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The influence of ankle-foot orthosis stiffness on walking performance in individuals with lower-limb impairments

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ABSTRACT

Background: Passive-dynamic ankle-foot orthoses utilize stiffness to improve gait performance through elastic energy storage and return. However, the influence of ankle-foot orthosis stiffness on gait performance has not been systematically investigated, largely due to the difficulty of manufacturing devices with precisely controlled stiffness levels. Additive manufacturing techniques such as selective laser sintering have been used to successfully manufacture ankle-foot orthoses with controlled stiffness levels. The purpose of this study was to use passive-dynamic ankle-foot orthoses manufactured with selective laser sintering to identify the influence of orthosis stiffness on walking performance in patients with lower-limb neuromuscular and musculoskeletal impairments.
Methods: Thirteen subjects with unilateral impairments were enrolled in this study. For each subject, one passive-dynamic ankle-foot orthosis with stiffness equivalent to the subject's clinically prescribed carbon fiber orthosis, one 20% more compliant and one 20% more stiff, were manufactured using selective laser sintering. Three-dimensional kinematic and kinetic data and electromyographic data were collected from each subject while they walked overground with each orthosis at their self-selected velocity and a controlled velocity.
Findings: As the orthosis stiffness decreased, ankle range of motion and medial gastrocnemius activity increased while the knee became more extended throughout stance. Minimal changes in other kinematic, kinetic and electromyographic quantities were observed.
Interpretation: Subjects effectively compensated for changes in ankle-foot orthosis stiffness with altered gastrocnemius activity, and the stiffness levels analyzed in this study had a minimal effect on overall walking performance.

1. Introduction

Ankle-foot orthoses (AFOs) are commonly prescribed to help improve gait in patients with various lower-limb neuromuscular and musculoskeletal impairments (Owens et al., 2011). AFOs can improve gait by mechanically compensating for weakness of the plantarflexor and dorsiflexor muscles, which have been shown to be important contributors to body support, forward propulsion and mediolateral balance in walking (Neptune et al., 2001; Liu et al., 2006; Pandy et al., 2010; Allen and Neptune, 2012). Passive-dynamic AFOs (PD-AFOs) are a category of AFOs that rely on design characteristics, such as stiffness, to improve gait performance through elastic energy storage and return (ESAR). Although several studies have demonstrated the beneficial effects of PD-AFOs on pathological gait compared to walking without an AFO (Danielsson and Sunnerhagen, 2004; Desloovere et al., 2006; Van Gestel et al., 2008; Patzkowski et al., 2012) or with more traditional AFOs (Desloovere et al., 2006; Bartonek et al., 2007; Van Gestel et al., 2008; Wolf et al., 2008; Patzkowski et al., 2012), few studies have examined the influence of PD-AFO stiffness characteristics on walking performance.

Two studies that have investigated the influence of AFO stiffness on walking performance found that stiffness can affect the energy cost of walking (Bregman et al., 2011) and influence joint kinematics (Kobayashi et al., 2011, 2013). In addition, recent studies that have varied the stiffness characteristics of ankle-foot prosthetic devices used by transtibial amputees, which function similarly to PD-AFOs by providing some level of body support and forward propulsion, found that as stiffness decreased the prosthesis contributed less to body support. The decreased stiffness of the prosthesis necessitated an increase in the activity of muscles that contribute to body support, specifically the vasti and rectus femoris (Fey et al., 2011; Ventura et al., 2011a,b), which resulted in increased knee extensor moments (Fey et al., 2011; Ventura et al., 2011b). These studies also showed that as stiffness decreased, the prosthesis' contribution to forward propulsion increased resulting in a decrease in the hamstring muscle activity which normally contributes to forward propulsion (Fey et al., 2011; Ventura et al., 2011a,b). Fey et al. (2011) also found that as stiffness decreased,

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Fig. 1. Clinically prescribed carbon fiber (CF) PD-AFO (Intrepid Dynamic Exoskeletal Orthosis (IDEO), Brooke Army Medical Center, San Antonio, TX, USA).

prosthesis energy storage in early and mid-stance and energy return in late stance increased. However, the designs of PD-AFOs and ankle-foot prostheses are fundamentally different, and no study has systematically investigated whether similar results exist when PD-AFO stiffness is varied.

