Clinical Biomechanics 29 (2014) 47–56

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Effect of alignment changes on socket reaction moments while walking in transtibial prostheses with energy storage and return feet

Toshiki Kobayashi [a,*], Adam K. Arabian [b], Michael S. Orendurff [a], Teri G. Rosenbaum-Chou [a], David A. Boone [a]

[a] Orthocare Innovations, Mountlake Terrace, WA, USA
[b] Department of Engineering and Computer Science, Seattle Pacific University, WA, USA

ARTICLE INFO

Article history:
Received 6 June 2013
Accepted 5 November 2013

Keywords:
Amputation
Direct measurement
Load
Malalignment
Kinetics

ABSTRACT

Background: Energy storage and return feet are designed for active amputees. However, little is known about the socket reaction moments in transtibial prostheses with energy storage and return feet. The aim of this study was to investigate the effect of alignment changes on the socket reaction moments during gait while using the energy storage and return feet.

Methods: A Smart Pyramid™ was used to measure the socket reaction moments in 10 subjects with transtibial prostheses while walking under 25 alignment conditions, including a nominal alignment (as defined by conventional clinical methods), as well as angle malalignments of 2°, 4° and 6° (flexion, extension, abduction, and adduction) and translation malalignments of 5 mm, 10 mm and 15 mm (anterior, posterior, lateral, and medial) referenced from the nominal alignment. The socket reaction moments of the nominal alignment were compared with each malalignment.

Findings: Both coronal and sagittal alignment changes demonstrated systematic effects on the socket reaction moments. In the sagittal plane, angle and translation alignment changes demonstrated significant differences ($P < 0.05$) in the minimum moment, the moment at 45% of stance and the maximum moment for some comparisons. In the coronal plane, angle and translation alignment changes demonstrated significant differences ($P < 0.05$) in the moment at 30% and 75% of stance for all comparisons.

Interpretation: The alignment may have systematic effects on the socket reaction moments in transtibial prostheses with energy storage and return feet. The socket reaction moments could potentially be a useful biomechanical parameter to evaluate the alignment of the transtibial prostheses.

1. Introduction

Energy storage and return (ESR) feet are designed for active amputees with prostheses. They have been claimed to assist push-off by releasing energy stored in the flexible keel during mid to late stance. The ratio between stored and returned energy (energy efficiency) depends on the design of the foot, and returned energy is inherently less than absorbed energy as some is lost due to inefficiency of the spring (Czerniecki et al., 1991; Ehara et al., 1993; Geil et al., 2000; Prince et al., 1998). A reduction in stiffness of the ESR foot results in an increase of mid-stance energy storage and late-stance energy return (Fey et al., 2011). How ESR feet may benefit amputees gait and better clinical care has been studied extensively (Gailey et al., 2012; van der Linde et al., 2004).

A variety of ESR feet are currently available in the market. Their characteristics are partly determined by their inherent features, such as the stiffness of the keel or the axis of rotation. However, detailed mechanical characteristics of each ESR foot is a proprietary to each manufacture. It is generally difficult to relate the results of biomechanical analyses of ESR feet to amputee's preference of the foot in the clinic (Hafner et al., 2002). A review paper showed that a number of studies compared the effects of ESR feet to SACH (solid ankle cushion heel) feet, but no robust evidence exists that ESR feet outperform SACH feet (van der Linde et al., 2004). Comparisons of SACH and ESR feet in transtibial prostheses did not demonstrate differences in various clinical assessment parameters, including metabolic cost (Torburn et al., 1995), amputees' preference of feet (Postema et al., 1997b), and temporal–spatial parameters of gait (Perry et al., 1997; Postema et al., 1997a). However, differences in ankle kinematics were reported (Postema et al., 1997a; Schmalz et al., 2002; Torburn et al., 1990).

The alignment of transtibial prostheses is the spatial relationship between the socket and foot. It is tuned by a prosthetist through bench, static and dynamic alignment procedures in the clinic (Ikeda et al., 2012). The effects of alignment changes on amputees have been investigated in gait symmetry (Andres and Stimmel, 1990; Chow et al., 2006; Hannah et al., 1984), socket-residual limb interface pressures or loadings on the limb while walking (Pinzur et al., 1995; Sanders et al., 1998; Seelen et al., 2003; Zhang et al., 1998), and balance or muscular activity while standing (Blumentritt et al., 1999; Isakov et al., 1994). It is anecdotally believed that the alignment is important

* Corresponding author at: Orthocare Innovations, 6405 218th St. SW, Suite 301 Mountlake Terrace, WA 98043-2180, USA.
E-mail addresses: tkobayashi@orthocareinnovations.com, toshiki42@gmail.com (T. Kobayashi).

0268-0033/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.clinbiomech.2013.11.005

Table 1
Demographic data of the subjects.

