss of control of the prosthetic limb, or an inability to fully extend at the hip joint with limited ankle joint plantar flexion. Yet, the prosthetic Flex had a greater range of motion than the prosthetic SACH primarily due to a greater degree of hip joint flexion during the swing phase. The greater hip joint flexion may have been a reflection of the prosthetic swing limb experiencing the energy release of the Flex-Foot™ after toe off. Therefore the participant was able to attain a greater degree of hip joint flexion during the swing phase which assisted in the longer stride length and thus the greater speed of running.

Not only did the prosthetic Flex attain a greater magnitude of hip joint flexion but also a greater magnitude of knee joint flexion, relative to the prosthetic SACH. The knee

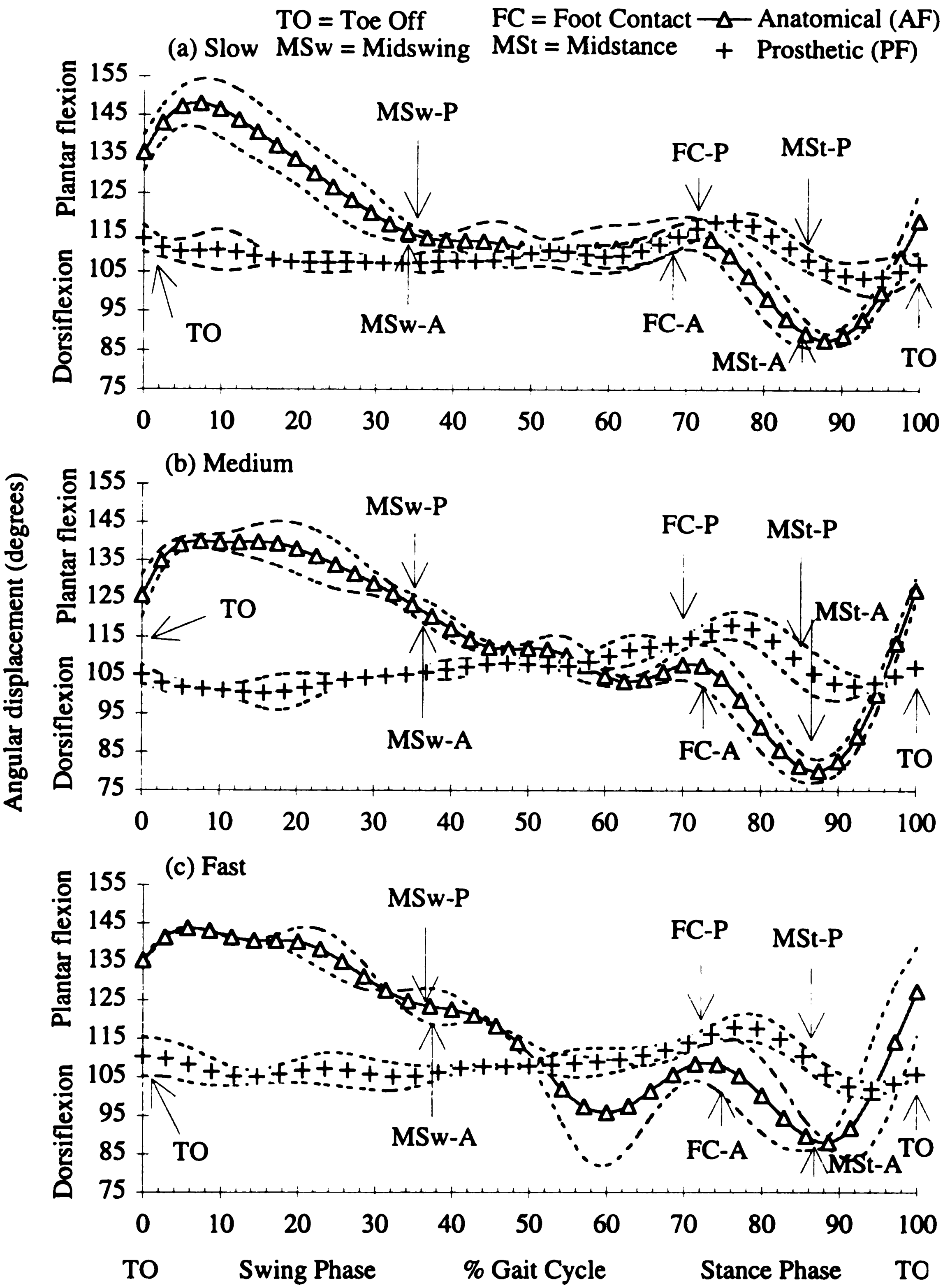


Figure 22. Ankle joint angular displacements (mean ± 1SD), from toe off to toe off, of the anatomical Flex and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

joint flexion during the swing phase was a passive motion and was due to the forward rotation of the thigh segment during hip joint flexion in the swing phase. During the swing phase then, the prosthetic Flex shank segment rotates forward through a greater degree of rotation given the greater amount of knee flexion.

At the level of the prosthetic foot, where the effect of energy storage and return would be greatest, the results of the ankle joint were consistent with those of the hip and knee joints. The ankle joint range of motion was greater with the prosthetic Flex than the prosthetic SACH primarily due to a greater magnitude of ankle joint dorsiflexion during the stance phase. During that phase the shank rotated over the stationary prosthetic foot which resulted in prosthetic foot deformation, energy storage. Therefore, the greater amount of stance phase dorsiflexion with the prosthetic Flex possibly meant that there was a greater amount of energy stored in the Flex-Foot™ and thus a greater amount of energy released. Hypothetically then, the prosthesis energy release aided in the greater knee joint flexion and hip joint flexion, which ultimately resulted in a longer swing phase.

Taken together, the results from the joint angular displacement data indicate that the Flex-Foot™ was superior in attaining greater magnitudes of range of motion at the lower limb joints than the SACH foot. The advantage of larger ranges of motion is a sequential process of that resulted in a longer swing phase and thus a longer stride length and faster running speed.

<u>Total Lower Limb Angular Displacement</u>

In Figures 23 though 28, the angular motion of the (a) hip, (b) knee, and (c) ankle joints were grouped together for each prosthetic foot at each velocity to represent the synchronized motion of the lower limb joints during the gait cycle. Although the magnitudes of motion were different for each velocity at each joint, for purposes of describing the overall motion of the lower limb joints, the angular displacement values were generally not included in the discussion.

The angular displacements of the lower limb joints at the slow speed with the SACH foot were illustrated in Figure 23. Discussion of the anatomical limb motion was first. At the beginning of the anatomical limb stance phase, the hip joint maintained a position of extension, there was knee joint flexion and a peak ankle joint plantar flexion that reversed to dorsiflexion. The motions of the knee and ankle joints helped to absorb the impact of ground contact. Prior to midstance, peak knee joint flexion occurred, while the hip joint maintained extension and the ankle joint continued to dorsiflex. At midstance, maximum ankle joint dorsiflexion occurred while the knee and hip joints progressively extended. During the end of the stance phase, hip and knee joint extension and ankle joint plantar flexion occurred as the body propelled forward into the swing phase. After toe off, the ankle joint reached a peak plantar flexion position, then the hip joint reached a peak extension position during which the knee joint was in progressive flexion. The hip joint progressively flexed through midswing, the knee joint progressively flexed to just before midswing for the prosthetic SACH and just after midswing for the anatomical SACH, and the ankle joint maintained a position of plantar flexion from approximately 10% to 26% of the gait cycle. After midswing, the maximum knee flexion angle occurred, a motion before the beginning of the shank's swing forward, while the hip continued to flex and the ankle began to dorsiflex. During the middle to latter part of the swing phase (from 32% to 50% of the gait cycle), maximum hip joint flexion was reached, there was progressive knee joint extension and ankle joint dorsiflexion. Prior to foot contact, there was progressive hip joint extension, peak knee joint extension and progressive ankle joint plantar flexion.

Discussion of the motions of the lower extremity joints with the prosthetic SACH follows. The motions of the prosthetic SACH during the stance phase were different than what was found with the anatomical SACH. From foot contact to midstance, there was progressive hip joint extension, a maintained position of extension at the knee joint, and an initial plantar flexion motion that reversed to dorsiflexion. From midstance to toe off, a hip joint extension position was maintained, there was reversal of the knee joint to flexion and

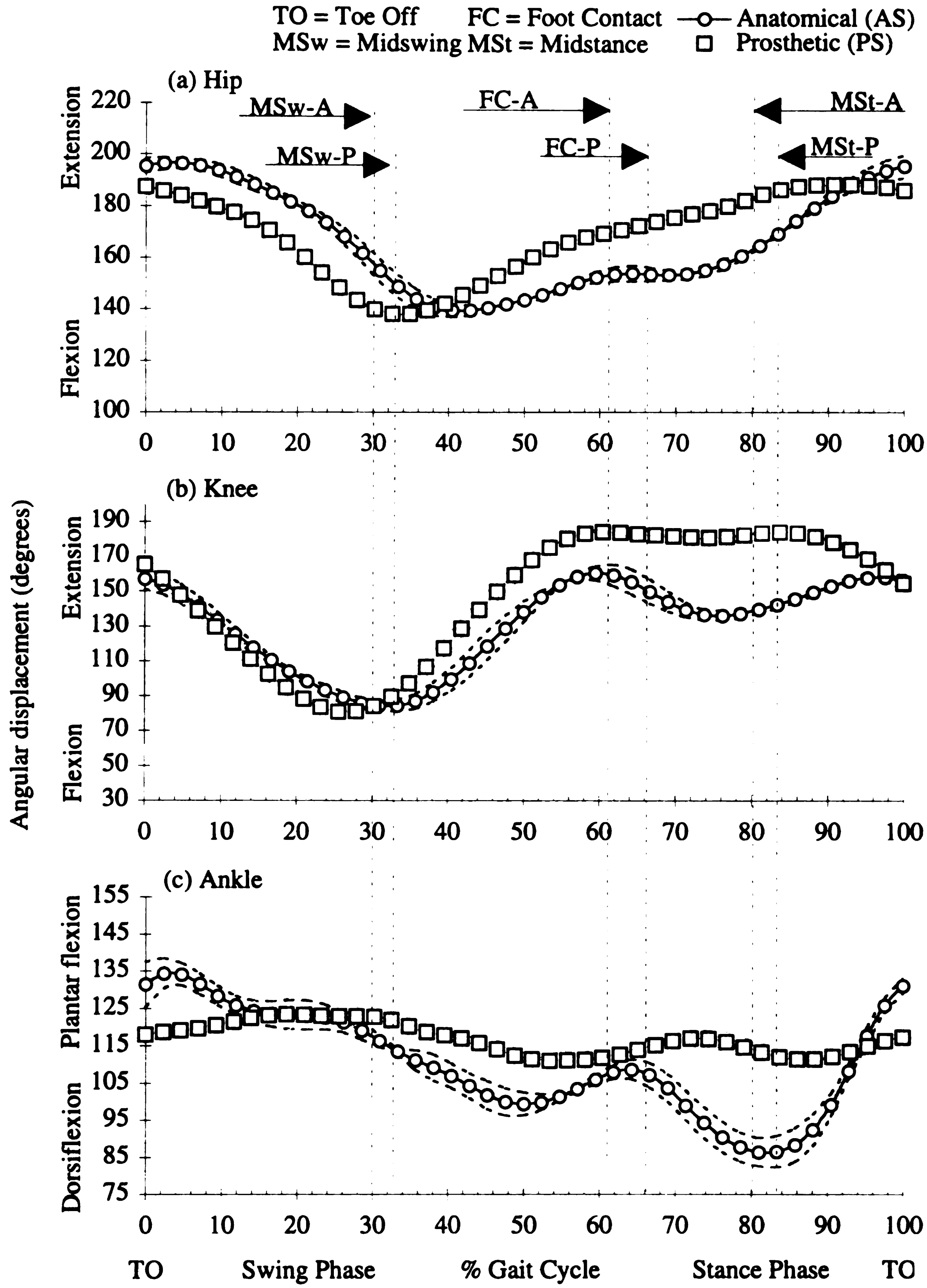


Figure 23. Angular displacements (mean ± 1SD) at the (a) hip, (b) knee, and (c) ankle joints, from toe off to toe off, with the SACH foot at the slow velocity.

there was gradual plantar flexion at the ankle joint. The motion of the knee joint and position of the ankle joint were not advantageous for helping propel the body forward into the swing phase. From toe off to midswing, the prosthetic limb motion was similar to the anatomical limb motion. There was prosthetic hip and knee joint flexion, but not peak hip joint extension immediately after toe off as was found with the anatomical limb. The peak prosthetic knee flexion occurred prior to midswing, whereas the peak anatomical knee flexion occurred after midswing. The ankle joint motion was minimal from toe off to midswing with a plantar flexion position maintained. From midswing to foot contact, there was progressive hip and knee joint extension, with the knee joint maintained in an extended position just prior to foot contact, and moderate ankle joint dorsiflexion.

The angular displacements of the lower limb joints at the medium velocity with the SACH foot were illustrated in Figure 24. Discussion of the anatomical and prosthetic limb motions was limited to differences found between the slow and medium velocities. During the stance phase, the plantar flexion peak for the anatomical ankle joint occurred during foot contact (68% of the gait cycle) at the medium speed, whereas at the slow speed it occurred after foot contact (64% of the gait cycle). During the swing phase, the anatomical limb peak hip extension and the anatomical limb peak ankle plantar flexion occurred simultaneously at 6% of the gait cycle. These occurrences happened after foot contact at the medium velocity. At the slow velocity on the anatomical limb, the ankle peak plantar flexion occurred before the hip peak extension. The prosthetic maximum flexion angle during the swing phase occurred after midswing at the medium velocity compared to a simultaneous occurrence with midswing at the slow velocity. Finally, during the middle to latter part of the swing phase, the anatomical ankle joint was maintained in plantar flexion unlike the progressive dorsiflexion found at the slow velocity. The timing of this minimal ankle movement occurred between maximum knee joint flexion and maximum hip joint flexion.

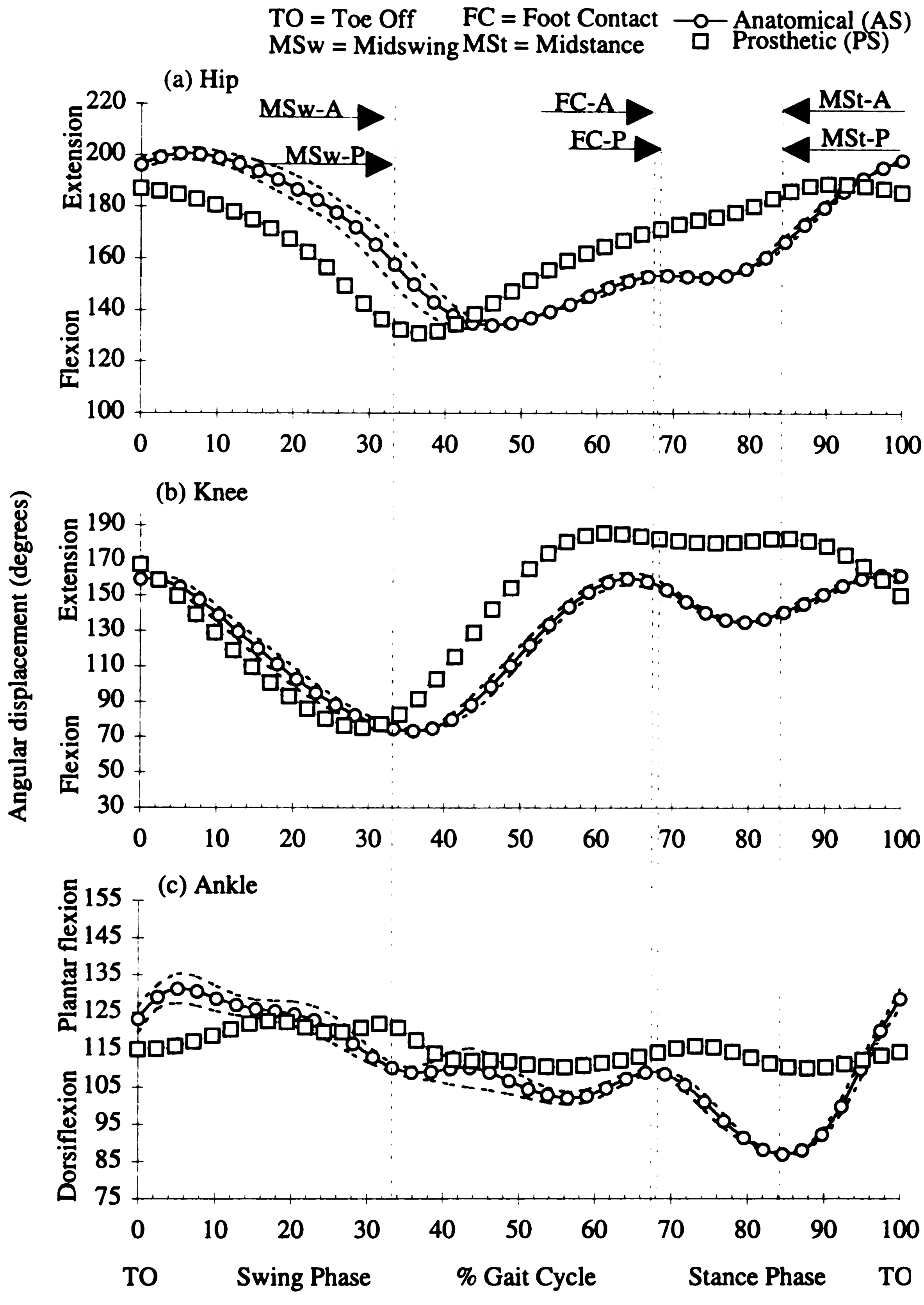


Figure 24. Angular displacements (mean ± 1SD) at the (a) hip, (b) knee, and (c) ankle joints, from toe off to toe off, with the SACH foot at the medium velocity.

