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Knee adduction moment peak and impulse do not change during the first six months of walking with a prosthesis

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ABSTRACT

Background: Individuals with unilateral lower limb loss are at increased risk for developing knee osteoarthritis in their contralateral limb. The mechanisms underlying this phenomenon are unknown, but large or unusual loads on the limb are thought to contribute to osteoarthritis development. Yet, to our knowledge, there have been no longitudinal assessments of knee joint kinetics to assist with identifying the origin or progression of such loads.
Research question: This study aimed to examine knee joint kinetics of individuals with lower limb loss as a function of time from independent ambulation.
Methods: Eight male Service Members with unilateral lower limb loss (3 transfemoral/5 transtibial) completed gait analyses, walking at self-selected speed and cadence, at 0, 2, and 6 months following initial independent ambulation.
Results: Although there was a significant time effect on stride length ($p = 0.047$), there were no pairwise differences (all $p \geq 0.152$). Additionally, there was not a significant effect of time on the peak ($p = 0.666$), loading rate ($p = 0.336$), or impulse ($p = 0.992$) of knee adduction moment (KAM), peak knee flexion moment (KFM) ($p = 0.128$), or the peak ($p = 0.485$) or loading rate ($p = 0.130$) of vertical ground reaction force (VGRF).
Significance: The results of the current study demonstrate that major features of knee joint loading do not change over the first 6 months of independently walking with a prosthesis. The magnitude of these loads are similar to loads observed in individuals with lower limb loss further from injury/initial ambulation, but the present results do not imply that no changes occur after 6 months.

1. Introduction

Individuals who have sustained a traumatic injury resulting in lower limb loss are at particularly high risk for developing knee osteoarthritis in their intact limb [1,2]. Service Members with limb loss, specifically, are typically young at time of injury and thus will likely face many more years of joint pain and activity limitations associated with osteoarthritis compared to their older counterparts. The causal mechanisms that initiate knee osteoarthritis are unknown, but abnormal joint mechanics during activities of daily living (i.e., walking)[3,4] are suspected to play a major role. Identifying abnormal walking mechanics early in the rehabilitation process of younger limb loss patients could allow for a focus on early interventions, potentially delaying or preventing the onset of osteoarthritis.

Individuals with unilateral lower limb loss tend to place greater loads on the intact limb during activities of daily living [5,6]. This limb preference is thought to contribute to the high risk for knee osteoarthritis through the 'wear-and-tear' model of osteoarthritis development and progression [7,8]. The role of the knee adduction moment (KAM) in knee osteoarthritis has received considerable attention as KAM affects the distribution of frontal plane knee loads and medial tibiofemoral joint loading [9,10]. Features of the KAM such as peak [11,12], impulse [13,14], and loading rate [15] have been previously associated with measures of cartilage degeneration. For example, greater KAM loading rate during walking in individuals with lower limb loss is associated with greater image-based evidence of medial tibiofemoral degeneration [15], and KAM impulse can distinguish between radiographic severity of knee osteoarthritis [16]. Peak knee flexion moment (KFM) has also been associated with osteoarthritis severity [17] and progression [11,18]. Data on the association between joint moments and the

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initiation of knee osteoarthritis are sparse, but older adults with relatively high peak KAMs appear to be at a greater risk for knee osteoarthritis initiation [3,4]. While previous studies did not include individuals with limb loss, they motivate examination of variables like KAM in this population prior to the initiation of knee osteoarthritis.

To our knowledge, there exist no longitudinal assessments of joint moments related to knee osteoarthritis initiation and/or progression in individuals with lower limb loss. Examining the longitudinal adaptations of gait mechanics in individuals with lower limb loss after initial ambulation with a prosthesis can provide insight into gait changes during the rehabilitation process that may represent risk for future knee osteoarthritis in the form of excessive or unusual knee joint loading. If an individual exhibits large or unusual knee joint loads when first walking with a prosthesis, they may continue to walk with large or unusual knee joint loads throughout their rehabilitation, and possibly long-term, increasing their risk for developing knee osteoarthritis in the intact limb. Relatedly, longitudinal assessment of gait can help determine at what point in the rehabilitation process gait mechanics have stabilized and reflect the joint loading the individual will experience in daily life.

Therefore, the purpose of this study was to examine changes in intact limb knee joint kinetics of individuals with unilateral lower limb loss as a function of time from independent ambulation. Due to expected increases in stride length and/or walking speed during early rehabilitation as individuals become more familiar with prosthesis use, we hypothesized that features of the KAM and KFM would increase throughout the first 6 months of initial ambulation.

