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Ankle rotation changes and its influences in knee osteoarthritis

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Abstract

Background: Biomechanical factors are known to be important in knee osteoarthritis (OA) development and progression. This study was designed to determine changes of hamstrings muscle activation, knee adduction moment and ankle rotation angle in two knee osteoarthritis (mild and moderate) and a healthy control group.

Methods: 16 females (10 with mild and 6 with moderate medial knee osteoarthritis) and 10 control matched females were recruited. A 3D gait analysis was performed on the subjects while they walked along the walkway. Electromyography data was also collected during gait from lateral and medial hamstrings. Post Hoc Tukey HSD (multi comparison) was performed to compare knee adduction moment, ankle rotation angle and medial and lateral hamstrings activity at early and late stance, between three groups.

Results: Ankle rotation angle, knee adduction moment and lateral hamstrings activation showed no significant difference between three groups. Interestingly, medial hamstrings activity was significantly higher at late stance in moderate group compared with asymptomatic and mild groups (*p*=0.03, 0.02 respectively). Also knee adduction moment at late stance was significantly and directly correlated with ankle rotation angle, and lateral hamstrings activity at early stance was significantly and inversely correlated with this angle.

Conclusions: It can be concluded that, increased lateral hamstrings activity can increase external ankle rotation and consequently decrease knee adduction moment.

Keywords: Knee osteoarthritis, Gait, Knee adduction moment, Hamstrings activation, Ankle rotation.

Introduction

The cause of osteoarthritis (OA), as the most prevalent form of arthritis is unknown, but biomechanical factors are important in the etiopathogenesis of this disease (1-5). Acute joint loading may cause damage to the joint tissues and lead to the development of OA in the lower extremities, but in the presence of joint pathology, i.e. malalignment, instability or laxity, even cyclic loading in the physiological range (e.g. walking) can increase the risk of OA development (5-7). Among the lower extremity joints, the knee and more specifically its medial compartment, is the most commonly affected joint by OA (4). Gait analysis is a very useful tool for quantitatively describe biomechanical factors leading to knee OA (8).

External knee adduction moment during walking, as one of the most important bio-

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mechanical factors is seen to be correlated with medial compartment knee loading and also with OA severity. In other words, greater amount of this moment indicates higher load in the medial compartment than in the lateral (9). Therefore, the common gait pattern in medial compartment knee OA patients includes a large external knee adduction moment (8, 10). To reduce this moment and the associated pain, this group of patients walk with an externally rotated foot (10-12). Another strategy to unload medial side of the knee is to increase lateral hamstrings activation and decrease medial hamstrings activation during gait (10, 13, 14). The suggested mechanism for this compensation strategy is that higher lateral hamstrings activity may increase internal muscular abduction moment at the knee which in turn, will counteract with external knee adduction moment (10, 13).

Most of the previous gait studies have compared gait characteristic differences between two groups: control and OA patients (1,15-18). Although, such comparison between only two groups brings valuable information available, a few key questions as follow cannot be answered: are these identified biomechanical changes the main developing factors of disease? Are these biomechanical changes secondary responses to degenerative damages of joint and soft tissue? and are the discussed biomechanical changes compensatory mechanisms to the disease process?(19). While longitudinal studies could identify predictive factors, cross-sectional data obtained from different levels of disease severity can provide useful information about specific characteristics of each disease stage (19). Furthermore, the majority of gait studies performed on knee OA patients have concentrated on the later stages of this disease and there have been made few attempts to reveal the biomechanical effects of early stages of knee OA (8). Such data can lead to the development of non- surgical treatments to reduce pain and slow the progression of disease (8).

In most of the studies performed on the knee OA patients' gait, there has been no distinction between the genders (both men and women were recruited). A significant interaction effect has been found between gender and knee OA in knee kinetics and kinematics during gait in previous studies (20). Therefore, it seems that investigating biomechanics of knee OA patients' gait with considering males and females distinctly will result in more precise outcomes. In the few studies that have done this distinction (20-22), to the authors' knowledge none of them has limited the participants' age under the age of menopause. There are some evidences that, sex hormones have important effects on the prevalence or incidence of knee OA (23).