The angular displacements of the lower limb joints at the fast velocity with the SACH foot were illustrated in Figure 25. During the stance phase, the anatomical ankle joint plantar flexion peak occurred during foot contact at the fast velocity, as was found at the medium velocity, whereas at the slow velocity it occurred after foot contact. Also, simultaneous occurrences of anatomical peak hip joint extension and ankle joint plantar flexion, during the swing phase, were found at the medium and fast velocities. However, at the slow velocity, the anatomical peak hip joint extension occurred after the ankle joint plantar flexion. At the fast velocity, the anatomical ankle joint maintained a plantar flexed position for a short period during the early part of the swing phase. Such a position was not seen at the slow and medium velocities.

The angular displacements of the lower limb joints at the slow speed with the Flex foot were illustrated in Figure 26. Discussion of the anatomical limb motion was first. At the beginning of the anatomical limb stance phase, hip and knee joint flexion, and ankle joint dorsiflexion occurred. Prior to midstance, there was hip joint reversal to extension while knee joint flexion and ankle joint dorsiflexion continued. At midstance, there was a peak knee joint flexion followed by a peak ankle joint dorsiflexion. Through the remainder of the stance phase, the hip and knee joints extended, and the ankle joint plantar flexed. Immediately after toe off, there was hip joint extension, a maintained extension position at the knee joint, and ankle joint plantar flexion. The knee joint began to flex before the hip joint reached a peak extension angle, and the ankle joint reached a peak plantar flexion angle. Through midswing, hip and knee joint extension, and ankle joint dorsiflexion occurred. At midswing, the knee joint flexion peaked while there was continued hip joint flexion and gradual ankle joint dorsiflexion. After midswing, the hip joint flexion peaked while the knee joint was in progressive extension and the ankle joint was plantar flexed. During the latter part of the swing phase, there was gradual extension at the hip joint, rapid extension at the knee joint until prior to foot contact when the knee joint reversed to flexion.

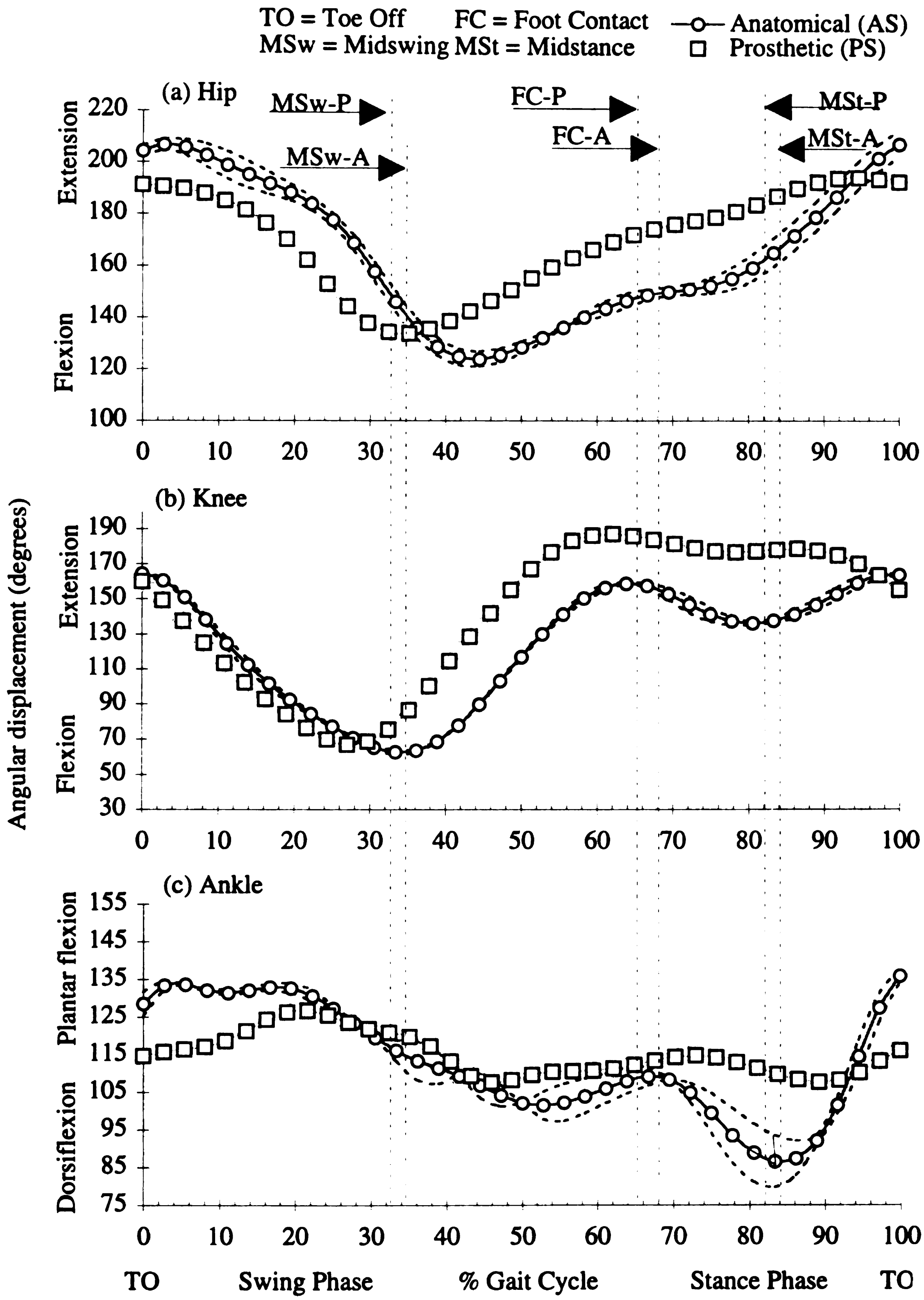


Figure 25. Angular displacements (mean ± 1SD) at the (a) hip, (b) knee, and (c) ankle joints, from toe off to toe off, with the SACH foot at the fast velocity.

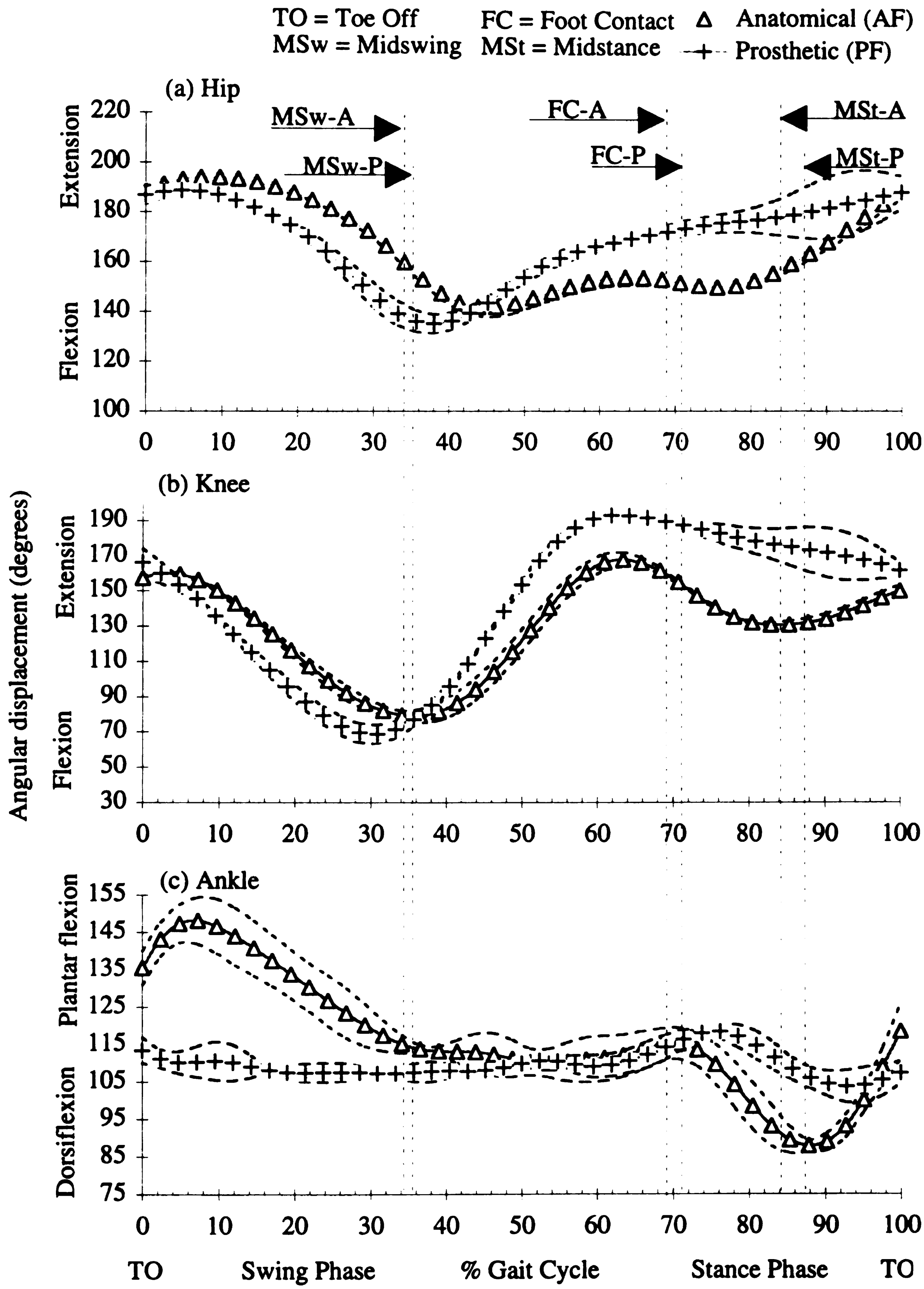


Figure 26. Angular displacements (mean ± 1SD) at the (a) hip, (b) knee, and (c) ankle joints, from toe off to toe off, with the Flex-FootTM at the slow velocity.

Discussion of the motions of the lower extremity joints with the prosthetic Flex follows. As was found with the SACH foot, the motions of the prosthetic Flex during the stance phase were different than what was found with the anatomical Flex. From foot contact to toe off, there was gradual hip joint extension and knee joint flexion. Immediately after foot contact, the ankle joint plantar flexed, then reversed to dorsiflexion through midstance, then reversed again to a slight plantar flexion position. After toe off, the hip joint maintained a position of extension and then began to flex, the knee joint rapidly flexed and the ankle joint maintained a mid position and then slight plantar flexion just before foot contact. Maximum knee joint flexion occurred prior to midswing and maximum hip joint flexion occurred after midswing. From the middle to latter part of the swing phase, hip and knee joint extension occurred. The hip joint continued extension to foot contact and the knee joint reversed direction to flexion prior to foot contact.

The angular displacements of the lower limb joints at the medium velocity with the Flex-Foot™ were illustrated in Figure 27. Discussion of the anatomical and prosthetic limb motions was limited to differences found between the slow and medium velocities. The most dramatic difference in lower extremity motion from the slow to medium velocity was in the prosthetic limb from midstance to toe off. At the prosthetic hip joint, there was rapid extension and a maintained extension position at the knee joint at the medium velocity. At the slow velocity there was gradual hip joint extension and knee joint flexion from midstance to toe off. So although the prosthetic appliance motion and degree of deformation was similar at the slow and medium velocities, the motion at the knee and hip joints indicated that the ability of the participant to propel the body forward while wearing the Flex-Foot™ was improved with increased velocity. Other less dramatic, differences noted were during the swing phase. The peak prosthetic knee and hip joint flexion angles occurred during and after midswing, respectively, at the medium velocity. At the slow velocity, the peak prosthetic knee and hip joint flexion angles occurred before and during midswing, respectively.

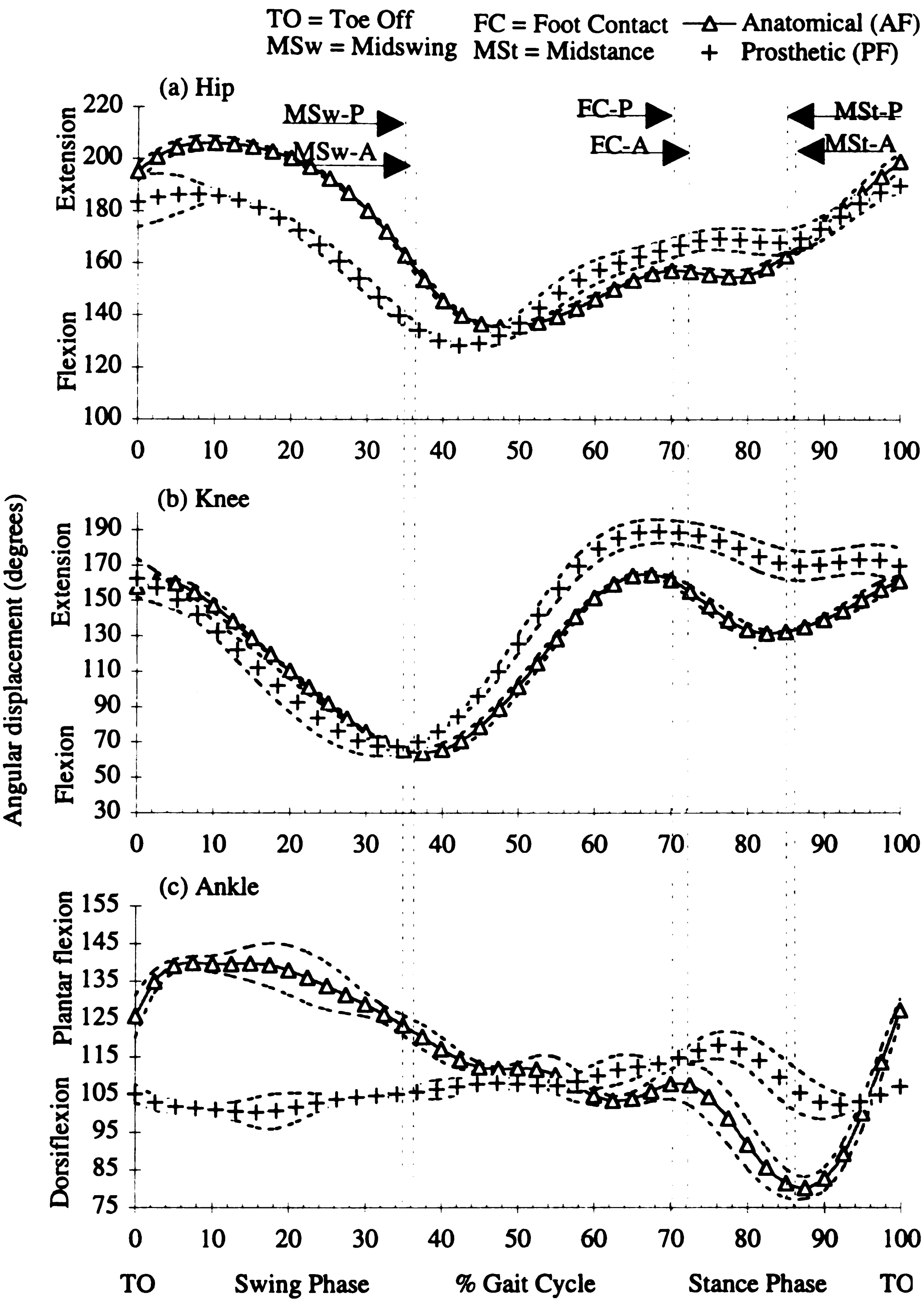


Figure 27. Angular displacements (mean ± 1SD)atf the (a) hip, (b) knee, and (c) ankle joints, from toe off to toe off, with the Flex-FootTM at the medium velocity.

The angular displacements of the lower limb joints at the fast velocity with the Flex-Foot™ were illustrated in Figure 28. Discussion of the anatomical and prosthetic limb motions was limited to differences found between the slow and fast velocities, and medium and fast velocities. As was found at the medium velocity, at the fast velocity the prosthetic hip and knee joint motions during the latter part of stance phase were different from what was found at the slow velocity. That is, the prosthetic hip joint had rapid extension and the knee joint maintained a position of extension from midstance to toe off. During the swing phase, the maximum prosthetic knee joint angle occurred before midswing at the fast and slow velocities, but during midswing at the medium velocity. The maximum prosthetic hip joint flexion angle occurred after midswing at the fast and medium velocities, but during midswing at the slow velocity. Therefore, the longest period of forward swinging motion of the shank while the hip joint was in flexion occurred at the fast velocity. The anatomical ankle joint had a longer period of dorsiflexion and a smaller peak plantar flexion angle during the second half of the swing phase at the fast velocity, when compared to the medium and slow velocities.

Angular Velocities

Angular velocities, in degrees per second, of the three lower extremity joints, for the four conditions at the three velocities, were presented and discussed in this section. For each lower extremity joint, the angular velocities throughout the gait cycle were illustrated.

