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# Three-dimensional joint reaction forces and moments at the low back during over-ground walking in persons with unilateral lower-extremity amputation

Brad D. Hendershot [a,b,*], Erik J. Wolf [a,c]

[a] Department of Rehabilitation, Walter Reed National Military Medical Center, Bethesda, MD 20889, USA
[b] Center for Rehabilitation Sciences Research, Department of Physical Medicine and Rehabilitation, Uniformed Services University of the Health Sciences, Bethesda, MD 20814, USA
[c] DOD — VA Extremity Trauma and Amputation Center of Excellence, Walter Reed National Military Medical Center, Bethesda, MD 20889, USA

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A B S T R A C T

*Background:* Abnormal mechanics of locomotion following lower-extremity amputation are associated with increases in trunk motion, which in turn may alter loads at the low back due to changes in inertial and gravitational demands on the spine and surrounding trunk musculature.

*Methods:* Over-ground gait data were retrospectively compiled from two groups walking at similar self-selected speeds (~1.35 m/s): 40 males with unilateral lower-extremity amputation (20 transtibial, 20 transfemoral) and 20 able-bodied male controls. Three-dimensional joint reaction forces and moments at the low back (L5/S1 spinal level) were calculated using top-down and bottom-up approaches. Peak values and the timings of these were determined and compared between and within (bilaterally) groups, and secondarily between approaches.

*Findings:* Peak laterally-directed joint reaction forces and lateral bend moments increased with increasing level of amputation, and were respectively 83% and 41% larger in prosthetic vs. intact stance among persons with transfemoral amputation. Peak anteriorly-directed reaction forces and extension moments were 31% and 55% larger, respectively, among persons with transtibial amputation compared to controls. Peak vertical reaction forces and axial twist moments were similar between and within groups. Peak joint reaction forces and moments were larger (3–14%), and the respective timing of these sooner (11–62 ms), from the bottom-up vs. top-down approach.

*Interpretation:* Increased and asymmetric peak reaction forces and moments at the low back among persons with unilateral lower-extremity amputation, particularly in the frontal plane, suggest potential mechanistic pathways through which repeated exposure to altered trunk motion and spinal loading may contribute to low-back injury risk among persons with lower-extremity amputation.



## 1. Introduction

Altered and asymmetric gait and movement are common among persons with lower-extremity amputation (LEA; Sagawa et al., 2011). Such changes in the mechanics of locomotion have been associated with the development of secondary physical conditions and pain (Gailey et al., 2008). Low back pain (LBP), in particular, represents a frequent and debilitating impairment in this population that can often limit physical performance and reduce quality of life (Ehde et al., 2001; Taghipour et al., 2009). Moreover, recent and projected increases in the number of persons with LEA, resulting from traumatic injuries sustained during times of war (Reiber et al., 2010) and complications of vascular disease (Ziegler-Graham et al., 2008), further highlight the importance of understanding the underlying mechanisms linking LEA and LBP; yet, such mechanisms are still unclear. Though most LBP remains idiopathic, physical (biomechanical) risk factors appear to play a more important role in this population.

Increased spinal loads have been identified as an important proximate cause of LBP (Kumar, 2001; McGill, 2007). Mechanical loads among tissues in/surrounding the spine are influenced by forces arising from gravity, inertia, and externally applied loads, as well as internal forces produced by ligaments and muscle contractions. Of particular interest here, the trunk (+ head and arms) accounts for nearly two thirds of total body mass (Winter, 1990), and as such even small displacements of the trunk center of mass can substantially alter muscular demands and joint reaction loads throughout the body (Gillet et al., 2003). For persons with unilateral LEA, increased and asymmetric trunk movements during locomotion have been observed (Cappozzo et al., 1982; Goujon-Pillet et al., 2008; Jaegers et al., 1995; Michaud et al., 2000; Tura et al., 2010), and which have been suggested to result from a neuromuscular/movement strategy that uses trunk weight/inertia to assist with forward progression and/or stabilizing the body.

