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Full length Article

Effect of end-stage hip, knee, and ankle osteoarthritis on walking mechanics

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ABSTRACT

This study tested the hypothesis that the presence of isolated ankle (A-OA; $N = 30$), knee (K-OA; $N = 20$), or hip (H-OA; $N = 30$) osteoarthritis (OA) compared to asymptomatic controls ($N = 15$) would lead to mechanical changes in the affected joint but also in all other lower limb joints and gait overall. Stride length, stance and swing times, as well as joint angles and moments at the hip, knee, and ankle were derived from 3-D kinematic and kinetic data collected from seven self-selected speed walking trial. Values were compared across groups using a 1×4 ANCOVA, covarying for walking speed. With walking speed controlled, the results indicated a reduction in hip and knee extension and ankle plantar flexion in accordance with the joint affected. In addition, OA in one joint had strong effects on other joints. In both H-OA and K-OA groups the hip never passed into extension, and A-OA subjects significantly changed hip kinematics to compensate for lack of plantar flexion. Finally, OA in any joint led to lower peak vertical forces as well as extension and plantar flexion moments compared to controls. The presence of end-stage OA at various lower extremity joints results in compensatory gait mechanics that cause movement alterations throughout the lower extremity. This work reinforces our understanding of the complex interaction of joints of the lower limb and the importance of focusing on the mechanics of the entire lower limb when considering gait disability and potential interventions in patients with isolated OA.

1. Introduction

Osteoarthritis is a multifactorial, progressive disease that afflicts almost fifty million adults in the United States [1–3], and, when present in even one lower limb joint leads to significant activity limitations [1]. Although OA is often limited to one joint, especially in its early stages, it is well-recognized that changes in function at one joint can lead to overall disability and changes in function at other. Much of the previous work exploring this question has focused on subjects with OA in a single joint, primarily the knee, on lower extremity kinematic and kinetics during walking [4–11]. The present study expands on previous work by comparing overall sagittal plane gait mechanics, ground reaction forces, and spatiotemporal parameters between patients with debilitating, isolated ankle, hip, and knee OA. The purposes of this study were to determine if: (1) OA in each of the major load-bearing joints of the lower extremity (hip, knee, ankle) affects overall gait disability, (2) OA in each joint affects the mechanical behavior of the other lower extremity joints, and (3) OA in certain joints have a differential effect on the remaining lower extremity joints or if gait is impacted in the same way independent of the joint impacted by OA.

This study tests the following hypotheses: All OA subjects will (1) walk at a slower velocity, (2) exhibit a shorter stride length, and (3) adopt strategies that lower ground reaction forces and joint moments to reduce painful limb loading when compared to the control group. In addition, the specific OA affected joint will lead to mechanical changes at the affected joint as well as impacting the other lower extremity joints during walking. In that context, it is hypothesized that isolated hip OA will result in reduced angular excursions, specifically a reduction in hip extension. This movement limitation could result in either greater knee flexion to allow for proper toe-off or ankle plantar flexion motion will be limited resulting in a more vertical toe-off. Similarly, isolated knee OA is expected to limit knee flexion resulting in a shortened effective limb. However, it is not hypothesized that these limitations in knee motion will result in changes at the hip or ankle. Ankle OA is expected to limit plantar flexion, therefore

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reducing the overall ankle motion resulting in alterations in hip mechanics during terminal stance.

2. Methods

2.1. Participants

For this study, 90 subjects with severe hip, knee, and ankle OA (30 hip, 30 knee, and 30 ankle) were enrolled. Subjects were between the ages of 40 and 80 years old and were diagnosed by a board certified orthopedic surgeon as having unilateral OA in a single joint and the absence of pain in all other joints. Establishing comparable levels of OA severity across joints is challenging. Kellegren–Lawrence grades can be determined for knee OA patients, however, at present, no established OA grading systems have been accepted for the ankle and hip. Therefore, in order to insure appropriate comparisons we included only subjects with symptomatic OA who were scheduled for a total joint replacement within 4 weeks of testing.

Subjects were excluded if they were unable to ambulate without the use of an assistive device, had pain at more than one lower extremity joint on either limb, or had prior joint replacement surgery. The control group was a sample of convenience based on available subjects. The fifteen healthy control subjects included in this analysis were matched as closely as possible for age and gender to the OA subjects, were pain free, had no history of lower extremity joint surgery and no clinical diagnosis of lower extremity OA. Prior to study initiation, all participants signed informed consent that had been approved by the medical center's institutional review board.