Hip Joint

In the following section, comparisons of the hip joint angular velocities during the gait cycle were made between the participant of this study and the able bodied population based on values reported in the literature. Literature reporting hip joint angular velocity values for able bodied individuals include maximum hip joint angular velocity but not minimum hip joint angular velocities. Also, this investigator was not able to find literature that reported hip joint angular velocities for individuals with below the knee amputations. Maximum hip joint angular velocity values for able bodied participants at velocities similar

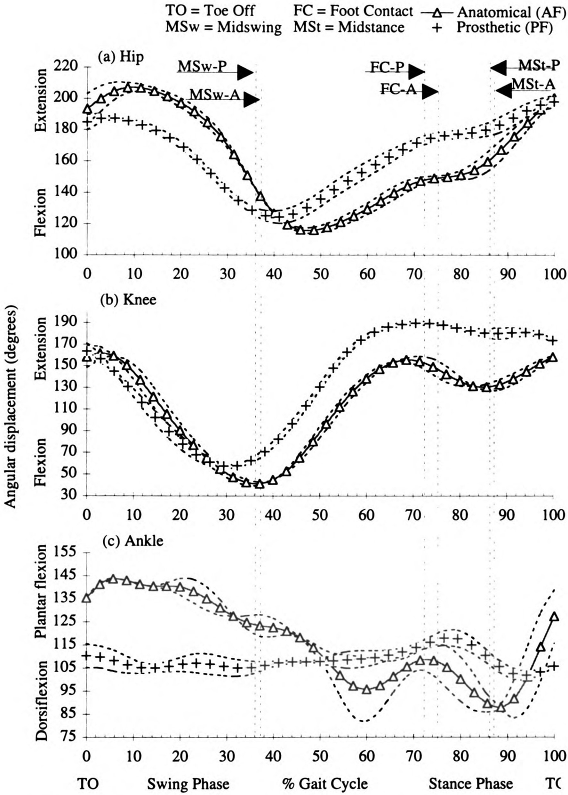


Figure 28. Angular displacements (mean ± 1SD) at the (a) hip, (b) knee, and (c) ankle joints, from toe off to toe off, with the Flex-FootTM at the fast velocity.

to those of the three categories in this study have been reported to range from: 360 to 449 deg/s (Ito, et al., 1983) at the slow velocity; 445 to 496 deg/s (Ito, et al., 1983) at the medium velocity; and 548 to 601 deg/s (Ito, et al., 1983; Jacobs, Bobbert, & van Ingen Schenau, 1993) at the fast velocity.

The hip joint angular velocities throughout the gait cycle for the anatomical SACH and the anatomical Flex, at the three velocities were illustrated in Figure 29. The maximum and minimum angular velocities for the anatomical SACH occurred earlier than and were smaller in magnitude than those for the anatomical Flex, at all velocities, except for the anatomical SACH at the medium velocity. At the medium velocity, the anatomical SACH maximum angular velocity was slightly greater than that of the anatomical Flex. The maximum hip joint angular velocities for both the anatomical SACH and the anatomical Flex occurred after midstance with magnitudes and gait cycle positions as follows: 301 deg/s at 86% and 314 deg/s at 95% at the slow velocity; 399 deg/s at 87% and 381 deg/s at 93% at the medium velocity; and 465 deg/s at 92% and 527 deg/s at 91% at the fast velocity, respectively. The gait cycle position during the maximum hip joint angular velocity was when the center of mass passed over the support limb and flexion occurred at the hip joint in preparation for forward propulsion into the swing phase. At the slow, medium, and fast velocities, the maximum hip joint angular velocities, for the participant in this study, were smaller in magnitude than the values reported for the able bodied participants. The minimum hip joint angular velocity for both the anatomical SACH and the anatomical Flex occurred at or shortly before midswing, which was just prior to the maximum hip joint flexion angular displacement (see Figure 11). For the anatomical SACH, the minimum hip joint angular velocity at the slow velocity was just before midswing. The magnitudes and the gait cycle positions of the minimum hip joint angular velocities for the atomic SACH and the anatomical Flex were: -409 deg/s at 29% and -412 deg/s at 34% at the slow velocity; -467 deg/s at 33% and -564 deg/s at 35% at the medium velocity; and -703 deg/s at 31% and -811 deg/s at 34% at the fast velocity, respectively.

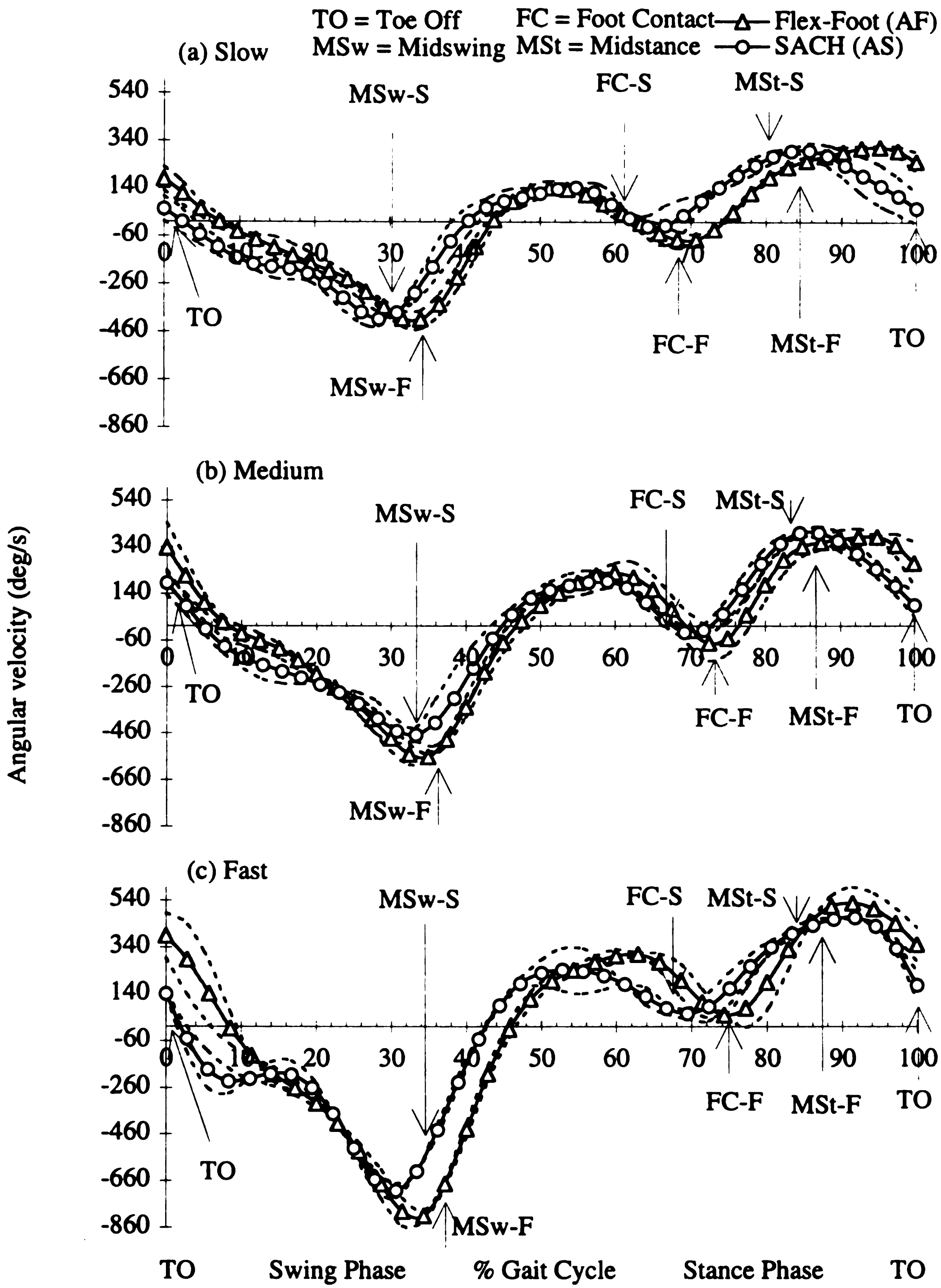


Figure 29. Hip joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical SACH and anatomical Flex at (a) slow, (b) medium, and (c) fast velocities.

After the minimum hip joint angular velocities, the anatomical SACH and the anatomical Flex increased in angular velocity and reached a peak between 51% and 63% of the gait cycle, at the end of the swing phase when the participant was in preparation for foot contact. Thereafter, there was a decrease in hip joint angular velocity that peaked at or just after foot contact which was the period of the gait cycle when hip joint extension was maintained or slightly increased (see Figure 11).

For the prosthetic limb, the hip joint angular velocities were not as consistent between the SACH foot and the Flex-Foot™ as was seen in the anatomical limb. Illustrated in Figure 30 was the hip joint angular velocities, throughout the gait cycle, for the prosthetic SACH and the prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities. The maximum hip joint angular velocity was smaller and earlier with the prosthetic SACH than with the prosthetic Flex and occurred during the swing phase for both prosthetic feet, not during the stance phase, as was seen with the anatomical limbs. The maximum hip joint angular velocity magnitudes for the prosthetic SACH and the prosthetic Flex and their respective gait cycle positions, were as follows: (a) 229 deg/s at 44% and 304 deg/s at 48% at the slow velocity, (b) 274 deg/s at 46% and 353 deg/s at 53% at the medium velocity, and (c) 268 deg/s at 49% and 364 deg/s at 50% at the fast velocity, respectively. As was found for the anatomical limbs, the maximum hip joint angular velocities were smaller in magnitude for the participant in this study, than the values reported for the able bodied participants, at all velocities. The minimum hip joint angular velocities were of greater magnitude for the prosthetic Flex than for the prosthetic SACH, except at the fast velocity where they were similar. The minimum hip joint angular velocities occurred before midswing for both limbs, a position in the gait cycle that was before the maximum prosthetic limb hip joint flexion angular displacement (see Figure 12). The minimum hip joint angular velocity magnitudes for the prosthetic SACH and the prosthetic Flex and the gait cycle positions, were as follows: (a) -357 deg/s at 21% and -414 deg/s at 26% at the

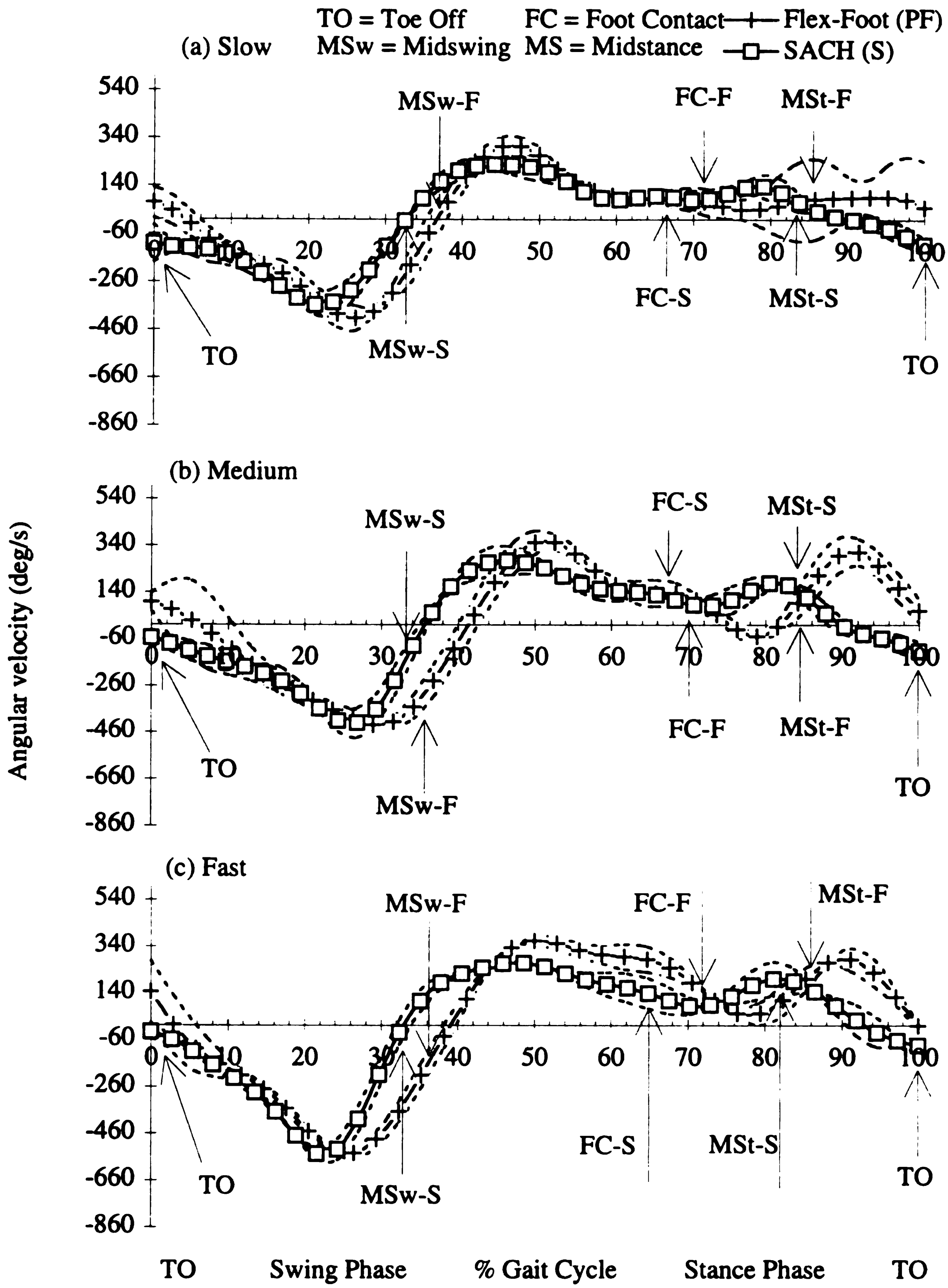


Figure 30. Hip joint angular velocities (mean ± 1SD), from toe off to toe off, of the prosthetic SACH and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

slow velocity, (b) -421 deg/s at 27% and -428 deg/s at 29% at the medium velocity, and (c) -547 deg/s at 22% and -545 deg/s at 26% at the fast velocity, respectively.

During the stance phase at the medium and fast velocities, there was an increase in angular velocity that peaked and occurred before midstance for the prosthetic SACH and after midstance for the prosthetic Flex. The increase in angular velocities during the stance phase were smaller in magnitude for the prosthetic limb than for the anatomical limb because the change in angular displacement of the prosthetic limb was less during the stance phase than the change in angular displacement for the anatomical limb (see Figures 15 and 16). Therefore, the degree to which the prosthetic limb could further extend was less than that of the anatomical limb.

Hip joint angular velocities, throughout the gait cycle, of the anatomical SACH and the prosthetic SACH at (a) slow, (b) medium, and (c) fast velocities were illustrated in Figure 31. The minimum hip joint angular velocity was earlier in the gait cycle, at 21% to 27%, and smaller in magnitude, except at the fast velocity they were similar, for the prosthetic SACH than for the anatomical SACH, at 29% to 33% of the gait cycle. The maximum angular velocities occurred during the swing phase for the prosthetic SACH, at 44% to 49% of the gait cycle, and during the stance phase for the anatomical SACH, at 86% to 92% of the gait cycle. The small hip joint angular velocity during the stance phase for the prosthetic SACH corresponded with the gradual increase in hip joint extension prior to and during the stance phase (see Figure 13).

The hip joint angular velocities, throughout the gait cycle, for the anatomical Flex and for the prosthetic Flex at slow, medium, and fast velocities were illustrated in Figure 32. As was seen when the SACH foot was worn, the prosthetic Flex minimum hip joint angular velocity was earlier in the gait cycle (26% to 29%) and smaller in magnitude than for the anatomical Flex (34% to 35%). And, the maximum angular velocities occurred during the swing phase for the prosthetic Flex (48% to 53% of the gait cycle) and during the stance phase for the anatomical Flex (91% to 95% of the gait cycle).

