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Dynamic Knee Joint Stiffness in Subjects with a Progressive Increase in Severity of Knee Osteoarthritis

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Abstract

Background—Persons with knee osteoarthritis demonstrate a reduction in knee joint excursion during loading response which is often coupled with a reduction in the moment acting to flex the knee. While these individual kinetic and kinematic changes are well documented, the interaction between changes in joint moment and changes in joint angle (dynamic joint stiffness) is not well understood in persons with knee osteoarthritis.

Methods—Twelve persons with severe knee osteoarthritis (Kellgren-Lawrence score 4) and twenty-two persons with moderate knee osteoarthritis (Kellgren-Lawrence score 2-3) were compared to a healthy control group ($n=22$). Dynamic knee joint stiffness was calculated during loading response and was defined as the slope of the linear regression when joint moment is plotted against joint angle. Group differences were compared at 1.0 m/s, self-selected and fast walking speeds using a one-way ANOVA, as well as a one-way ANCOVA to account for differences in freely chosen walking speed. Differences between speeds were compared using an ANOVA with one repeated measure (walking speed).

Findings—At all walking speeds, the severe group had significantly higher stiffness, even when accounting for differences in walking speed ($p \leq 0.038$). A significant increase in dynamic joint stiffness was found for all groups when speed was increased ($p=0.001$).

Interpretation—Persons with advanced stages of knee osteoarthritis develop higher joint stiffness irrespective of walking speed. While this may be a strategy to overcome knee instability often reported in this population during walking, the potential detrimental effects of higher dynamic joint stiffness should be explored in future research.

Introduction

Reduced knee flexion excursion during the loading response of gait is a kinematic characteristic that has been shown to be associated with a multitude of knee pathologies (Lewek et al., 2004, Ramsey et al., 2007). In persons with knee osteoarthritis (OA), this reduction in knee flexion during walking is often coupled with a reduction in the moment acting to flex the knee during loading response (Astefan et al., 2008a, Baliunas et al., 2002). However, the interaction between changes in joint moment and changes in joint angle, referred to as dynamic joint stiffness, is not well understood in persons with knee OA. Dynamic joint stiffness has

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been defined as the slope of the line when joint moment is plotted against joint angle (Davis and DeLuca, 1996, Hansen et al., 2004, Farley et al., 1998). It has also been identified as “quasi-stiffness” of a joint and the linear portions of this curve can be interpreted as the resistance that muscles and soft tissue provide during joint excursion (Latash and Zatsiorsky, 1993).

The ability to utilize muscle strategies that resist external forces is especially important in a population where joint stability is reduced during dynamic activities. Persons with knee OA report reduced joint stability during activities of daily living, and this instability interferes with their ability to function (Fitzgerald et al., 2004). Increased passive laxity in the medial direction has also been repeatedly found in persons with knee OA (Schmitt and Rudolph, 2007, Rudolph et al., 2007, Lewek et al., 2004). To overcome instability and joint laxity, persons with knee OA may utilize higher antagonistic muscle activity and develop higher dynamic joint stiffness during walking. However, joint stiffness in the OA population has not been explored.

Factors underlying increases in dynamic joint stiffness, such as higher antagonistic muscle activity, may overcome dynamic instability but potentially expedite the progression of cartilage deterioration through higher sustained joint compression forces (Piscoya et al., 2005, Griffin and Guilak, 2005). In order to better understand the progression of the disease, biomechanical alterations that may affect joint loading should be investigated. Analysis of dynamic joint stiffness may therefore provide information about strategies used to overcome instability while alluding to potential reasons for disease progression. To determine how gait alterations evolve with an increase in disease progression, it is important to differentiate between stages of the disease. Many previous authors who have investigated changes that occur in the presence of OA have not differentiated subjects into groups based on radiographic severity of the disease (Landry et al., 2007, Al-Zahrani and Bakheit, 2002, Kaufman et al., 2001), even though the severity of OA may influence walking patterns or vice versa (Astefan et al., 2008b). Joint moments, muscle activation patterns and freely chosen walking speeds have been shown to change with OA severity (Astefan et al., 2008b, Astefan et al., 2008a). It is unknown whether dynamic joint stiffness may also be dependent on the severity of knee OA.