Despite available data about correlation of

Table1. Inclusion/ exclusion criteria for selection of the patients.

Inclusion criteria	Exclusion criteria
• Female gender • 35-53 years of age • Pain in the medial knee compartment during weight- bearing activities • Medial tibiofemoral OA grade 2 or 3 based on Kellgren-Lawrence radiographic score	• Major surgery or trauma of lower extremities • Valgus alignment in the knee • Varus alignment more than 15 degrees • Cartilage degeneration in lateral tibiofemoral and patellofemoral more than medial compartment • Neuromuscular disorders • History of stroke • Gout or other forms of arthritis • Hip or ankle osteoarthritis • Intra knee injection during last 6 months before the project • Using gait aids during walking • BMI>40 • Menopause

foot rotation, knee adduction moment and hamstrings activity (10, 14), no study (to our knowledge) has assessed the correlation between ankle rotation angle and other parameters in knee OA patients. Therefore, this study examined and compared the changes and correlation of hamstrings muscle activation, knee adduction moment and ankle rotation angle in two knee OA severity (mild and moderate) and a healthy control group. All participants were recruited from non-menopausal women.

Method

Among 70 female patients visited by a knee orthopedic surgeon, 16 patients (aged 35-53 years) were recruited for the study based on clinical criteria for knee OA as indicated in the clinical criteria of the American College of Rheumatology (24) (demographic characteristics are listed in Table 2).

Ten randomly selected healthy age, height, weight, BMI and physical activity level matched women participated as control subjects. The control participants had no pain and clinical and radiological sign of knee OA or functional impairment in their lower extremities. The detailed exclusion criteria for all participants and inclusion criteria for patients are shown in Table 1. The ethics committee of Tehran University of Medical Sciences approved the study criteria.

Categorization into patient and control group was based on clinical and radiological assessments. All subjects had three radiographic images: standing postero – anterior view with the knee flexed to 30 degrees, anterior to posterior non weight-bearing knee and Merchant view to distinguish patellofemoral OA. All radiographic views were read by the knee orthopedic surgeon to confirm and classify the presence of medial tibiofemoral OA with Kellgren–Lawrence (KL) severity levels (25). Subjects were grouped into three categories: asymptomatic controls, mild and moderate medial knee OA. Kellgren-Lawrence radiographic score for medial tibiofemoral joint in all subjects with mild and moderate OA were 2 and 3, respectively. Each subject was made aware of the risks and benefits of the study and given the opportunity to withdraw from the study, without penalty, at any time. All subjects signed an informed consent form approved by the Ethics Committee of Tehran University of

Table 2. Subjects demographic characteristics, stride length and velocity.

	Asymptomatic (n=10) mean(SD)	Mild (n=10) mean(SD)	Moderate (n=6) mean(SD)
Age(year)	40.60(4.62)	43.10(3.14)	50.33(3.08)
Mass(kg)	62.30(8.43)	73.10(6.33)	78.2(1.85)
Height(m)	1.54(0.02)	1.59(0.05)	1.58(0.04)
BMI(kg/m^2)	26.13(3.92)	29.12(3.38)	31.34(3.71)
Stride length(m)	1.17(0.13)	1.16(0.08)	1.11(0.23)
Velocity (m/s)	0.96(0.25)	1.01(0.19)	0.88(0.31)

Table 3. Subjects demographic characteristics, stride length and velocity comparison between three groups. Post-Hoc Tukey HSD analysis was used for multiple comparisons ($p<0.05$), p-values are represented in this table.

	Asymptomatic vs. mild	Asymptomatic vs. moderate	Mild vs. moderate
Age (year)	0.32	<0.001	0.003
Mass (kg)	0.019	0.005	0.501
Height (m)	0.043	0.24	0.899
BMI (kg/m^2)	0.186	0.042	0.522
Stride length (m)	0.982	0.723	0.807
Velocity (m/s)	0.897	0.802	0.585

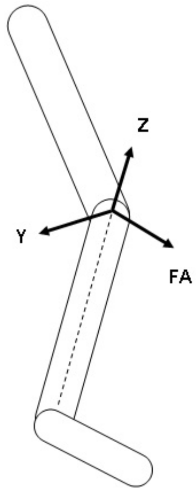

Fig. 1. Knee joint non-orthogonal coordinate system. The flexion/ extension axis (Y) is fixed to the thigh (proximal segment), the internal/external rotation axis (Z) is fixed to the shank (distal segment), and the abduction/ adduction axis (X) is perpendicular to these two axes.

