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Identification of trunk and pelvis movement compensations in patients with transtibial amputation using angular momentum separation

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ABSTRACT

Patients with unilateral dysvascular transtibial amputation (TTA) have a higher risk of developing low back pain than their healthy counterparts, which may be related to movement compensations used in the absence of ankle function. Assessing components of segmental angular momentum provides a unique framework to identify and interpret these movement compensations alongside traditional observational analyses. Angular momentum separation indicates two components of total angular momentum: (1) transfer momentum and (2) rotational momentum. The objective of this investigation was to assess movement compensations in patients with dysvascular TTA, patients with diabetes mellitus (DM), and healthy controls (HC) by examining patterns of generating and arresting trunk and pelvis segmental angular momenta during gait. We hypothesized that all groups would demonstrate similar patterns of generating/arresting total momentum and transfer momentum in the trunk and pelvis in reference to the groups (patients with DM and HC). We also hypothesized that patients with amputation would demonstrate different (larger) patterns of generating/arresting rotational angular momentum in the trunk. Patients with amputation demonstrated differences in trunk and pelvis transfer angular momentum in the sagittal and transverse planes in comparison to the reference groups, which indicates postural compensations adopted during walking. However, patients with amputation demonstrated larger patterns of generating and arresting of trunk and pelvis rotational angular momentum in comparison to the reference groups. These segmental rotational angular momentum patterns correspond with high eccentric muscle demands needed to arrest the angular momentum, and may lead to consequential long-term effects such as low back pain.

1. Introduction

Over one million Americans currently have a lower-limb amputation, and this number is projected to double by 2050 [1] due to dysvascular pathologies (e.g. diabetes mellitus (DM)) [2]. Patients with dysvascular amputation commonly have multiple comorbidities and 40–50% have limited physical function [3], which require different treatments apart from patients with traumatic amputation. Although patients with dysvascular amputation differ in age, BMI, prosthetic use time, and comorbidities from patients with traumatic amputation [3,4], it is common to combine them into a single group when investigating how amputation affects functional movement characteristics [5,6]. Because patients with DM prior to amputation move differently than healthy controls [7], differences in movement compensations between patients with dysvascular amputation to patients with DM alone could be used as physical rehabilitation targets for movement retraining following amputation.

Patients with unilateral transtibial amputation (TTA) are at increased risk of developing low back pain (LBP) [8], which may relate to necessary movement compensations to achieve forward progression and balance during walking. For example, to accomplish forward progression in the absence of an ankle plantar flexor, patients with unilateral TTA increase hip extensor power during the stance period of the residual limb [9]. Patients with unilateral TTA demonstrate exaggerated lateral trunk lean toward the amputated limb (compensated Trendelenburg) [10] and altered foot placement of the intact limb, which leads to uneven step length, swing time, and stance time [9]. While these compensations may be necessary to

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accomplish mobility, asymmetric movements are linked to the development of LBP [11]. This coordination of excessive trunk and pelvic motion during walking likely contributes to step-to-step asymmetric loading at the low back previously measured in patients with unilateral TTA [12], and may increase the risk of developing LBP, which was previously demonstrated in patients with transfemoral amputation [13,14].

Clinicians rely on observational gait analysis to identify movement compensations which is highly subjective and unreliable for identifying consequential movement compensations in amputees [15]. Although laboratory-based gait analysis is valid and reliable for quantitatively measuring movement, it is accompanied by high computational and economic expenses, and currently impractical in the vast majority of clinical settings. Because clinicians use observational gait analysis to guide interventions and gait retraining in patients with unilateral TTA, the ability to obtain accurate measures of trunk and pelvis movement patterns could help tailor treatment to patients and ultimately prevent injuries, such as LBP.

Identification of segmental strategies used to generate and arrest segmental angular momentum can provide insight into muscle demands following unilateral dysvascular TTA. During walking, muscles are used concentrically and eccentrically as the primary mechanisms to generate and arrest segment angular momentum [16]. Measuring and understanding segmental angular momentum is a promising approach to bridge the gap between observational and quantitative gait analysis. We previously demonstrate a framework to describe clinical movement compensations during gait using separation of translational angular momentum referenced to the stance foot [17]. Total segmental angular momentum can be separated into two components, each with a unique interpretation: (1) translational angular momentum (TAM): angular momentum created by linear velocity of the segment with mass with respect to a point and (2) rotational angular momentum (RAM): angular momentum created by the rotational velocity of an object with inertia [18].