Slower self-selected walking speeds have been well documented in persons with knee OA (Al-Zahrani and Bakheit, 2002, Kaufman et al., 2001). Reductions in walking speed have also been shown to alter joint angles and moments in healthy and pathological populations (Bejek et al., 2006). While the reduction of walking speed may be an effective mechanism to decrease joint reaction forces and moments (Robon et al., 2000, Mundermann et al., 2004), it is currently unclear whether this will also have an effect on the reduction of joint stiffness in persons with OA.

The magnitude of dynamic joint stiffness in persons with knee OA has not been explored. Understanding movement patterns in response to external forces and moments in a progressive OA population will shed greater insight into how the neuromuscular system coordinates movement in an impaired population. The purpose of this study was to evaluate dynamic knee joint stiffness at self-selected, control and fast walking speeds in persons with moderate and severe OA relative to a healthy control group. It is hypothesized that persons with higher grades of knee OA will develop higher levels of dynamic joint stiffness, irrespective of walking speed.

Methods

Subjects

Fifty six subjects (age 40-83 years) participated in the study. In order to reduce confounding variables and the chance of adverse events during walking trials, subjects were excluded if they had any other significant neurological, cardiopulmonary or orthopedic diseases. Subjects were also excluded if they had been diagnosed with any other lower extremity joint arthritis. All

subjects underwent 30 degree flexed knee posterior to anterior radiographs of both knees. Subjects were assigned to groups based on the presence of knee pain and Kellgren-Lawrence OA grades (Kellgren and Lawrence, 1957). Twenty-two subjects without knee pain with daily activities or radiographic evidence of knee OA were classified as control subjects, while 22 subjects had Kellgren-Lawrence grades of 2-3 and were classified as moderate. The remaining 12 subjects had grade 4 OA and were classified as severe. Demographics for all the subject groups are presented in Table 1. All subjects signed an informed consent form approved by the Human Subjects Review Board and were informed of the risks and benefits prior to participating in any facet of the study.

Data Collection and Reduction

Self-selected walking speed was determined by a 20m walk down a hallway in which the middle 10m were timed. All subjects walked at their self-selected speed and at a control speed of 1.0 m/s on an instrumented split-belt treadmill with dual force plates (Bertec Corp., Columbus, OH, USA). The control speed of 1.0 m/s was used to reduce the effect of differences in gait variables that may be directly related to walking speed (Bejek et al., 2006, Andriacchi et al., 1977). Subjects also walked at their fastest tolerable speed which was defined as the maximum speed at which the subjects were able to safely walk on the treadmill without running or holding onto the handrails. During all of the walking trials, three dimensional kinematic data was recorded at 60 Hz from 23 reflective markers using a six camera Motion Analysis system (Santa Rosa, CA, USA). Three-dimensional marker trajectories were smoothed in post-processing using a recursive Butterworth filter with a cutoff frequency of 6 Hz (EvaRT 5.0.4, Motion Analysis Corp., Santa Rosa, CA, USA). Ground reaction forces and center of pressure data were obtained at 1080 Hz from the two force plates. As a safety precaution, all subjects were harnessed to an overhead support and had access to an emergency stop button located on the handrail. The harness consisted of a belt that subjects wore around the chest and under the arms. No subjects reported any discomfort or difficulty walking while using the overhead harness.

Inverse dynamic calculations of joint moments were performed using OrthoTrak 6.3.5 (Motion Analysis Corp., Santa Rosa, CA, USA). Ground reaction force and center of pressure data was filtered with a recursive 4th order Butterworth filter with a cutoff frequency of 40 Hz. Joint moments were normalized to body mass and are presented as Nm/Kg. Gait events were determined from kinematic data and each gait cycle was time normalized to 101 points (Zeni Jr et al., 2008). At each walking speed, the kinematic and joint moment data from each 30 second trial were averaged to create a single trial for each subject. These averaged trials were used in the data analysis.

Dynamic joint stiffness at the knee was calculated for each subject and is defined as the change in joint moment (M) divided by the change in joint angle (θ):

$$K_{jnt} = \frac{\Delta M}{\Delta \theta} \quad (\text{Eq. 1})$$

For the convention of this paper, joint angle is plotted on the X-axis and an increase in the joint angle represents an increase in knee flexion. Joint moment is plotted along the Y-axis and an increase in joint moment represents an increase in the net external flexion moment. For the knee, dynamic joint stiffness was analyzed over the linear region during loading response, or 3-15% of the gait cycle. This time period starts when the average external knee flexion moment begins to increase and terminates with peak knee flexion. A larger positive slope indicates an increase in dynamic joint stiffness of the knee (Figure 1).

