Journal of Biomechanics 49 (2016) 2899–2908

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Stair ascent and descent biomechanical adaptations while using a custom ankle–foot orthosis ☆

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ARTICLE INFO

Article history:
Accepted 28 June 2016

Keywords:
Kinetics
Kinematics
Limb salvage
Limb preservation
Military
IDEO

ABSTRACT

The ability to navigate stairs step-over-step is an important functional outcome following severe lower leg injury and is difficult for many patients. Ankle–foot orthoses, such as the Intrepid Dynamic Exoskeletal Orthosis (IDEO), are often prescribed to improve function. This study compared stair climbing mechanics between IDEO users and able-bodied control participants. Thirteen IDEO users who sustained severe lower leg injury and 13 controls underwent biomechanical gait analysis. Participants ascended and descended a 16-step instrumented staircase without handrail use at a controlled cadence of 80 steps/min. Peak joint angles, moments, powers, and ground reaction forces, and integrated mechanical work were calculated. Independent *t*-tests with Bonferroni-Holm corrections were used to compare controls to IDEO and sound limbs. Reduced ankle range of motion on the IDEO limb resulted in compensatory strategies while ascending or descending stairs. During ascent, IDEO users had greater bilateral hip power during pull-up ($p < 0.007$) to compensate for the IDEO limb's reduced ankle dorsiflexion ($p < 0.001$) and knee extensor moment ($p = 0.001$) while it was leading, and reduced ankle plantarflexor power while it was trailing ($p < 0.001$). During stair descent, when the IDEO limb had was trailing, it had less ankle dorsiflexion during controlled lowering ($p < 0.001$), resulting in greater vertical ground reaction force ($p = 0.005$) and greater ankle and knee power absorption ($p < 0.001$). Reduced IDEO limb ankle power absorption during weight acceptance ($p < 0.001$) resulted in a large knee extensor moment ($p < 0.001$) on the trailing sound limb to lower the body. Despite gait deviations, IDEO users were able to climb stairs step-over-step unassisted.

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1. Introduction

Recent military conflicts have resulted in large numbers of traumatic musculoskeletal injuries to the lower extremities (Owens et al., 2008). Advancements in surgical techniques (Shawen et al., 2010) and rehabilitation (Castillo et al., 2008; Owens, 2010; Owens et al., 2011) have increased the number of individuals undergoing limb preservation procedures in lieu of amputation (Bedigrew et al., 2014). However, limb preservation often results in decreased function and persistent disability (Bosse et al., 2002; Doukas et al., 2013; MacKenzie and Bosse, 2006; MacKenzie et al., 2005). One important functional outcome following limb preservation is the ability to navigate stairs in a reciprocating, step-over-step manner (Kawamura et al., 1999), which is difficult, if not impossible, for many patients (Archer et al., 2006). In order to improve function, ankle–foot orthoses (AFOs) that provide external support to the injured limb (Esquenazi et al., 2009) are often prescribed to compensate for decreased muscle function and a decreased ability to load the limb following injury (Patzkowski et al., 2011; Patzkowski et al., 2012). However, limited research has investigated the effect that AFO use has on stair mechanics, especially in a population with traumatic musculoskeletal injury.

Stairs are commonly encountered in daily life and require greater lower extremity range of motion (ROM) and power (particularly at the ankle joint) than level ground walking (Andriacchi et al., 1980; Costigan et al., 2002; Nadeau et al., 2003; Rowe et al., 2000). Ankle dorsiflexion aids in toe clearance of the step and allows the tibia to progress over the foot during forward continuance in both stair ascent and descent. Toe clearance is also assisted by flexion at the knee and hip (McFadyen and Winter, 1988). Additionally, active ankle plantarflexion and power

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http://dx.doi.org/10.1016/j.jbiomech.2016.06.035
0021-9290/Published by Elsevier Ltd.

generation aid in trailing limb push-up during stair ascent (Wilken et al., 2011), and controlled ankle dorsiflexion and power absorption are critical during the weight acceptance phase of stair descent (McFadyen and Winter, 1988). When ankle ROM and power are limited by the use of an orthotic or prosthetic device, gait deviations are observed during stair ascent and descent (Aldridge et al., 2012; Alimusaj et al., 2009; Nahorniak et al., 1999; Radtka et al., 2006; Schmalz et al., 2007).

