NATIONAL JOURNAL OF CLINICAL ORTHOPAEDICS

ISSN (P): 2521-3466
ISSN (E): 2521-3474

www.orthoresearchjournal.com
2018; 2(3): 66-75
Received: 21-05-2018
Accepted: 22-06-2018

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The influence of prosthetic foot stiffness on energy expenditure in unilateral below-knee amputees

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Abstract
This paper investigates the relationship between prosthetic foot stiffness and energy expenditure. There are a multitude of different factors that can affect prosthetic foot stiffness that should be taken into consideration when determining which foot to select for each patient. Energy expenditure is a factor that is important to healthcare professionals to consider as amputees will expend more energy than an able-bodied person. Any way to reduce energy expenditure is beneficial to the patient. This project investigated the topic of prosthetic foot stiffness and energy expenditure. Its purpose was to determine if there was an optimum prosthetic foot stiffness for transtibial amputees that would reduce energy expenditure. Following a review of existing research, there may be a correlation between the two, but further research needs to be continued on the topic. Prosthetists and other healthcare professionals must consider all available aspects that could affect in reducing energy expenditure of amputees.

Keywords: Prosthetic foot stiffness, stiffness, energy expenditure, metabolic cost, transtibial amputee

Introduction

Limb loss is an issue that has become more prevalent in recent years. Prosthetics have become more innovative and creative making this life changing situation better for amputees in getting their life back to ‘normal’. The incidence of limb loss secondary to diabetes mellitus, dysvacular disease, and malignancy of the bone and joint are among the leading contributors to this projected increase (Ziegler-Graham, Mac Kenzie, Ephraim, Travison, and Brookmeyer, 2008) [33]. “Over the next 45 years, the number of persons living with the loss of a limb is expected to more than double from 1.6 million in 2005 to 3.6 million in 2050” (Zielgler-Graham *et al*., 2008, p. 424) [33]. With the number of new products and services in the prosthetic and orthotic industry, there continues to be an abundance for physicians, prosthetist(s), and physical therapists to choose, however, these choices sometimes make it difficult for healthcare professionals to decide which device is best for the patient.

Prosthetic feet have continued to technologically develop over the recent years making it more feasible for prosthetists and their patients to find and use a foot that will benefit the patients’ lifestyle and activity level (Wing & Hittenberger, 1989) [31]. There are multitudes of prosthetic feet available, providing a range of different stiffness energy return and shock absorption. Feet are categorized by the various brands as well as companies producing their own types of feet, to include a single-axis, multi-axis, dynamic-response, flexible keel, solid ankle cushioned heel, and microprocessor (Krajbich, Pinzur, Potter, & Stevens, 2016) [18]. Upon discussing goals with the patients, the prosthetist makes an educated decision on the type of prosthetic foot to choose for that individual.

Walking ability is important to almost everyone, but many who are very active and perform a multitude of starting and stopping activities may benefit from a stiffer prosthetic foot. In addition, there are other amputees who may spend a substantial amount of time standing who could benefit from a more compliant foot to cushion the limb and provide shock absorption. Therefore, the prescribed foot must be a compromise of multiple standards out of functional necessity (Peterson, 2012, p. 1) [20]. Many factors go into making the decision when choosing a prosthetic foot. Reducing energy expenditure for amputees would be beneficial and knowing the energy expenditure and its correlation to prosthetic foot stiffness could assist in making the decision. Energy expenditure in correlation with amputation has been a concern for prosthetists, physicians, and physical therapists for a long time (Gailey *et al*., 1994) [7]. Many studies have been conducted pertaining to the energy consumption of amputees.

Energy expenditure values for amputees due to biomechanical changes imposed by assistive devices and prosthetic use is of concern to rehabilitation professionals because of its influence on available rehabilitation time and technique. Determined that hip disarticulation and hemipelvectomy amputees spent between 82 and 125% more energy, respectively, than able-bodied subjects. For unilateral above- knee amputees, found a 49 to 65% increase in energy consumption at half the walking speeds of comparable able-bodied subjects. Below-knee amputee energy expenditure increases have been shown to vary anywhere from 9% to 25% and up to 42%. (as cited in Hunter, Smith, Murray, & Murray, 1995, p. 209) [14]

With energy expenditure being a primary concern for amputees, finding ways to increase efficiency is very beneficial. Many studies have examined energy expenditure of amputees, but they have not considered how it is related prosthetic foot stiffness. Studies conducted by Schmalz, Blumentritt, and Jarasch (2002) [22], Jeans and Karol (2006) [15], and Starholm *et al*. (2016) [25] have researched various ways in which energy expenditure is influenced by various knees, and treadmill walking and walking speeds, respectively. Large differences are found for the amputee's energy expenditure between treadmill and floor walking (Starholm *et al*., 2016) [25]. Amputees, though they have similar standing oxygen consumption rates as non-amputees, have increased metabolic consumption during walking (Schmalz *et al*., 2002) [22]. The consumption also increases with increased walking speed (Schmalz *et al*., 2002) [22]. Amputees of all levels also tend to reduce their walking speeds (Jeans & Karol, 2006) [15]. It would be valuable to all parties involved to be able to decrease energy expenditure in amputees.

The purpose of this review was to determine how different foot stiffness affects energy expenditure while ambulating with unilateral, below knee amputees. There are two specific aims to this literature review: primary aim and exploratory aim. The *primary aim* will hope to determine what stiffness is most beneficial to patients based on weight and activity levels. Energy expenditure data was collected as patients walk with different stiffness of same type of prosthetic foot. The proposed *hypothesis* is improper foot stiffness, based on weight and activity level, will result in greater energy expenditure throughout the gait cycle. The *exploratory aim* hoped to determine adverse effects of improper stiffness of prosthetic feet, i.e. balance, stability, confidence, and improper gait. Determining the effect of improper foot stiffness in correlation to energy expenditure will hope to assist prosthetists correctly determine what foot to use for patients in the future.