Statistical Analysis

Group means of the slope (K_{jnt}) for the self-selected, control and fast walking conditions were determined. Differences between group means were assessed with individual one-way ANOVAs and Tukey post-hoc testing when appropriate. Differences in dynamic joint stiffness were also analyzed with individual one-way ANCOVAs using respective walking speed as a covariate to determine whether speed impacted the differences between groups. Individual ANOVAs with one repeated measure (walking speed) were used to determine differences in joint stiffness between the self-selected and 1.0 m/s speeds, as well as between the self-selected and fast walking speeds. All statistical tests were performed using SPSS software v.16 (Chicago, IL, USA).

Results

Between group differences

Subjects with different severity of knee OA walked with different freely chosen speeds and different temporo-spatial values at the self-selected and fast walking conditions (Table 2). The severe group had the slowest self-selected and fast walking speed, while the control group had significantly higher speeds at both conditions ($p < 0.02$). No significant differences in freely chosen walking speed were found between the moderate and severe OA group ($p > 0.13$). Corresponding to the differences in freely chosen walking speed, differences were seen between the OA and control groups for stride duration and stride length. No differences were found between subjects for cadence at the self-selected ($p \geq 0.25$) or the fast walking speed ($p \geq 0.13$). At 1.0 m/s no differences were found between groups for any of the temporo-spatial variables ($p \geq 0.20$).

At 1.0 m/s, subjects with severe OA had the highest dynamic joint stiffness values (0.098 Nm/degree) (Figure 2). This was significantly higher than the moderate group (0.067 Nm/degree) ($p = 0.034$) and the control group (0.066 Nm/degree) ($p = 0.025$). No differences were found between the control and moderate group at 1.0 m/s ($p = 0.993$). At the self-selected and the fast walking speeds, the severe OA group also had the highest dynamic joint stiffness values (0.084 and 0.095 Nm/degree, respectively) (Figure 3). At the self-selected walking speed, differences were significant between the severe OA and control groups ($p = 0.038$). At the fast walking speed, subjects with severe OA had significantly higher stiffness values than the control and moderate OA groups ($p = 0.022$ and 0.017 respectively). No significant differences were seen between the control and moderate OA groups at any of the speeds ($p > 0.79$). When the data was analyzed using an ANCOVA to account for differences in walking speed, significant differences between groups were still found at both the self-selected and fast walking speed.

Between speed differences

Dynamic joint stiffness values were significantly higher at the fast walking speed compared to the self-selected speed ($p = 0.001$) (Figure 3). The speed by group interaction effect was not significant ($p = 0.27$). Although not significant, the severe group did have a higher percentage increase in dynamic joint stiffness (7.4% control, 4.5% moderate, 13% severe) for a lower percentage increase in walking speed (40% control, 34% moderate, 33% severe). Differences in dynamic joint stiffness between 1.0 m/s and self-selected walking speed were not significant ($p = 0.075$), however there was a significant interaction effect (group $\times$ speed) ($p = 0.025$). Pair-wise comparison revealed significant differences in dynamic joint stiffness for the severe group between self-selected and 1.0 m/s speeds ($p = 0.005$), while the moderate OA and control groups showed no difference between the two conditions.

Discussion

The purpose of this study was to evaluate the effects of increased OA severity on dynamic joint stiffness during walking. From our results we can conclude that subjects with more advanced disease ambulate with higher dynamic joint stiffness values at the knee. We also found that increasing walking speed resulted in further increases in dynamic joint stiffness values (Figure 3). Moreover, subjects with severe OA have higher dynamic knee joint stiffness values irrespective of freely chosen walking speed.