2.2. Experimental design and procedure

Each subject was asked to wear form fitting shorts and a shirt and to walk barefoot during testing in order to control for changes in the ground reaction forces (GRF) associated with variations in footwear. Kinematic data was collected using an eight camera motion capture system sampling at 120 Hz (Motion Analysis Corporation; Santa Rosa, CA) and kinetic data were collected with four embedded force plates, sampling at 1200 Hz, (AMTI, Watertown, MA). A modified Helen-Hayes marker set was used for testing. This marker set has been previously used when testing patients with ankle [12–15], hip [16–19], and knee OA [20,21], as well as healthy control subjects [22]. Each subject was asked to stand within the capture volume to record a static standing trial. Each subject was asked to complete seven self-selected speed (speed you would normally walk while grocery shopping), walking trials during a single data collection session.

The kinematic and kinetic data were collected bilaterally during all trials; however, only the affected limb was used for statistical analysis. The dominant leg (one the subject preferred to use when hopping on one foot) was used for analysis for the control subjects. The spatiotemporal parameters of interest were stance time, step time, swing time, step length, and stride length. Walking speed was assessed because it has been identified as a measure of the differences in functional ability in OA populations [6,23,24]. Sagittal plane joint mechanics, GRF and joint moments were assessed during the stance phase of gait.

The 3D coordinate data and GRF data were filtered using a low-pass Butterworth filter at 7 Hz and 100 Hz, respectively. Spatiotemporal variables as well as time series, stance phase normalized data for the kinematics and kinetics variables were calculated using Visual 3D software (C-Motion, Bethesda, Maryland, USA). Joint angles were calculated as Cardan angles between adjacent local segments with an order of rotation of flexion–extension, abduction–adduction, and internal–external rotation. Joint moments were calculated through an inverse dynamic approach and transferred into the local segment coordinate system and were expressed as internal moments. Ground reaction forces were normalized to body weight while joint moments were reported as N m/kg.

This study focuses on key behavioral outcomes such as walking speed, stride length, and sagittal joint range of motion, all of which profoundly influence gait disability. There are a wider range of mechanical factors, some of which are known to contribute to disease progression that are not examined here but can be explored in future studies. This work focuses on the mechanical interaction throughout the lower extremity and the resulting locomotor disability.

2.3. Statistical analysis

In order to assess the differences in subject demographics between the 4 groups (control, H-OA, K-OA, A-OA) a 1×4 ANOVA was completed with an alpha level of 0.05 to indicate statistical significance. The average angles, moments, GRF, and spatiotemporal parameters were determined from the 7 trials and were used for analysis. All data were compared with a 1×4 ANOVA and those values are reported in the text. However, it is recognized that speed can influence a number of the study variables and may lead to incorrect conclusions about the influence of joint disability on other limb joints. To examine those interactions a further 1×4 ANCOVA analysis was completed, where walking speed was the covariate with the same alpha level to indicate statistical significance. Tukey's HSD post-hoc testing was completed on any variable that was statistically different in the initial analysis. A large number of comparisons could increase the chances of type II error and therefore the alpha levels need to be adjusted accordingly [25]. The methods for adjustment and the need for adjustment remain controversial [25–30]. Therefore, to adjust the alpha level, the Dunn–Sidak method was used [25]. To test three general hypotheses in this study there were 12 variables of interest. For each variable four groups were compared yielding six pairwise comparisons for each variable. The adjusted alpha level for this study was $\alpha' = 0.0082$. In the text all values $P < 0.05$ are presented but the reader may choose to discount that values not less than 0.008 based on the adjustment for multiple comparisons.

3. Results

After study enrollment, 10 of the K-OA patients had incomplete data and were therefore excluded from the final analysis resulting in a total of 95 subjects (15 healthy controls, 30 H-OA, 30 A-OA, and 20 K-OA subjects).

3.1. Subject demographics and spatiotemporal variables

The gender breakdown of the study groups as well as the demographic information for each of the study groups are reported in Table 1. The groups were significantly different from each other with regards to age and weight only, with the control group being both younger ($P < 0.001$) and lighter ($P = 0.007$) than the OA groups (Table 1). Differences also existed between the OA groups, with the K-OA group being older than both the H-OA ($P < 0.001$) and A-OA ($P = 0.011$) groups, who were not different from each other (Table 1).

Walking speed was faster in the control group (1.38 ± 0.22 m/s) when compared to all OA groups ($P < 0.001$). H-OA subjects walked faster than the A-OA subjects ($P < 0.001$) (Table 1). Stance time and step time differed in only a few comparisons across groups with knee OA subjects having longer stance time than control or ankle OA subjects and subjects with ankle OA having longer step time than