Medical Sciences Board prior to participation in any portion of the study.

Gait analysis

Gait analysis was performed on all subjects. A motion tracking system with 6 infrared cameras (Vicon 460, Oxford Metrics, Oxford, UK) was used to track participants as they walked .Three dimensional kinematic data were recorded at a sample rate of 100 Hz. Markers were placed on anterior superior iliac spines, posterior superior iliac spines, sacrum, mid-thigh, lateral femoral epicondyle, mid-shank, lateral malleolus, distal head of the second metatarsal and posterior aspect of the calcaneus. Two force platforms (Kistler 9286BA, Switzerland) embedded in the walkway recorded the subject's ground reaction forces and moments at a sampling rate of 100 Hz. Subjects were instructed to walk barefoot at a self-selected speed along the walkway.

Electromyography (EMG)

A ME6000 EMG system (MT-M6T16-0, Finland) with 16 channels was used to collect EMG data at 1020 Hz (preamplified with a gain of 305, CMRR>110 dB). Following standard skin preparation, electrodes were applied in line with the muscles fibers over the muscle bellies of the biceps femoris (lateral hamstrings) and semitendinosus (medial hamstrings). The electrodes were fixed in bipolar fashion, with two active (measuring) electrodes above the muscle. The ground connector connected to the ground electrode, which was placed about 10cm away from the measuring electrodes. Before gait trails, maximum voluntary isometric contraction (MVIC) from hamstrings was recorded manually during three 5 second trials (26).

Data processing

Ankle joint rotation angle and knee adduction moment were calculated about the non-orthogonal joint coordinate system as represented by Grood and Suntay (27). Knee non-orthogonal coordinate system is illustrated in Figure 1. In this coordinate system, the *y* axis was the flexion/ extension axis of the knee joint fixed in the thigh segment. The direction of this axis was calculated at every time instant with three di-

Table 4. Gait parameters descriptive statistics.

Gait measure	Asymptomatic Mean (SD)	Mild Mean (SD)	Moderate Mean (SD)
Knee adduction moment, First peak, (N.m/Bw.Ht)	0.13(0.13)	0.08(0.11)	0.12(0.11)
Knee adduction moment, second peak, (N.m/Bw.Ht)	0.21(0.11)	0.11(0.13)	0.18(0.08)
Ankle rotation angle, early stance (degree)	-7.90(13.68)	-14.46(10.80)	-2.48(2.75)
Ankle rotation angle, late stance(degree)	-2.24(11.12)	-10.09(13.68)	1.53(5.82)
Medial hamstrings, early stance (gait EMG/MVIC)	0.16(0.10)	0.08(0.04)	0.13(0.08)
Medial hamstrings, late stance (gait EMG/MVIC)	0.07(0.06)	0.06(0.05)	0.18(0.14)
Lateral hamstrings, early stance (gait EMG/MVIC)	0.12(0.10)	0.15(0.14)	0.13(0.07)
Lateral hamstrings, late stance (gait EMG/MVIC)	0.09(0.09)	0.14(0.10)	0.24(0.17)

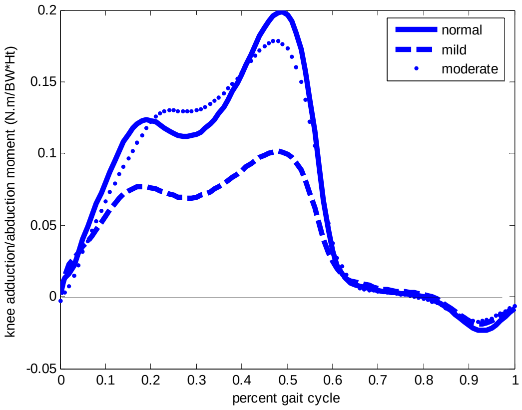

Fig. 2. Knee adduction moment in three groups.