In this study, persons with more severe knee OA presented with lower functional ability compared to healthy controls and persons with moderate OA (Table 1). Since instability is related to a person's self-perceived functional ability, individuals with more severe OA may also demonstrate the highest amount of instability during walking (Fitzgerald et al., 2004). This may result in the need for higher muscular resistance to external forces. It is known that persons with severe OA utilize a motor coordination strategy that results in higher antagonistic muscle activity at the knee (Lewek et al., 2004, Astephen et al., 2008b). The increase in stabilizing muscle forces may decrease the sagittal plane knee range of motion during loading response and result in the larger dynamic joint stiffness values that were found in this study when persons with severe OA were compared to healthy controls and persons with less severe OA. This result is similar to previous findings (Lark et al., 2003) Although they compared younger individuals to healthy elderly individuals, they concluded that the increased dynamic joint stiffness in the elderly group may represent a compensatory strategy to overcome a reduced ability to generate quick ankle torques in response to changes in external forces. Because persons with OA have decreased joint stability, reduced proprioception, and reduced efferent response to changes in external forces, they may develop higher dynamic joint stiffness as a method to safely navigate through their environment (Shakoor et al., 2008, Hortobagyi et al., 2004, Sharma and Pai, 1997, Fitzgerald et al., 2004).

While an increase in dynamic joint stiffness and antagonistic muscle activity may act to maintain stability of the knee that has been compromised as a result of the disease process, it may have deleterious effects on the integrity of the cartilage. It has been shown in vivo and experimentally that higher amounts of muscular forces can result in higher amounts of joint compression forces (Kellis, 2001, Taylor and Walker, 2001). This increase in compression force may advance the disease process (Griffin and Guilak, 2005). Coupled with the fact that the severe persons were also significantly heavier than persons without OA, this may dramatically increase the compression forces in these subjects (Messier et al., 2005).

With our present subject population, we found no differences in dynamic joint stiffness between persons with moderate OA and persons without radiographic evidence of the disease. It should be noted, however, that subjects in the moderate OA group had knee excursions that were smaller than the control group and similar to that of the severe OA group (Figure 3). Although the range of motion was similar, the subjects with severe OA had a larger average change in knee moment at each time step resulting in higher dynamic joint stiffness values. It is possible that higher loads over a smaller range of articular surface may initiate the disease process or expedite cartilage degeneration. Diseased cartilage has a reduced ability to repair itself in the presence of external loads (Griffin and Guilak, 2005). If similar loads were to be placed on a smaller range of articular surface (or if these loads were to remain on the same area for longer periods of time), this may result in further deterioration of the articulating surface. Increased dynamic joint stiffness values, or higher loads over a smaller range, may play an important role in OA pathogenesis.

Unlike other gait parameters in persons with knee OA, differences in dynamic joint stiffness between healthy controls and persons with severe OA does not seem to be related to self-

selected walking speed. While it has been shown that persons with knee OA may walk with reduced joint moments and excursions, many previous studies have not accounted for differences in walking speed between healthy subjects and persons with knee OA (Al-Zahrani and Bakheit, 2002, Astephen et al., 2008a, Gok et al., 2002). It has been well documented that these variables are highly influenced by walking speed (Chiu and Wang, 2007, Bejek et al., 2006, Landry et al., 2007, Mockel et al., 2003, Lelas et al., 2003, Andriacchi et al., 1977). In this study, we found that dynamic joint stiffness significantly increased with an increase in walking speed. Intuitively we would expect that if differences between subjects were a result of differences in walking speed, the subjects that walked slower (persons with severe knee OA) would have lower stiffness values. We found the exact opposite relationship such that subjects with severe OA had the highest stiffness values at freely chosen walking speeds. This was further highlighted by the fact that differences also existed when subjects walked at a constrained speed. Additionally, when walking speed was included as a covariate in the analysis at freely chosen walking speeds, the severe group still showed statistically higher dynamic joint stiffness values. We can conclude that persons with knee OA demonstrate higher dynamic joint stiffness, irrespective of freely chosen walking speed.

Differences in temporo-spatial variables may also influence joint excursions, joint moments and subsequently dynamic joint stiffness. Despite this, it appears that inter-group alterations in these variables cannot explain all of significant differences that we found between groups for dynamic joint stiffness. At 1.0 m/s, no differences were found for stride duration, stride length and cadence between groups, although we still saw differences in dynamic joint stiffness between the severe and control and moderate groups. This further supports the thought that higher dynamic joint stiffness is used by the severe group as an intrinsic response to instability or the result of higher muscular forces at the knee joint, not merely a result of altered walking speed and temporo-spatial values.

