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Biomechanical response to ankle–foot orthosis stiffness during running☆

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ABSTRACT

Background: The Intrepid Dynamic Exoskeletal Orthosis (IDEO) is an ankle–foot orthosis developed to address the high rates of delayed amputation in the military. Its use has enabled many wounded Service Members to run again. During running, stiffness is thought to influence an orthosis' energy storage and return mechanical properties. This study examined the effect of orthosis stiffness on running biomechanics in patients with lower limb impairments who had undergone unilateral limb salvage.

Methods: Ten patients with lower limb impairments underwent gait analysis at a self-selected running velocity. 1. Nominal (clinically-prescribed), 2. Stiff (20% stiffer than nominal), and 3. Compliant (20% less stiff than nominal) ankle–foot orthosis stiffnesses were tested.

Findings: Ankle joint stiffness was greatest in the stiffest strut and lowest in the compliant strut, however ankle mechanical work remained unchanged. Speed, stride length, cycle time, joint angles, moments, powers, and ground reaction forces were not significantly different among stiffness conditions. Ankle joint kinematics and ankle, knee and hip kinetics were different between limbs. Ankle power, in particular, was lower in the injured limb.

Interpretation: Ankle–foot orthosis stiffness affected ankle joint stiffness but did not influence other biomechanical parameters of running in individuals with unilateral limb salvage. Foot strike asymmetries may have influenced the kinetics of running. Therefore, a range of stiffness may be clinically appropriate when prescribing ankle–foot orthoses for active individuals with limb salvage.

1. Introduction

The majority (54%) of combat-related injuries sustained during Operations Iraqi Freedom and Enduring Freedom involved the extremities (Owens et al., 2007, 2008). Orthopaedics has made marked advances in its ability to repair and rehabilitate severely-injured limbs (Castillo et al., 2008; Owens, 2010; Owens et al., 2011; Shawen et al., 2010) and, as a result, limb salvage, or reconstruction, has become a viable option for many individuals who would otherwise undergo amputation (Shawen et al., 2010). However, complete recovery and return to full function are not always possible due to factors such as instability, chronic pain, nerve injury and muscle loss (e.g. (Eiser et al., 2001; Grogan et al., 2011)).

Limited function in walking, running and other activities has been reported following limb salvage (Bosse et al., 2002; Doukas et al., 2013; MacKenzie et al., 2004). Although ambulation with minimal pain is generally considered a successful outcome, this level of function is often not regarded as adequate and leaves many patients unsatisfied. Reduced ankle function is typically associated with lower leg injuries requiring salvage, often requires compensations at more proximal joints (Lewis and Ferris, 2008; Nadeau et al., 1999), and can result in a mechanically inefficient gait (Collins and Kuo, 2010; Kuo, 2002) and elevated energy cost (Waters and Mulroy, 1999). Ankle–foot orthoses (AFOs) are frequently prescribed to help compensate for biological limitations and provide mechanical support during gait and other functional activities. This support counteracts joint torque and improves proprioception, which can lead to improved performance outcomes (Bedigrew et al., 2014; Greene and Hillman, 1990; Greene and Wight, 1990; Patzkowski et al., 2012; Wiley and Nigg, 1996), enhanced stability (Lehmann et al., 1987), and a lower risk of secondary injury (Surve et al., 1994). Overall, the desired outcome of using an AFO is to reduce the demands on the musculoskeletal system during locomotion (Ferris et al., 2006).

Most AFOs are passive devices and constitute a class of ankle braces that rely on design features, such as material properties, thickness and shape (Bartonek et al., 2007b; Major et al., 2004; Sumiya et al., 1996a, 1996b), and spring-like mechanisms (Yamamoto et al., 1999) to provide mechanical energy storage when initially deformed in mid stance and energy return in late stance (Bartonek et al., 2007a; Desloovere et al., 2006; Wolf et al., 2008). Until recently, AFOs were prescribed to individuals with limb salvage only to improve walking gait, since high-energy activities, such as running, were largely not possible.

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However, novel improvements in AFO design have resulted in notable performance benefits. To address the desire of the wounded service member with limb salvage to return to running and other high-energy activities, a custom carbon-fiber, passive-dynamic orthosis, the Intrepid Dynamic Exoskeletal Orthosis (IDEO), was developed to improve upon previous designs and facilitate the return to high-energy, performance-based tasks (Fig. 1) (Patzkowski et al., 2012). The IDEO, in combination with the Return to Run clinical pathway (Bedigrew et al., 2014; Owens, 2010; Owens et al., 2011), was designed to improve the physical performance and function of previously highly active individuals. Patzkowski et al. (2012) compared the IDEO to commercially available AFOs and found the greatest performance outcomes in the IDEO. Bedigrew et al. (2014) found that the IDEO made lasting improvements in pain, function and physical performance. The customizable nature of the IDEO allows certain features, such as its stiffness, to be tailored to meet the needs of the individual.

Optimizing the stiffness of supportive devices, such as AFOs, can alleviate certain gait-related problems (Bregman et al., 2010; Fey et al., 2012, 2013; Harlaar et al., 2010; Sumiya et al., 1996b). Stiffness determines the extent to which the AFO maintains the ankle in a neutral position, offers mediolateral stability, and assists in propulsion through energy storage and return mechanisms (Sumiya et al., 1996b). Variations in AFO stiffness about the ankle joint would likely affect biomechanical parameters of gait, such as the ankle plantar flexor moment and power at terminal stance, mechanical work dissipation and joint stiffness. In a forward dynamics simulation, Bregman et al. (2011) found that AFO stiffnesses corresponding to both the maximal energy storage and the maximal energy return were both relatively inefficient. Instead, optimal stiffness during walking was identified by lowest energy cost and corresponded to the greatest ankle plantar flexion velocity just prior to contralateral foot strike. At more superior joints, Russell Esposito et al. (2014) found that knee flexion decreased as the AFO became more compliant. Therefore, AFO stiffness may also influence the stiffness or compliancy of the lower extremity joints.