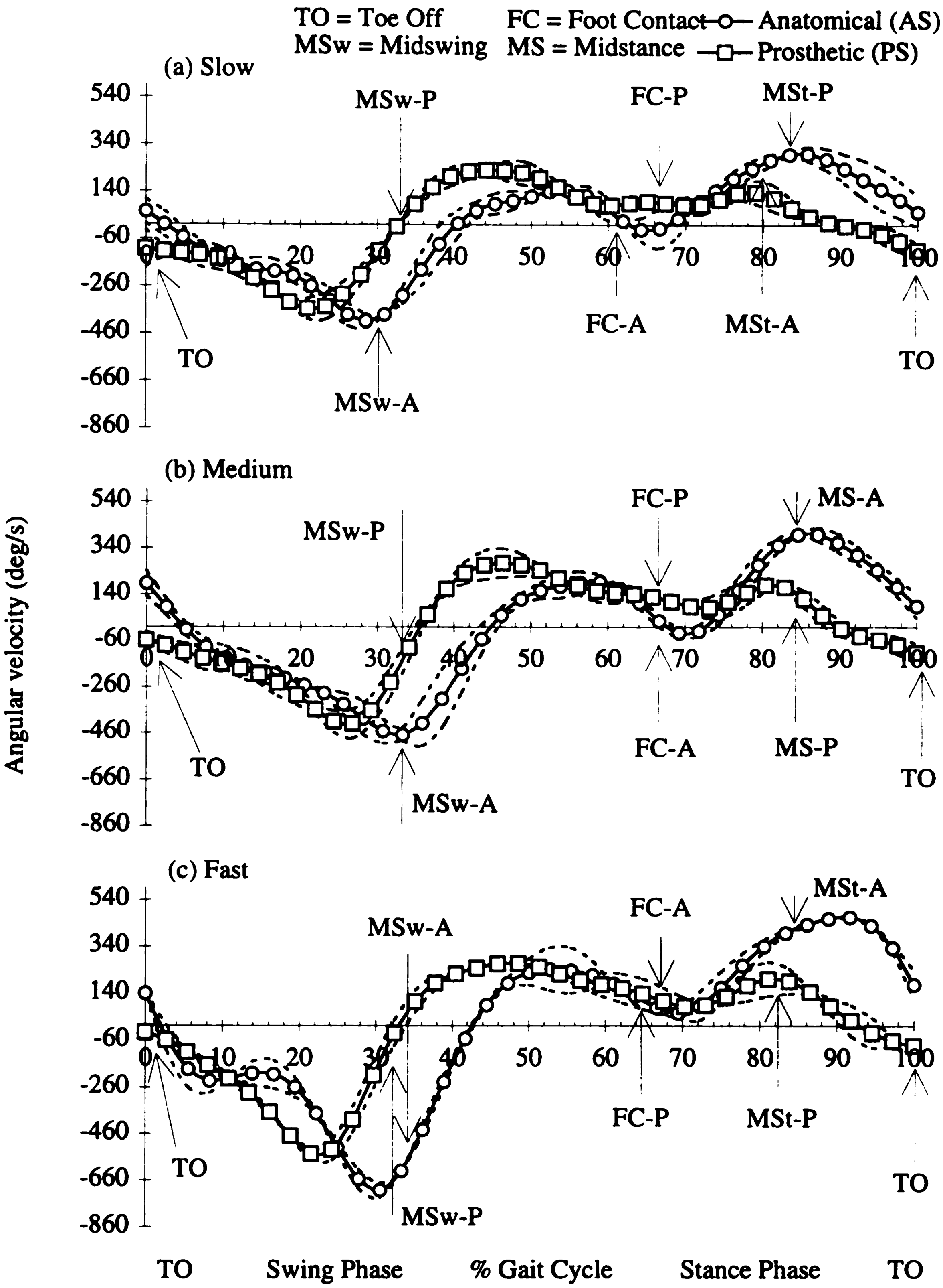


Figure 31. Hip joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical SACH and prosthetic SACH at (a) slow, (b) medium, and (c) fast velocities.

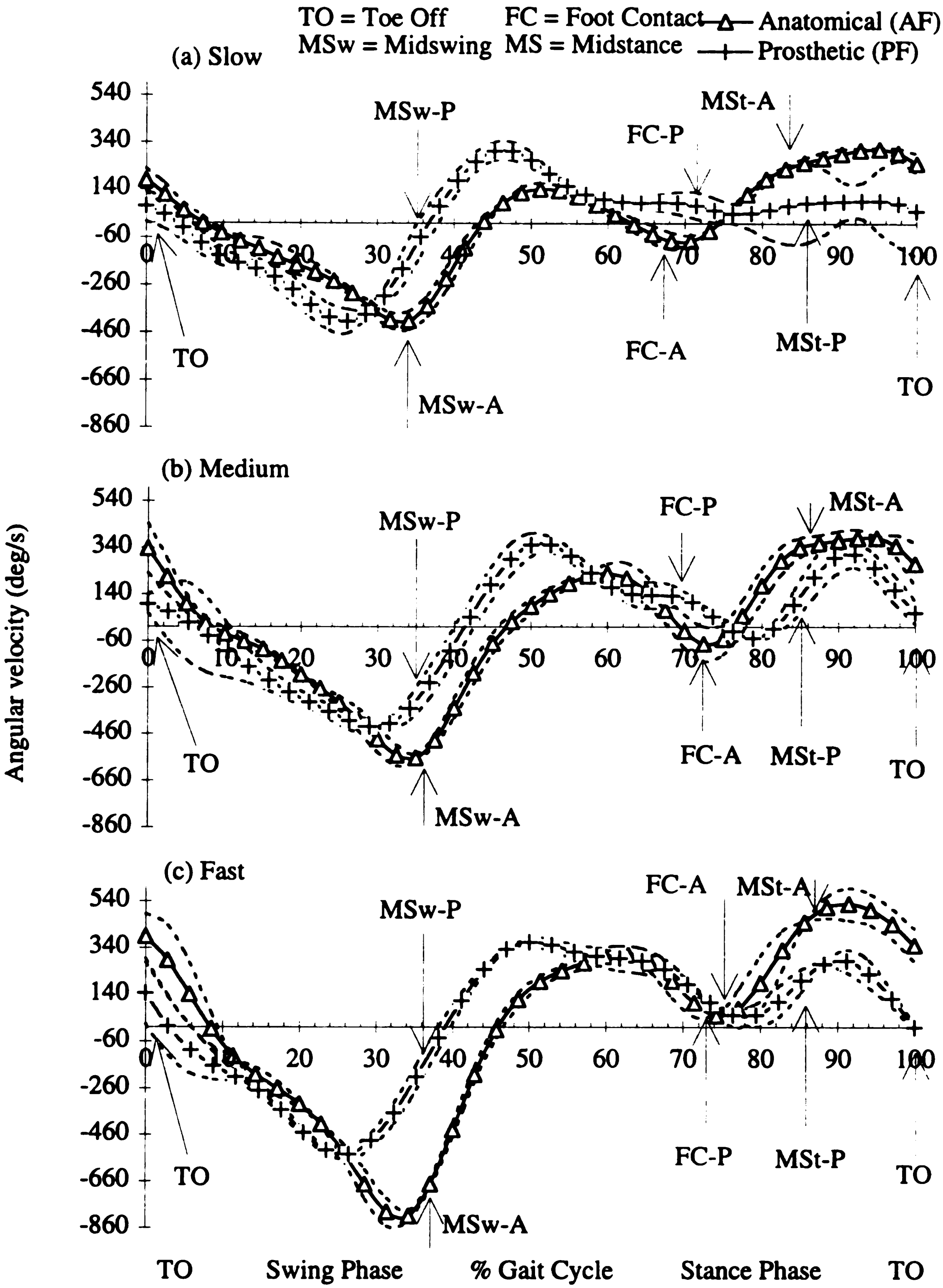


Figure 32. Hip joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical Flex and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

Knee Joint

In the following section, comparisons of the knee joint angular velocities during the gait cycle were made between the participant of this study and the able bodied population based on values reported in the literature. Knee joint maximum and minimum angular velocities during the stance phase for able bodied participants at velocities similar to those of the three categories in this study have been reported to range from: (a) 320 to 442 deg/s and -307 to -493 deg/s (Ito, et al., 1983) at the slow velocity, (b) 373 to 468 deg/s and -395 to -478 deg/s (Buczek & Cavanagh, 1990; Ito, et al., 1983) at the medium velocity, and (c) 444 to 499 deg/s and -355 to -491 deg/s (Ito, et al., 1983; Jacobs, et al., 1993) at the fast velocity. This investigator was not able to find literature that reported knee joint angular velocities for individuals with below the knee amputations for either the anatomical or prosthetic limbs.

The knee joint angular velocities of the anatomical SACH and the anatomical Flex were presented in Figure 33. The maximum knee joint angular velocity occurred about midway through the gate cycle, although earlier in the gait cycle (45% to 49%) and smaller in magnitude (603 to 832 deg/s) for the anatomical SACH compared with anatomical Flex (49% to 53% and 763 to 992 deg/s, respectively), at each velocity. At all velocities, the maximum knee joint angular velocity occurred before the maximum knee joint extension angular displacement, and therefore occurred before foot contact (see Figure 15). The minimum knee joint angular velocity occurred during the first half of the swing phase, between 8% and 17% of the gait cycle at each velocity, when the knee was flexing and the thigh was moving forward. The minimum angular velocities of the anatomical Flex at the slow and medium velocities were points within a plateau with the following approximate magnitudes and gait cycle positions: (a) -530 deg/s at 12 to 20% at the slow velocity, and (b) -540 deg/s at 10 to 23% at the medium velocity, respectively. The rate of knee flexion during that first half of the swing phase was approximately constant. However, at the fast

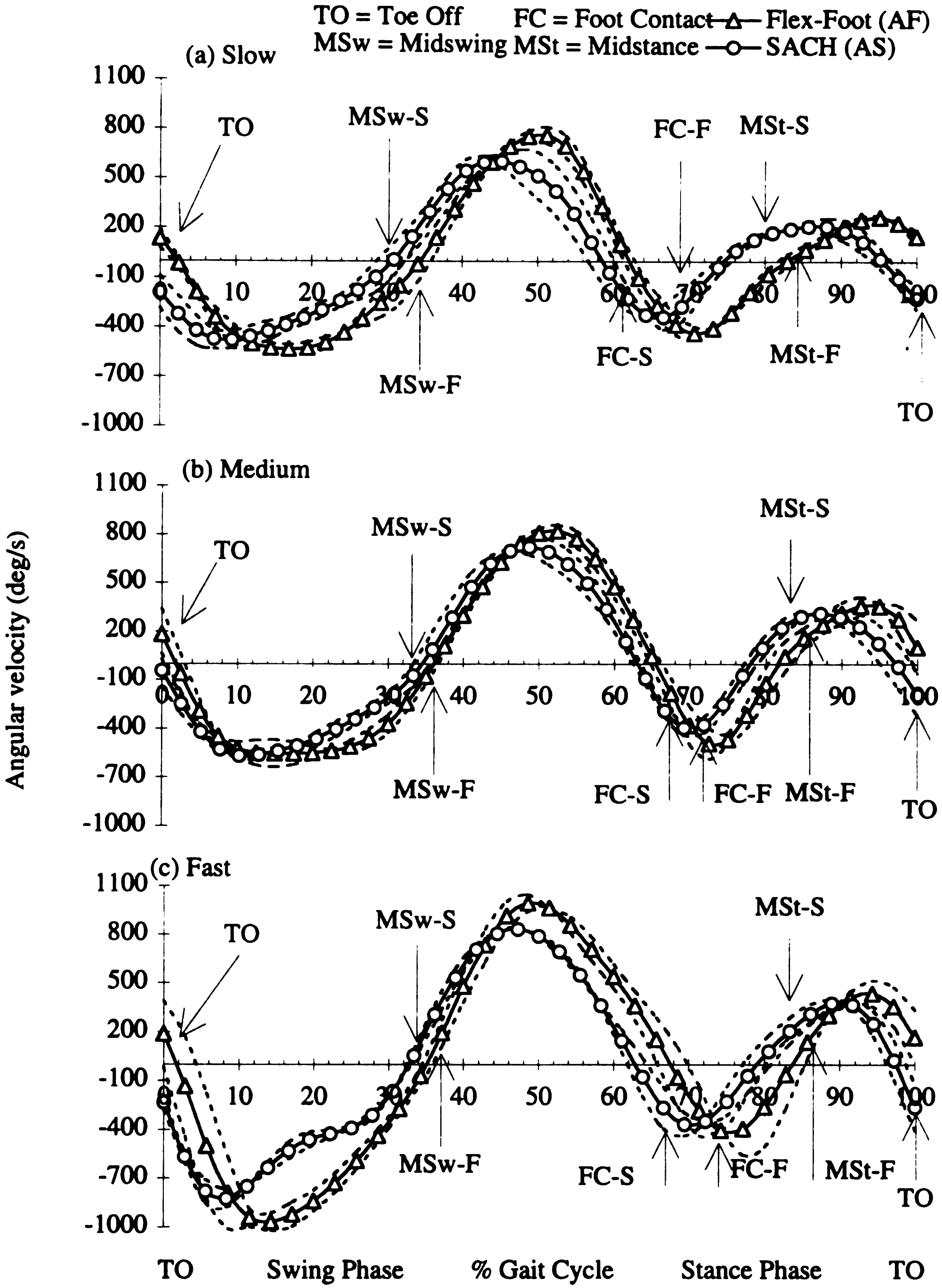


Figure 33. Knee joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical SACH and anatomical Flex at (a) slow, (b) medium, and (c) fast velocities.

velocity, the rate of knee joint flexion changed throughout the swing phase, as indicated by the angular velocities.

Additional peak knee angular velocities for the anatomical SACH and the anatomical Flex occurred at or after foot contact and after midstance. Those angular velocities coincided with the knee joint flexion during impact absorption and knee joint extension in preparation for push off, respectively. The magnitudes of the peak angular velocities near foot contact and after midstance were as follows: (a) -341 and -438 deg/s, and 211 and 265 deg/s at the slow velocity; (b) -395 and -492 deg/s, and 310 and 357 deg/s at the medium velocity; and (c) -368 and -407 deg/s, and 375 and 435 deg/s at the fast velocity, for the SACH foot and Flex-Foot™, respectively. The secondary peak angular velocities near foot contact, at the slow and fast velocities for the anatomical SACH and the anatomical Flex, and at medium velocity for the anatomical SACH, were within the values reported for able bodied participants. The secondary peak knee joint angular velocities after midstance for the anatomical SACH and the anatomical Flex were smaller in magnitude than those reported for able bodied participants at all velocities.

Illustrated in Figure 34 were the knee joint angular velocities, throughout the gait cycle, for the prosthetic SACH foot and the prosthetic Flex for the three velocities. The maximum knee joint angular velocity occurred late in the swing phase as the knee extended to lower the foot in preparation for foot contact. The maximum angular velocities were smaller in magnitude and earlier in the gait cycle for the prosthetic SACH than for the prosthetic Flex, with magnitudes and gait positions as follows: (a) 669 deg/s at 40% and 921 deg/s at 45% at the slow velocity, (b) 810 deg/s at 41% and 964 deg/s at 50% at the medium velocity, and (c) 856 deg/s at 38% and 1061 deg/s at 47%, respectively. The minimum knee joint angular velocity occurred between 5% and 13% of the gait cycle as the thigh moved the leg forward and knee flexion continued after toe off and occurred earlier in the gait cycle for the prosthetic SACH, than for the prosthetic Flex. The minimum angular velocity magnitudes and gait cycle position for the prosthetic SACH and the prosthetic Flex

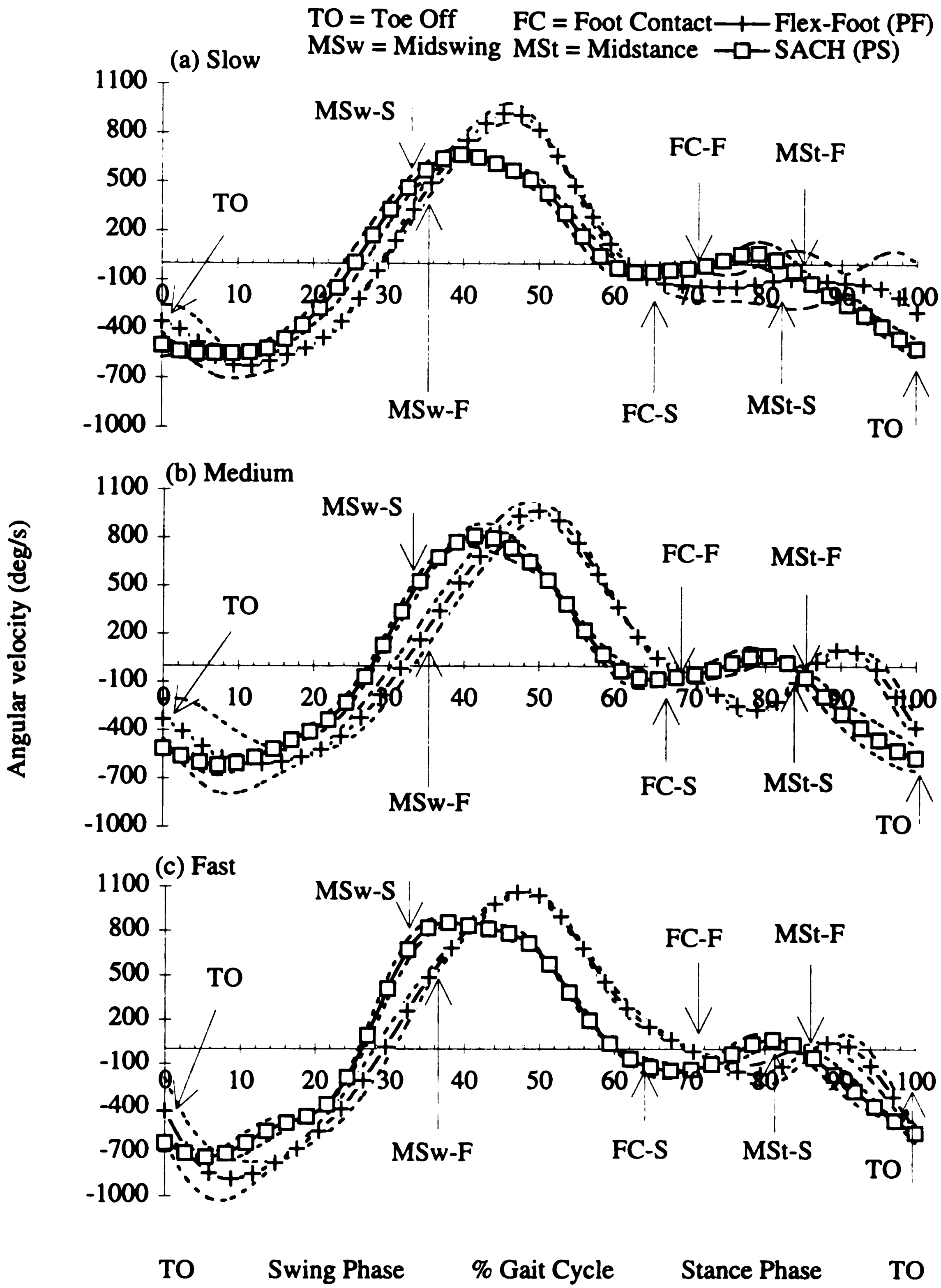


Figure 34. Knee joint angular velocities (mean ± 1SD), from toe off to toe off, of the prosthetic SACH and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

were as follows: (a) -550 deg/s at 6% and -626 deg/s at 12% at the slow velocity, (b) -619 deg/s at 7% and -612 deg/s at 13% at the medium velocity, and (c) -739 deg/s at 5% and -885 deg/s at 9%, respectively. Those values for minimum angular velocity, reflected the difference in the rate of change of the displacement values for knee joint movement.

