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Interlimb symmetry of dynamic knee joint stiffness and co-contraction is maintained in early stage knee osteoarthritis

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Abstract

Individuals with knee OA often exhibit greater co-contraction of antagonistic muscle groups surrounding the affected joint which may lead to increases in dynamic joint stiffness. These detrimental changes in the symptomatic limb may also exist in the contralateral limb, thus contributing to its risk of developing knee osteoarthritis. The purpose of this study is to investigate the interlimb symmetry of dynamic knee joint stiffness and muscular co-contraction in knee osteoarthritis.

Muscular co-contraction and dynamic knee joint stiffness were assessed in 17 subjects with mild to moderate unilateral medial compartment knee osteoarthritis and 17 healthy control subjects while walking at a controlled speed (1.0 m/s). Paired and independent t-tests determined whether significant differences exist between groups ($p < 0.05$).

There were no significant differences in dynamic joint stiffness or co-contraction between the OA symptomatic and OA contralateral group ($p = 0.247$, $p = 0.874$, respectively) or between the OA contralateral and healthy group ($p = 0.635$, $p = 0.078$, respectively). There was no significant difference in stiffness between the OA symptomatic and healthy group ($p = 0.600$); however, there was a slight trend toward enhanced co-contraction in the symptomatic knees compared to the healthy group ($p = 0.051$).

Subjects with mild to moderate knee osteoarthritis maintain symmetric control strategies during gait.

Keywords

Stiffness; Co-contraction; Knee; Osteoarthritis; Symmetry

1. Introduction

Osteoarthritis (OA) is an increasingly prevalent condition affecting approximately 27 million people in the US alone (Helmick et al., 2007), with osteoarthritis of the knee being especially common and debilitating (Felson et al., 1987). Knee OA is characterized by pain, stiffness, and often results in abnormal gait mechanics (Kaufman et al., 2001; Mundermann et al., 2005; Al-Zahrani and Bakheit, 2002) which have been shown to relate to disease severity (Hunt et al., 2010; Astephen et al., 2008). Current studies investigating these measures in knee OA commonly focus on the symptomatic or more painful limb; however, the assessment of gait mechanics in the contralateral limb is also important as those with asymmetric knee loading have been shown to have an increased risk of developing OA in the unaffected or less severe knee (Shakoor et al., 2002, 2003).

Alterations to gait mechanics have been shown in those with knee OA and include increased loading rates (Mundermann et al., 2005) and reduced internal knee extensor moment (Kaufman et al., 2001). One such gait alteration of importance to the current study is co-contraction of the quadriceps and hamstrings muscles (Zeni et al., 2010). Muscular co-contraction is thought to be an important component of increased knee joint stiffness in those with knee OA. More specifically, those with OA of the knee utilize a strategy of antagonistic muscle activity which may lead to increases in dynamic joint stiffness during gait (Zeni and Higginson, 2009b).

The observed gait alterations on the symptomatic limb mentioned previously may, in turn, necessitate stiffening of the contra-lateral knee through co-contraction of the quadriceps and hamstrings muscles in order to accept loads resulting from weight shifting off the symptomatic limb. However, the degree and role of co-contraction on the contralateral limb and its relationship to dynamic knee joint stiffness in knee OA remains unclear.

Dynamic knee joint stiffness is a measure which considers both the external knee flexion moment and knee flexion angle and has been used to assess joint stability during dynamic tasks such as walking (Dixon et al., 2010; Zeni and Higginson, 2009b). This stiffness arises in the presence of joint laxity, instability (Rudolph et al., 2007), and increased co-contraction (Schmitt and Rudolph, 2007) and is commonly utilized as a means of stabilizing the joint (Pettersen et al., 2008). Dynamic knee joint stiffness has not been extensively studied in those with knee OA with the few studies that have looked at this measure solely investigating the symptomatic knee with mixed results (Zeni and Higginson, 2009b; Dixon et al., 2010). Dixon et al. reported higher knee joint stiffness in individuals with varying severities of knee OA compared to asymptomatic controls when walking at a controlled speed of 1.0 m/s (Dixon et al., 2010). The results of their study conflicted with those of Zeni et al. who demonstrated no significant difference in dynamic knee joint stiffness between healthy control subjects and those with moderate knee OA while also walking at the same controlled speed (1.0 m/s) (Zeni and Higginson, 2009b). Despite utilizing the same walking speed, differences in the results of these studies may be attributed to their varying methods for calculating dynamic joint stiffness. While these studies investigated joint stiffness between healthy subjects and those with knee OA, no previous work has determined

whether this measure is symmetric between the symptomatic and contralateral limbs in knee OA.