Previous research has examined energy expenditure in amputees as well as the different types of prosthetic feet that are available, including types of stiffness and the effects on gait. The gap in the research seems to extend to identifying the relationship between the two. This review hopes to assist in providing healthcare professionals with the knowledge in providing amputees with the appropriate prosthetic foot in order to expend the least amount of energy as possible.

Materials and Methods

Databases used in this search for this literature review were PubMed, Concordia University Library, and EBSCO Host. The following search strategies were used: "amputee energy expenditure", "prosthetic foot stiffness", "amputee metabolic cost", and "prosthetic foot metabolic cost". All four databases were searched with limitations; articles were published between 1974-2016. The online search recognized a total of forty-four articles. The exclusion criteria included: letters to the editor, editorials, language other than English, and abstract analyses. A total of twelve articles were excluded after the title and abstract analysis and thirty-two articles were selected for full text analysis. After narrowing search results, articles were read for review.

The availability of various prosthetic feet has tremendously increased in recent years with the technological advances that have affected the prosthetic field. In the past, the solid ankle cushioned heel (SACH) was primarily the most commonly foot prescribed. This type of prosthetic foot, as the name suggests, reduces the impact an amputee has at heel strike. Though this reduces the overall impact, this foot provides little to no energy, which could potentially improve gait; providing the user with energy return after heel strike and through roll-over. There are still many properties that influence the prosthetic foot on different portions of gait that are not understood. What is known is that the prosthesis has to support the body with maximal stability while walking and has to demand as little energy as possible (Van Jaarsveld, Grootenboer, De Vries, & Koopman, 1990) [28].

There are four mechanical properties of prosthetic feet that may influence stability, energy consumption, and roll-over behavior (Van Jaarsveld *et al*., 1990) [28]. The first of these properties includes the shape and alignment of the foot. A study by Koopman (1989) [17] shows that shape influences both vertical and horizontal movement of the prosthesis during gait. Secondly, mass, as well as mass-distribution, of the prosthetic foot affects the affected limb's swing behavior (Van Jaarsveld *et al*., 1990) [28]. Donn, Porter, and Roberts (1989) [2] experimented with mass of prosthetic feet and found that choice of mass can significantly improve some symmetry aspects of walking. The third property that is discussed quite frequently is hysteresis. This term, in relation to stiffness, "is pure energy issue and represents an energy loss due to internal friction when loading and unloading a deformable object" (Van Jaarsveld *et al*., 1990, p. 118) [28]. If there is minimal hysteresis of the foot, the patient should have decreased energy cost if the stored energy is returned positively. Lastly, stiffness of the prosthetic foot can affect the foot shape through foot deformation through bearing weight (Van Jaarsveld *et al*., 1990) [28]. This is important as "energy storage and release during the progress of weight bearing since a soft foot can store more energy than a stiff foot when the same load is applied" (Van Jaarsveld *et al*., 1990, p. 118) [28]. Each of the four properties are important and understanding how they affect the patient can be quite beneficial to both the prosthetist in choosing appropriate foot for future patients as well as the patients themselves. With advanced technology, the prosthetic feet that are on the market make for more realistic gait patterns for amputees. There are many types of prosthetic feet, and the development of material science has attributed the design and manufacturing of a multitude of prosthetic feet.

Stiffness

Stiffness, in regards to prosthetic feet, is quite difficult to define. Stiffness is categorized into stiffness grades with each manufacturer using their own guidelines in determining stiffness of their prosthetic feet. The prosthetist uses the patient weight and activity level to properly select an appropriate category of foot for their patient. The stiffness is often mostly restricted to the heel grade of one-foot type (Van Jaarsveld *et al*., 1990) [28]. As previously discussed, the material used in the prosthetic foot often affects stiffness. Because each manufacturer differs in their categorization, the process is unknown as to how the different

foot types vary in stiffness.
There are an increasing number of foot types, with more developing each year. Therefore, it is important for healthcare professionals and, more specifically, prosthetists to understand the advantages a particular stiffness can provide. Because there is not a set of guidelines for measuring stiffness, testing is often performed and discussed on a regular basis. Various studies have been performed in hopes to find a common theme in stiffness as it relates to certain aspects of gait as well as additional information important in assisting the amputee to ambulate as best as possible. One of the areas of research has been in regards to energy expenditure.

Types of Prosthetic Feet

As previously alluded to, there have been many advances to the field of prosthetics within the past, which have contributed to several categories of prosthetic feet. Though this is not meant to be a comprehensive list as some include subcategories, etc., prosthetic feet most notably include the SACH, Single Axis, Multi-Axial, Dynamic Response, Energy Storing, Hydraulic, and Externally Powered. Within these categories, there are various prosthetic feet developed and sold by a multitude of manufacturers. Each category has advantages, disadvantages, stiffness, and energy return, making it important for the prosthetist and healthcare team to choose the proper prosthetic foot accordingly.