The use of a solid AFO that limits ankle motion in healthy adults reduces the leading limb knee extensor moment and power generation during the pull-up phase of stair ascent compared to not using an AFO (Radtka et al., 2006). This is similar to what has been observed in individuals with transtibial amputation (TTA) during stair ascent. Individuals with TTA compensate for the reduction in knee power by adopting a “hip strategy” characterized by greater bilateral hip flexion and power generation (Aldridge et al., 2012; Alimusaj et al., 2009). An increased reliance on the hip joint has not been observed with AFO use, but may be the result of reduced stair climbing cadence while using the AFO (Radtka et al., 2006). It has been suggested that compensations observed during stair ascent are either a function of reduced ankle dorsiflexion (Aldridge et al., 2012; Alimusaj et al., 2009) or reduced knee extensor strength of the leading limb during the pull-up phase (Sanderson and Martin, 1997). Dorsiflexion also plays a role in stair descent. Healthy individuals using a solid AFO and individuals with TTA tend to “fall” onto their uninjured limb because limited ankle dorsiflexion of the trailing limb during forward continuance does not allow for controlled lowering of the body to the next step (Alimusaj et al., 2009; Nahorniak et al., 1999; Radtka et al., 2006; Schmalz et al., 2007).

The Intrepid Dynamic Exoskeletal Orthosis (IDEO; Fig. 1), a novel semi-rigid AFO, was developed to improve functional outcomes of service members with traumatic, musculoskeletal, lower extremity injuries. The IDEO incorporates a footplate design that provides medio-lateral support, a posterior carbon strut that stores energy as it deforms under a load and releases stored energy when unloaded to provide trailing limb power at push-off, and a proximal cuff used to off-load the injured limb (Patzkowski et al., 2011). The IDEO allows for limited ankle dorsiflexion (Russell Esposito et al., 2014) and users are taught to contact the stair on the forefoot to allow for a greater tibial progression angle in lieu of ankle dorsiflexion, which may aid in stair climbing. Patzkowski et al. (2012) found that IDEO users performed better on a series of functional tests, including timed stair ascent, while wearing the IDEO compared to other commercially available AFOs. However, the biomechanics of individuals with lower extremity injury using a passive-dynamic orthotic device during stair ascent and descent are unknown and are an important consideration given that stairs are commonly encountered in daily living.

The purpose of this study was to compare lower extremity biomechanics during stair ascent and descent between healthy uninjured control subjects and IDEO users. Additionally, we sought to determine the relationship between factors that have been suggested to increase reliance on the hip joint, such as pre-positioning of the limb on the stair and knee extensor strength, and the generation of leading limb knee and hip power during the pull-up phase of stair ascent.

Fig. 1. The Intrepid Dynamic Exoskeletal Orthosis (IDEO) is a novel, semi-rigid ankle–foot orthosis that was developed to improve functional outcomes of service members with traumatic musculoskeletal lower extremity injuries. The IDEO is comprised of: (1) a proximal cuff that off-loads the injured limb, (2) a posterior carbon fiber strut that stores and returns energy, (3) a cushioned foam heel wedge that softens the impact and aids in placing the device in a toe down position, and (4) a foot plate that provides a lever to allow deformation of the posterior strut and provides control of frontal plane foot motion.

2. Methods

2.1. Participants

Thirteen male participants with unilateral traumatic lower extremity injuries that resulted in the use a custom ankle–foot orthosis (IDEO) participated in the study. All participants had been ambulating independently in their IDEO for at least three months (average 9.6 months) and were enrolled in an intensive physical therapy program (Owens et al., 2011). Individuals were excluded from participation in the study if they had a neurological, musculoskeletal, or other disease state on the uninjured limb that limited normal ambulation, or had ankle plantarflexion or dorsiflexion weakness that was the result of a spinal cord injury or central nervous system pathology. Additionally, data were obtained from 13 mass ($\pm$5%) and height ($\pm$5%) matched individuals without a lower extremity injury to serve as a control group (CONT) for biomechanical comparison (Table 1). The study was approved by the local institutional review board and all participants provided written informed consent.

2.2. Experimental set-up

The laboratory consisted of a 26 camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) sampling at 120 Hz and a 16-step instrumented staircase (Della Croce and Bonato, 2007; Sinitski et al., 2012) (1200 Hz, Advance Mechanical Technology, Inc., Watertown, MA). Each step had a rise of 18 cm and a run of 26.5 cm. IDEO users had been previously fit by a certified prosthetist/orthotist and the stiffness characteristics of the custom posterior carbon strut were determined by clinical expertise (based on the patient's available ROM, activity level, body mass, and load carriage requirements), and were not standardized across participants. Strut stiffness values included in the present study were based on the results of three-point bend testing and were, on average, 81.8 $\pm$ 18.5 kgf/mm with a range of 50.0–105.2 kgf/mm. Both the IDEO and CONT groups wore their