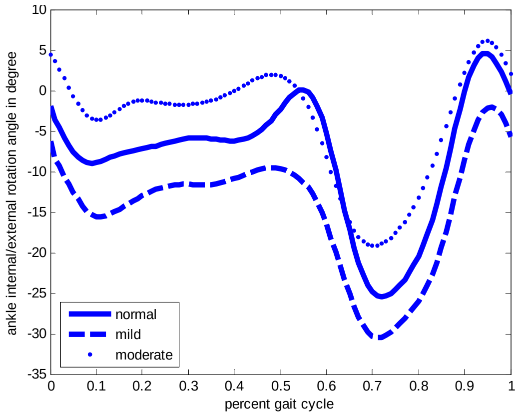

Fig. 3. Ankle rotation angle in three groups (positive sign indicates internal rotation and negative, external rotation).

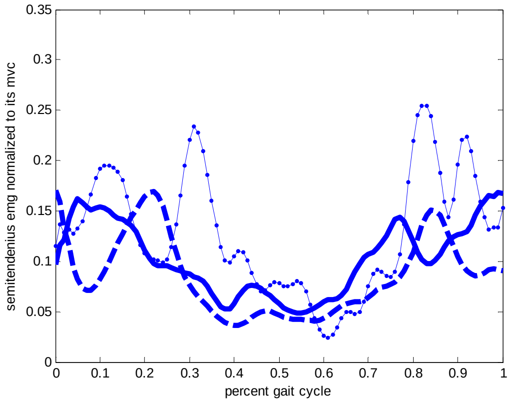

Fig. 4. Medial hamstrings (semitendinosus) activation in three groups (thick solid line represents normal, light line moderate and dashed line mild

mensional coordinates of markers placed on the thigh segment. The *z* axis was the internal/external rotation axis of the knee joint fixed in the shank segment. The direction of this axis at every time instant was calculated by shank marker coordinates. Finally, the *x* axis was the adduction/abduction axis of the knee joint, which also called floating axis (FA) and perpendicular to the plane of *z* and *y* axes at every time instant. Consequently, y and z axes may not be perpendicular all the times. That is why this coordinate system is called non-orthogonal.

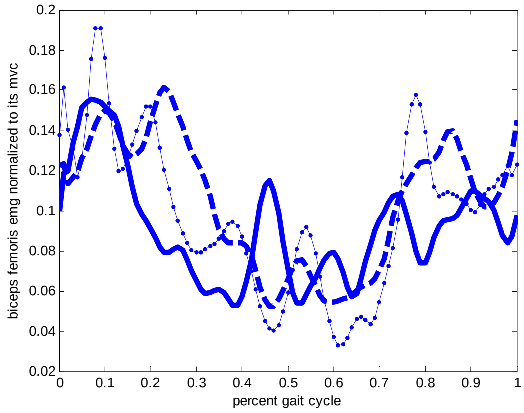

Fig. 5. lateral hamstrings (biceps femoris) activation in three groups (thick solid line represents normal, light line moderate and dashed line mild group).

External moments were calculated by the inverse dynamics method. In this procedure the lower extremity was modeled as a linkage of three rigid bodies (thigh, shank, foot) connected to each other by three ball and socket joints (hip, knee, ankle). Newton- Euler equations were used to calculate external moments. Kinematic data filtered with woltring filter (33) at mean square error (MSE) of 15 and force plate data were low pass filtered at 8 Hz. Knee adduction moment was normalized to body weight and height.

The EMG data during gait trials and also MVIC data were high pass filtered at 15 Hz, rectified and then low pass filtered at 6 Hz (13). Then the EMG data during gait were normalized against the MVIC maximum value.

Three trials were obtained for each subject in which the foot of the test limb successfully landed on the force platform, and all markers were visible by the cameras. The averaged kinematics, kinetics and EMG data were used in statistical analysis.

The duration of all gait events (kinematics, kinetics and EMG) were normalized to

Table 5. Gait parameters differences between three groups. Post-Hoc Tukey HSD analysis was used for multiple comparisons ($p<0.05$), p-values are represented in this table.