Progression & Development of Foot Materials

Material science in all aspects of the prosthetic (and orthotic) field has complemented the field in its advancement. This includes socket, plastic, suspension sleeves, liners, and of course feet. A variety of rigid plastics and rubbers were initially used in the field, but as technology and material science has developed so have the types of materials used in prosthetics.
SACH feet have long been the “go-to” for prosthetists. “The SACH foot is manufactured in more models than any other prosthetic foot” (Edelstein, 1988, p. 1876) [3]. These feet are identified as nonarticulated, because of its construction of “a central rigid keel (solid ankle) that terminates at a point corresponding to the metatarsophalangeal joints, a posterior wedge of resilient material (cushion heel), and a covering of slightly resilient synthetic rubber” (Edelstein, 1988, p. 1876) [3]. The foot itself is one solid piece, making it fairly streamlined and contoured. These materials allow for durability, inexpensiveness, allowing the foot to be relatively waterproof. Though there are benefits, patients with these feet have a decreased ability to push-off (Wing & Hittenberger, 1989) [31]. The inability to push-off creates the drop-off phenomenon. This phenomenon is quite notable when patients try to walk quickly or run in SACH or single axis feet. Due to the rigidity of the keel of the SACH foot, the patient is also unable to dorsiflex. The combination of both of these aspects makes it quite difficult to walk on certain terrains and at different speeds.
As for rigidity or stiffness, the SACH foot’s heel can be manufactured in a variety of grades. This accommodates the force the patient applies while ambulating and is dependent on the weight and K-level of the patient. The prosthetist will have to take into consideration all aspects of the patient’s life when deciding stiffness for these feet. Researchers needed to “incorporate a mechanism to simulate the push-off phase of normal running” to allow patients the ability to aid them in returning to a normal gait when performing a variety of activities (Wing & Hittenberger, 1989, p. 330) [31]. With the advent of new materials, this foot has lost some of its popularity as newer materials have allowed for a more dynamic response and natural gait.
There are many new materials used to manufacture prosthetic feet, but carbon fiber seems to be the most common. Carbon fiber is “a high-strength and lightweight composite, which has allowed for the successful development of energy storage and return (ESAR) feet” (South, Fey, Bosker, & Neptune, 2010, p. 1) [24]. The discovery of energy storage has generated an abundance of research within the field of material science. Allowing patients to have this energy stored and then released during toe-off aids propulsion and swing initiation in the gait cycle (South *et al*., 2010) [24].
Energy-storing prosthetic feet (ESPF), which include the use of carbon fiber and other materials, are an attempt to represent an approach to normal gait patterns (Wing & Hittenberger, 1989) [31]. Heel-strike is the point during the gait cycle in which there is a noticeable difference between materials used in prosthetic feet. With ESPF, the energy stored during heel-strike is then used later during toe-off. This increases forward acceleration of both the leg and body. The forward acceleration aids the patient in a multitude of ways, but most notably, it allows the patient to ambulate more smoothly; conserving more energy than traditional prosthetic feet, i.e. the SACH foot (Wing & Hittenberger, 1989) [31]. In general, the more natural the gait, the less energy is expended throughout the gait, as the amputee is not ‘working against’ the prosthesis during ambulation.
Another material that has recently been used in prosthetic feet is Flexeon™. This material is a departure away from the carbon fiber based feet, as carbon fiber is fairly rigid and less flexible in comparison. Flexeon™ is the specific material trademarked and used in the Ability Dynamics’s Rush™ feet line. It is made up of a reinforced fiberglass material. Tests completed demonstrated being “three times more flexible than carbon and much more durable than current standard carbon fiber products” (Swain, 2013, para. 1) [26]. Other manufacturers in prosthetic feet are also using the lightweight fiberglass. Freedom Innovations also has developed the Maverick™, composed of a similar lightweight fiberglass. As technology has progressed, there has been a noticeable advance in overall weight in the feet as well as energy storage and release due to the amount of materials that are available. “ESPF vary in performance levels and can vary from providing a great deal of damping with little energy storage (unresponsive and slow), to a great deal of energy storage and little damping (responsive and fast)” (Wing & Hittenberger, 1989, p. 330) [31]. Proper component selection will allow a balance between all aspects of the feet in order to hopefully; attain a symmetrical and normalized gait pattern.

Roll-Over Shape & Alignment Characteristics

Prosthetic feet are designed to mimic the characteristics of the human anatomy as best as possible. There are many aspects of gait making it difficult for the prosthetic foot to identically mimic the anatomical foot. Some characteristics of the prosthetic foot include radius of curvature, center of pressure, and the instantaneous radius of the curvature, each needing to be considered (Curtze *et al*., 2009) [1]. Various prosthetic feet are available, but often the stiffness of the foot can be the difference, as stiffness will affect the arc length. An arc length that is longer has been shown to exhibit the most symmetrical gait for amputees (Hansen, Meier, Sessoms, & Childress, 2006) [12].
Roll-over shape properties are a piece of information that should be carefully examined by the prosthetist when assessing the patient and choosing the foot itself. Each prosthetic foot is usually designed for specific activities and levels of activity.

Longer levers will increase roll-over shape and short lever will provide shorter roll-over shape. Longer roll-over shapes are designed for patients who tend to move quite often, whether it be running, walking, etc. Shorter roll-over shapes would be more appropriate for standing. Each prosthetic foot have their own limitations, however, alignment has a larger effect on what these limitations may be. The prosthetist must properly align the prosthesis in the sagittal plane in order to provide the patient with the correct roll-over properties (Hansen, 2006) [12].

Combining roll-over shape concepts with further research on the proper socket position and orientation may lead to prior knowledge of appropriate alignment so that prostheses could be fabricated with the alignment built-in, reducing the need for expensive and heavy alignment hardware. (Hansen, Meier, Sam, Childress, & Edwards, 2003, p. 98) [11]

Hansen (2008) [10] shows the importance of proper alignment for good function of the patient. An understanding of the biomechanics of the body for alignment process is beneficial. If alignment were based of scientific principles instead of heuristics, it would eliminate the need for alignment hardware, as well as alleviate some of the length and stress throughout the fitting process for prosthetists and patients (Hansen, 2008) [10]. Based on this information, further research should be completed to accomplish this goal, although there are several roll-over variables within prosthetic feet which should be taken into consideration by the prosthetist based on the amputee's height, weight, and activity level. This is vital to ensure the patient is getting the best functioning foot to suit their activities of daily living.

Prosthesis Mass & Distribution of Prosthetic Mass

The mass of the entire prosthesis, to include the socket, pylon (other componentry), and prosthetic foot, has uncovered multiple research studies resulting in various findings. Typically, the thought has been the lighter the prosthesis, the less energy necessary, benefiting the patient. “In the literature, however, there is no consensus” as to what actually is optimal mass for the prosthesis (Selles, Bussmann, Wagenaar, & Stam, 1999, p. 1593) [23, 12]. There are several theoretical models that have been created to help explain influence of mass on gait.