Subject	Gender	Age	Height (m)	Mass (kg)	Residual limb length (cm)	Years since amputation	Amputated side	Foot
1	Male	46	1.85	85	18	6	Left	Multiflex foot
2	Male	53	1.85	93	13	9	Left	Flex walk
3	Male	70	1.78	83	16	48	Left	Seattle light foot
4	Female	50	1.64	63	13	18	Right	Seattle voyager foot
5	Female	64	1.75	64	13	32	Right	Seattle carbon light foot
6	Male	45	1.83	101	14	20	Right	Cadence HP
7	Male	35	1.73	75	13	15	Left	Seattle catalyst foot
8	Female	49	1.65	112	14	9	Left	Century XXII AHHF
9	Female	35	1.63	62	16	12	Left	Renegade LP
10	Male	51	1.73	98	20	1	Right	Seattle light foot

to maximize the benefit from ESR feet. However, prosthetists have shown a large range of alignment variations as optimal (Zahedi et al., 1986) and amputees' perception of alignment might not be fully reliable (Boone et al., 2012).

Socket reaction moments are conceptually acting around the center of the socket to balance the rotating effect of ground reaction forces during gait (Kobayashi et al., 2013b). They represent the way a residual limb is loaded inside the socket. An external extension moment suggests more loading at proximal–anterior and distal–posterior aspects of the residual limb in the sagittal plane, while an external varus moment suggests more loading at proximal–medial and distal–lateral aspects of the residual limb (Boone et al., 2013). Previous studies demonstrated that socket reaction moments were systematically influenced by alignment changes in transtibial prostheses with SACH feet (Boone et al., 2013; Kobayashi et al., 2013b). A similar effect may be expected in transtibial prostheses with ESR feet.

ESR feet are commonly prescribed for amputees, however; little is known about the effect of alignment changes on the socket reaction moment in prostheses with ESR feet. Therefore, this warrants further work to build more evidence in prosthetic alignment. The aim of this study was to investigate the effect of systematic alignment changes on the socket reaction moments in transtibial prostheses with ESR feet. The hypothesis of the study was that alignment changes in prostheses with ESR feet would have significant effects ($P < 0.05$) on the socket reaction moments.

2. Methods

2.1. Subjects

Ten subjects (4 females/6 males) aged 50 (11) years old with transtibial prostheses were recruited from the community (Table 1). Their mean height was 1.74 (0.08) m and their mean body mass was 83.6 (17.5) kg. All subjects were users of ESR feet in their daily life. Nine subjects had an amputation because of trauma, while the other subject had an amputation due to peripheral vascular disease. The ESR feet worn by the subjects included Multiflex Foot (Endolite, Miamisburg, OH, USA), Flex Walk (Ossur, Foothill Ranch, CA, USA), Seattle Light Foot (Trulife, Poulsbo, WA, USA), Seattle Voyager Foot (Trulife, Poulsbo, WA, USA), Seattle Carbon Light Foot (Trulife, Poulsbo, WA, USA), Cadence HP (Trulife, Poulsbo, WA, USA), Seattle Catalyst Foot (Trulife, Poulsbo, WA, USA), Century XXII adjustable heel height foot (Century XXII Innovations, Jackson, MI, USA), and Renegade LP (Freedom Innovations, Irvine, CA, USA). This study was approved by the institutional review board governing the institution, and informed consent was obtained from each subject.

2.2. Instrument

Measurement of the socket reaction moments was conducted using an instrumented prosthetic pyramid adaptor: Smart Pyramid™

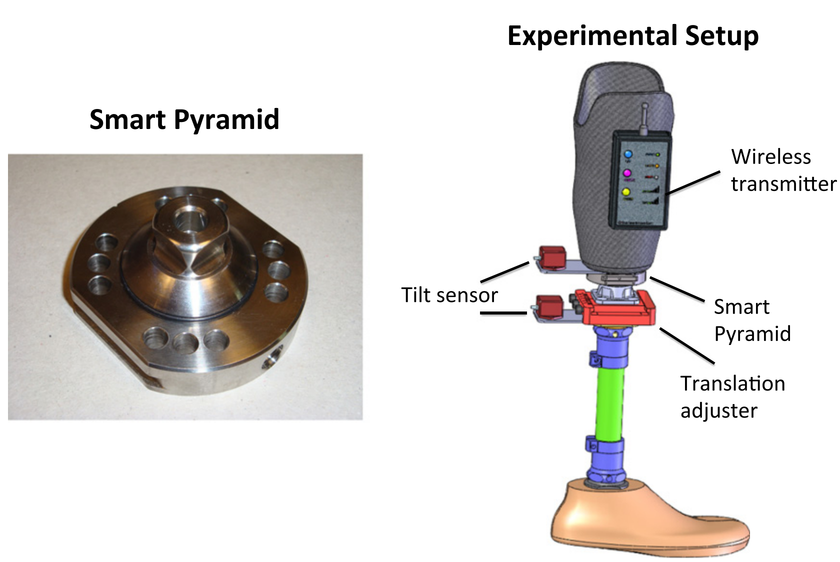

Fig. 1. Smart Pyramid™ and experimental setup.