Journal of Biomechanics 46 (2013) 1907–1912

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

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

Persons with unilateral lower-limb amputation have altered and asymmetric trunk mechanical and neuromuscular behaviors estimated using multidirectional trunk perturbations

Brad D. Hendershot [a], Babak Bazrgari [b], Maury A. Nussbaum [a,c,*]

[a] Virginia Tech-Wake Forest School of Biomedical Engineering and Sciences, Virginia Tech, Blacksburg, VA 24061, USA
[b] Center for Biomedical Engineering, University of Kentucky, Lexington, KY 40506, USA
[c] Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA 24061, USA

ARTICLE INFO

Article history:
Accepted 20 April 2013

Keywords:
Lower extremity
Amputation
Trunk stiffness
Reflex
Position perturbation

ABSTRACT

Among persons with unilateral lower-limb amputation (LLA), proximal compensations and preferential use of the sound limb during gait and movement may lead to chronic alterations and/or asymmetries in trunk mechanical and neuromuscular behaviors. Trunk stiffness, the magnitude and timing of maximum reflex force, and EMG reflex delays of superficial trunk muscles, were estimated here using multi-directional (anteriorly- and laterally-directed) position-controlled horizontal trunk perturbations ($\pm$5 mm, applied at T8) with the pelvis immobilized. Alterations and asymmetries in these trunk behaviors were quantified and compared among eight males with unilateral LLA, and eight male non-amputation controls. During anteriorly-directed perturbations, trunk stiffness and maximum reflex force were 24% and 23% lower, respectively, among participants with LLA compared to non-amputation controls, and the timing of maximum reflex force was 8% later. During lateral perturbations, trunk stiffness and maximum reflex force were also significantly lower among participants with LLA, by 22% and 27%, respectively. Bilateral asymmetries were present in trunk stiffness and the timing of maximum reflex force among persons with LLA. Specifically, trunk stiffness was 20% lower and timing of maximum reflex force was 9% later during perturbations involving spinal tissues and muscles ipsilateral to the side of amputation. Reduced and asymmetric trunk mechanical and neuromuscular behaviors may suggest a condition of reduced trunk stability among individuals with LLA, which could be due to repeated exposure to altered and asymmetric gait and movement and/or compensatory muscle recruitment in response to lost or altered musculature subsequent to LLA.

1. Introduction

Low back pain (LBP) remains a prevalent and costly musculoskeletal disorder (Dagenais et al., 2008), and while causal links between biomechanical factors and LBP have been investigated, these factors may play a more important role in certain populations. For example, there is a considerably higher prevalence of LBP among persons with lower-limb amputation (LLA; 52–71%) versus the general population (6–33%; Ehde et al., 2001; Smith et al., 1999). Asymmetries exist in the kinetics and kinematics of gait and movement among persons with unilateral LLA (Sagawa et al., 2011), often indicating a favoring of the sound limb. Subsequent alterations in trunk (and pelvic) motion with LLA (Goujon-Pillet et al., 2008; Jaegers et al., 1995; Michaud et al., 2000) likely result in spinal loading patterns distinct from able-bodied individuals, due to changes in trunk inertial and gravitational demands on the trunk neuromuscular system to maintain control of equilibrium and stability of the spine. Repeated exposures to such alterations could chronically alter trunk motor control strategies and/or functional properties of the passive spine. Yet, despite the important role of trunk mechanical and neuromuscular behaviors (i.e., voluntary or reflexive muscle responses) in the development of LBP, it is unknown whether there are changes in these due to LLA and the subsequent repeated exposure to altered gait/movement mechanics and compensatory proximal muscle recruitment in response to lost or altered musculature.