Donn *et al*. (1989) [2] discussed one of these theories. They examined the prosthetic side through the swing phase, referring this portion of gait as a pendulum. As a pendulum, something as small as footwear selection (mass) has been shown to affect gait mechanics. Alteration of shoe mass changed the swing time, and in this study, six out of 10 subjects preferred a heavier shoe (Donn *et al*., 1989) [2]. Based on this information, the prosthetic foot mass should then be taken into consideration. A lightweight prosthesis does not mean a symmetrical gait (Donn *et al*., 1989) [2]. Patients are quite different, and though the exact effect that mass has on gait is not fully understood or agreed upon, the patient will often know what ‘feels’ best while ambulating based on the overall mass of their prosthesis.

Hysteresis

The hysteric property of prosthetic feet is an aspect that coincides with stiffness and energy expenditure. Commonly in prosthetic research articles, hysteresis is measured “as the amount of energy absorbed in loading minus the amount of energy released in unloading” (Geil, 2001, p. 71) [8]. In some instances, it can also be expressed as percentage of the loading energy (Geil, 2001) [8]. Measuring the hysteric properties of particular prosthetic feet can be beneficial, as each foot differs in storage and release of energy.

Hysteresis of feet can be directly interpreted (Van Jaarsveld *et al*., 1990) [28]. Often times, hysteresis is measure or examined as loop and is the process of absorbed energy to released energy in a cycle. In this case, the smaller the loop, the better, as a smaller amount of energy is released. “The absorbed energy depends on the area of this loop and it is to be expected that a low value of hysteresis will reduce the energy needed for walking” (Van Jaarsveld *et al*., 1990, p. 121) [28]. The different materials often show different hysteresis as well.

In general, rubber shows less hysteresis loss when deformed below 100% than at more deformation (Powell & Housz, 1998). Applying this to the authors' measurements explains why at foot flat position, where stiffness is high, and deformation is low, hysteresis is at a minimum. (Van Jaarsveld *et al*., 1990, p. 121) [28]

There have been many studies that have examined the several hysteresis of prosthetic feet, including Postema, Hermens, De Vries, Koopman and Eisma (1997) [21], in which three Ottobock feet and a Quantum foot were measured. Currently, few research studies are found relating to information regarding hysteric properties of feet. It would be beneficial for practitioners to have access to information related to hysteresis when selecting an appropriate prosthetic foot for patients. Information related to the testing and research of each prosthetic foot would provide a greater understanding of the energy absorption and unloading for each prosthetic foot.

Energy Expenditure

Energy expenditure is a term that is discussed quite frequently in the field of prosthetics and orthotics. The optimal goal for practitioners and other healthcare professionals in the field is to have their patients expend as least amount of energy as possible during ambulation. Before diving into the increased metabolic costs of ambulating without a limb, the definition of energy expenditure during the gait cycle and how to measure should be noted.

Defining Energy Expenditure

In the most generic sense of the term, energy expenditure can be explained as the measurement of the rate of oxygen consumption throughout an activity, i.e. walking, running (Waters & Mulroy, 1999) [29]. Oxygen cost is used to determine how much energy is required for specific tasks, and this can be altered by speed/pace or oxygen rate (Waters & Mulroy, 1999) [29]. Power and work are also used as terms to describe energy expenditure. Oxygen cost can be determined by dividing power (oxygen rate consumption) by the speed of walking (Waters & Mulroy, 1999) [29]. A comparison between normal gait and pathological gait of energy cost, gait efficiency can be found.

Increased Concern for Energy Expenditure

As was previously discussed, amputations have become increasingly more prevalent throughout the world, and particularly in the United States. With the number of individuals dealing with this traumatic experience, it is important to allow patients to return to a lifestyle that they can actively enjoy. The technology that has become readily available is steps in the right direction as it has become more realistic to aiding the patient achieve a realistic gait. Though the technology is contributing heavily, there are many physiologic considerations that need to be taken in account. Among these is the metabolic cost of walking.

Normal gait or walking speed can range depending on the individual, and is usually determined by several factors. The determining factors are addressed in order to optimize energy consumption during walking (Krajbich *et al*., 2016) [18]. Metabolic efficiency is at its best when the individual is healthy, and the efficiency is often decreased if the individual is sick or injured, i.e. loss of a limb. If there is a sickness or injury, the patient is more disposed to discomfort during the activity. Overall, a prosthesis is not as efficient as the normal limb.

In normal gait, the body does its best to conserve energy in as many ways as possible throughout the gait cycle. This is done through energy transfer and the principle of conservation of energy. In normal gait, the body uses 'movements' to aid in the conservation of energy (Waters & Mulroy, 1999) [29]. "Pelvic rotation, pelvic tilt, and stance knee flexion minimize the shock absorption and smooth out the points of inflection of vertical rise" (Waters & Mulroy, 1999, p. 207-8) [29]. Lateral pelvic displacement aids in minimizing lateral shift of the body's center of gravity (Waters & Mulroy, 1999) [29]. Amputees tend to take a similar number of steps every day. This metabolic cost affects a patient's daily life and often causes an amputee to ration the number of steps taken.

Walking speed can have a great effect on energy expenditure. Most adults tend to walk at speeds ranging from 1.0 to 1.67 m/s (Waters & Mulroy, 1999) [29]. Finding this information aids in testing and comparisons between normal and pathologic (amputee) gait. The ability to control pace during testing, while on a treadmill, is convenient as it is easier to measure energy expenditure and control the variables, however, patients with gait disabilities can have a difficult time adjusting to walking on a treadmill (Waters & Mulroy, 1999) [29]. Customary walking gait (CWS) is thus used most often in testing. This is the patient's natural and most comfortable pace. Many times, this differs from one individual to another, so the range that has been defined is quite beneficial for analysis. "For these reasons, most investigators have found it preferable to perform testing on a track allowing the patient to select [their] CWS" (Waters & Mulroy, 1999, p. 210) [29].