Gait measure	Asymptomatic vs. mild	Asymptomatic vs. moderate	Mild vs. moderate
Knee adduction moment, First peak, (N.m/Bw.Ht)	0.66	1.00	0.77
Knee adduction moment, second peak, (N.m/Bw.Ht)	0.16	0.90	0.51
Ankle rotation angle, early stance (degree)	0.42	0.66	0.14
Ankle rotation angle, late stance (degree)	0.32	0.83	0.18
Medial hamstrings, early stance (gait EMG/MVIC)	0.09	0.85	0.39
Medial hamstrings, late stance (gait EMG/MVIC)	0.95	0.03	0.02
Lateral hamstrings, early stance (gait EMG/MVIC)	0.82	0.96	0.96
Lateral hamstrings, late stance (gait EMG/MVIC)	0.74	0.07	0.23

1 second, to be able to get average between trials and also between subjects.

Statistical analysis

Key outcome measures were the early and late stance peak values of knee adduction moment, time-matched with ankle rotation and hamtrings activity waveforms. Other variables that were measured included gait speed and stride length. Post Hoc Tukey HSD (multi comparison) was performed for the comparison of mass, height, BMI, age, stride length, velocity, and the parameters extracted from waveforms between three groups. Partial correlation analysis was performed by considering age and BMI as control variables to calculate correlation between variables. The level of significance was set at 0.05.

Results

Demographic and stride characteristics

Table 2 shows the demographic characteristics and also stride length and velocity in three groups and Table 3 represents the differences in these parameters between three groups. As Table 3 shows, there was no significant difference in stride length and gait velocity between three groups. Age difference was significant between moderate and two other groups ($p=0.003$) and BMI difference was significant between asymptomatic and moderate group ($p=0.042$).

Ankle rotation and knee adduction moment

Tables 4 and 5 show gait parameters descriptive statistics and their comparisons between three groups, respectively. Figure 2 illustrates knee adduction moment during gait for three groups. As it is evident from the figure, subjects in mild group exerted less adduction moment about their knee joint during gait than two other groups, but statistically the difference was not significant at early and late stance peak values, also subjects in moderate group did not exhibit significant difference in these parameters (Table 5). Figure 3 illustrates ankle rotation in three groups. Subjects in mild group rotated their ankle more externally with respect to two other groups and subject in moderate group, rotated their ankle more internally with respect to other two groups. But the differences were not significant at early and late stance between any two groups (Table 5).

Hamstrings activation

The only significant difference in hamstrings activation at early and late stance was in medial hamstrings at late stance between moderate group and asymptomatic and mild groups (Table 5) ($p=0.03,0.02$ respectively). Subjects in this group activated this muscle more than two other groups at late stance. To detect more significant differences, perhaps other points should be analyzed. Figure 4 and 5 illustrate medial and lateral hamstrings activity, respectively.

Correlation between gait parameters

Second peak knee adduction moment was significantly and directly correlated with ankle rotation angle ($p=0.002$, $r=0.625$).

Lateral hamstrings value at early stance was significantly and inversely correlated with this angle (p=0.037, *r*=-0.447).

Discussion

Main findings

The purpose of this investigation was to determine whether patients with mild to moderate knee OA develop alterations in hamstrings muscle activation, knee adduction moment and ankle rotation angle ssecondary to their knee joint pathology. All participants were recruited from non-menopausal women. The findings report that patients with moderate knee OA had significantly decrease at late stance in medial hamstrings activation compared with asymptomatic and mild groups (p=0.03,0.02 respectively) (Table 5). Additionally, second peak knee adduction moment was significantly and directly correlated with ankle rotation angle (p=0.002, *r*=0.625). Lateral hamstrings value at early stance was significantly and inversely correlated with this angle (p=0.037, *r*=-0.447). On the other hand, no significant difference was seen in velocity and stride length between any two groups (Table 3). The differences were not significant at early and late stance in knee adduction moment, ankle rotation angle and lateral hamstrings activation and at early stance in medial hamstrings activation between any two groups (Table 5).

Walking speed

Previous studies have shown that walking speed influences kinematic and kinetic gait parameters (28). In this study, no significant difference was seen between the gait speeds of any two groups. It shows that probable differences in gait parameters can be related to disease intrinsic factors or other reasons (2).