Secondary peak angular velocities were near foot contact. Specifically with the SACH foot, secondary peak angular velocities were before foot contact at the slow and medium velocities and after foot contact at the fast velocity, and with the Flex-Foot™ they were after foot contact at all velocities. Although at the slow velocity, the secondary peak angular velocities were within a plateau during the gait cycle from 63% to 70% with the SACH foot and 70% to 81% with the Flex-Foot™. The secondary peak angular velocities corresponded with the point in the prosthetic limb knee joint angular displacement when the knee flexed slightly after maximum extension. Other secondary peak angular velocities occurred near midstance. The peak angular velocities occurred before midstance at all velocities with the SACH foot, and for the Flex-Foot™ were non existent at the slow velocity and occurred after midstance at the medium and fast velocities. The peak angular velocities near midstance corresponded with the point in the gait cycle when the prosthetic limb changed direction slightly toward extension.

Knee joint angular velocities, throughout the gait cycle, for the anatomical SACH and for the prosthetic SACH were presented in Figure 35. Again, the minimum angular velocities occurred during the time of knee flexion following toe off, between 5% and 10% of the gait cycle. However, at the slow and medium velocities, the minimum angular velocities were within a plateau of angular velocity values which indicated that the rate of flexion was relatively constant soon after toe off. The maximum knee joint angular velocities were larger in magnitude and occurred earlier in the gait cycle for the prosthetic SACH (38% to 41%), than for the anatomical SACH (45% to 49%). The maximum angular velocity for the prosthetic SACH, corresponded with the rapid knee extension during the late stage of the swing phase (see Figure 17) in preparation for foot contact.

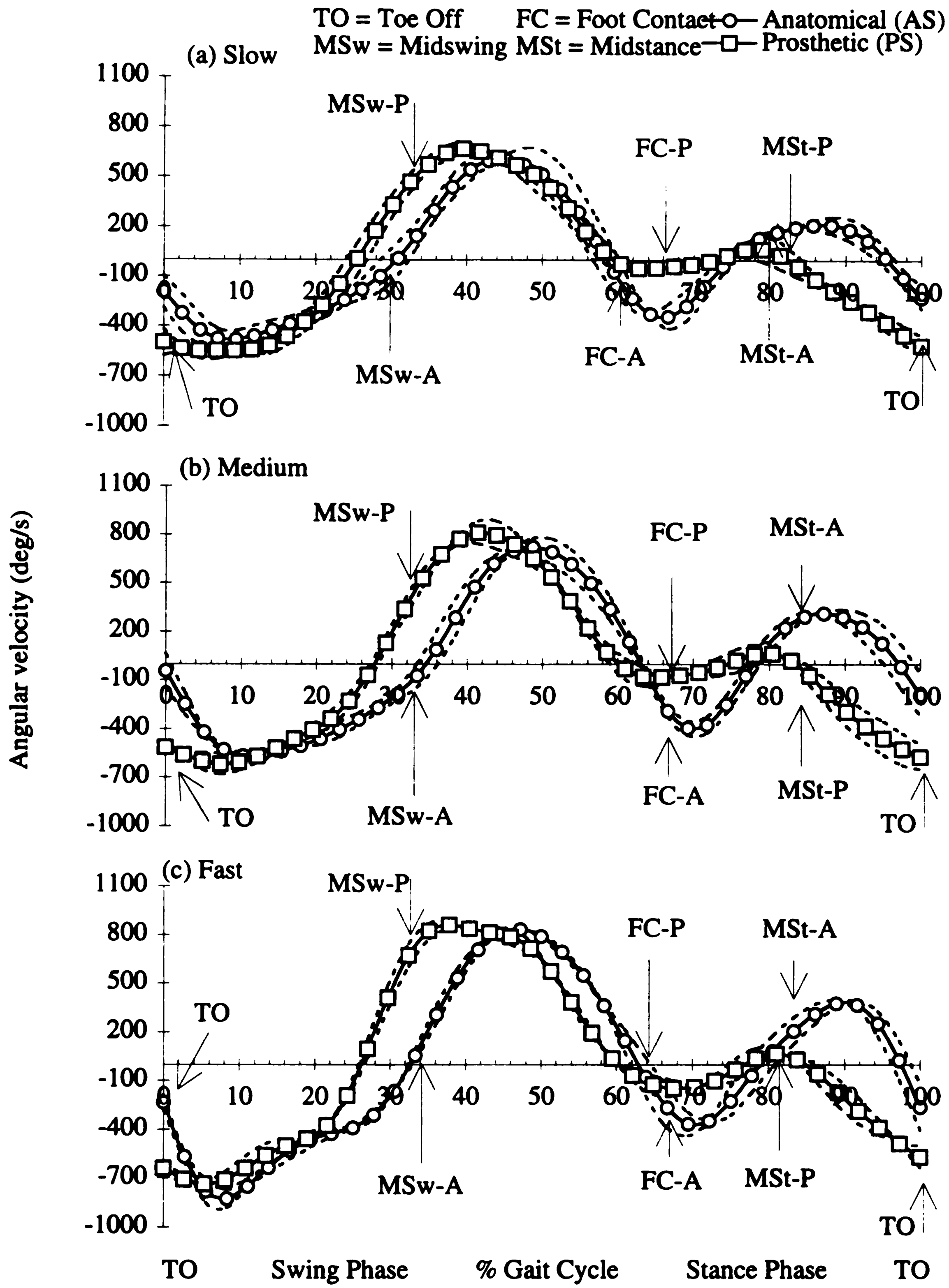


Figure 35. Knee joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical SACH and prosthetic SACH at (a) slow, (b) medium, and (c) fast velocities.

Secondary peak angular velocities near foot contact were larger in magnitude for the anatomical limb than for the prosthetic limb. The point in the gait cycle that the secondary peak angular velocities occurred was after foot contact with the anatomical limb and was within a plateau of values beginning prior to foot contact, and lasted after foot contact with the prosthetic limb. Although both limbs had another secondary peak angular velocity, during the middle to ladder part of the stance phase, the anatomical SACH peak occurred later in the gait cycle (87% to 89%), and was larger in magnitude than the prosthetic SACH (79% to 81%). As prosthetic SACH knee joint extension during the stance phase was minimal or absent, its velocity appeared as a small angular velocity.

Illustrated in Figure 36 were knee joint angular velocities, throughout the gait cycle, for the anatomical Flex and the prosthetic Flex at the three velocities. The minimum knee joint angular velocity with the Flex-Foot™ occurred in the beginning of swing phase, between 9% and 17% of the gait cycle. The maximum knee joint angular velocity occurred earlier in the gait cycle, at 45% to 50%, and was larger in magnitude for the prosthetic Flex than the anatomical Flex, at 40% to 53%. Secondary peak angular velocities near foot contact, and during the late stance phase, were of larger magnitude for the anatomical Flex, than for the prosthetic Flex. The specific point in the gait cycle at which the secondary peak velocity occurred was at, or immediately after, foot contact with the SACH foot at all velocities, was within a plateau of values that occurred before and after midstance at the slow velocity for the Flex-Foot™, and was after foot contact during the first half of the stance phase for the Flex-Foot™ at the medium and fast velocities. The secondary peak angular velocities during the late stance phase occurred between 93% and 95% of the gait cycle for the anatomical Flex at all velocities, and between 88% and 89% of the gait cycle for the prosthetic Flex at the medium and fast velocities. At the slow velocity, a secondary peak angular velocity for the prosthetic Flex was not seen, which was consistent with the minimal knee flexion that occurred during the stance phase (see Figure 18). At the medium and fast velocities, the secondary peak angular velocity was larger for the anatomical Flex,

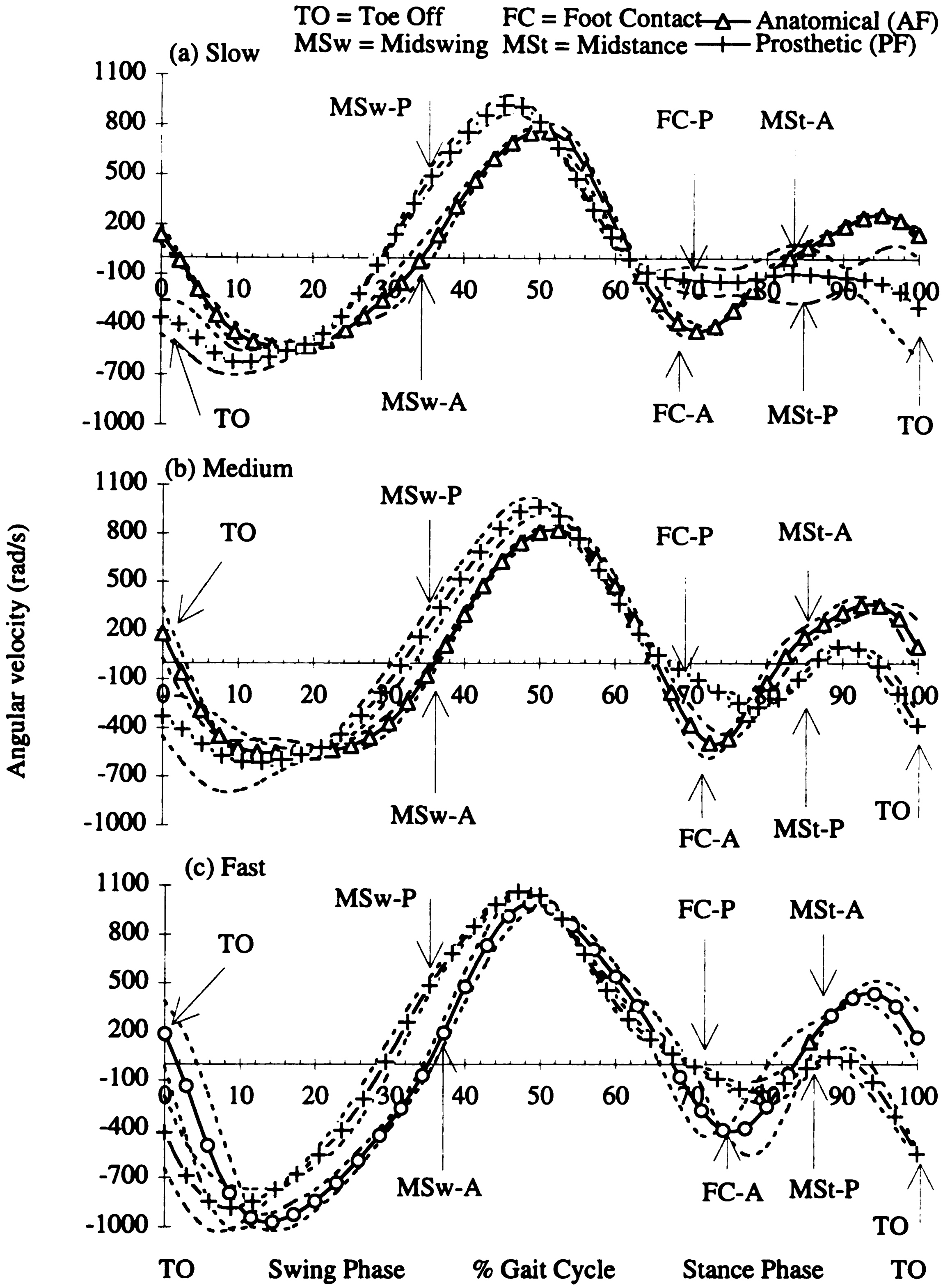


Figure 36. Knee joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical Flex and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

than for the prosthetic Flex. The larger angular velocity corresponded with the knee flexion and extension in the anatomical limb angular displacement, as was seen with the SACH foot.

Ankle Joint

In the following section, comparisons of the ankle joint angular velocities during the gait cycle were made between the participant of this study and the able bodied population based on values reported in the literature. Maximum and minimum ankle joint angular velocities during the stance phase, for able bodied participants at velocities similar to those of the three categories in this study have been reported to range from: (a) 481 to 617 deg/s and -278 to -386 deg/s at the slow velocity (Ito, et al., 1983), (b) 530 to 698 deg/s and -258 to -356 deg/s at the medium velocity (Buczek & Cavanagh, 1990; Ito, et al., 1983), and (c) 729 to 1056 deg/s and -332 to -391 deg/s at the fast velocity (Ito, et al., 1983; Jacobs, et al., 1993).

The ankle joint angular velocities, throughout the gait cycle, for the anatomical SACH and the anatomical Flex, at the slow, medium, and fast velocities were illustrated in Figure 37. More variation occurred in the ankle joint angular velocity curves than in the hip and knee joint angular velocity curves, but three patterns emerged. First, there was an initial decrease in ankle joint angular velocity immediately following toe off corresponding to the continued ankle joint plantar flexion following push off. Second, before and after foot contact there was decrease in angular velocity that peaked at the minimum ankle joint angular velocity. Those angular velocity patterns were due to the ankle joint dorsiflexion when the shank moved forward and over the planted foot. The minimum ankle joint angular velocity magnitudes and gait cycle positions for the anatomical SACH and the anatomical Flex were as follows: (a) -282 deg/s at 71% and -346 deg/s at 78% at the slow velocity, (b) -307 deg/s at 74% and -411 deg/s at 78% at the medium velocity, and (c) -367 deg/s at 75% and -380 deg/s at 78% at the fast velocity, respectively. The anatomical SACH minimum angular velocities occurred earlier in the gait cycle and were of smaller

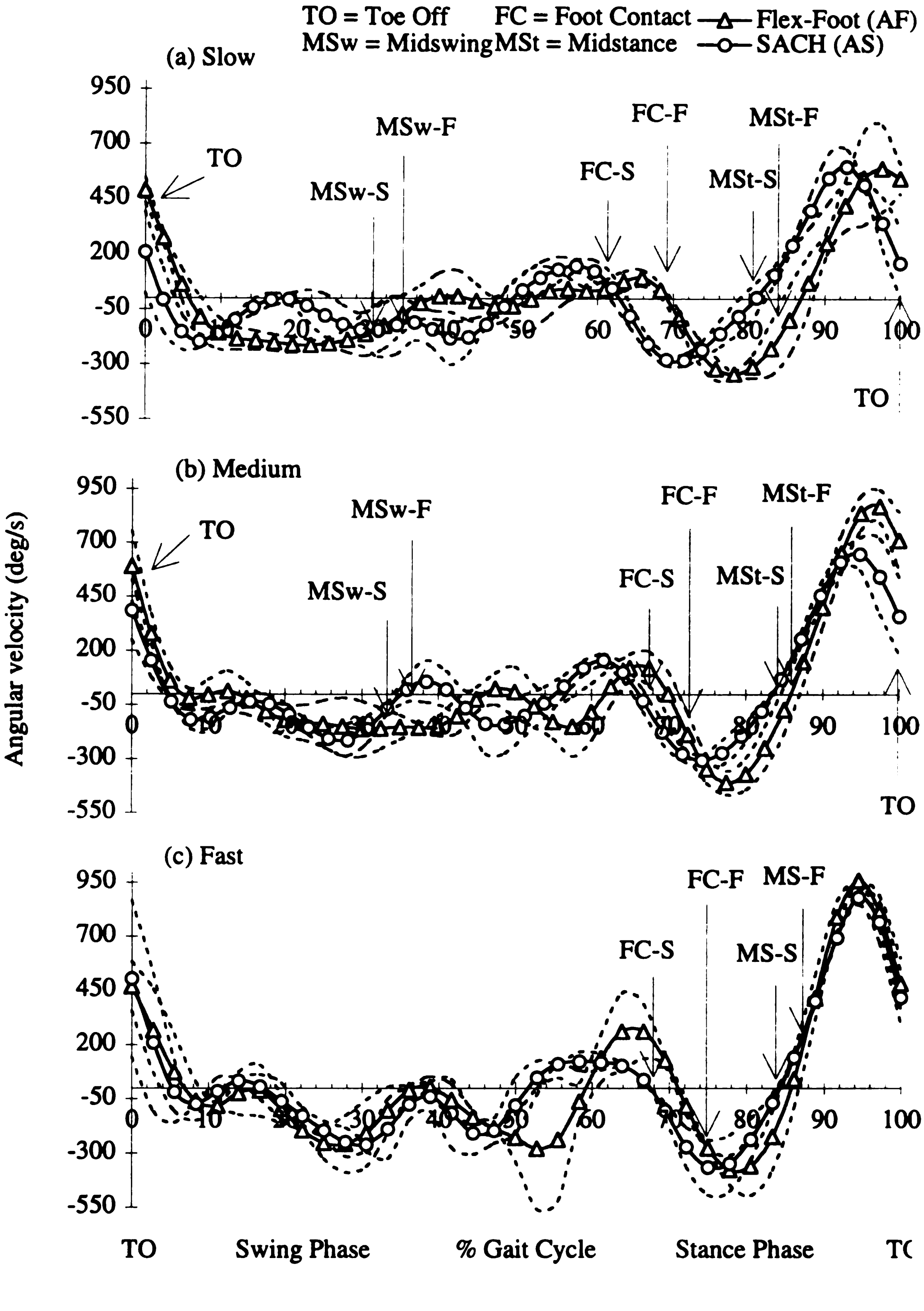


Figure 37. Ankle joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical SACH and anatomical Flex at (a) slow, (b) medium, and (c) fast velocities.

magnitude than those of the anatomical Flex, at each velocity. The minimum angular velocities for the participant in this study, relative to the able bodied participants, were similar in magnitude for the anatomical SACH at all velocities, similar in magnitude for the anatomical Flex at the slow and fast velocities, and larger in magnitude for the anatomical Flex at the medium velocity. The higher rate of change with the anatomical Flex in the ankle joint angular displacement was a reflection of the short stance phase, at 28%, and the large ankle joint range of motion, at 47 degrees, found with the anatomical Flex at the medium velocity. That is, with the anatomical Flex, there was a limited proportion of the gait cycle in which the ankle joint displacement occurred, resulting in a large magnitude of angular velocity during the stance phase.