As previously stated, in normal gait the body tries to conserve as much energy as possible throughout the gait cycle. This is done through motions of the trunk and limb(s), and any interruption to the gait or conservatory motions can result in increased energy expenditure (Waters & Mulroy, 1999) [29]. This is often the case for amputees or any persons with a gait disability as well. The patient will develop and perform compensatory movements in gait in order to ease their gait cycle; hoping to decrease energy expended. Obviously, each patient will differ and these movements may not be effective. Often times, the effectiveness is based on the severity of the disability as well as the overall health and wellness of the patient (Waters & Mulroy, 1999) [29].

Types of Amputations & Associated Energy Costs

The type and or level of amputation often affect the amount of energy expended while ambulating. In general, the higher the amputation, the higher the associated energy costs. Because the patient has lost all musculature, which was utilized to move their intact limb, the remaining muscles proximal to this amputation are what are used as a substitute for ambulation. Aging can also be a concern in regards to energy expenditure. The exercise ability of the older population is already reduced, so when an amputation occurs [to this population], it is difficult to regain the ability to ambulate at their previous energy expenditure levels. Commonly associated diseases, such as diabetes and heart and peripheral vascular disease, also attribute to this decline of exercise ability and increase in energy expenditure (Waters & Mulroy, 1999) [29]. There are many variables when testing energy expenditure in amputees that make it quite difficult to accurately compare results from one study to another. Age of the amputee, use of an assistive device while ambulating, overall prosthetic fit, and user experience can all play a role in how much energy is expended (Waters & Mulroy, 1999) [29]. These variables make it important for professionals to carefully address all inclusionary/exclusionary criteria before comparisons and data are drawn from previous studies.

Unilateral amputees are the most commonly researched population for energy expenditure studies with a majority of patients being trans-tibial amputees. In most cases, studies have found that there is a correlation between amputation level and associated energy costs. Patients with the higher amputations had the higher O2 costs and a less efficient gait in comparison to the lower level amputations. Findings show that patients with amputations alter their speed at higher amputation levels. This demonstrates that the increased loss of joints and musculature of the leg due to a higher amputation level, the greater energy cost for the individual. The only variance of these results would be in that of younger individuals and individuals who are in good physical condition. Torburn, Powers, Guiterrez, and Perry (1995) [27] discussed the significance of physical fitness for amputees and importance of maintaining a healthy fitness level in order to retain a normal walking speed while having an increase O2 rate. Fitness is something that may go unnoticed by some amputees, although it can greatly benefit walking and functional level of individuals with an amputation.

Bilateral amputees seem to be at an increased risk for higher energy expenditure when examining information about unilateral amputees, although there are few studies that have been completed analyzing this patient population. A unilateral amputee can often utilize their sound side to compensate for their loss of limb, but bilateral patients will not be able to do so. However, the limited studies show that bilateral lower extremity amputee expend more effort that unilateral amputees (Waters & Mulroy, 1999) [29]. From the limited research, there are many parallels between amputees with unilateral amputations in correlation to amputation level. This means a bilateral amputee with trans-tibial amputations will expend less energy than a bilateral transfemoral amputee.

The type of amputation may also play an important role. Traumatic versus vascular amputations seem to be a key factor in how the patient heals and continues on as they begin to ambulate. A study performed by Gonzalez (1974) [9] discussed that 24-35% of patients that experience an amputation due to diabetes will lose the contralateral limb within three years. This makes it quite important to ensure the patient preserve the knee joint if possible. If a trans-tibial amputee were to undergo another trans-tibial amputation, now becoming a bilateral amputee, this individual would still expend less energy than a patient with a unilateral transfemoral amputation (Gonzalez, 1974) [9]. A younger, physically fit individual does not have the same amount of troubles regarding ambulation and energy expenditure when compared to a vascular amputate. The aerobic capacity and muscle strength greatly play a factor in O2 cost, thus vascular patients often have more difficulties ambulating, especially with high amputation levels. It is important to maintain length of the residual limb in vascular patients so that further revision is not necessary; possibly leading to an increase energy expenditure and possibility of being non-ambulatory.

Residual limb length is another aspect that has been explored by researchers, however, much like bilateral amputation studies, significant results that have been found. Studies performed by Gonzalez (1974) [9] and Waters, Perry, and Chambers (1989) [30] found no significant differences among amputees at varying lengths in speed or energy expenditure, and of O2 uptake or O2 cost. Interesting, as many believe that a longer residual limb may be more beneficial, frequently due to short residual limbs being unstable at the knee. This instability may attribute to increased energy costs, although it is not supported within the literature. A residual limb that is as short as nine centimeters can produce acceptable performance in comparison to knee disarticulation and transfemoral amputees (Waters & Mulroy, 1999) [29]. Table 1 summarizes the characteristics of the studies discussed.