Investigating the relationship between interlimb dynamic joint stiffness and muscular co-contraction in knee OA may elucidate whether the detrimental changes seen in the symptomatic limb demand excessive loading on the asymptomatic limb, thus contributing to its risk of initiating or furthering disease progression (Shakoor et al., 2002). A better understanding of the presence and severity of between-limb asymmetries in knee OA is essential when considering the design of early disease intervention strategies, such as strength training. Therefore, the purpose of this study was to investigate interlimb symmetry of muscular co-contraction and its relation to dynamic knee joint stiffness in a population with osteoarthritis of the knee. We hypothesized there would be a significant difference in both dynamic knee joint stiffness and muscle co-contraction between the OA symptomatic limb and the healthy control group as well as between the OA contralateral limb and the healthy control group. Additionally, we hypothesized the OA subjects would demonstrate interlimb symmetry, with no significant difference between limbs with regard to either dynamic knee joint stiffness and muscle co-contraction.

2. Methods

2.1. Subjects

After receiving Institutional Review Board approval, 17 subjects with mild to moderate (Kellgren Lawrence grade 2–3), unilateral, medial compartment knee OA and 17 healthy control subjects were recruited and participated in this study (Table 1). Subjects' knee OA grade was assessed using the Kellgren Lawrence (KL) grading system (Kellgren and Lawrence, 1957) by inspection of bilateral, anterior–posterior, 30° flexed knee radiographs. Subjects were included in the study if they had a diagnosis of knee OA confirmed by a physician through radiographs. Subjects were excluded from participation if they had severe knee OA (KL grade = 4), any neurologic or cardiopulmonary conditions, musculoskeletal disease or joint replacement, gout, rheumatoid or other systemic inflammatory arthritis, or had intra-articular injections within 6 months prior to testing. Additionally, subjects were excluded if they were unable to walk on a treadmill without an assistive device such as a cane or walker, or without the use of handrails.

2.2. Data collection

Electromyographic data were obtained from dual Ag/AgCl surface electrodes (Noraxon U.S.A. Inc., Scottsdale, AZ) positioned parallel to the muscle fibers over the muscle belly center of the vastus lateralis (VL) and semimembranosus (SM) bilaterally. Proper placement of the electrodes was verified by isolation of each muscle's movements against resistance.

Subject's maximal voluntary isometric contraction (MVIC) was measured using manual resistance and used for normalizing data during the walking trials. Subjects were seated and asked to maximally extend their leg against an external load while the VL MVIC was measured. In order to measure the SM MVIC, subjects stood supported and were asked to

maximally flex their knee while motion of the tibia was resisted. During all MVIC trials, subjects were provided visual feedback of the EMG signal as well as verbal encouragement.

For the walking trials, subjects were asked to walk on an instrumented split-belt treadmill (Bertec Corp., Columbus, OH) at a controlled speed of 1.0 m/s. A speed of 1.0 m/s was used in order to reduce the effect of differences in gait variables that may be directly affected by walking speed (Bejek et al., 2005). Subjects were allowed a familiarization period with treadmill walking in order to collect accurate data for gait analysis (Zeni and Higginson, 2010). Data was then collected for a period of 30 seconds while subjects continued walking. Subjects were also connected to an overhead safety harness which safeguarded against falling. Raw analog EMG signals were digitally sampled at 1080 Hz. Center of pressure and ground reaction force data from both the left and right force plates were also collected at 1080 Hz. Three-dimensional kinematics were obtained via 23 retroreflective markers placed bilaterally (Zeni and Higginson, 2009b). An eight camera motion capture system (Motion Analysis, Santa Rosa, CA) collected kinematic data at 60 Hz. Joint moments were determined by inverse dynamics using Orthotrak 6.3.4 (Motion Analysis) and normalized to subject's body mass. In the healthy control subjects, the limb chosen for analysis alternated between right and left for each consecutive subject.

2.3. Data processing

All marker coordinate data was smoothed with a 4th order Butterworth filter with a cutoff frequency of 6 Hz.

Raw EMG data collected during all walking and MVIC trials were bandpass filtered at 20–400 Hz with a 4th order Butterworth filter. The data were then rectified and passed through a low pass 8th order filter with a cutoff frequency of 20 Hz in order to create a linear envelope. The data was then normalized to peak values obtained during MVICs.

Gait events were determined from kinematic data and each gait cycle was time normalized to 101 points. Kinematic, EMG, and joint moment data were averaged to create a single trial for each subject.

