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Sound limb loading in individuals with unilateral transfemoral amputation across a range of walking velocities☆

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ABSTRACT

Background: Individuals with unilateral transfemoral amputation demonstrate significantly increased rates of osteoarthritis in their sound knee. This increased risk is likely the result of altered knee mechanical loading and gait compensations resulting from limited function in the prosthetic limb. Altered knee loading as calculated using loading rates and peak external knee adduction moments and impulses have been associated with both the development and progression of knee osteoarthritis in other populations. The purpose of this study was to determine if young individuals with transfemoral amputation demonstrate biomechanical indicators of increased knee osteoarthritis risk.

Methods: Fourteen young male Service Members with unilateral transfemoral amputation and 14 able-bodied service members underwent biomechanical gait analysis at three standardized walking velocities. A two-way ANOVA (group × speed) with unpaired comparisons with Bonferroni–Holm post-hoc corrections assessed statistical significance and effect sizes (d) were calculated.

Findings: Normalized peak external knee adduction moments and impulses were 25.7% ($P < 0.014$, $d > 0.994$) and 27.1% ($P < 0.012$, $d > 1.019$) lower, respectively, in individuals with trans-femoral amputation than controls when averaged across speeds, and effect sizes were large. External knee flexor moments were not, however, different between groups and effect sizes were generally small ($P > 0.380$, $d < 0.338$). Maximal loading rates were significantly greater in individuals with amputation and effect sizes were large ($P < 0.001$, $d > 1.644$).

Interpretation: Individuals with transfemoral amputation did not demonstrate biomechanical risk factors for high medial compartment knee joint loads, but the increased loading rates could place the sound knee at greater risk for cartilage or other tissue damage, even if not localized to the medial compartment.

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1. Introduction

Knee osteoarthritis (KOA) is a degenerative joint disease and common cause of disability. The knee is the most frequent site of OA due to its load bearing requirements and the accumulation of load on the knee can deteriorate the cartilage that protects and cushions the knee. Some populations are at greater risk for disease development, including individuals who are obese (Felson et al., 1988), have varus or valgus malalignments (Sharma et al., 2001; Felson et al., 2013), or have undergone amputation of their contralateral limb (Norvell et al., 2005). For individuals with lower extremity amputations, the prevalence of this degenerative disease in the intact limb is up to 10 times higher than in able-bodied individuals and onset ages are younger (Hungerford and Cockin, 1975; Burke et al., 1978; Lemaire and Fisher, 1994; Kulkarni et al., 1998; Melzer et al., 2001; Norvell et al., 2005; Gailey et al., 2008; Robbins et al., 2009; Struyf et al., 2009). When stratified by amputation level, individuals with transfemoral amputations (TFA) have a higher incidence of KOA than individuals with transtibial (TTA) amputations (Norvell et al., 2005) and incidence rates have been reported to be 63% in veterans and 41% in civilians with TFA compared with 41% in veterans and 39% in civilians with TTA (Hungerford and Cockin, 1975; Struyf et al., 2009). Both amputee cohorts are more likely to develop the disease in their sound limb than able-bodied individuals, even after accounting for age, body mass and a history of intact knee injury (Norvell et al., 2005).

Mechanical loading is thought to play an important role in the etiology of KOA development and progression. Individuals with amputations rely heavily on their sound limb to support a greater portion of the load than the amputated limb (Sanderson and Martin, 1997; Bateni and Olney, 2002). The medial compartment of the tibiofemoral joint bears a greater percentage of the load than the lateral (Schipplein and Andriacchi, 1991; Mundermann et al., 2008b) and studies on cartilage deterioration (Melzer et al., 2001) and bone mineral density (Royer

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and Koenig, 2005) have shown the medial compartment of the sound knee to be affected in individuals with amputations. The external knee adduction moment (EKAM) is a frequently used surrogate measure of internal load on the medial compartment of the knee joint (Zhao et al., 2007; Kutzner et al., 2013) and the angular impulse of the EKAM represents the overall loading exposure in magnitude and duration. Both variables are associated with the severity of KOA (Mundermann et al., 2005; Thorp et al., 2006; Astephen et al., 2008) and greater values at baseline are predictive of disease development and progression in a non-amputee population (Sharma et al., 1998; Miyazaki et al., 2002; Bennell et al., 2011). For individuals with a lower extremity amputation, greater EKAM values are also related to medial compartment cartilage deterioration on the sound limb (Morgenroth et al., 2014).

Other variables also play a role in the mechanical loading of the knee joint. The peak external knee flexor moments (EKFMs) represent the overall load on the knee and large EKFMs are related to greater EKAMs (Kulmala et al., 2013). Other variables related to limb loading include peak vertical ground reaction forces (GRF) and loading rates, both of which increase with KOA (Messier et al., 1992; Mundermann et al., 2005) and while walking at faster velocities (Hunt et al., 2010). Peak GRFs and loading rates may not directly relate to the distribution of the load between the medial and lateral compartments of the knee joint but they contribute to the overall knee joint contact force and therefore compression of the cartilage. When articular cartilage is loaded at faster rates, its ability to dissipate contact forces is reduced (Radin and Paul, 1971).