Table 1: Characteristics of Studies

Study	Problem Statement	Participant Description	Instrument	Procedure and Design	Finding
Curtze *et al.*, (2009) [1]	Estimate effective biomechanical implications for prosthetic gait	N/A; simulated for a hypothetical subject with a body mass of 70 kg and a body height of 1.80 m	Inverted pendulum apparatus; various shoes and 7 prosthetic feet	The experimenter applies a horizontal force to the top weight necessary for an angular velocity of 710 deg/s, making the foot roll over from heel to toe and back. The measurement range was 151 to 201 with respect to the absolute vertical, corresponding to heel-contact and toe-off. The testing procedure was repeated three times for each foot–shoe combinations.	Available prosthetic feet have widely different biomechanical properties, including strongly distinct roll-over shapes. Shoes modulate these roll-over shapes slightly, but most likely functionally significantly
Donn, Porter, & Roberts, (1989) [2]	Effect of shoe mass on gait patterns of unilateral BK amputees	10 unilateral BK amputees (9 male, 1 female)	VICON 3-D gait analysis system; orthopedic shoes; plasticine	Mass of current shoe is recorded; Drushoes were issued and plasticine was added to front of shoe and data was recorded each time	Choice of mass can significantly improve some symmetry aspects of walking; prosthetic foot mass should be taken into consideration
Van Jaarsveld *et al.*, (1990) [28]	Measure differences of foot stiffness and hysteresis	9 different prosthetic feet	3-D stiffness measuring device	Foot is placed through 66 positions in device; vertical and horizontal force is registered at each	Substantial differences in stiffness between different prosthetic feet exist
Hansen, (2008) [10]	Examine if alignment of prosthetic foot changes roll-over shape	Prosthetic Feet: Kingsley Solid Ankle Cushioned Heel & Freedom Innovations Highlader	Advanced Mechanical Technology force platform; Motion Analysis Corporation measurement system	9 alignment conditions were used for each foot and roll-over shapes and measurements were recorded	If alignment were based on scientific principles instead of heuristics, it would eliminate the need for alignment hardware, as well as some of the length and stress throughout the fitting process
Torburn *et al*. (1995) [27]	Compare energy expenditure of 5 prosthetic feet during level walking	17 male unilateral BK amputees (10 traumatic; 7 dysvascular)	Douglas Bag Technique, 20 min walk test (outdoor track); 5 prosthetic feet (1 SACH, 4 DER)	Patients walked on outdoor track with each of the prosthetic feet; data was recorded;	DER prosthetic feet did not reduce energy expenditure; Similar O2 costs between patient populations
Geil, (2001) [8]	Provide measurement of material and structural properties for a broad sample of prosthetic feet	11 prosthetic feet	Instron 8521 Biaxial Servohydraulic Material Testing System; Instron Series IX software	Each foot was individually placed in fixture; energy and hysteresis data were recorded	Each foot lost energy during loading and unloading; Each foot also fell into one of four general levels of stiffness
Hansen, Meier, Sessoms, & Childress, (2006) [12]	Examine the effect of arc length on gait	14 unilateral transtibial prosthetic users	Shape&Roll prosthetic foot; AMTI force platforms; Motion analysis system	Shape&Roll feet were placed on existing sockets; Long, medium, and short arc lengths were used while patient ambulated and data was recorded at self-selected, slow-selected, and fast-selected walking speed	Short arc reduced max external DF moment; Arc length affected initial loading on sound limb at normal and fast speeds; Drop-off affect may be present on prosthetic feet with short roll-over shape arc lengths
Hansen *et al*. (2003)	Understanding the goal of the alignment process could lead	7 unilateral transtibial	4 different prosthetic feet; Motion analysis	Proper alignment was achieved then walking trials	Goal of alignment is to match the prosthetic

[10]	to new methods that allow alignment to be built into prostheses without the iterative process currently used. This understanding could eliminate the need for expensive and heavy alignment hardware, which could be especially beneficial in low-income countries and for construction of lightweight lower-limb prostheses for elderly people	amputees	system	began; data from the walking trials were used to create roll-over shapes during walking for the prostheses in their various alignments	foot's roll-over shape, as closely as possible, with an "ideal" shape
Hunter *et al*. (1995) [14]	Compare the energy expenditure of healthy below-knee amputee volunteers with healthy able-bodied volunteers during harness-supported treadmill ambulation in order to determine if energy conservation is achieved	7 transtibial amputees; 10 able-bodied	ZUNI Incremental Weight bearing System; calibrated motorized treadmill; telemetry system; Parkinson-Cowendry gas meter; open circuit spirometry techniques	Subjects performed 6 trials at 0.67 m/sec at 5 min. each; 20%, 40%, and full-body weight were used; after completion of six trials, max VO2 test was performed	Justification for physical therapists to utilize harness-supported treadmill ambulation with amputees when energy expenditure savings would be advantageous.

Researched Topics

Research studies have been found determining surgical procedures carried out as well as componentry benefits of the patients. At times, there were limited options in regards to the type of surgery that could be performed as trauma or vascular issue left the surgeon with no choice. This is the case for many instances for amputees, however, when possible, it is important to consider the results of research. Various studies have been completed in relation to alignment, pace, limb length, prosthesis type/design, and many more in comparison to energy expenditure. The one area needing additional research is the correlation between prosthetic foot stiffness and energy expenditure.

Completed Research

Limited research analyzing the correlation between prosthetic foot stiffness and energy expenditure contributing to a practitioners' decisions in type of prosthetic feet have been found. The literature review found nine relevant studies that had been performed addressing the correlation between prosthetic foot stiffness and energy expenditure. Each of the studies were performed differently with varying results; displaying important aspects in which the practitioners, physical therapists, and other healthcare professionals took into consideration.

One of the common themes from the available research was the benefit of a less stiff prosthetic foot. Fey, Klute, & Neptune (2011; 2012; 2013) [4, 5, 6], along with Major, Twiste, Kenney, and Howard (2014) [19] all found that decreasing at least some aspect of prosthetic foot stiffness can be beneficial to the patient's metabolic cost. Major *et al*. (2014) [19] found that lower dorsiflexion stiffness reduced the ground reaction force throughout prosthetic stance and it also reduced net metabolic cost. However, Zelik *et al*. (2011) [32] determined that intermediate foot stiffness was most beneficial for low energy expenditure. This study found the softest spring might lead to excessive heel displacement during ambulation. Hsu, Nielsen, Lin-Chan, and Shurr (2006) [13] discovered that there was aspects of energy-storing feet that improved gait performance to include reduced metabolic cost. A study done by Klodd, Hansen, Fatone, and Edwards (2010) [16] found no significant differences between prosthetic foot stiffnesses. Relevant research completed is outlined in Table 2.