All joint moments are reported as external joint moments. Dynamic joint stiffness (K_{joint}) was defined as the change in knee flexion moment (M) divided by the change in knee flexion angle (θ):

$$K_{\text{joint}} = \frac{\Delta M}{\Delta \theta} \quad (1)$$

Joint stiffness was analyzed over the period of minimum knee joint flexion moment to the point of peak knee flexion angle during the stance phase of gait (Fig. 1). Joint stiffness was calculated as the slope of the regression line between knee flexion moment and angle during this period (Fig. 2).

The co-contraction index (CCI) was defined as the simultaneous activation of the hamstrings and quadriceps muscle pair and was calculated using the equation below:

$$CCI = \frac{\sum_{i=1}^{100} \left[\left(\frac{LowerEMG_i}{HigherEMG_i} \right) \times (LowerEMG_i + HigherEMG_i) \right]}{100} \quad (2)$$

where the less active muscle is represented by *LowerEMG* and the more active muscle is represented by *HigherEMG* (2) (Schmitt and Rudolph, 2007). Similar to joint stiffness, CCI was analyzed over the period of minimum knee joint flexion moment to the point of peak knee flexion angle during the stance phase of gait.

2.4. Statistical analysis

A paired *t*-test was performed to determine whether significant differences exist in both dynamic joint stiffness and CCI between the OA symptomatic and OA contralateral groups. Independent *t*-tests were performed between the healthy and OA symptomatic groups and the healthy and OA contralateral groups to determine whether significant differences exist in co-contraction and dynamic joint stiffness ($p < 0.05$). Statistical analysis was performed using SigmaPlot (Systat Software Inc., San Jose, CA).

3. Results

There were no differences in dynamic knee joint stiffness between the OA symptomatic and contralateral limbs. Independent *t*-tests revealed no differences between the healthy and OA symptomatic group or between the healthy and OA contralateral group.

Paired *t*-tests revealed no significant differences in co-contraction index between the OA symptomatic and contralateral limbs. Additionally, independent *t*-tests showed a slight, but not statistically significant difference in co-contraction between the healthy and OA symptomatic group. There was also no significant difference in co-contraction between the healthy and OA contralateral group. All outcome measure results are presented in Table 2.

4. Discussion

This study is the first to examine interlimb symmetry of dynamic knee joint stiffness and muscular co-contraction in those with knee OA. A secondary purpose of this study was to determine whether these measures were similar between healthy and OA symptomatic knees as well as between healthy and OA contralateral knees. We found no significant differences in either the dynamic joint stiffness or co-contraction between limbs or between the OA and healthy groups.

It has been shown that those with knee OA demonstrate heightened co-contraction of antagonistic muscle groups, specifically the quadriceps and hamstrings muscle groups (Childs et al., 2004), which is a natural compensatory adaptation to quadriceps weakness and pain (Sharma, 2001). Childs et al. found significant increases in co-activation of the vastus lateralis and medial ham-strings during walking in those with grade 2 or greater knee OA compared to a healthy control group (Childs et al., 2004). However, our data indicate there is no difference in co-contraction between those with OA and a healthy group or

between limbs in those with early stage knee OA during the loading response phase of gait which may be a direct result of the mild to moderate nature of OA severity in our cohort.

As muscle co-contraction is presumed to relate to dynamic knee joint stiffness and we found symmetric muscle strategy patterns between limbs, it is not surprising that we found no statistically significant differences in dynamic knee joint stiffness between limbs or between the OA and healthy groups. Our results are similar to a previous study by Zeni and Higginson (2009b) that investigated dynamic knee joint stiffness in a population with different severities of knee OA and found no differences between a group with moderate OA and a healthy control group. However, when comparing between the different severities of OA, Zeni et al. found significant differences in stiffness between severe knee OA and moderate OA ($p = 0.034$) and between severe knee OA and the healthy control group ($p = 0.025$). This interesting point leads one to question when a trigger such as pain or instability comes into play in the joint degeneration timeline, forcing alterations in muscle strategy and subsequent changes to measures such as joint stiffness. Our findings of interlimb symmetry of co-contraction and joint stiffness indicate that pain and instability may not influence gait mechanics in those with mild to moderate knee OA.