The third pattern was the increase in angular velocity from just before midswing to between 93% and 98% of the gait cycle, when the maximum angular velocity occurred. Those patterns in ankle joint angular velocity were due to the rapid ankle joint plantar flexion just before and during toe off. The maximum ankle joint angular velocity magnitudes and gait cycle positions for the anatomical SACH and the anatomical Flex were as follows: (a) 604 deg/s at 93% and 593 deg/s at 98% at the slow velocity, (b) 647 deg/s at 95% and 868 deg/s at 98% at the medium velocity, and (c) 881 deg/s at 94% and 959 deg/s at 94%. The maximum ankle joint angular velocities for the anatomical SACH and the anatomical Flex, were of similar magnitudes at the slow and fast velocities, and were of smaller magnitude for the anatomical SACH than for the anatomical Flex at the medium velocity. The maximum ankle joint angular velocities for the participant in this study, relative to the able bodied participants, were similar in magnitude for the anatomical SACH at all velocities, similar in magnitude for the anatomical Flex at the slow and fast velocities, and larger in magnitude for the anatomical Flex at the medium velocity.

The ankle joint angular velocities, throughout the gait cycle, for the prosthetic SACH and the prosthetic Flex, at the three velocities, were illustrated in Figure 38. Two patterns of ankle joint angular velocities existed for both the prosthetic SACH and the

Angular velocity (deg/s)

Figure
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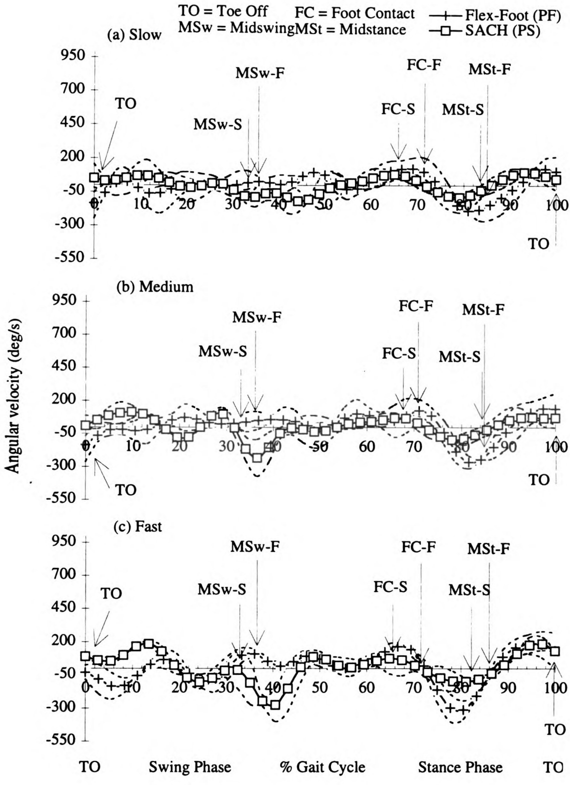

Figure 38. Ankle joint angular velocities (mean ± 1SD), from toe off to toe off, of the prosthetic SACH and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

prosthetic Flex. First, at all velocities, following foot contact there was a decrease in angular velocity that peaked before midstance. Those patterns of angular velocity were due to the rate of dorsiflexion angular displacement during the end of the stance phase (see Figure 20). The magnitudes and gait cycle positions of the peak angular velocity between foot contact and midstance, for the prosthetic SACH and the prosthetic Flex, were as follows: (a) -91 deg/s at 79% and -190 deg/s at 81% at the slow velocity, (b) -97 deg/s at 78% and -265 deg/s at 82% at the medium velocity, and (c) -100 deg/s at 81% and -314 deg/s at 81% at the fast velocity, respectively. The angular velocity of the prosthetic Flex was larger than that of the prosthetic SACH because there was a larger dorsiflexion displacement in a similar time period with the Flex-Foot™ than with the SACH foot. The peak angular velocity values for the participant in this study, relative to the able bodied participants, were smaller in magnitude for the prosthetic SACH at all velocities, smaller in magnitude for the prosthetic Flex at the slow and fast velocities, and similar in magnitude for the prosthetic Flex at the medium velocity.

The second trend for both the prosthetic SACH and the prosthetic Flex was the increased angular velocity from just prior to midstance to a peak between 93% and 98% of the gait cycle. Those patterns of ankle joint angular velocity were due to the gradual motion of dorsiflexion. The magnitudes and gait cycle positions of the peak angular velocity between midstance and toe off, for the prosthetic SACH and the prosthetic Flex, were as follows: (a) 96 deg/s at 93% and 123 deg/s at 98% at the slow velocity, (b) 75 deg/s at 95% and 141 deg/s at 97% at the medium velocity, and (c) 186 deg/s at 97% and 182 deg/s at 94%, respectively. The prosthetic SACH angular velocity was of smaller magnitude than the prosthetic Flex at the slow and medium velocities, but of similar magnitude at the fast velocity. The peak angular velocity values for the participant in this study, relative to the able bodied participants, were smaller in magnitude for the prosthetic SACH and the prosthetic Flex at all velocities.

The ankle joint angular velocities for the anatomical SACH and the prosthetic SACH, at the three velocities, were illustrated in Figure 39. After toe off, there was a decrease in angular velocity with the anatomical SACH, but not with the prosthetic SACH, and was due to the change in anatomical SACH ankle joint displacement from plantar flexion to dorsiflexion after toe off. At all velocities, the magnitude of the maximum and minimum angular velocities during the stance phase, were greater with the anatomical limb than with the prosthetic limb. The larger magnitudes of the anatomical limb angular velocities were due to the larger angular displacements of the anatomical SACH, compared with the prosthetic SACH (see Figure 21).

The ankle joint angular velocities for the anatomical Flex and the prosthetic Flex at the three velocities were illustrated in Figure 40. At toe off, a decrease in angular velocity was seen with the anatomical Flex across all velocities. At toe off, the prosthetic Flex had slightly increased in ankle joint angular velocity at the slow and medium velocities and slightly decreased in ankle joint angular velocity at the fast velocity. One explanation of the difference in angular velocities of the Flex-Foot appliance is the response of the foot at differing speeds. The Flex-Foot movement that occurred during the early portion of the stance phase, similar to ankle joint dorsiflexion, and the end of the stance phase, similar to ankle joint plantar flexion, resulted from the appliance deforming and then returning to the original shape, respectively (Ehara, et al., 1993). If the appliance returned to the original shape prior to toe off, there would not be any noticeable angular displacement. That lack of motion was likely the case for the prosthetic Flex at the fast velocity, thereby resulting in a decrease in angular velocity after toe off. If the appliance moves beyond the original shape during the late portion of the stance phase, similar to ankle joint plantar flexion, the appliance would return to the original shape after toe off, a motion similar to ankle joint dorsiflexion. That Flex-Foot deformation may explain the dorsiflexion motion of the Flex-Foot found at the slow and medium velocities, which resulted in a slight increase in ankle joint angular velocity. At all velocities, the anatomical Flex maximum and minimum

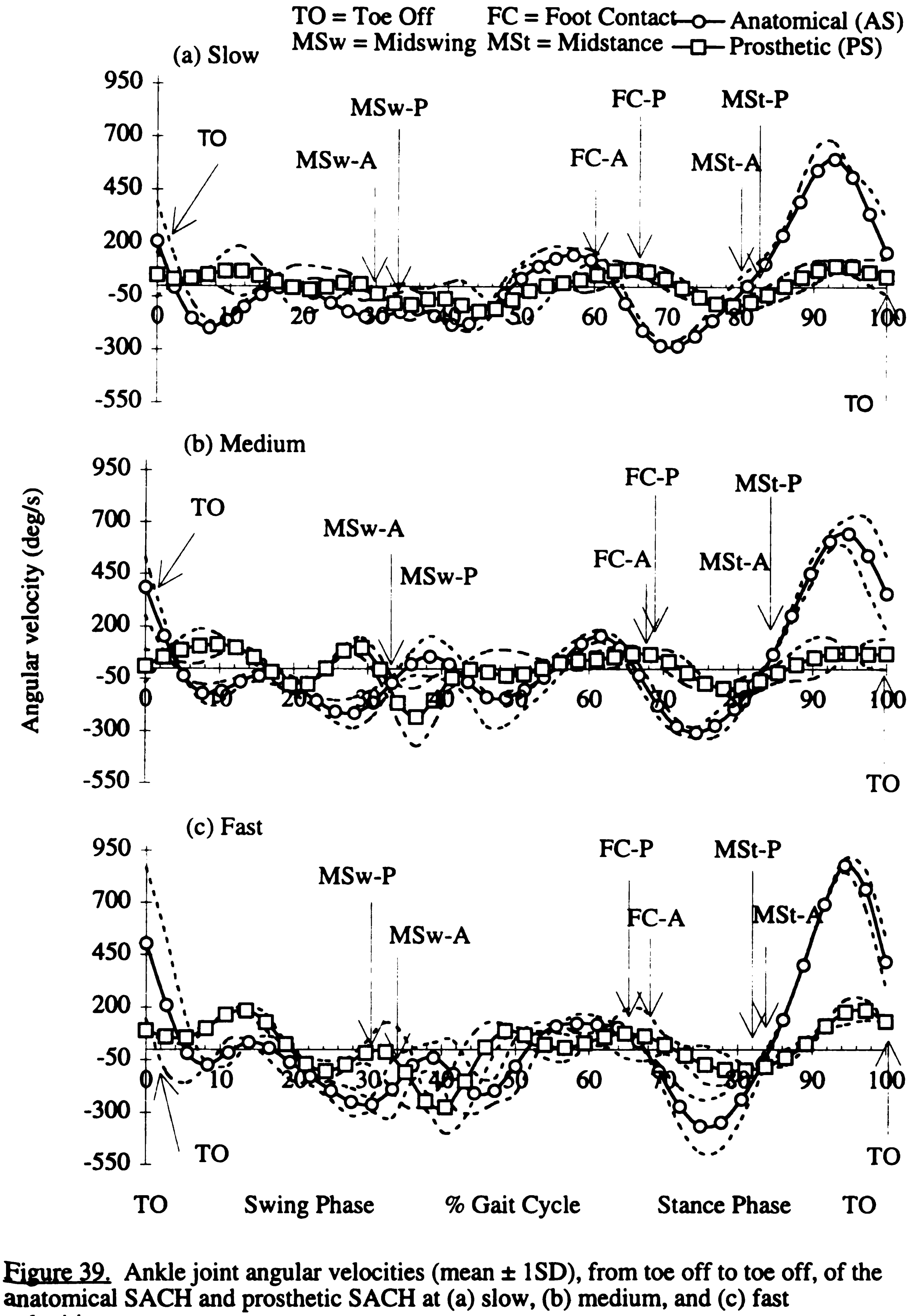

Figure 39. Ankle joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical SACH and prosthetic SACH at (a) slow, (b) medium, and (c) fast velocities.

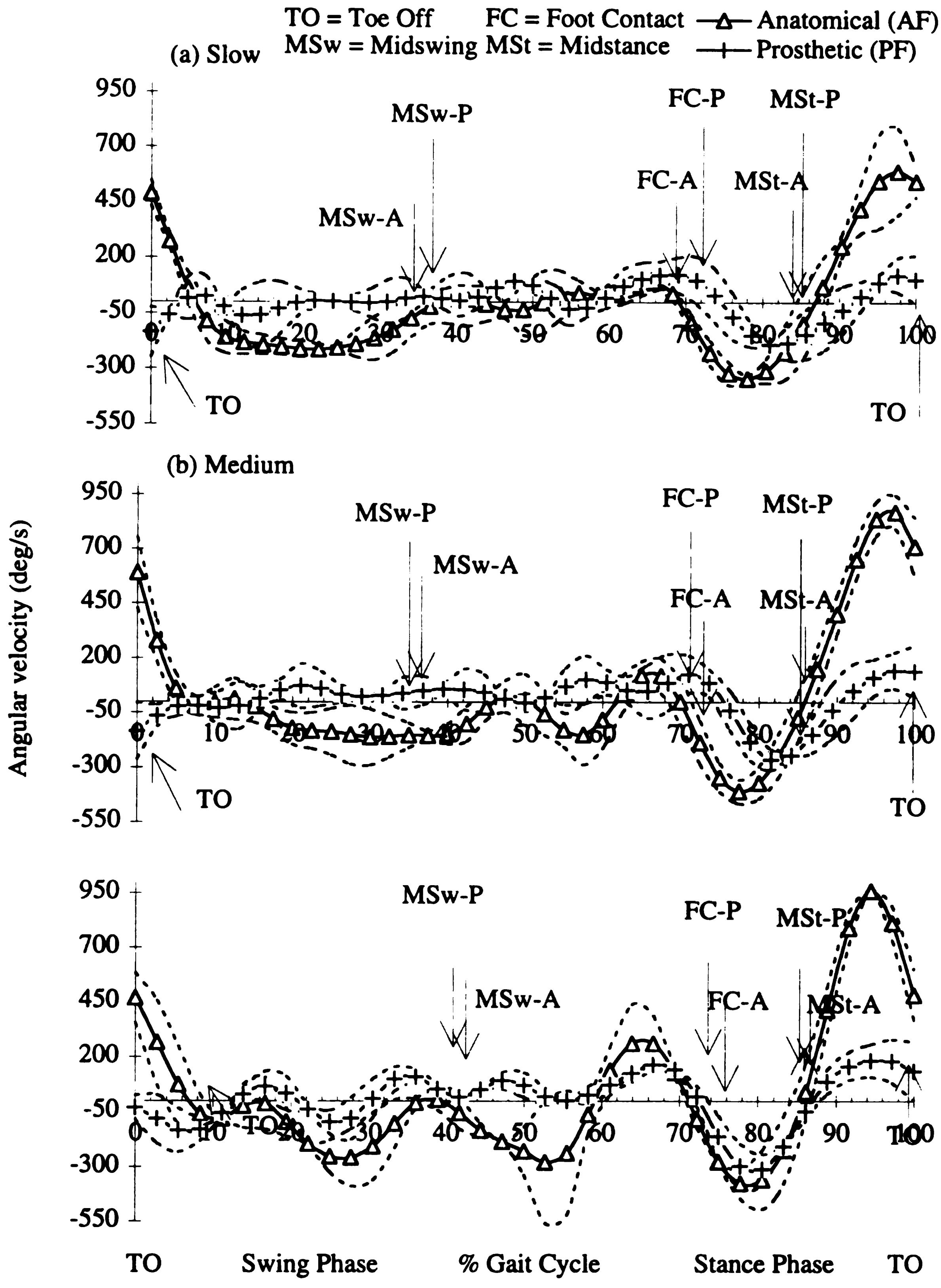

Figure 40. Ankle joint angular velocities (mean ± 1SD), from toe off to toe off, of the anatomical Flex and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

angular velocities during the stance phase were larger in magnitude than for the prosthetic Flex. The greater magnitude of angular velocity of the anatomical Flex was due to the larger dorsiflexion and plantar flexion angular displacements of the anatomical Flex relative to the prosthetic Flex (see Figure 22).

Summary of Angular Velocities

For all conditions the minimum hip joint angular velocities occurred prior to or during midswing when hip joint flexion occurred. The maximum hip joint angular velocities did not occur during the same section of the gait cycle for the anatomical and prosthetic limbs. Like that of able bodied individuals, the maximum angular velocity of the anatomical limb occurred during the second half of the stance phase, when rapid extension of the hip joint occurred in preparation for toe off and forward propulsion. The maximum angular velocities of the prosthetic limb occurred during the latter half of the swing phase when hip joint extension occurred in preparation for foot contact.

The minimum knee joint angular velocities were within a plateau of values that occurred during the early section of the swing phase at the slow and medium velocities for both prosthetic feet and both lower extremity limbs, and represented a constant rate of knee joint flexion at those velocities during that period of the gait cycle. At the fast velocity, the existence of peak angular velocity values meant that the rate of knee joint flexion was rapid after toe off. Under all conditions, the maximum knee joint angular velocities occurred during the second half of the swing phase. Within each velocity category, the maximum knee joint velocity was of greater magnitude for the Flex-Foot™ than for the SACH foot for both limbs, and for the prosthetic limb than the anatomical limb for both prosthetic feet. The two secondary peak angular velocities with the anatomical limb, occurred at or after foot contact and after midstance. The point in the gait cycle where the secondary peak angular velocities occurred for the prosthetic limb were mixed. The secondary peak angular velocities near foot contact for the prosthetic limb, were either within a plateau of values around foot contact, or occurred after foot contact. The secondary peak angular velocities near midstance for the prosthetic limb, also were either within a plateau of values, occurred prior to midstance, or occurred after midstance.