Table 2. Characteristics of Studies (Prosthetic Foot Stiffness and Energy Expenditure)

Characteristics of Studies					
Study	**Problem Statement**	**Participant Description**	**Instrument(s)**	**Procedure and Design**	**Finding**
Major *et al*. (2014) [19]	Relationship between rotational stiffness properties & gait performance	5 males: mean (SD): 48 years	Treadmill, Custom-built Foot-Ankle Mechanism, Calorimetry device	3 visits to lab, walking trials on multiple speed/grade treadmill	Lower DF stiffness resulted in reduced net metabolic cost
Fey, Klute, & Neptune, (2013) [6]	Identify the influence of prosthetic foot stiffness on muscle & foot function	Dynamic Simulations	SIMM/Dynamics Pipeline	Simulations were used to run through a series of tests; "amputee" walked with nominal, compliant, and stiff feet	Decreased stiffness provided increased support and braking, absorbed less power from the leg which several muscle compensation-s were necessary; appropriate foot stiffness is important and can substantially influence gait performance
Fey, Klute, & Neptune, (2012) [5]	Identify optimal foot stiffness that minimizes metabolic cost and intact knee joint loading	Amputee (Left BK) planar bipedal musculoskeletal model	SIMM/Dynamics Pipeline	Simulations were used to run through a series of tests; "amputee" walked with a series of different foot stiffnesses based on current prosthetic feet	Altering foot stiffness by stiffening toe and midfoot while making the ankle and heel less stiff improved ESAR foot performance by offloading the intact knee and reducing metabolic cost
Selles *et al*., (1999) [23]	Introduce the theoretical models used in literature that describe the relation between prosthetic inertial loading and amputee	Studies selected from Medline and from examining references in the	Studies included theoretical models that were used in the present literature to predict the effects of prosthetic mass and mass	The design and methodologic quality was assessed using a checklist of nine criteria. Data on economy, self-	Predictions of the theoretical models suggest that inertial loading of the present lightweight prostheses need not be decreased and sometimes

	gait and to derive specific predictions from these models; to systematically review experimental studies on the relation between prosthetic inertial loading and energetics and kinematics of lower-limb prosthetic gait; and to compare the review outcomes with predictions derived from theoretical models,	selected Medline publications	distribution on kinematics and energetics of prosthetic gait & experimental studies were selected that investigated the effects of prosthetic mass or center of mass location on the economy, self-selected walking speed, stride length, or stride frequency of lower limb amputee patients.	selected walking speed, stride frequency, and stride length were extracted from the studies selected.	may need to be increased to improve the gait of amputee patients. The methodologic quality of most of the experimental studies was limited. Review of the experimental studies suggests that the inertial loading of the present lightweight prostheses need not be further reduced. The discrepancy between theoretical models and experimental findings may be related to both the poor methodologic quality of the experiments as well as to the limited predictive value of the existing models.
Postema *et al.*, (1997)	Obtain a better understanding related to user benefits of energy storing and release behavior of some prosthetic feet	10 transtibial amputees	4 prosthetic feet; VICON motion analysis system; special test device to measure hysteresis; AMASS software for kinematic data	Double blind randomized trial; every time a new foot was supplied, 2-week period was provided and then measurements were carried out	Energy storage and release of the prosthetic foot seem only to be important when the gain in net absorption is much larger than for the energy storing feet in this study
Hsu *et al.*, (2006)	Investigate the difference during treadmill walking and physical activity profiles for three prosthetic feet	8 male unilateral transtibial amputees	Three prosthetic feet; Yamax Digiwalker pedometer; treadmill (not specified); MedGraphics CardiO2 cart	Repeated measure design with three prostheses; each time the subject returned a single prosthesis was tested	Energy storing-releasing feet appeared to have certain trends of improved gait performance compared with the SACH foot
Fey, Klute, & Neptune, (2011) [4]	Identify the influence of foot stiffness on kinematic, kinetics, muscle activity, prosthetic energy storage and return, and mechanical efficiency during amputee walking	12 unilateral below-knee amputees	10-meter walkway with embedded force plates; TeleMyo 900 EMG surface electrodes; Visual3D (for kinematic data)	Subjects walked overground at 1.2 m/s with three prosthetic feet of varying keel and heel stiffness levels	Decreasing foot stiffness can increase prosthesis ROM, mid-stance energy storage, and late-stance energy return
Klodd *et al.*, (2010) [16]	Determine the effects of prosthetic foot forefoot flexibility on oxygen cost and subjective preference rankings of 13 unilateral transtibial prosthesis users	13 unilateral transtibial amputees	5 experimental feet; COSMED K4b2 portable spirometer; cuts were determined by a custom MATLAB program	Participants walked at the same comfortable, freely selected speed on the treadmill for 7 min with each foot while energy expenditure was measured	No significant difference was found in oxygen cost (mL O_2/kg/m) between the different feet, and the order of use was also not significant. However, the preference ranking was significantly affected by the flexibility of the feet, with the most flexible foot (F1) ranking significantly poorer. Users may prefer prosthetic feet that match the flexibility of an intact ankle-foot system, even though we did not detect an energetic benefit at freely selected speeds.
Zelik *et al.*, (2011) [32]	Systematically study the effect of prosthetic foot mechanics on gait, to gain insight into fundamental prosthetic design principles	5 unilateral transtibial amputees; 11 non-amputees	CESR foot (3 stiffness levels), simulator boots	All subjects walked with 3 different springs, Amputee subjects walked at 1.14 m/s and Non-Amputees at 1.25 m/s to approximate typical self-selected walking speeds. We measured ground reaction forces, full-body kinematics, and oxygen consumption and carbon dioxide production. These tests were conducted on the three springs, applied in random order	Softer springs led to greater energy storage, energy return and prosthetic limb COM push-off work. But metabolic energy expenditure was lowest with a spring of intermediate stiffness, suggesting biomechanical disadvantages to the softest spring despite its greater push-off. Disadvantages of the softest spring may include excessive heel displacements and COM collision losses

Results and Discussion

With the vast amount of prosthetic feet available, it is important for prosthetists to understand how their patients react to the variations in each foot. Energy expenditure is a high priority for amputees, as the patient requires doing more work in order to ambulate and performance of activities of daily living. Researchers have completed a multitude of research studies to find whether there are certain aspects of a prosthesis that can aid in reducing the energy expended by amputees upon ambulation. There is limited research combining the two topics, in addition, extensive research has not been performed regarding the effects of prosthetic foot stiffness on energy expenditure on unilateral below-knee amputees. The current literature outlines stiffnesses and hysteresis of some common prosthetic feet, foot design and materials on physical activity, mass on metabolic cost, roll-over shape, and associated energy expenditure costs.