* Corresponding author at: Walter Reed National Military Medical Center, America Building No. 19, Room B322, 8901 Wisconsin Ave, Bethesda, MD 20889, USA.
*E-mail address:* bradford.d.hendershot.ctr@health.mil (B.D. Hendershot).

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Hence, altered trunk motions during gait among persons with LEA may result in spinal loading patterns distinct from able-bodied individuals, due to changes in the inertial and gravitational demands on the spine and surrounding trunk musculature. Despite the aforementioned alterations in trunk kinematics with LEA, there exists only limited preliminary work indicating altered spinal loads during gait in persons with LEA (Cappozzo and Gazzani, 1983).

Linked-segment models are a common non-invasive method for estimating reactive joint loads during movement (e.g., Kingma et al., 2001; MacKinnon and Winter, 1993). In able-bodied individuals, these models have been used to quantify net reaction forces and moments at the low back during occupational tasks, such as lifting (Kingma et al., 1996; Plamondon et al., 1996), as well as during walking and running (Callaghan et al., 1999; Cappozzo, 1983; Khoo et al., 1995; Seay et al., 2008). These models and analyses typically originate either at the head and work down (i.e., top-down approach), or from the feet and work up (i.e., bottom-up approach). Despite inherent limitations of linked-segment models (Winter, 1990), and specific criticisms for the application of top-down and bottom-up approaches to locomotion (Callaghan et al., 1999; Riemer et al., 2008; Seay et al., 2008), these models have been extensively validated for *estimating* forces and net moments acting at the low back during a variety of tasks (Iino and Kojima, 2012; Kingma et al., 1996; Kingma et al., 2001). The primary goal of this study was to investigate triaxial joint reaction forces and moments at the low back (L5/S1 spinal level) in persons with unilateral LEA during over-ground walking. We hypothesized that persons with LEA would have increased and asymmetric lumbosacral joint loads compared to uninjured controls, due to changes in the gravitational and inertial contributions resulting from increased trunk motion. We further hypothesized that these changes would be larger for persons with transfemoral vs. transtibial amputation, as larger trunk motions are generally associated with a higher level of amputation. As a secondary goal, we also explored differences in the approach (bottom-up vs. top-down) used to calculate L5/S1 reaction forces and moments in this population.

## 2. Methods

### 2.1. Participants

Data were retrospectively compiled and analyzed from 40 males with unilateral LEA – 20 transtibial (TTA) and 20 transfemoral (TFA) – and 20 male able-bodied controls (CTRL) that had previously completed gait evaluations (Table 1). All amputations were a result of traumatic injuries, and the mean (SD) duration since amputation was 2.6 (1.3) years. Inclusion criteria for the participants with LEA included: (1) unilateral transtibial or transfemoral amputation with no contralateral functional impairments, (2) regular (daily) use of a prosthetic device (≥1 year post-amputation), (3) independent ambulation without the use of an upper-extremity assistive device (e.g., cane, crutches, walker), and (4) having no other underlying musculoskeletal or neurologic conditions (excluding amputation) that may affect gait or balance. Also, participants (in all groups) were only included if their self-selected walking velocity was between 1.25 and 1.40 m/s, as walking speed influences kinetic and kinematic biomechanical measures (Cheng et al., 1998). These retrospective analyses were approved by the local Institutional Review Board.