The ankle joint angular velocities were variable during the swing phase for both anatomical limbs and both prosthetic limbs. However, with both the anatomical SACH and the anatomical Flex, there was a decrease in angular velocity following toe off. During the stance phase, there were peak minimum and maximum angular velocity values seen with the anatomical limbs. However, with two exceptions, with the prosthetic limbs, the peak minimum and maximum angular velocity values were of dramatically smaller magnitude than those seen for the anatomical limbs. The two exceptions were the similar minimum angular velocity values for the anatomical Flex and the prosthetic Flex. In all conditions and at all velocities, the peak minimum ankle joint angular velocity occurred before midstance and the peak maximum ankle joint angular velocity occurred after midstance

Vertical Displacement

The greater trochanter was used as a close approximation of the center of mass of the body to investigate the vertical displacement of the participant throughout the gait cycle. The range of vertical displacement of the greater trochanter for the prosthetic SACH and the prosthetic Flex at the slow, medium, and fast velocities were presented in Table 14. At each velocity, the prosthetic Flex had a smaller vertical displacement range than the did prosthetic SACH. The smaller minimum and maximum values for the prosthetic Flex indicated that the greater trochanter elevation was less than that for the prosthetic SACH. For example, at the fast speed the prosthetic Flex range was 10 cm. with a minimum value of 70 cm. and a maximum value of 80 cm compared to the prosthetic SACH values of 13 cm., 73 cm., and 86 cm, respectively.

In Figure 41, the mean vertical displacements of the greater trochanter throughout the gait cycle for the prosthetic SACH and the prosthetic Flex at the three velocities were illustrated. As was reported earlier, the vertical displacement of the prosthetic Flex was smaller compared to that of the prosthetic SACH. When the Flex-Foot™ was worn, the

Table 14.

Vertical Displacement Range of the Greater Trochanter on the Prosthetic Limb Side at Each Velocity.

Velocity (m/s)	Prosthetic foot SACH (cm)	Flex-Foot™ (cm)
Slow	13 (75 - 88)	12 (71 - 83)
Medium	11 (76 - 87)	11 (69 - 80)
Fast	13 (73 - 86)	10 (70 - 80)

greater trochanter elevation was minimized throughout the gait cycle through greater hip and knee joint flexion, and ankle joint dorsiflexion during anatomical stance and prosthetic stance. During prosthetic swing, the greater trochanter reached the minimum value between 24% and 34% of the gait cycle during the time of the anatomical Flex stance phase (Enoka, 1988). Hip flexion (see Figure 11), knee flexion (see Figure 15), and ankle dorsiflexion (see Figure 19) of the anatomical Flex during the first half of the stance phase allowed the vertical displacement of the greater trochanter to move closer toward the ground. The greater trochanter for the prosthetic Flex maintained a lower position, relative to the prosthetic SACH, during the stance phase through greater magnitudes of hip joint flexion (see Figure 12), and ankle joint dorsiflexion during the second half of the stance phase (see Figure 20).

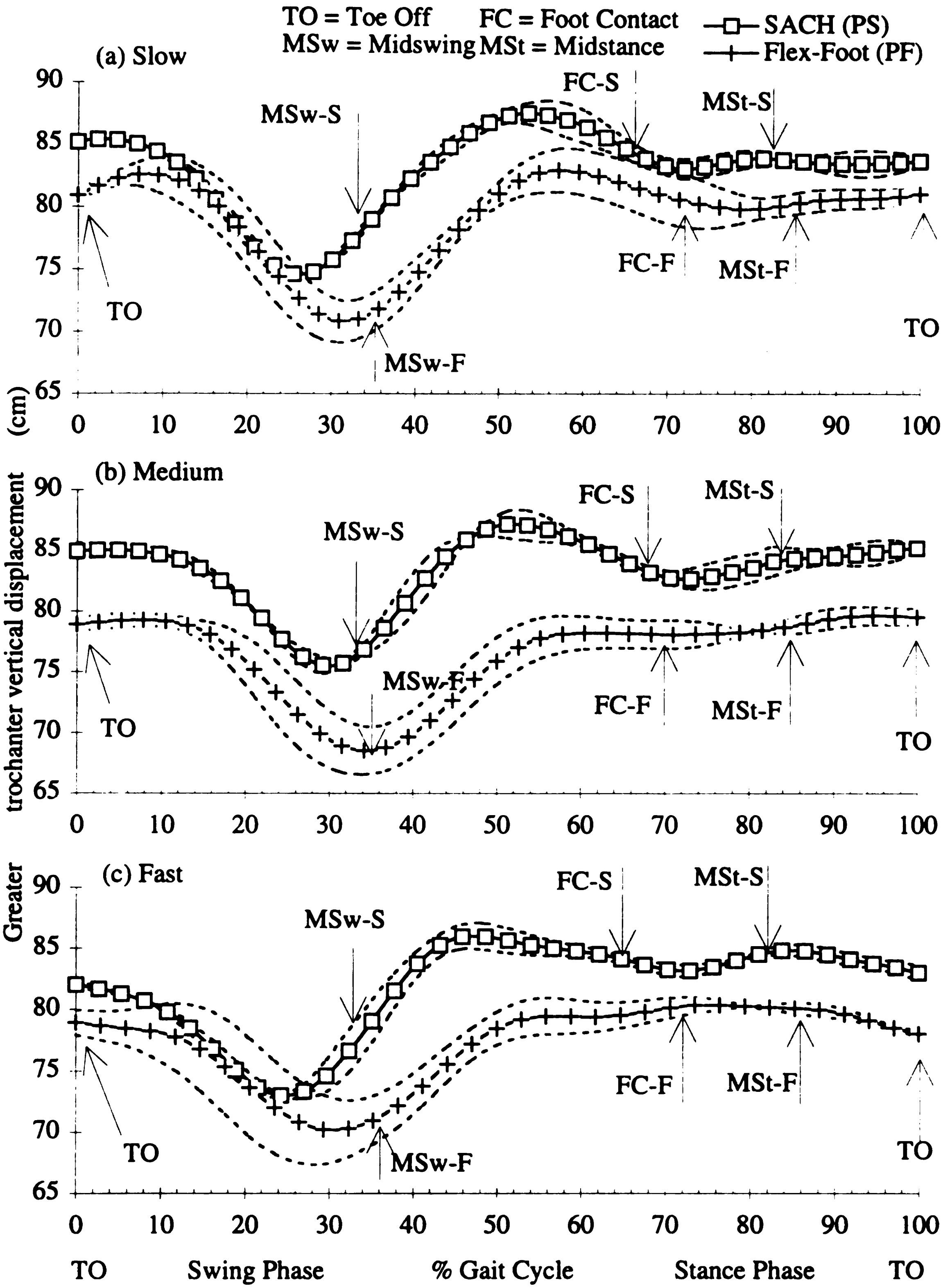

Figure 41. Greater trochanter vertical displacements (mean ± 1SD), from toe off to toe off, of the prosthetic SACH and prosthetic Flex at (a) slow, (b) medium, and (c) fast velocities.

The smaller vertical displacement of the greater trochanter while wearing the Flex foot indicated that the participant was able to maintain a more efficient gait (Dillman, 1970) and that the Flex-Foot™ dorsiflexion contributed to minimizing the vertical displacement of the body, a finding consistent with those of Perry, Powers, Torburn, and Ayyappa (1994) from their work on walking.

Chapter V

Summary and Conclusions

Summary

The purpose of this project was to study selected kinematic variables of the run of an adult with a below the knee amputation. The kinematic variables were quantified for comparisons that were made among: (a) two prosthetic appliances, the SACH foot and Flex-Foot™, worn by the participant; (b) the participant's lower extremity limbs, the anatomical and prosthetic limbs; and (c) the participant and results reported from investigations on able bodied individuals. The movement patterns were compared for stride characteristics, gait cycle characteristics, and greater trochanter vertical displacement, used as an approximation of the center of mass of the body.

The participant for this study was an adult male, 24.8 years of age, competitive athlete. At the time of filming, the participant had been wearing the Flex-Foot™ for nine months and wore it for approximately 16 hours per day for daily, recreational and competitive activities. The SACH foot was fitted for the participant three weeks prior to filming. During those three weeks, the participant wore the SACH foot for work, recreational and competitive activities. The participant participated in several sport activities both recreationally and competitively. The participant trained five days per week for three hours per day in kick boxing and/or track and field.

The data collection consisted of two separate visits to the Intramural Sports Circle facility at Michigan State University. The questionnaire was completed and anthropometric data collection occurred in a conference room, and kinematic data collection occurred in a dance studio. On the first visit, the participant completed a prosthetic usage and activity history questionnaire, anthropometric data was measured and recorded, and the first filming session for kinematic data collection of one prosthetic appliance was completed. On the second visit, only kinematic data were collected for the second prosthetic appliance.

The participant was prepared for filming by placing eleven reflective markers that served as reference points for digitizing. The anatomical landmarks used for the markers were, one on the neck at the vertebral body of C7; and one each on the right and left side of the body at the greater trochanter, lateral femoral condyle, lateral malleolus, heel, and head of the fifth metatarsal. Following a warm up, the participant was directed to run at one of three randomly ordered self selected running velocities of slow, medium or fast. In order to film both the anatomical and the prosthetic limbs, the participant was asked to run down the pathway in both the negative X-direction and the positive X-direction. Three trials of one complete running cycle per limb, at each of the three speeds was filmed.

Two Panasonic S-VHS video camcorders operating at 60 Hz were used to collect the kinematic data for this study. One complete running cycle was filmed with both cameras positioned along the same sagittal plane of the body's motion. One timing light box, accurate to 1/1000 of a second, was placed in the field of view of both cameras to synchronize the film data.

The video images were transferred from the video image to a digital graphic image using the Ariel Performance Analysis System (APAS). The markers within each frame were then manually digitized for each trial of the running cycle. Numeric tables and graphic representations were created to examine: stride length and stride rate; stance and swing phases; and hip, knee, and ankle joint ranges of motion, angular displacements and angular velocities.

Hypotheses

The results were influenced by several factors and therefore must be considered when presenting the results. First, there was one participant in the study, an adult male with a traumatic amputation. Therefore, the findings can not be generalized to the adult female or male population, or to the youth and children population of individuals with below the knee amputations, traumatic or congenital. Second, the length of the runway may not have been of sufficient length to allow the participant to attain his running velocities of slow, medium, and fast. Third, the data were collected in a dance studio that had a wooden floor with some spring motion. That additional motion may have affected the vertical and horizontal motion of the lower extremities. Finally, the data were collected in a laboratory setting which may not produce the same results if the data were collected in the field.

Decisions regarding support or non-support of a hypothesis were based on the outcome of the variable of interest in each of the six conditions (two limbs x three speeds or two prosthetic feet x three speeds). Only when the stated criteria of the hypothesis was met in all six conditions was the hypothesis supported, otherwise the hypothesis was not supported.

Tables 15 and 16 were created to assist in the examination of the variables during the discussion of the hypotheses. Table 15 provides a summary of the findings from the comparisons of the kinematics variables between the anatomical and the prosthetic limbs at each velocity. The comparisons were made between the anatomical Flex (F) and the anatomical SACH (S), and between the prosthetic Flex (F) and the prosthetic SACH (S). In Table 16, is a summary of the findings from the comparisons of the kinematics variables between the SACH foot and the Flex-Foot™, at each velocity. The comparisons were between the anatomical SACH (A) and the prosthetic SACH (P), and between the anatomical Flex (A) and the prosthetic Flex (P). In both tables, the following abbreviations were used; ROM, refers to range of motion; min, refers to minimum; and max, refers to maximum.

Table 15.

Summary of comparisons of kinematic variables between the anatomical and prosehtic limbs.

	Limb					
	Anatomical Velocity (m/s)			Prosthetic Velocity (m/s)		
Variable	S	M	F	S	M	F
Velocity	*F>*S	F>S	F>S	F>S	F>S	F>S
Stride length	F>S	F>S	F>S	F>S	F>S	F>S
Stride rate	F>S	F<S	F=S	F=S	F>S	F>S
Stance phase	F<S	F<S	F<S	F<S	F<S	F<S
Swing phase	F>S	F>S	F>S	F>S	F>S	F>S
Hip ROM	F<S	F>S	F>S	F>S	F>S	F>S
Hip min flexion	F>S	F>S	F<S	F<S	F<S	F<S
Hip max extension	F<S	F>S	F<S	S=F	F>S	F>S
Knee ROM	F>S	F>S	F>S	F>S	F>S	F>S
Knee min flexion	F<S	F<S	F<S	F<S	F<S	F<S
Knee max extension	F>S	F>S	F<S	F>S	F>S	F>S
Ankle ROM	F<S	F>S	F<S	F>S	F>S	F>S
Ankle min dorsifleixon	F>S	F<S	F>S	F<S	F<S	F<S
Ankle max plantar flexion	F<S	F<S	F<S	F>S	F>S	F>S
Hip min angular velocity	F>S	F>S	F>S	F>S	F>S	F<S
Hip max angular velocity	F>S	F<S	F>S	F>S	F>S	F>S
Knee min angular velocity	F>S	F<S	F>S	F>S	F<S	F>S
Knee max angular velocity	F>S	F>S	F>S	F>S	F>S	F>S
Ankle min angular velocity	F>S	F>S	F>S	F>S	F>S	F>S
Ankle max angular velocity	F<S	F>S	F>S	F>S	F>S	F<S
Greater trochanter vertical displacement				F<S	F=S	F<S

*F = Flex-Foot™ , S = SACH foot,

Table 16.

Summary of comparisons of kinematic variables between the SACH foot and the Flex-Foot™.

	Prosthetic Foot					
	SACH Velocity (m/s)			Flex Velocity (m/s)		
Variable	S	M	F	S	M	F
Velocity	*A=*P	A<P	A>P	A>P	A<P	A>P
Stride length	A<P	A<P	A>P	A>P	A>P	A>P
Stride rate	A=P	A>P	A>P	A>P	A<P	A<P
Stance phase	A>P	A>P	A<P	A>P	A<P	A<P
Swing phase	A<P	A<P	A>P	A<P	A>P	A>P
Hip ROM	A>P	A>P	A>P	A<P	A>P	A>P
Hip min flexion	A>P	A>P	A<P	A>P	A>P	A<P
Hip max extension	A>P	A>P	A>P	A>P	A>P	A>P
Knee ROM	A<P	A<P	A<P	A<P	A<P	A<P
Knee min flexion	A>P	A<P	A<P	A>P	A<P	A<P
Knee max extension	A<P	A<P	A<P	A<P	A<P	A<P
Ankle ROM	A>P	A>P	A>P	A>P	A>P	A>P
Ankle min dorsifleixon	A<P	A<P	A<P	A<P	A<P	A<P
Ankle max plantar flexion	A>P	A>P	A>P	A=P	A>P	A>P
Hip min angular velocity	A>P	A>P	A>P	A<P	A>P	A>P
Hip max angular velocity	A>P	A>P	A>P	A>P	A>P	A>P
Knee min angular velocity	A<P	A<P	A>P	A<P	A<P	A>P
Knee max angular velocity	A<P	A<P	A<P	A<P	A<P	A<P
Ankle min angular velocity	A>P	A>P	A>P	A>P	A>P	A>P
Ankle max angular velocity	A>P	A>P	A>P	A>P	A>P	A>P

*A = Anatomical limb, P = Prosthetic limb

Hypothesis 1

Stride length and stride rate will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.

The hypothesis was not supported for stride length and stride rate data. The stride rate with the Flex-Foot™ was lesser than or equal to the stride rate of the SACH foot at the slow velocity with the prosthetic limb, and at the medium and fast velocities with the anatomical limb. However, the stride length values for the Flex-Foot™ were greater than the SACH foot at all velocities. The longer stride lengths with the Flex-Foot™ corresponded with the higher velocities of running the participant achieved while wearing the Flex-Foot™. The results of stride rate were mixed and may have been a function of the variation in the participant's ability to rotate the lower extremity limb through the swing phase.

Hypothesis 2

Stride length and stride rate will be less for the prosthetic limb than the anatomical limb while wearing either the Flex-Foot™ or the SACH foot.

The hypothesis was not supported for stride length and stride rate data. The stride length was greater for the prosthetic limb than the anatomical limb with the SACH foot at the slow and medium velocities, and the stride rate was greater for the prosthetic limb than the anatomical limb with the Flex-Foot™ at the medium and fast velocities.

Hypothesis 3

Stance phase will be less and swing phase will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.

The hypothesis was supported based on the results of the study for stance phase and swing phase. The stance phase magnitude was lesser and the swing phase magnitude was greater with the Flex-Foot™ than with the SACH foot at all velocities. The shorter stance phase with the Flex-Foot™ may have been an indirect result of the ability of the Flex-Foot™ to propel the body forward into the swing phase, thereby decreasing the proportion of the gait cycle in the stance phase and increasing the proportion of gait cycle in the swing phase.

Hypothesis 4

Stance phase will be less and swing phase will be greater for the prosthetic limb than for the anatomical limb, while wearing either the Flex-Foot™ or the SACH foot.

The hypothesis was not supported for the stance phase and the swing phase. The stance phase was greater and the swing phase was lesser for the prosthetic limb than for the anatomical limb while wearing the Flex-Foot™ at the medium and fast velocities and while wearing the SACH foot at the fast velocity.