Performing such studies can be challenging due to the difficulty of manufacturing custom AFOs with precisely controlled stiffness levels. Previous studies have modified stiffness through fluid mechanics (Yamamoto et al., 2005; Yokoyama et al., 2005; Kobayashi et al., 2011), springs (Yamamoto et al., 1999), elastic components (Bleyenheuft et al., 2008) and design features (Desloovere et al., 2006), but these techniques provided stiffness levels that were either difficult to precisely control or limited to discrete levels of resistance at the AFO hinge. An alternative approach is to use advanced additive manufacturing techniques such as selective laser sintering (SLS), which enable more precise control of design characteristics such as stiffness. SLS has recently been used to successfully manufacture PD-AFOs (Faustini et al., 2008; Schrank and Stanhope, 2011), traditional AFOs (Creylman et al., 2013), foot orthoses (Pallari et al., 2010; Salles and Gyi, 2013), prosthetic sockets (Faustini et al., 2006; Rogers et al., 2007, 2008), prosthetic feet (Fey et al., 2011) and prosthetic ankles (Ventura et al., 2011a,b).

Therefore, the overall goal of this study was to use SLS-manufactured PD-AFOs to identify the influence of PD-AFO stiffness on walking performance in individuals with lower-limb neuromuscular and musculoskeletal impairments. We hypothesize that as PD-AFO stiffness decreases: 1) sagittal plane ankle joint range of motion (RoM) and work will increase in the PD-AFO limb; 2) the PD-AFO's contribution to body support will decrease and corresponding knee joint extensor moments and work and the activity of muscles that contribute to body support will increase to compensate; and 3) the PD-AFO's contribution to forward propulsion will increase and hip joint extensor moments and work and the activity of muscles that contribute to forward propulsion will decrease to compensate. Through testing these hypotheses, this study will help guide the development of more effective PD-AFO designs and quantitative prescription criteria for subject-specific devices.

2. Methods

Subject-specific PD-AFOs with different stiffness levels were created using SLS. Each subject's clinically prescribed PD-AFO was a modular, carbon fiber (CF) design consisting of a footplate, tibial cuff and a connecting posterior strut (Intrepid Dynamic Exoskeletal Orthosis (IDEO), Brooke Army Medical Center, San Antonio, TX, USA; Fig. 1). The PD-AFO stiffness was modified by altering the geometry of the posterior strut. A SLS strut with stiffness equivalent to the CF strut was designed and manufactured for each patient as well as SLS struts that were 20% more compliant and 20% more stiff than the CF strut. This range was selected to represent typical modifications to the IDEO stiffness that can occur during the clinical prescription process. The stiffness of each SLS strut was verified post-build by performing a three-point-bend test and destructive testing to measure the maximum deflection and ultimate strength was also performed on duplicate struts to ensure their structural integrity. The struts were then evaluated on subjects through a comprehensive biomechanical gait assessment during overground walking to quantify the influence of PD-AFO stiffness on walking performance. From this point forward the PD-AFOs will be referred to as AFOs for brevity.

2.1. Subjects

Thirteen active military personnel with unilateral lower extremity injuries, consistent with those previously reported (Bedigrew et al., 2014), and resulting ankle muscle weakness participated in the study

Table 1
Characteristics for subjects with unilateral neuromuscular and musculoskeletal impairments due to various limb salvage procedures and resultant ankle muscle weakness. L indicates a left-side impairment and R indicates a right-side impairment.

	Mean	Std dev	Max	Min		# Male	# Female
Age (years)	29.4	5.8	40.0	21.0	Gender	13	0
Height (m)	1.80	0.08	1.95	1.64			
Body mass (kg)	88.2	10.8	113.6	75.5		# Right	# Left
Leg length (m)	1.01	0.07	1.14	0.91	Affected limb	6	7

	Subject												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Neuropathy	R					L			R				R
Paresis		R											
Tissue loss			R					R	R				
Fracture(s)				L	L	L	L			L	L	L	
Osteoarthritis				L									
Equinovarus									R				
Shrapnel											L		
Vascular injury											L		