One limitation of this study is the inability to determine the physiological cause of altered dynamic joint stiffness. While neuromuscular changes are often cited as the reason for increases in joint stiffness during dynamic activities (Rudolph et al., 2007), it is possible that changes in intrinsic joint mechanics result in higher joint stiffness. Alterations in the joint environment have been cited in the presence of degenerative changes to the articular surface (Link et al., 2003, Phan et al., 2006). Although medial laxity may persist in the presence of advanced disease, a reduction in the anterior/posterior laxity of the knee joint has been found with end-stage knee OA (Wada et al., 1996). Physical changes such as the presence of osteophytes and hardening of the joint capsule have been suggested as potential causes for the increased stiffness.

Anterior/posterior stiffness coupled with increased friction due to osteophyte formation and incongruent joint surfaces may reduce the ability of the tibiofemoral joint to translate during knee flexion. While this may increase dynamic joint stiffness, it may also increase the pain response associated with knee flexion during the loading phase of gait. Higher muscle activity aimed at reducing the knee flexion and pain with movement would also result in higher dynamic joint stiffness. Future research aimed at determining the underlying cause of joint stiffness would greatly improve our knowledge of mechanical and neuromuscular changes that occur in the presence of advanced knee OA.

In the current study, we evaluated a cross-sectional sample of persons with progressive grades of knee OA. Thus, we are unable to determine whether the differences that we see in joint stiffness arise as a result of the increase in OA severity, or whether changes in joint stiffness may be partially responsible for the progression of the disease. Future work should include a longitudinal assessment to determine if subjects that present with high dynamic joint stiffness at baseline show advanced disease progression at follow-up.

From this study, we conclude that persons with advanced stages of OA walk with greater dynamic joint stiffness. While further research into the cause of dynamic joint stiffness is warranted, subjects with severe OA may reduce knee joint excursion in an attempt to stabilize the joint against external joint moments. Similar to other gait parameters, dynamic joint stiffness values increase in the presence of increased walking speeds. Despite this, persons with severe OA develop a higher level of dynamic joint stiffness irrespective of freely chosen walking speed which may have detrimental consequences for disease progression.

References

- Al-Zahrani KS, Bakheit AM. A study of the gait characteristics of patients with chronic osteoarthritis of the knee. *Disabil Rehabil* 2002;24:275–80. [PubMed: 12004973]
- Andriacchi TP, Ogle JA, Galante JO. Walking speed as a basis for normal and abnormal gait measurements. *J Biomech* 1977;10:261–8. [PubMed: 858732]
- Astephen JL, Deluzio KJ, Caldwell GE, Dunbar MJ. Biomechanical changes at the hip, knee, and ankle joints during gait are associated with knee osteoarthritis severity. *J Orthop Res* 2008a;26:332–41. [PubMed: 17960658]
- Astephen JL, Deluzio KJ, Caldwell GE, Dunbar MJ, Hubley-Kozey CL. Gait and neuromuscular pattern changes are associated with differences in knee osteoarthritis severity levels. *J Biomech* 2008b; 41:868–76. [PubMed: 18078943]
- Baliunas AJ, Hurwitz DE, Ryals AB, Karrar A, Case JP, Block JA, Andriacchi TP. Increased knee joint loads during walking are present in subjects with knee osteoarthritis. *Osteoarthritis Cartilage* 2002;10:573–9. [PubMed: 12127838]
- Bejek Z, Paroczai R, Illyes A, Kiss RM. The influence of walking speed on gait parameters in healthy people and in patients with osteoarthritis. *Knee Surg Sports Traumatol Arthrosc* 2006;14:612–22. [PubMed: 16331521]
- Chiu MC, Wang MJ. The effect of gait speed and gender on perceived exertion, muscle activity, joint motion of lower extremity, ground reaction force and heart rate during normal walking. *Gait Posture* 2007;25:385–92. [PubMed: 16814548]
- Davis RB, DeLuca P. Gait characterization via dynamic joint stiffness. *Gait and Posture* 1996;4:224–231.
- Farley CT, Houdijk HH, Van Strien C, Louie M. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *J Appl Physiol* 1998;85:1044–55. [PubMed: 9729582]
- Fitzgerald GK, Piva SR, Irrgang JJ. Reports of joint instability in knee osteoarthritis: its prevalence and relationship to physical function. *Arthritis Rheum* 2004;51:941–6. [PubMed: 15593258]
- Gok H, Ergin S, Yavuzer G. Kinetic and kinematic characteristics of gait in patients with medial knee arthrosis. *Acta Orthop Scand* 2002;73:647–52. [PubMed: 12553511]
- Griffin TM, Guilak F. The role of mechanical loading in the onset and progression of osteoarthritis. *Exerc Sport Sci Rev* 2005;33:195–200. [PubMed: 16239837]
- Hansen AH, Childress DS, Miff SC, Gard SA, Mesplay KP. The human ankle during walking: implications for design of biomimetic ankle prostheses. *J Biomech* 2004;37:1467–74. [PubMed: 15336920]
- Hortobagyi T, Garry J, Holbert D, Devita P. Aberrations in the control of quadriceps muscle force in patients with knee osteoarthritis. *Arthritis Rheum* 2004;51:562–9. [PubMed: 15334428]
- Kaufman KR, Hughes C, Morrey BF, Morrey M, An KN. Gait characteristics of patients with knee osteoarthritis. *J Biomech* 2001;34:907–15. [PubMed: 11410174]
- Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthritis. *Ann Rheum Dis* 1957;16:494–502. [PubMed: 13498604]
- Kellis E. Tibiofemoral joint forces during maximal isokinetic eccentric and concentric efforts of the knee flexors. *Clin Biomech* 2001;16:229–36.
- Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, Deluzio KJ. Knee biomechanics of moderate OA patients measured during gait at a self-selected and fast walking speed. *J Biomech* 2007;40:1754–61. [PubMed: 17084845]