2. Methods

2.1. Participants

An *a priori* power analysis indicated that approximately 5–10 subjects were required to detect differences in peak KFM with effect sizes of at least $d = 0.8$–1.9 as statistically significant ($\alpha = 0.05$, $\beta = 0.20$). This effect size was calculated using data from Esposito et al. [19], comparing the peak KFM from the intact limb of individuals with lower limb loss to controls. In the present study, participants were eight Service Members with unilateral lower limb loss due to traumatic injury (three transfemoral, five transtibial; 26 ± 5 yrs, 1.76 ± 0.04 m, 83.8 ± 13.5 kg). All participants received standard-of-care rehabilitation at Walter Reed Army Medical Center. Inclusion criteria were: no previous diagnosis of osteoarthritis, no pain during activities of daily living greater than four on a ten point scale, no limb loss elsewhere on the body, no history of traumatic injury to the intact limb, and no history of traumatic brain injury or other medical issues known to affect gait. All participants provided written informed consent to procedures approved by the Walter Reed Army Medical Center Institutional Review Board.

2.2. Protocol

Gait analyses were performed at 0, 2, and 6 months after initial independent ambulation (defined as able to walk 50-ft independently without assistive devices). Participants were instructed to walk at a "normal and comfortable" self-selected speed and cadence at each visit. While such an approach allows for the possibility of changing speed/cadence across visits, no further controls were implemented as to obtain data that best reflect how subjects walk in daily life. At least five acceptable trials were collected, which were defined as a clean footstrike within the bounds of a single forceplate. Clinical observations of Service Members with limb loss at this treatment facility have shown a leveling off of self-selected walking speed and metabolic cost around 6 months, supporting visit timing selection.

2.3. Experimental setup

Participants wore shorts, their own athletic shoes and clinically prescribed energy-storage and return ankle prostheses and, for transfemoral participants, unpowered microprocessor knee prostheses. Five participants (1 transfemoral, 4 transtibial) wore different ankle-foot prostheses at their 2- and/or 6-month visits than at their initial 0-month visit. Similar to not controlling speeds/cadences, prosthesis changes are normal and common during the first six months of rehabilitation after limb loss and thus enhance ecological validity and clinical applicability of the current study. Moreover, peak knee extension moments in the intact limb are not very sensitive to transtibial prosthesis stiffness [20]; thus, it is unlikely that differences in prosthetic ankles between testing sessions resulted in meaningful differences in primary outcomes.

Positions of retroreflective markers on the pelvis and lower limbs [21] were captured at 120 Hz using a 23-camera motion capture system (Vicon, Oxford, UK). Joint marker placements were completed by one of two trained study investigators with extensive experience in identifying anatomical landmarks. Although the same investigator did not necessarily conduct all three participant visits, the same guidelines for marker placement were used by both investigators for all visits, and intersession reliability of 3D gait data at military treatment centers is high [22]. Ground reaction force data were captured at 1200 Hz using six force platforms (AMTI, Watertown, MA, USA) embedded in the walkway.

2.4. Data processing

Marker position and ground reaction force data were exported to Visual3D (C-Motion, Germantown, MD, USA) and smoothed using a 4th-order-dual-pass Butterworth filter with cutoff frequencies of 6 Hz and 50 Hz, respectively. A linked-segment model of the pelvis and both legs was created for each subject from marker positions during a standing calibration trial. The knee joint center was defined as the midpoint between the femoral condyles. The longitudinal axis was defined as the cross-product of the longitudinal axis and the vector between the knee markers, and the mediolateral axis was defined as the cross-product of the anteroposterior and longitudinal axes. Joint angles about these axes were calculated using a Cardan Xyz rotation sequence [23]. Iterative Newton-Euler inverse dynamics within Visual3D was used to calculate joint forces and moments [24].

2.5. Statistical analysis

Outcome variables were the peak, impulse, and loading rate of KAM, and peak KFM. These variables were chosen because they have been previously associated with the progression and/or initiation of osteoarthritis in individuals without limb loss [11,13–15]. In addition, results are provided for the peak and loading rate of the vertical ground reaction force (VGRF). Walking speed and stride length were included in the analysis to determine if they should be covariates since both affect joint moments. Variables were determined from each trial and averaged over trials to produce a representative value for each participant. Impulse was calculated as the integral of the moment-time series. KAM and VGRF loading rates were calculated as the slope between 20 and 80% of the time from minimum KAM to the first KAM peak, and time from 20-80% of the VGRF profile from heel strike to peak force, respectively. All KAM and KFM outcome variables were scaled by total bodyweight (including prosthesis) and height (% BW*Ht), and VGRF outcome variables were scaled by bodyweight (BW) using the participant mass recorded at each respective timepoint. A one-way repeated measures ANOVA was used to compare outcome variables between 0, 2, and 6 months. Bonferonni post-hoc testing was performed to test for differences between conditions. The significance level was set at $p < 0.05$. To complement the significance testing and add an additional check on the potential effect of time, JZS Bayes