Available Research

Currently, available research is limited in terms of number of studies performed to include prosthetic foot stiffness and energy expenditure. This literature review found nine studies fitting the criteria. With this small number of studies performed to date, it is difficult to develop a firm understanding of what prosthetic foot stiffness provides the most benefits for amputees' energy expenditure and metabolic costs. Of the nine studies, there were mixed findings. Five of these found that some form of a softer stiffness benefitted energy expenditure, while there were others that found no significant differences. Overall, one could conclude that a softer stiffness has obvious benefits to the patients after reading the results of available studies.

Each study demonstrated a method of determining measurement of proper foot stiffness, resulting in various findings and or outcomes. A majority of the studies included actual patient models, although Selles *et al*. (1999) [23] was a systematic review of available literature. In addition, studies performed by Fey *et al*. (2012) [5] and Fey *et al*. (2013) [6] used biomechanical models instead of actual patient models. With only nine studies and mixed results, it was difficult to properly determine the proper stiffness.

Limitations of Available Research

The results were varied with the limited amount of studies found. Most would consider that performing the studies with actual amputees would be most beneficial, and though it is important to understand the amputee's results, it can be difficult to measure physiologic data due to variation in health issues. Traumatic amputees often vary from diabetic or vascular amputees in terms of overall health; possibly skewing results of studies, especially research which involves measuring metabolic cost and energy expenditure. The biomechanical models that were utilized in Fey *et al*. (2012, 2013) [5, 6] could be quite beneficial in future studies, possibly eliminating any variations that may occur on a patient to patient basis.

Studies involving prosthetic feet pose limitations, as a large number and variety of feet are currently available within the industry. There are a multitude of manufacturers that sell prosthetic feet and often times offering more than one foot. For example, Ottobock currently offers 49 prosthetic feet, each made of special materials affecting the stiffness of the foot. With numerous options from a variety of manufacturers, research can vary as not one foot is made the same. Zelik *et al*. (2011) [32] and Klodd *et al*. (2010) [16] both used experimental feet in their studies with varying stiffness. Though this can be useful in determining what stiffness levels offer the most benefits to energy expenditure, one would have to determine what available prosthetic foot is most similar to this experimental foot's stiffness level. A practitioner or other healthcare professional most likely would not have the time to complete this process. Even if the research were to determine an appropriate stiffness level benefiting energy expenditure, with the available options of prosthetic feet on the market, it would be difficult to identify the specific prosthetic foot for each individual patient.

Conclusions

Amputees will have their own health history, which can vary their metabolic costs upon ambulation. As previously alluded to, there can be considerable variance between a diabetic amputee and a traumatic amputee. Diabetic patients, in general, tend to be a little older and less active than a traumatic amputee. Thus, it is important to conserve as much energy as possible during ambulation. An amputee expends more energy than an able-bodied person due to loss of limb, and their remaining musculature is what is utilized to move their prosthesis during ambulation. Besides the patient's overall health and well-being, there are numerous factors that can affect energy expenditure. Age, use of an assistive device while ambulating, overall prosthetic fit, and user experience all combine to greatly affect the amputee during gait (Waters & Mulroy, 1999) [29].

Experience may be a larger factor effecting energy expenditure. New amputees take time to become accustomed to the use of a prosthesis. Often times, requiring physical therapy of some degree in order to retrain their gait mechanics. This is the time when minimizing energy expenditure seems most beneficial. Thus, the utilization of appropriate foot stiffness could benefit amputees if alternative ways were found to reduce energy expenditure throughout the beginning stages of rehabilitation.

As amputees progress and become accustomed to utilizing their prosthesis, they often will have an opinion as to what type of componentry they prefer. This can include sleeves, liners, and prosthetic feet, while some may prefer a stiffer or softer heel in their prosthetic foot. This preference may be a more important aspect than energy expenditure in the later stages of the amputee's use of their prosthesis. Comfort provides a sense of security for the individual. Each amputee is unique in regards to health history, experience, and preferences, making it difficult to decide on a specific prosthetic foot that is best for each amputee. As discussed, there are several factors that can affect energy expenditure, although if prosthetists and other healthcare professionals utilize appropriate knowledge on all aspects, amputees should be provided with the appropriate prosthetic foot stiffness.

Keeping Up with New Trends & Research

Technological advances have had a prominent effect on the field of prosthetics. The material science and development of new products have benefited amputees of all activity levels. Prosthetists and other healthcare professionals must stay current with the new and emerging products, trends and research available, allowing for proper componentry selection for each patient. It can be difficult to stay abreast with every single product, although it they have a basic understanding of the effects certain products have on amputees, the amputees will experience additional benefits. Research within aspect of prosthetics has progressively advanced in the recent years as researchers are trying to assist amputees with alternative ways of comfort, safety and mobility. Prosthetists and others need to utilize these studies to aid their patients.

Recommendations for Further Research

Currently, the research that has been completed involving the correlation between prosthetic foot stiffness and energy expenditure is limited. This literature review found nine studies fitting the criteria, and though the findings were helpful, additional research is needed to properly determine the appropriate foot stiffness for amputees. Current research is not consistent although this could be attributed to the various methods and approaches. Researching the how various manufacturers determine their own stiffness levels would be a start, as this would provide a basis for further research to be continued.

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