- Lark S, Buckley J, Bennett S, Jones D, Sargeant A. Joint torques and dynamic joint stiffness in elderly and young men during step down. *Clinical Biomechanics* 2003;18:848–55. [PubMed: 14527812]
- Latash M, Zatsiorsky V. Joint stiffness: Myth or reality? *Human Movement Science* 1993;12:653–692.
- Lelas JL, Merriman GJ, Riley PO, Kerrigan DC. Predicting peak kinematic and kinetic parameters from gait speed. *Gait Posture* 2003;17:106–12. [PubMed: 12633769]
- Lewek MD, Rudolph KS, Snyder-Mackler L. Control of frontal plane knee laxity during gait in patients with medial compartment knee osteoarthritis. *Osteoarthritis Cartilage* 2004;12:745–51. [PubMed: 15325641]
- Link TM, Steinbach LS, Ghosh S, Ries M, Lu Y, Lane N, Majumdar S. Osteoarthritis: MR imaging findings in different stages of disease and correlation with clinical findings. *Radiology* 2003;226:373–81. [PubMed: 12563128]
- Messier SP, Guekuntz DJ, Davis C, DeVita P. Weight loss reduces knee-joint loads in overweight and obese older adults with knee osteoarthritis. *Arthritis Rheum* 2005;52:2026–32. [PubMed: 15986358]
- Mockel G, Perka C, Labs K, Duda G. The influence of walking speed on kinetic and kinematic parameters in patients with osteoarthritis of the hip using a force-instrumented treadmill and standardised gait speeds. *Arch Orthop Trauma Surg* 2003;123:278–82. [PubMed: 12748870]
- Mundermann A, Dyrby CO, Hurwitz DE, Sharma L, Andriacchi TP. Potential strategies to reduce medial compartment loading in patients with knee osteoarthritis of varying severity: reduced walking speed. *Arthritis Rheum* 2004;50:1172–8. [PubMed: 15077299]
- Phan CM, Link TM, Blumenkrantz G, Dunn TC, Ries MD, Steinbach LS, Majumdar S. MR imaging findings in the follow-up of patients with different stages of knee osteoarthritis and the correlation with clinical symptoms. *Eur Radiol* 2006;16:608–18. [PubMed: 16222533]
- Piscocya JL, Fermor B, Kraus VB, Stabler TV, Guilak F. The influence of mechanical compression on the induction of osteoarthritis-related biomarkers in articular cartilage explants. *Osteoarthritis Cartilage* 2005;13:1092–9. [PubMed: 16168680]
- Ramsey DK, Snyder-Mackler L, Lewek M, Newcomb W, Rudolph KS. Effect of anatomic realignment on muscle function during gait in patients with medial compartment knee osteoarthritis. *Arthritis Rheum* 2007;57:389–97. [PubMed: 17394224]
- Robon MJ, Perell KL, Fang M, Guererro E. The relationship between ankle plantar flexor muscle moments and knee compressive forces in subjects with and without pain. *Clin Biomech* 2000;15:522–7.
- Rudolph KS, Schmitt LC, Lewek MD. Age-related changes in strength, joint laxity, and walking patterns: are they related to knee osteoarthritis? *Phys Ther* 2007;87:1422–32. [PubMed: 17785376]
- Schmitt LC, Rudolph KS. Influences on knee movement strategies during walking in persons with medial knee osteoarthritis. *Arthritis Rheum* 2007;57:1018–1026. [PubMed: 17665469]
- Shakoor N, Agrawal A, Block JA. Reduced lower extremity vibratory perception in osteoarthritis of the knee. *Arthritis Rheum* 2008;59:117–21. [PubMed: 18163397]
- Sharma L, Pai YC. Impaired proprioception and osteoarthritis. *Curr Opin Rheumatol* 1997;9:253–8. [PubMed: 9204262]
- Taylor SJ, Walker PS. Forces and moments telemetered from two distal femoral replacements during various activities. *J Biomech* 2001;34:839–48. [PubMed: 11410168]
- Wada M, Imura S, Baba H, Shimada S. Knee laxity in patients with osteoarthritis and rheumatoid arthritis. *Br J Rheumatol* 1996;35:560–3. [PubMed: 8670577]
- Zeni J Jr, Richards J, Higginson J. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait Posture* 2008;27:710–4. [PubMed: 17723303]