The next two hypotheses, five and six, are related to the lower extremity joints angular displacements. This investigator used the minimum flexion and maximum extension angles of the hip and knee joints, and the minimum dorsiflexion and maximum plantar flexion angles of the ankle joint during the stance phase as the criteria for differences in joint angular displacement. Only when both the minimum and maximum angles met the stated criteria of the hypothesis did this investigator state that the hypothesis was supported.

Hypothesis 5

Joint angular displacements of the hip, knee and ankle will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.

Hip joint.

The hypothesis was not supported for the hip joint angular displacement data. For the prosthetic limb, the hip joint angular displacements were not greater while wearing the Flex-Foot™ than the SACH foot due to equal maximum hip joint extension angles for the Flex-Foot™ and the SACH foot. For the anatomical limb, the hip joint angular displacement was lesser while wearing the Flex-Foot™ than the SACH foot at the slow velocity. The lesser hip joint angular displacement of the Flex-Foot™ was based on the greater magnitude of minimum hip joint flexion and lesser magnitude of maximum hip joint extension.

Knee joint.

The hypothesis was supported with the prosthetic limb at all velocities. The knee joint angular displacements were greater while wearing the Flex-Foot™ than the SACH foot for the prosthetic limb at all velocities. The knee joint angular displacements were greater for the Flex-Foot™ because of the lesser minimum flexion and greater maximum extension magnitudes for the Flex-Foot™ than for the SACH foot.

The hypothesis was not supported for the knee joint angular displacement data for the anatomical limb based on the lesser maximum extension magnitude, at the fast velocity, with the Flex-Foot™ than with the SACH foot.

Ankle joint.

The hypothesis was supported with the prosthetic limb at all velocities. The ankle joint angular displacements were greater while wearing the Flex-Foot™ than the SACH foot for the prosthetic limb at all velocities. The greater angular displacements of the Flex-Foot™ were based on the lesser minimum dorsiflexion and greater maximum plantar flexion magnitudes for the Flex-Foot™ than for the SACH foot.

The hypothesis was not supported for the ankle joint angular displacement data for the anatomical limb. That conclusion was based on the greater minimum dorsiflexion and lesser maximum plantar flexion magnitudes for the Flex-Foot™ than for the SACH foot at the slow velocity.

Hypothesis 6

Joint angular displacements of the hip will be greater, and the knee and ankle will be less for the prosthetic limb than the anatomical limb, while wearing either the Flex-Foot™ or the SACH foot.

Hip joint.

The hypothesis was not supported for the hip joint angular displacement data. Under all conditions, the maximum hip joint extension angles were of lesser magnitude with the prosthetic limb than with the anatomical limb when either the Flex-Foot™ or the SACH foot were worn at all velocities.

Knee joint.

The hypothesis was not supported for the knee joint angular displacement data. Under all conditions, the maximum knee joint extension angles were of greater magnitude with the prosthetic limb than with the anatomical limb when either the Flex-Foot™ or the SACH foot were worn.

Ankle joint.

The hypothesis was supported for the SACH foot at all velocities. The ankle joint angular displacements were lesser for the prosthetic limb than for the anatomical limb while wearing the SACH foot at all velocities. The lesser angular displacement for the SACH foot were due to the greater magnitude of minimum dorsiflexion and lesser magnitude of maximum plantar flexion with the prosthetic limb than for the anatomical limb.

The hypothesis was not supported for the ankle joint angular displacement data for the Flex-Foot™ based on the equal magnitudes of maximum plantar flexion for the anatomical and prosthetic limbs.

Hypothesis 7

Ranges of motion of the hip, knee, and ankle joints will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.

Hip joint.

The hypothesis was supported for the prosthetic limb at all velocities. The hip joint range of motion, for the prosthetic limb, was of greater magnitude for the Flex-Foot™ than for the SACH foot at all velocities. The hypotheses was not supported for the hip joint range of motion for the anatomical limb. The range of motion of the hip joint was lesser while wearing the Flex-Foot™ than the SACH foot for the anatomical limb at the slow velocity.

Knee joint.

The hypothesis was supported for the knee joint range of motion data. The knee joint range of motion was of greater magnitude for the Flex-Foot™ than for the SACH foot for both the prosthetic and anatomical limbs at all velocities. The greater magnitude of knee joint range of motion with the Flex-Foot™ was primarily a function of a smaller magnitude of maximum knee joint flexion. That is, there was more knee joint flexion with the Flex-Foot™ than with the SACH foot for both the prosthetic and anatomical limbs.

Ankle joint.

The hypothesis was supported for the ankle joint range of motion data for the prosthetic limb at all velocities. The ankle joint range of motion was of greater magnitude for the Flex-Foot™ than for the SACH foot for the prosthetic limb at all velocities. Under these conditions, the Flex-Foot™ had a greater ankle joint range of motion than the SACH foot due primarily to the smaller magnitude of ankle joint dorsiflexion.

The hypothesis was not supported for the ankle joint range of motion data for the anatomical limb. The ankle joint range of motion was of lesser magnitude for the Flex-Foot™ than for the SACH foot at the slow and fast velocities due to a lesser magnitude of ankle joint plantar flexion for the Flex-Foot™.

Hypothesis 8

Ranges of motion of the hip, knee, and ankle joints will be less for the prosthetic limb than the anatomical limb, while wearing either the Flex-Foot™ or the SACH foot.

Hip joint.

The hypothesis was supported for the SACH foot at all velocities. The range of motion of the hip joint was less for the prosthetic limb than the anatomical limb while wearing the SACH foot at all velocities. The lesser range of motion with the prosthetic limb was due primarily to a lesser magnitude of hip joint maximum extension compared with the anatomical limb. The hypothesis was not supported for the Flex foot. The range of motion of the hip joint was greater for the prosthetic limb than the anatomical limb while wearing the Flex-Foot™ at the slow velocity because the prosthetic limb had a smaller magnitude of hip joint flexion than did the anatomical limb.

Knee joint.

The hypothesis was not supported for knee joint range of motion. The knee joint range of motion was of greater magnitude for the prosthetic limb than for the anatomical limb, under all conditions. The greater magnitude of range of motion with the prosthetic limb compared to the anatomical limb, was due to the greater magnitude of knee joint extension.

Ankle joint.

The hypothesis was supported for the ankle joint range of motion. The ankle joint range of motion was of lesser magnitude for the prosthetic limb than for the anatomical limb while wearing either the Flex-Foot™ or the SACH foot at all velocities. The smaller range of motion found with the prosthetic limb, compared with the anatomical limb, was due to the limited dorsiflexion motion of the prosthetic appliance.

The next two hypotheses, nine and ten, were related to the lower extremity joints angular velocities. This investigator used the minimum and maximum angular velocities of the hip, knee and ankle joints as the criterion for differences in joint angular velocities. Only when both the minimum and maximum angular velocities met the stated criteria of the hypothesis did this investigator state that the hypothesis was supported.

Hypothesis 9

Angular velocities of the hip, knee, and ankle joints will be greater while wearing the Flex-Foot™ than the SACH foot for both the prosthetic and anatomical limbs.

Hip joint.

The hypothesis was not supported for the angular velocities of the hip joint for either the prosthetic or the anatomical limbs. For the prosthetic limb, the angular velocity of the hip joint was not greater while wearing the Flex-Foot™ than the SACH foot based on the smaller magnitude of minimum angular velocity with the Flex-Foot™ at the fast velocity. For the anatomical limb, the angular velocity of the hip joint was not greater while wearing the Flex-Foot™ than the SACH foot based on the smaller magnitude of maximum angular velocity with the Flex-Foot™ at the medium velocity.

Knee joint.

The hypothesis was not supported for the angular velocities of the knee joint for either the prosthetic or the anatomical limbs. For the prosthetic limb, the angular velocity of the knee joint was not greater while wearing the Flex-Foot™ than the SACH foot based on the smaller magnitude of minimum angular velocity with the Flex-Foot™ at the medium velocity. For the anatomical limb, the angular velocity of the knee joint was not greater while wearing the Flex-Foot™ than the SACH foot based on the smaller magnitude of minimum angular velocity with the Flex-Foot™ at the medium velocity.

Ankle joint.

The hypothesis was not supported for the angular velocities of the ankle joint for either the prosthetic or the anatomical limbs. For the prosthetic limb, the angular velocity of the ankle joint was not greater while wearing the Flex-Foot™ than the SACH foot based on the smaller magnitude of maximum angular velocity with the Flex-Foot™ at the fast velocity. For the anatomical limb, the angular velocity of the ankle joint was not greater while wearing the Flex-Foot™ than the SACH foot based on the smaller magnitude of maximum angular velocity with the Flex-Foot™ at the slow velocity.

Hypothesis 10

Angular velocities of the hip, knee, and ankle joints will be less for the prosthetic limb than the anatomical limb, while wearing either the Flex-Foot™ or the SACH foot.

Hip joint.

The hypothesis was supported for the hip joint angular velocities for the SACH foot at all velocities. The hip joint angular velocity was less for the prosthetic limb than for the anatomical limb while wearing the SACH foot. The angular velocity was less for the SACH due to greater and lesser magnitudes of minimum and maximum angular velocities, respectively, with the prosthetic limb than the anatomical limb at all velocities.

The hypothesis was not supported with the Flex-Foot™. The angular velocity of the hip joint was not less for the prosthetic limb than for the anatomical limb while wearing the Flex-Foot™ because the minimum angular velocity was of greater magnitude for the prosthetic limb than for the anatomical limb, at the slow velocity.

Knee joint.

The hypothesis was not supported for the knee joint angular velocities. The angular velocities of the knee joint were not less for the prosthetic limb than for the anatomical limb because, under all conditions, the knee joint maximum angular velocities were of greater magnitude with the prosthetic limb than with the anatomical limb when either the SACH foot or the Flex-Foot™ were worn.

Ankle joint.

The hypothesis was supported for the ankle joint angular displacements. Angular velocities of the ankle joint were less for the prosthetic limb than for the anatomical limb while wearing either the Flex-Foot™ or the SACH foot. The lesser angular velocities for the prosthetic limb were due to the greater and lesser magnitude of minimum and maximum, respectively, angular velocities.

Hypothesis 11

The greater trochanter vertical displacement will be less while wearing the Flex-Foot™ than the SACH foot.

The hypothesis was not supported for the greater trochanter vertical displacement. The greater trochanter vertical displacement was not less while wearing the Flex-Foot™ than the SACH foot at all velocities. At the medium velocity, the greater trochanter vertical displacement was the same for the Flex-Foot™ and the SACH foot.

Conclusions

As a result of this study, four conclusions seem evident regarding the gait patterns of running of an adult with a traumatic below the knee amputation. First, the data revealed that wearing the Flex-Foot™ was superior to the activity of running than wearing the SACH foot. The participant of this study was able to achieve gait patterns more similar to what has been found with able bodied individuals and he was able to achieve higher velocities of running accompanied by longer stride lengths and swing phases. The sequential process of ankle to hip joint motion that lead to the longer swing phases, longer stride lengths and ultimately higher running speeds was related to the unmeasured factor of energy storage and release of the prosthesis. This investigator believed that the higher magnitude of prosthetic ankle joint dorsiflexion during the stance phase resulted in energy storage, the energy was then released after toe off and resulted in a greater magnitude of knee and hip joint flexion during the swing phase, relative to the SACH foot.

Second, and of concern, was the excessive prosthetic limb knee joint hyperextension during the stance phase when either the SACH foot or the Flex-Foot™ were worn. That rigid position may have been used because of lack of quadriceps strength to support the weight of the body upon impact, which would then eliminate the fear of the knee buckling upon impact. Or, the hyperextension may have been a result of the thigh, on the prosthetic side, rotating backward to help propel the lower segment forward. Also, due to the higher range of motion found with the knee joint on the prosthetic limb, due primarily to the hyperextension, the knee joint maximum angular velocity was of larger magnitude relative to the anatomical limb.

Third, increases in the velocity of gait were achieved in a similar pattern as has been found with able bodied individuals. At the slower velocities, increments in velocity were attained by increasing the stride length, whereas at higher velocities, increases in velocity were primarily gained by increasing the frequency of strides. Also, as the velocity of gait increased, there were increased ranges of motion at the hip and knee joints in both the anatomical and the prosthetic limbs. However, a trend for the ankle joint range of motion was not found across speed and may have been due to the variation in the point of foot contact and toe off as the participant ran faster.

Finally, the lower extremity joint motion of the anatomical limb when either the SACH foot or the Flex-Foot™ were worn was similar to that of an able bodied individual. However, the prosthetic limb of an individual with a below the knee amputation was not similar to the individual's anatomical limb or similar to the limbs of an able bodied individual. The participant was not able to attain the same level of push off with the prosthetic limb as with the anatomical limb because of limited hip joint extension, and ankle joint dorsiflexion and plantar flexion at toe off.

Recommendations for Future Research

The recommendations for future work were related to design improvement, validation of the findings, and inclusion of other variables to enhance the understanding of the running performance of individuals with below the knee amputations. The inclusion of more participants would greatly enhance the application of the findings to a greater population of individuals with amputations below the knee. Also, the use of a longer runway or an outdoor running track might assure participants that they can attain any speed.

Future work that investigates the gait of running of individuals with below the knee amputations need to report the kinematic variables. Several investigators reported their findings graphically without also reporting the actual values of the variables of interest, thereby limiting future investigator's abilities to compare results. Future investigators need to include graphic representations as well as tables with the values of the kinematic variables measured.

Inclusion of additional variables would also enhance the understanding of the gait of an individual with an amputation. Inclusion of participant energy output measures and prosthesis energy storage and release would help answer the question of what prosthetic feet are energy efficient and how does that related to the energy output of the user. Conducting a three dimensional study that included the analysis of the movement at the socket and stump interface would lend insight into the movement of the socket during the gait cycle. An investigation of the lower limb muscular activity through electromyography would enhance the understanding of the effect of limb and muscle loss on running performance. The inclusion of other energy storing prosthetic appliances would enable the investigator and the users to differentiate between appliances designed for athletic use.

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List of References

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Appendices

Appendix A

Informed Consent

The measurement procedures and running test procedures have been explained to me and I understand what is required of me. I understand that participation is voluntary and that I may quit at any time. I understand that this research is being undertaken to further knowledge concerning the effect of different prosthetic feet on the running pattern of individuals with below the knee amputations.

I have had the opportunity to ask questions regarding the test and procedures to be used. Furthermore, I have been informed that I am free to withdraw my consent and to discontinue my participation at any time.

I understand that the results of this study may be used in scientific oral and/or written presentations. Since I will be filmed on video tape, I realize that my anonymity will not be preserved, but all viewing of the original video tape will be done by the primary investigator only. I understand that a copy of the tape, which blocks out the region of my face, may be viewed by other persons or used in scientific presentations. I understand that my confidentiality has been assured by a subject code. The code will be used in scientific oral and/or written presentations of this study's results. I may request my results from this study at any time.

I understand that I will experience no greater risk than during my normal running exercise routine. I understand that if I am injured as a result of my participation in this research project, Michigan State University will provide emergency medical care if necessary. I further understand that if the injury is not caused by the negligence of MSU I am personally responsible for the expense of this emergency care and any other medical expenses incurred as a result of this injury.

I consent to participate in this study.

____________________________ __________________

(Your Signature) (Date)

____________________________ __________________

(Investigator Signature) (Date)

Appendix B

Anthropometric Measurements

Below knee residual limb length.

The residual limb length will be measured according to Radcliffe and Foort (1961). Two measurements are possible, a stump length and a tibial length. The stump length will be used as the residual limb length as this is the longer of the two lengths and includes any soft tissue at the distal end of the tibia and fibula.

The subject stands erect with a slight bend in the residual limb knee. The stump length is measured from the medial tibial plateau (MTP) to the very distal end of the residual limb. The MTP is located on the proximal edge of the medial tibial condyle and is the space between the tibia and femur.

Prosthetic foot length.

The prosthetic foot length will be measured between the two most protruding ends of the heel and toe region.

Appendix C

Subject Information

Date ____________________

Subject Code	________________ (Initials and Number)	
Date of Birth	________________ (month/day/year)	
Gender	________________	
Weight	________________ (kg) (without prosthesis)	________________ (kg) (with SACH)
		________________ (kg) (with Flex-Foot™)
Stature	________________(cm) (without shoes)	________________(cm) (with shoes)
Sitting Height	________________(cm)	
Leg Length (Stature - Sitting Height)	________________(cm) (anatomical limb)	
Below Knee Residual Limb Length	________________(cm)	
Foot Length	________________(cm) (anatomical limb)	________________(cm) (SACH)
		________________(cm) (Flex-Foot™)

Appendix D

Questionnaire

Date of Amputation ____________________ Side of Amputation ____________________
(month/year)

Prosthetic Foot and Suspension Device Usage History

Prosthesis	Suspension	Date of Prosthetic Fit (month/year)	Length of Time Used	Type of Usage	Frequency and Duration of Usage

Activity History: Pre-Amputation

Activity	Level of Participation (Recreation and/or Competitive)	Length of Time Participated (years/months)	Season of Activity	Seasonal Frequency of Activity	Duration of Activity (hours/minutes)	Prosthesis and Suspension Device Used

Activity History: Post-Amputation

Activity	Level of Participation (Recreation and/or Competitive)	Length of Time Participated (years/months)	Season of Activity	Seasonal Frequency of Activity	Time of Activity (hours/minutes)	Prosthesis and Suspension Device Used

Competition Summary (Pre- and Post-Amputation)