**Table 1**
Mean (SD) participant characteristics for the control ("CTRL"), transtibial ("TTA"), and transfemoral ("TFA") groups. Time since amputation ("Time") is also indicated.

| | CTRL ($n = 20$) | TTA ($n = 20$) | TFA ($n = 20$) |
|---|---|---|---|
| Age (year) | 28.1 (4.8) | 27.7 (6.5) | 29.2 (6.7) |
| Stature (cm) | 181.0 (6.1) | 180.4 (5.0) | 176.2 (6.7) |
| Body mass (kg) | 83.9 (8.6) | 87.2 (13.3) | 80.6 (12.2) |
| Time (year) | – | 1.8 (1.5) | 3.1 (1.4) |

### 2.2. Experimental Procedures

Participants walked at their self-selected velocity across a 15 m level walkway. During walking trials, full-body kinematics were tracked (120 Hz) via retro-reflective markers using a 23-camera motion capture system (Vicon, MX F40, Oxford, UK). Markers were placed in the mid-sagittal plane over the sacrum (S1), T10, and C7 spinous processes, sternal notch, and xiphoid; and bilaterally over the acromion, ASIS, PSIS, and lower extremities (modified Cleveland Clinic marker set). Ground reaction forces were sampled (1200 Hz) from four force platforms (AMTI, OR6-7-2000, Watertown, MA, USA) centrally located and embedded in the walkway. Raw marker and force platform data were low-pass filtered using a fourth-order, bidirectional, Butterworth filter with a 6 Hz and 50 Hz cutoff frequency, respectively.

### 2.3. Dependent measures and analyses

Joint reaction forces and moments at the low back (L5/S1) were estimated using a three-dimensional linked-segment model in Visual3D (C-Motion Inc., Germantown, MD, USA), which included fifteen segments defined by the markers: bilateral feet, shanks, and thighs; a pelvis; a trunk; bilateral upper arms, lower arms, and hands; and a head. The trunk was considered a single rigid segment, defined proximally by the acromia, C7, and sternal notch, and attached distally to the pelvis at the lumbosacral (L5/S1) joint (cf., Kingma et al., 1996). The location of the L5/S1 joint was estimated using the bony pelvis landmarks (ASIS, PSIS, and S1) and scaled to pelvis width (right ASIS to left ASIS; Reed et al., 1999). Segment inertial and anthropometric properties were calculated according to the regression equations of Hanavan and Dempster, respectively, and the residual limbs/prostheses were modeled using parameters identical to participants' intact segments. Three-dimensional trunk kinematics (and angular velocities/accelerations; Kinzel et al., 1972) were calculated, relative to the pelvis, using an X–Y–Z (sagittal–coronal–transverse) rotation sequence.

Two modeling approaches were then used to estimate reaction forces and moments at the L5/S1 joint: 1) a bottom-up approach, commencing at the feet and working up, and 2) a top-down approach, commencing at the head (arms) and working down. In both approaches, the analyses finished at the L5/S1 joint. For the bottom-up approach, ground reaction forces from both lower extremities were required as inputs into the model. Thus, data from multiple walking trials were identified which contained 5 "clean" strides; clean strides were defined by *both* the right and left foot remaining completely inside the boundary of two consecutive force platforms during successive initial contacts of the same foot. Although ground reaction forces are not required for the top-down model, the same five "clean" strides were used in subsequent analyses for both approaches. No verbal instructions were initially given that would indicate consecutive clean foot strikes were required, as these would likely influence gait. To resolve the kinetics at the low back in a more clinically relevant reference frame, an anatomical coordinate system was defined by aligning the pelvis with a marker projected directly below the L5/S1 joint at the mean height of the two hip joint centers (cf. Seay et al., 2008). Net lumbosacral forces and moments were resolved with respect to the trunk local coordinate system, and normalized to body mass and the product of body mass $*$ stature, respectively.

Following the calculation of L5/S1 reaction forces and moments using both approaches, all data were time-normalized to a stride (100% gait cycle). Strides were defined from right heel strike to subsequent right heel strike for able-bodied controls, and from intact heel strike to subsequent intact heel strike for persons with LEA. Peak values of the three components of joint reaction force and moment were extracted from each side (i.e., left/right stance for controls, and intact/prosthetic stance for the TTA and TFA groups). The timings of these peaks, relative to ipsilateral heel strike, were also determined. Temporal–spatial parameters were also calculated (per side, where relevant), including walking speed, step length, and the duration of stance and swing.