Age

Although, there was significant difference between moderate group's age and the other two groups, but all the participants were in the range of 35-53 years old, which is the middle age. Most of the previous studies selected their cases from wide ranges of age (19, 29, 30). There are several evidence that age has been considered as an important risk factor for knee OA etiology and its progression (23, 31, 32). Therefore it seems that to have more reliable results on the role of mechanical factors in knee OA progression, age range should be restricted to younger ages.

Knee adduction moment

Figure 2 shows that patients in mild group exhibit less knee adduction moment compared with two other groups. Although it is not a meaningful difference, it is still a highlighted result. This moment reduction is in support of Mundermann idea (2). They found that patients with less severe knee OA (corresponds to mild group in this study) adopt a gait pattern which reduces knee adduction moment especially at late stance (2). Patients in moderate group did not exhibit significant difference in knee adduction moment at early and late stance compared to two other groups. Based on Mundermann's study, more severe knee OA patients (corresponds to moderate group in this study), have greater knee adduction moment at early stance than their matched control group (2). We hypothesize that this lack of similarity in statistical results may be contributed to age and sex differences in subjects of these two studies. Also it is possible that moderate OA patients in this study have adopted some gait patterns that resulted no increase in knee adduction moment.

Ankle rotation angle

As it is evident from Figure 3, women in mild group rotated their ankles more externally than the asymptomatic group during the gait cycle, but statistically this difference was not significant at early and late stance. On the other hand, patients in moderate group, rotated their ankle more internally than the asymptomatic group during the stance phase of gait, again the differences were not significant at early and late stance. It seems that more external rotation of the ankle joint in mild group is one of the gait adaptation strategies that they have used to reduce knee joint loading and specifically knee adduction moment (Figure 2). Previous studies have found that external foot rotation (the angle of the long axis of the foot segment in the lab coordinate system) decreased late stance knee adduction moment (10). The results of the present study show that in addition to foot rotation angle, ankle rotation angle can be considered as a strategy to reduce knee adduction moment. More internal rotation angle during stance phase of gait in women with moderate OA should result in increased knee joint load (10), but as evident from Figure 2 and the statistical results, knee adduction moment was not increased in this group compared to asymptomatic group. Patients in this group may have adopted other strategies to reduce this moment.

Hamstrings activation

Although not significant, but medial hamstrings activation was decreased in mild group at early stance (Fig. 4). This reduction in medial hamstrings activation that was in accordance with previous studies (10, 13, 14) resulted in decreased internal varus (adduction) moment at the knee and consequently decreased load on the medial knee compartment (14). Interestingly, the activation of this muscle was significantly greater in moderate group than the control group at late stance. This result was in contrast with previous studies (10, 13, 14). In these studies a single OA group consisted of mild and moderate knee OA cases were studied and the results were not stated distinctly for each disease stage. Therefore, it can be a source of difference in results between our study and these studies. Higher activity of this muscle should resulted in higher knee adduction moment in this group. But as implied before, this group of patients may have used many other strategies that resulted in not increased knee adduction moment. During the majority of stance phase of gait cycle, women in moderate and mild group, activated their lateral hamstrings more than the asymptomatic group (10, 13, 14) (Fig. 5), but these differences were not significant at early and late stance. This increase was even more evident in mild group during mid-stance. Lateral hamstrings muscle produces an internal knee valgus moment which counteracts with the external knee adduction moment and reduces the load on the medial knee compartment (10).

Correlation between gait parameters

As was indicated, lateral hamstrings activation value at early stance was significantly and conversely correlated with ankle rotation angle. It means that, as this muscle was activated more, ankle rotation angle tended to external (negative) side. Second peak knee adduction moment was statistically and directly correlated with ankle rotation angle. It implies that, as ankle rotation angle tended to the positive side (internal rotation), knee adduction moment was increased. Based on the results of the previous studies external foot rotation decreased the late stance knee adduction moment and hamstrings activation ratio (the ratio of medial to lateral hamstrings activation)(10). The same result was found in this study with ankle rotation angle in replace of foot rotation angle. Therefore, external ankle rotation angle can be interpreted as a compensatory mechanism also. Women in mild group, by increasing lateral hamstrings activity, rotated their ankle more externally and consequently reduced knee adduction moment. But this strategy was not used by patients in moderate group. In this group, increased medial hamstrings activation caused increased internal ankle rotation angle, but increase in this angle did not cause increase in knee adduction moment. Therefore, it seems that this group of patients has used other strategies that lead to no increase in knee adduction moment.