The objective of this investigation was to assess movement compensations in patients with unilateral dysvascular TTA and patients with DM by examining translational angular momentum and rotational angular momentum of the trunk and pelvis during walking for patterns of generating/arresting momentum. We hypothesized that patients with unilateral dysvascular TTA, patients with DM, and healthy control participants would demonstrate similar patterns of generating/arresting TAM of the trunk and pelvis when walking at similar speeds. We also hypothesized that patients with unilateral dysvascular TTA would demonstrate higher RAM of the trunk and pelvis than the other groups, which illustrates potentially consequential movement compensations that can be retrained through clinical intervention.

2. Methods

2.1. Participants

Ten patients with DM and unilateral TTA 1–3 years post amputation (AMP) (Table 1) (10 M; age: 56.8 ± 4.3 years; mass: 97.6 ± 15.2 kg; height: 1.8 ± 0.1 m), 11 patients with DM (2F, 9 M; age: 61.4 ± 8.0 years; mass: 94.3 ± 22.0 kg; height: 1.7 ± 0.1 m), and 13 healthy control patients (HC) (3 F, 10 M; age: 63.1 ± 7.7 years; mass: 77.7 ± 13.2 kg; height: 1.7 ± 0.1 m) were enrolled. Eligibility criteria included: age: 50–85 years; BMI ≤ 40 kg/m^2; independent community ambulation (ability to walk for 4 min without rest or assistive device); 1–3 years post amputation (AMP group); controlled Type-II diabetes mellitus (AMP and DM groups); no traumatic or cancer-related amputation (AMP group); no major amputation on contralateral limb (AMP group); no cardiovascular, orthopedic, neurologic, wounds, or ulcers that limit physical function; no history of LBP (HC group); no diagnosed rheumatoid arthritis (HC group); no diagnosed osteoarthritis (HC group); and no total hip/knee joint arthroplasty (HC group). Each participant provided a written, informed consent in accordance with the Colorado Multiple Institutional Review Board prior to the start of the experimental session and completed one data collection in which whole body kinematics were collected.

Table 1
Participant characteristics for patients with dysvascular unilateral transtibial amputation (AMP) group.

Time since amputation (months)	Residual limb length (cm)	Socket type	Prosthetic foot
17.4 ± 5.1	14.8 ± 2.5	Total contact carbon fiber	Dynamic elastic response

2.2. Motion analysis

Each participant was instrumented with 63 reflective markers used to obtain whole-body kinematics during gait. Motion was recorded from eight infrared cameras (Vicon) sampled at 100 Hz. Each participant performed three gait trials at 1.0 m/s (±0.05 m/s) on a 10-m walkway. Motions were averaged across the three trials and used for group comparisons.

2.3. Data analysis

Kinematic data were low-pass filtered with a 4th-order Butterworth filter (6 Hz cutoff frequency). A 15-segment subject-specific model (head, upper arms, forearms, hands, trunk, pelvis, thighs, shanks, and feet) was created in Visual 3D (C-Motion, Inc.). Segment masses were based on a percentage of total body weight and segment inertias were based on segment geometry [19]. For the AMP group, mass the center of mass position, and inertial properties of the prosthetic shank (residual limb + prosthetic socket) and prosthetic foot were determined using a reaction board technique and oscillation method [20].

TAM (angular momentum of a segment with respect to the stance foot) is described as:

$$\mathbf{h}_{i/\mathrm{Foot}} = (\mathbf{r}_i - \mathbf{r}_{\mathrm{Foot}}) \times m_i(v_i - v_{\mathrm{Foot}}) \tag{1}$$

where $\mathbf{r}_i$ and $\mathbf{r}_{\mathrm{Foot}}$ are the position vectors of the ith segment and foot, respectively, m_i is the mass of the ith segment, and $\mathbf{v}_i$ and $\mathbf{v}_{\mathrm{Foot}}$ are the velocities of the ith segment and foot respectively. RAM (angular moment of a segment with respect to its center of mass) is described as:

$$\mathbf{h}_i = \mathbf{I}_i \cdot \boldsymbol{\omega}_i \tag{2}$$

where $\mathbf{I}_i$ is the moment of inertia tensor and $\boldsymbol{\omega}_i$ is the angular velocity of the segment. To facilitate planar analyses, all angular momenta vectors were expressed in a path reference frame, that is defined by the velocity vector of the body COM: $\mathbf{e}_{\mathrm{frontal}}$ (tangent to the horizontal path of the body COM), $\mathbf{e}_{\mathrm{transverse}}$ (opposite direction of the gravity vector), and $\mathbf{e}_{\mathrm{sagittal}}$ ($\mathbf{e}_{\mathrm{frontal}} \times \mathbf{e}_{\mathrm{transverse}}$). Within the path reference frame, positive momenta values in each plane are defined as: sagittal – posterior rotation away from stance foot, frontal – medial-lateral rotation toward stance foot, transverse – rotation away from stance foot.