Passive spinal tissues/structures and neuromuscular responses from surrounding trunk musculature play important roles in maintaining spinal stability (e.g., Moorhouse and Granata, 2007; Panjabi, 1992). Several alterations in these have been identified in patients with LBP, including increased passive trunk stiffness (Hodges et al., 2009), altered trunk muscle recruitment patterns (Radebold et al., 2000), and delayed/reduced reflex responses

* Correspondence to: Department of Industrial and Systems Engineering, Virginia Tech, 250 Durham Hall (0118), Blacksburg, VA 24061, USA. Tel.: +1 540 231 6053; fax: +1 540 231 3322.
E-mail address: nussbaum@vt.edu (M.A. Nussbaum).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.04.018

(Radebold et al., 2001), suggesting an association between altered trunk mechanical and neuromuscular behaviors and the occurrence of LBP. Similar disturbances in passive spinal tissues and trunk neuromuscular behaviors among healthy persons have also been found following acute exposure to mechanical loading and atypical postures that are prevalent in occupations with high LBP risk, further suggesting a causal role for altered trunk mechanical and neuromuscular behaviors in the development of LBP. For example, prolonged static or dynamic forward trunk flexion reduces passive support of the spine (McGill and Brown, 1992), causing mechanical/sensory deficits (Olson, 2011; Solomonow, 2012) and reduced reflex responses (Rogers and Granata, 2006). Preferential use of the sound limb in persons with LLA during gait alters kinematics of the trunk, thus likely exposing the spine and trunk neuromuscular system to repeated atypical mechanical loading and postures, and which over time could lead to similar alterations and/or asymmetries in trunk mechanical and neuromuscular responses.

Sudden-loading paradigms, using external perturbations, have been used to estimate trunk mechanical and neuromuscular responses (e.g., Brown and McGill, 2009; Gardner-Morse and Stokes, 2001). Trunk perturbations are frequently applied in the antero-posterior direction. Studies using multidirectional force perturbations (Gardner-Morse and Stokes, 2001; Masani et al., 2009; Stokes et al., 2006) have demonstrated that the overall trunk dynamic response depends on perturbation direction, though muscle responses were typically bilaterally symmetric among healthy individuals. However, due to the noted asymmetries with LLA, multidirectional perturbations are expected to provide a better understanding of how repeated exposures to asymmetric movement could affect the symmetry of trunk mechanical and neuromuscular behaviors among persons with LLA. The goal of the present work was therefore to use multi-directional trunk perturbations to investigate the effects of LLA on several aspects of trunk mechanical and neuromuscular behaviors. It was hypothesized that persons with LLA would present with different trunk mechanical and neuromuscular behaviors similar to those observed with LBP, specifically increased intrinsic trunk stiffness and delayed/reduced trunk reflex forces. It was further hypothesized that asymmetries in these behaviors will exist in persons with LLA, as a result of preferential use of the sound limb, reducing trunk mechanical and neuromuscular behaviors on the side of amputation.

2. Methods

2.1. Participants

Eight males with unilateral LLA – four transtibial (3 right leg, 1 left leg) and four transfemoral (2 right leg, 2 left leg) – and eight male, non-amputation controls completed the study. Members of the control group were recruited to match participants with LLA, at the individual level, in terms of age, stature, and body mass (within < 8 years, < 5 cm, and < 5 kg, respectively). Respective means (SD) for participants with LLA were 41.1 (18.7) years, 175.0 (5.0) cm, and 76.6 (10.2) kg, and corresponding values for the control group were 36.9 (13.4) years, 174.2 (3.8) cm, and 80.3 (11.4) kg; there were no significant differences between groups ($p \geq 0.5$ from unpaired *t* tests). Participants in the LLA group were 12.3 (10.1) years post amputation, and reasons for amputation included trauma (5), congenital deformity or abnormality (2), and cancer (1). Inclusion criteria for participants with LLA were consistent with previous biomechanical studies (Segal et al., 2011; Vrieling et al., 2008), and the same criteria (and participants) were used in a prior study (Hendershot and Nussbaum, in press). Briefly, these criteria included that participants must be adults with a unilateral above- or below-knee amputation (≥1 year post-amputation), wear their prosthesis on a daily basis, and be moderately active and capable of independent locomotion without the use of walking aids (e.g., crutches, walkers, canes). Potential participants (in both groups) were excluded if they had any recent history (6 months) of falls or any underlying musculoskeletal disorders (not including amputation) that may confound the results. In particular, none of the participants self-reported having LBP at the time of testing. Participants provided informed consent prior to data collection, and all experimental procedures were approved by the Virginia Tech Institutional Review Board. Participants with LLA wore their prosthetic device during all testing procedures.