Figure 1.

Dynamic joint stiffness was calculated as the slope of the linear regression line when knee joint moment is plotted as a function of knee joint angle. This was done over the linear region during loading response, represented by the shaded region on the joint moment and angle plots.

Figure 2.

Calculated dynamic joint stiffness for all three groups at the control walking speed of 1.0 m/s. At 1.0 m/s, subjects with in the severe OA group had significantly higher dynamic joint stiffness values than either the moderate or control groups.

Figure 3.

Dynamic joint stiffness for all three groups at the self-selected (*left*) and fast (*right*) walking conditions. Subjects with severe OA had significantly higher dynamic joint stiffness values when compared to the control and moderate OA groups. Subjects with OA have lower mean knee joint excursion as evidenced by the smaller change in knee angle compared to the control group.

Table 1

Demographic data from each of the subject groups. Means are given with the standard deviation in parentheses below each group mean. Differences between the respective group and the control group are represented by (*) ($p \leq 0.05$).

	Control	Moderate	Severe
Age (years)	58.9 (11.4)	62.9 (7.8)	60.5 (9.5)
BMI (kg/m ²)	24.9 (3.7)	30.2* (4.6)	30.7* (5.0)
Height (m)	1.66 (0.05)	1.70 (0.09)	1.75 (0.11)
KOOS score	481.6 (25.1)	304.5* (96.1)	227.4* (94.0)

Temporo-spatial characteristics of the subjects at the different walking speeds. The severe group had significantly lower freely chosen walking speeds (*). Significant differences in stride length and stride duration were found between the OA groups and the control group at the freely chosen walking speeds (*). Significant differences between the severe group and moderate group are denoted (^{ab}). All variables were determined from the involved limb for the OA groups.

Self-selected			Fastest			1.0 m/s		
Walking Speed (m/s)	Control	1.25	(0.20)	1.75	(0.21)			
	Moderate	1.14	(0.12)	1.53	(0.20)			
	Severe	*1.05	(0.21)	*1.43	(0.21)			
Stride duration (s)	Control	1.06	(0.06)	0.90	(0.08)		1.13	(0.08)
	Moderate	1.07	(0.08)	0.94	(0.08)		1.11	(0.09)
	Severe	* ^a 1.15	(0.09)	*1.00	(0.06)		1.12	(0.08)
Stride length (cm)	Control	124.6	(16.30)	161.21	(19.05)		108.70	(11.39)
	Moderate	*111.1	(10.45)	*141.64	(17.51)		102.52	(8.02)
	Severe	*105.99	(26.07)	*136.02	(23.58)		109.21	(15.58)
Cadence (steps/minute)	Control	118.87	(11.79)	141.96	(15.47)		109.13	(8.14)
	Moderate	114.04	(12.04)	132.51	(12.87)		107.85	(9.04)
	Severe	110.94	(20.85)	131.87	(19.58)		113.14	(10.09)