The exclusion of severe knee OA from our study is a limiting factor and may be the reason no statistically significant differences were found between limbs or between groups. Previous studies examining gait in knee OA have included this subpopulation (Schmitt and Rudolph, 2007; Dixon et al., 2010; Hunt et al., 2010) and have found that parameters such as impact loading and stiffness are affected by increasing OA severity (Hunt et al., 2010; Zeni and Higginson, 2009b). However, we elected to study the early knee OA cohort since the literature is lacking in this area. Additionally, walking speed has been shown to be an important factor as studies have demonstrated alterations in gait mechanics with increases in walking speed (Zeni and Higginson, 2009a). In the present study, we conducted our analysis at a controlled walking speed (1.0 m/s) and found no differences in either joint stiffness or co-contraction. Similarly, Zeni et al. found no differences in sagittal plane hip, knee or ankle joint moments or knee joint excursion when subjects walked at 1.0 m/s (Zeni and Higginson, 2009a). It is possible that utilizing faster walking speeds or the subject's own self-selected walking speed would have elicited greater changes in dynamic knee joint stiffness and muscular co-contraction (Zeni and Higginson, 2009a). However, the study's overall question involved the effect of OA status and by controlling for walking speed we eliminated the need to consider additional factors in our analysis.

5. Conclusions

From this study, we found that interlimb symmetry of co-contraction and dynamic knee joint stiffness is maintained in those with mild to moderate medial knee OA. This finding may shed new light on the timeline of OA progression as interlimb asymmetry may present itself much later in the course of the disease. Future work should investigate these measures between limbs in those with severe knee OA.

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Biography

Amber Collins holds advanced degrees in Biomedical Engineering in addition to an undergraduate degree in Chemical Engineering. Dr. Collins' main research interest is in osteoarthritis of the knee, specifically investigating novel imaging modalities that can help to better understand the course of osteoarthritis progression. Dr. Collins has written several articles on the use of subthreshold electrical stimulation to improve gait, proprioception, and posture in those with knee OA in addition to papers investigating interlimb symmetry in those with early stage knee OA. More recently, Dr. Collins has explored and published articles describing the use of magnetic resonance imaging modalities to measure morphological and compositional changes in knee cartilage that occur acutely with mechanical loading and more long term as a result of injury.

Tyler Richardson received his B.S. in Mechanical Engineering ('10) and his M.S. in Biomechanics and Movement Science ('12) from the University of Delaware. He is currently pursuing a Ph.D. in Biomechanics and Movement Science from the University of Delaware. His research interests include musculoskeletal modeling of the shoulder and upper extremity and developing new techniques to measure scapular kinematics.

Dr. Higginson is an Associate Professor in the Departments of Mechanical Engineering and Biomedical Engineering at the University of Delaware. She has also served as the Director of the Center for Biomechanical Engineering Research and Associate Director of Biomedical Engineering at UD. She trained at Cornell University (BS Mechanical Engineering '96), Penn State University (MS Bioengineering '98), and Stanford University (PhD Mechanical Engineering '05). Her research applies experimental and computational techniques to study muscle coordination during walking in healthy and impaired populations. Ongoing projects supported by the NIH target abnormal muscle control strategies in stroke and osteoarthritis.

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Fig. 1.

Dynamic joint stiffness was calculated from the point of minimum knee flexion moment to the point of maximum knee flexion angle during the stance phase of gait.

Fig. 2.

Dynamic knee joint stiffness was calculated as the slope of the line when flexion moment is plotted against flexion angle within the bounds described in Fig. 1.

Table 1

Mean (sd) demographic information for all male (M) and female (F) test subjects.

	OA			Healthy		
	F (n = 10)	M (n = 7)	n = 17	F (n = 9)	M (n = 8)	n = 17
Age (years)	60 (9.0)	66.4 (8.4)	62.6 (9.1)	57.2 (7.2)	66.1 (11.5)	61.4 (10.2)
Weight (kg)	84.6 (13.4)	89.5 (11.1)	86.6 (12.4)	65.6 (10.7)	81.1 (10.2)	72.9 (12.9)
BMI (kg/m ²)	31.1 (5.9)	29.0 (2.0)	30.3 (4.7)	24.0 (3.0)	25.9 (2.0)	24.9 (2.7)
KL grade	2.6 (0.52)	2.3 (0.49)	2.47 (0.51)	0.97 (0.08)	0.94 (0.18)	0.95 (0.02)

Table 2

Co-contraction indices (CCI) and dynamic knee joint stiffness (K_{joint}) mean (sd) values.

	OA Symptomatic	OA Contralateral	<i>p</i>	Healthy	<i>p</i> ^a	<i>p</i> ^b
K_{joint}	0.052 (0.022)	0.047 (0.014)	0.247	0.049 (0.011)	0.600	0.635
CCI	0.218 (0.167)	0.212 (0.175)	0.874	0.125 (0.078)	0.051	0.078

^aIndicates significance between the OA symptomatic limb and healthy group.

^bIndicates significance between the OA contralateral limb and healthy group.