Study limitations

One of the reasons that resulted in not significant differences in gait parameters between groups may be the small sample size of the groups. But with the inclusion/ exclusion criteria that was used no more patients could be found.

There was significant difference in BMI between moderate and control group (p=0.042). It has been proven that obesity is a risk factor for knee OA development and progression (4).

We only had considered the knee as the target joint. Because of radiating entity of osteoarthritis to distal and proximal joints (2,19,30) and consequent compensatory mechanisms in other joints, it was better to focus on the entire lower extremity to ensure an integrated approach to OA.

In this study, knee external moment was calculated and compared between groups. But a complex joint like the knee consists of many tissue types. The contribution of each of these tissues in counterbalancing the external moments in different directions is different. Therefore to investigate the role of biomechanical factors in the development and progression of knee OA, it seems to be better to have a more accurate biomechanical model.

Conclusion

This study determined that kinematics, kinetics and muscle activation patterns were different in various knee OA stages. Patients in each severity level take use of different strategies to reduce pain. Some of these strategies may result in increased joint load and consequently faster progression of disease and some of them may even result in the development of OA in other lower extremity joints. But some of the strategies may be effective and successfully reduce knee OA progression. Increased lateral hamstrings muscle activation and consequently increased ankle external rotation angle were the strategy used by mild knee OA group that resulted in decreased knee adduction moment. Patients in moderate group did not use this strategy but they may have used other ways to reduce knee joint load. Investigating biomechanical parameters of other lower extremity joints seems to be essential to decide about the success of different strategies used by different patients groups.

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References

1. Kaufman KR, Hughes C, Morrey BF, Morrey M, An KN. Gait characteristics of patients with knee osteoarthritis. Journal of Biomechanics. 2001; 34(7): p. 907-915.

2. Mündermann A, Dyrby C, Andriacchi T. Secondary gait changes in patients with medial compartment knee osteoarthritis: increased load at the ankle, knee, and hip during walking. Arthritis & Rheumatism. 2005; 52(9): p. 2835-2844.

3. Brandt KD, Radin EL, Dieppe PA, van de PL. Yet more evidence that osteoarthritis is not a cartilage disease. Annals of the Rheumatic Diseases 2006; 65(10): p. 1261

4. Felson DT, Zhang Y. An update on the epidemiology of knee and hip osteoarthritis with a view to prevention. Arthritis & Rheumatism. 1998; 41(8): p. 1343-1355.

5. Liikavainio T, Bragge T, Hakkarainen M, Karjalainen PA, Arokoski JP. Gait and muscle activation changes in men with knee osteoarthritis. The Knee. 2010; 17(1): p. 69-76.

6. Nuki G, Salter D. The Impact of Mechanical Stress on the Pathophysiology of Osteoarthritis. Osteoarthritis: a companion to Rheumatology. Philadelphia, PA: Elsevier; 2007:33-52.

7. Buckwalter J. Osteoarthritis and articular cartilage use, disuse, and abuse: experimental studies. The Journal of rheumatology. Supplement 1995. 43: 13.

8. 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. Journal of Biomechanics. 2007;40(8): 1754-1761.

9. Brandon S, Deluzio K. Robust features of knee osteoarthritis in joint moments are independent of reference frame selection. Clinical Biomechanics. 2011; 26: 65–70.

10. Lynn S, and Costigan P: Effect of foot rotation on knee kinetics and hamstring activation in older adults with and without signs of knee osteoarthritis. Clinical Biomechanics (Bristol, Avon). 2008; 23(6): 779.

11. Guo M, Axe MJ, and Manal K. The influence of foot progression angle on the knee adduction moment during walking and stair climbing in pain

free individuals with knee osteoarthritis. Gait & posture. 2007; 26(3): 436-441

12. Wada M, Imura S, Nagatani K, Baba H, Shimada S, Sasaki S. Relationship between gait and clinical results after high tibial osteotomy. Clinical Orthopaedics and Related Research. 1998; 354: p. 180.