Joint stiffness plays a role not only in the neuromuscular control of movement, but also in performance and biomechanical risk factors for injury (Butler et al., 2003; Stefanyshyn and Nigg, 1998). Stiffness relates to the deformation of a body under an applied force and, therefore, some stiffness is important for performance and function but too much or too little may result in injury. The stiffness about one joint plays an important role in how the surrounding joints respond during motion. For example, the stiffness of the ankle joint is primarily responsible for whole leg stiffness during activities such as hopping in healthy subjects (Farley and Morgenroth, 1999). In pathological populations using AFOs, as the stiffness of the device increases, compliance is increased in other joints to maintain whole limb stiffness (Ferris et al., 2006).

Despite the availability of information on AFO stiffness during walking in pathological populations and hopping in healthy populations, limited work has investigated the effects of AFO stiffness during running. Because a passive-dynamic AFO undergoes greater mechanical deformation with the forces applied during running compared to walking, stiffness is expected to be a particularly important design characteristic for energy storage and return. There is a growing population of patients who have undergone limb salvage procedures and wish to return to these high impact activities, and the optimization of AFO design is an important consideration for regaining proper running mechanics. However, it is unknown how AFO stiffnesses would affect joint angles, moments, powers, mechanical work, and joint stiffness during running in this population. Therefore, the purpose of this study was to examine lower extremity running biomechanics in a population of injured service members wearing AFOs of different stiffness characteristics. We hypothesized that as AFO stiffness decreased 1) sagittal plane ankle joint range of motion and power generation would increase, and 2) ankle joint stiffness would decrease and mechanical work would increase. At the knee, we hypothesized that knee joint stiffness would increase with decreasing ankle joint stiffness. We also hypothesized that, compared to the unaffected limb, the AFO limb's 3) sagittal plane ankle joint range of motion and power generation would be lower and 4) ankle joint stiffness would be greater and mechanical work lower.

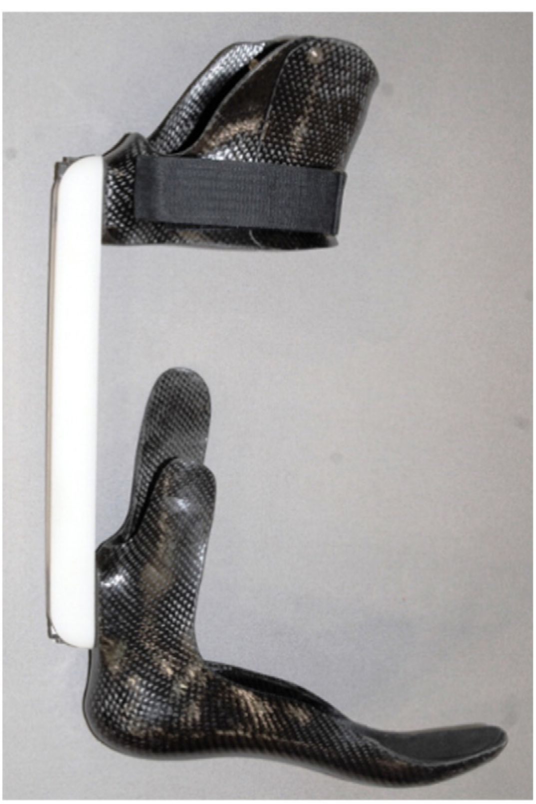

Fig. 1. Intrepid Dynamic Exoskeletal Orthosis (IDEO). This custom AFO was created and fit by the same orthotist for all limb salvage subjects. The IDEO comprises of a carbon fiber distal supramalleolar ankle–foot orthosis, a proximal tibial cuff, and a removable, connective, posterior-mounted strut. A foam heel wedge was often placed beneath the heel at the recommendation of the orthotist.

2. Methods

Ten male subjects with traumatic, unilateral lower limb salvage (Table 1) gave written informed consent to participate in the study (mean age 29.2 (4.6) years, height 1.80 (0.09) m, body mass 87.2 (11.6) kg). All subjects were frequent or constant users of the IDEO and the range of use time spanned from approximately 4 to 21 months. All subjects wore the IDEO for running activities and only those participants exhibiting a flight phase during running were included in the study. Participants were under the care of the same certified orthotist (RVB) and were involved in a running program under the care of the same physical therapist (JGO) (Owens et al., 2011). This program encouraged a midfoot strike pattern when running with the IDEO.

The IDEO is a custom, passive-dynamic AFO with mechanical properties designed to store energy as the ankle dorsiflexes during mid stance and return energy in the form of positive ankle power during terminal stance. The distal carbon fiber footplate and proximal tibial cuff are designed to be lightweight and to improve upon the mechanical properties of previous AFO materials (Bartonek et al., 2007a, 2007b; Desloovere et al., 2006; Wolf et al., 2008). A foam wedge is often placed underneath the carbon fiber heel to attenuate high frequency impacts and position the foot in a slight toe-down position to take advantage of the energy-storage-and-return mechanical properties of the IDEO. A posterior strut connects the footplate and