2.2. Experimental design and procedures

Trunk mechanical and neuromuscular behaviors were compared between persons with and without unilateral LLA. Initially, participants performed standing maximum voluntary contractions (MVC) in trunk extension and left/right lateral bending, with the pelvis restrained. During MVCs, electromyographic (EMG) activities of the bilateral lumbar (L3) erector spinae (ES) and external oblique (EO) muscles were recorded using bipolar Ag/AgCl surface electrodes, and following existing electrode placement protocols (e.g., Granata and Wilson, 2001). Prior to applying electrodes, the skin was abraded and cleaned with alcohol, and inter-electrode impedance was maintained below 10 KΩ. Raw EMG signals were preamplified (× 100) near the collection site, bandpass filtered (10–500 Hz) and amplified in hardware (Measurement Systems Inc., Ann Arbor, MI, USA), and then sampled at 1000 Hz. Peak EMG-RMS values were identified for each muscle, and used subsequently for normalization.

Trunk mechanical and neuromuscular behaviors (see below) were then quantified using a sudden-perturbation paradigm (Bazrgari et al., 2011; Hendershot et al., 2011). Here, participants were exposed to sequences of horizontal trunk perturbations in each of three configurations (Fig. 1) that were completed in a random order. During perturbations, participants maintained a relaxed, upright posture in a rigid frame, and adjustable straps were used to restrain the pelvis and lower limbs. Each sequence consisted of 12 position perturbations (± 5 mm) generated by a servomotor (Kollmorgen AKM53K, Radford, VA, USA), and which were applied to the trunk (at T8) through a custom chest harness and rigid rod (Fig. 1). A perturbation sequence was completed in ~45 s, and each perturbation was completed within 40 ms. Pseudorandom delays were included between each perturbation to minimize anticipation of perturbation timing by participants and thereby reduce potentially confounding effects from variations in anticipatory muscle activation (Grondin and Potvin, 2009).

Postural displacements were measured with a laser displacement sensor (Keyence LK-G 150, Osaka, Japan) and servomotor encoder. The laser sensor was directed at the dorsal aspect of the trunk harness for anterior perturbations, and at a rigid plate attached to the side(s) of the harness during lateral perturbations. Applied loads were measured with a load cell in-line with the connecting rod (Interface SM2000, Scottsdale, AZ, USA). Load cell, motor encoder, and laser sensor

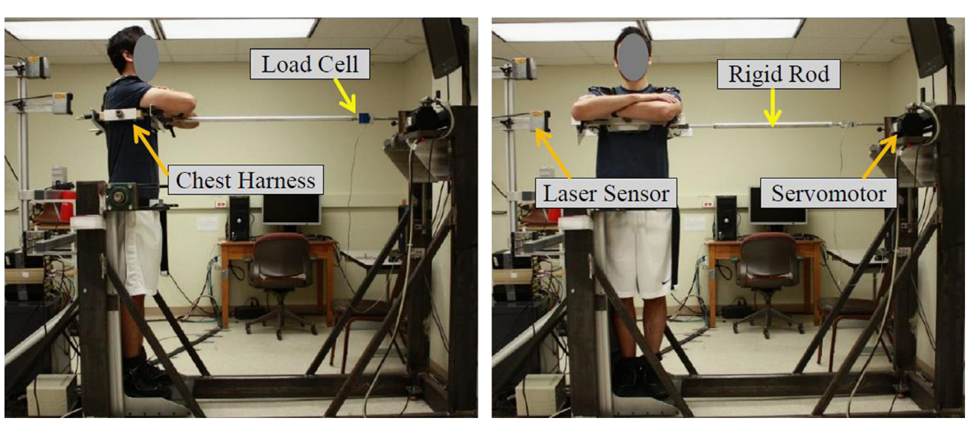

Fig. 1. Experimental set-up demonstrating a control participant in both ANT (left) and LEFT (right) configurations. Participants were turned 180° and reconnected to the motor for RIGHT perturbations. Participants' arms were similarly folded across the chest and rested on the harness for all three perturbation directions.