13. Hubley-Kozey C, Deluzio K, Landry S, McNutt J, Stanish W. Neuromuscular alterations during walking in persons with moderate knee osteoarthritis. Journal of Electromyography and Kinesiology. 2006; 16(4): 365-378.

14. Lynn SK, Kajaks T, Costigan PA. The effect of internal and external foot rotation on the adduction moment and lateral-medial shear force at the knee during gait. Journal of Science and Medicine in Sport. 2008; 11(5): 444-451

15. Al-Zahrani K, Bakheit A. A study of the gait characteristics of patients with chronic osteoarthritis of the knee. Disability & Rehabilitation. 2002; 24(5): 275-280.

16. Hilding MB, Lanshammar H, Ryd L. A relationship between dynamic and static assessments of knee joint load: gait analysis and radiography before and after knee replacement in 45 patients. Acta Orthopaedica. 1995; 66(4): 317-320.

17. Baliunas AJ, Hurwitz DE, Ryals AR. Increased knee joint loads during walking are present in subjects with knee osteoarthritis. Osteoarthritis and Cartilage. 2002; 10(7): 573-579.

18. Hurwitz D. The knee adduction moment during gait in subjects with knee osteoarthritis is more closely correlated with static alignment than radiographic disease severity, toe out angle and pain. Journal of Orthopaedic Research. 2002; 20(1): 101-107.

19. Astephen J, Kevin J. Graham D. Caldwell E, Dunbar MJ. Biomechanical changes at the hip, knee, and ankle joints during gait are associated with knee osteoarthritis severity. Journal of Orthopaedic Research. 2008; 26(3): 32.

20. McKean KA, Landry SC, Hubley-Kozey, CL, Dunbar MJ, Stanish WD, Deluzio KJ. Gender differences exist in osteoarthritic gait. Clinical Biomechanics. 2007; 22(4): 400-409.

21. Vanwanseele B, Eckstein F, Eckstein F. The relationship between knee adduction moment and cartilage and meniscus morphology in women with osteoarthritis. Osteoarthritis and Cartilage. 2010; 18(7): 894-901.

22. Segal NA, Yack HJ, Brubaker M, ET AL. Association of dynamic joint power with functional limitations in older adults with symptomatic knee osteoarthritis. Archives of Physical Medicine and Rehabilitation. 2009; 90(11): 1821-1828.

23. Arden N, Nevitt M. Osteoarthritis: epidemiology. The osteoarthritis initiative: report on the design rationale.J Bone Miner Res 2005;20:131-40.

24. Altman R, Alarcon G, Appelrouth D. The American College of Rheumatology criteria for the classification and reporting of osteoarthritis of the hip. Arthritis Rheum. 1991; 34(5): 505-514.

25. Kellgren J, Lawrence J. Radiological assessment of osteo-arthrosis. Annals of the Rheumatic Diseases. 1957; 16(4): 494.

26. Konrad P. The abc of emg. A Practical Introduction to Kinesiological Electromyography 2005

27. Grood E, Suntay W. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. Journal of Biomechanical Engineering. 1983; 105: 136.

28. Zeni J, Rudolph K, Higginson J. Alterations in quadriceps and hamstrings coordination in persons with medial compartment knee osteoarthritis. Journal of Electromyography and Kinesiology. 2010; 20(1): 148-154.

29. Mündermann A, Asay JL, Mündermann L, Andriacchli TP. Implications of increased mediolateral trunk sway for ambulatory mechanics. Journal of Biomechanics. 2008; 41(1): 165-170.

30. Briem K, Snyder-Mackler L. Proximal gait adaptations in medial knee OA. J Orthop Res. 2009; 27(1): 78–83.

31. Anderson A, Loeser R. Why is osteoarthritis an age-related disease? Baillière's best practice & research. Clinical Rheumatology. 2006; 24(1): 15-26.

32. Cheung P, Gossec L, Dougados M. What are the best markers for disease progression in osteoarthritis (OA)? Best Practice & Research Clinical Rheumatology. 2010; 24(1): 81-92.

33. Woltring HJ. A FORTRAN package for generalized. Advances in Engineering Software. 1986;8: 104-13.