Reducing the magnitudes of these variables is particularly important for younger individuals with amputations to avoid the risk of early KOA onset. For example, Service Members with lower extremity amputations represent a unique population because they are physically fit and motivated to return to high levels of function, sport and prior duty status. KOA development would hinder their ability to accomplish these goals. Recently, Pruziner et al. (2014) published a study on sound limb loading in individuals with amputations and found that young, active Service Members with TFA do not experience greater medial compartment knee joint loads (calculated by the peak EKAM) than their able-bodied counterparts at self-selected walking velocities (SSWV). These results are novel in that they are the first to show that individuals with TFA do not display indicators of a mechanical risk for KOA during walking in the relatively early stages of prosthetic use. Russell Esposito and Wilken (2014) found that young, active individuals with TTA also do not exhibit greater peak EKAMs or EKAM impulses than able-bodied individuals across a range of standardized velocities, but EKFMs and loading rates were increased. These results were unexpected due to the high risk of KOA development after amputation, and were attributed to the youth, strength and physical fitness of the service members relative to the older, less fit and dysvascular amputee population who tend to show increases in the peak EKAM and EKFM compared to controls.

Identification of these biomechanical risk factors in younger individuals with amputations who have not developed OA is important because of the decades of cumulative loading that the sound limb will sustain. Moreover, prolonged prosthetic use increases the risk of joint pain and OA (Burke et al., 1978; Lemaire and Fisher, 1994). No study to date has investigated sound limb loading in individuals with TFA and able-bodied individuals across a series of controlled velocities. Instead, the majority of previous comparisons have been done at SSWVs, which were generally different between groups. Therefore, the purpose of this study was to identify biomechanical risk factors for KOA in young service members with traumatic TFA. We hypothesized that, similar to the results of Pruziner et al. (2014) and Russell Esposito and Wilken (2014), individuals with TFA would not display greater EKAMs and peak GRFs than able-bodied controls but would have greater EKFMs and loading rates. We also hypothesized that all variables calculated to assess sound limb loading would increase with walking velocity.

2. Methods

2.1. Participants

Fourteen individuals with unilateral TFA between the ages of 18 and 45 participated in this study. Sample size was based on peak EKAM values from Morgenroth et al. (2014), a power of 0.8, and alpha of 0.05. All subjects were male, Service Members in relatively early stages of ambulation with a prosthetic device compared to the literature. Amputations were the result of high energy impacts, explosions or motor vehicle accidents. Other inclusion criteria consisted of independent ambulation with a prosthetic limb for at least three months, and the ability to walk without the use of an external device other than a prosthesis. Twelve subjects with amputations wore the C-Leg microprocessor knee (Ottobock, Duderstadt, Germany) and two wore a mechanical Total Knee (Össur, Reykjavik, Iceland); foot prostheses differed among subjects and types were not recorded but all were passive-dynamic in nature. Walking data from 14 uninjured individuals were selected from a set of normative data to best mass and height match the groups. All subjects provided written informed consent for the research procedures approved by the Brooke Army Medical Center Institutional Review Board.

2.2. Experimental setup

The experimental setup consisted of a 26-camera motion capture system (120 Hz; Cortex, Motion Analysis Corp, Santa Rosa, CA) integrated with five force platforms (1200 Hz; AMTI, Watertown, MA, USA) in series in the center of the capture volume. Three-dimensional marker trajectories were tracked from 57 markers placed on anatomical landmarks and segments (Wilken et al., 2012). A digitization pointer (C-Motion, Inc. Germantown, MD, USA) was used to identify 20 bilateral anatomical landmarks.

2.3. Protocol

All data were collected on a single day. Study participants walked across 20 m of level ground at a self-selected walking velocity and three standardized velocities based on leg length and dimensionless Froude numbers of 0.10 (velocity 1—slow), 0.16 (velocity 2—moderate) and 0.23 (velocity 3—fast) (Vaughan and O'Malley, 2005). The Froude number for the moderate velocity was selected as a close approximation to an average self-selected walking velocity in able-bodied individuals and the use of Froude velocities was chosen to facilitate equivalent task demands across individuals of varying leg lengths.

$$\text{Velocity} = \sqrt{\text{Froude number} \cdot \text{gravity} \cdot \text{leg length}}$$

An auditory tone based on the forward velocity of the seventh cervical vertebrae marker provided feedback when the intended velocity fell within a 5% range. SSWV was collected first and the standardized Froude-based velocities were collected in ascending order to end with the most physically demanding condition.

2.4. Data analysis

Marker trajectories and analog data were exported from Cortex and imported to Visual3D (C-Motion, Inc. Germantown, MD). A 13-segment full body model was created from anatomical markers, digitized points and Dempster's body segment parameters (Dempster, 1955). Marker trajectories were interpolated and filtered using a fourth order Butterworth low pass filter with a cutoff frequency of 6 Hz and analog data were filtered at 50 Hz. Six stance phases in which the sound limb made full contact with one of the force platforms were selected for analysis for the TFA group. For able-bodied control subjects, six stance phases from the right limb were selected for analysis. The stance