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Smoothness of the knee joint movement during the stance phase in patients with severe knee osteoarthritis

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ABSTRACT

Background: Patients with knee osteoarthritis can significantly affect the function of the knee joint in terms of joint range and mobility and have a stereotypical pattern of knee stiffness during gait, caused by an increased resistance in the muscles and soft tissues during the stance phase of knee joint movement. Smoothness in movement, such as during walking and running, is assumed to be attained by adulthood; however, disruptions in gait pattern due to injury or performance enhancement can alter the smoothness of the movement, and this is often quantified in terms of “jerk”. A higher jerk value is linked with a decrease in smoothness. However few have reported to evaluate the smoothness of the knee joint movement during walking in patients with knee osteoarthritis. The purpose of the present study was to quantify the smoothness of the knee joint movement during walking in people with knee osteoarthritis. **Methods:** Patients were classified as having early or severe knee osteoarthritis. There were eight patients in each group (16 knees; three males, five females). The normalized angular jerk was calculated as an indicator of the walking knee joint smoothness in each of the four periods of the stance phase. Two-way ANOVA was performed to compare the smoothness of knee joint movement between groups and between each period of the stance phase.

Results: The angular change in the sagittal plane of those with severe knee osteoarthritis was smaller than that of those with early knee osteoarthritis in all periods of the stance phase. Normalized angular jerk did not significantly differ between groups in all periods. In both groups, the normalized angular jerk in the sagittal plane was significantly larger in the mid-stance and terminal stance periods than in the early stance and pre-swing periods. Only in patients with severe knee osteoarthritis, there was a significantly larger jerk in the frontal plane in the mid-stance period.

Conclusion: The present results revealed that the smoothness of joint movement decreases during the single leg supporting phase of the stance phase in the frontal plane with severe knee osteoarthritis, although there is no difference in smoothness of joint movement according to the severity of knee osteoarthritis. The instability during single leg support due to increase of the knee joint load and destruction cause the impaired smoothness of the knee joint movement.

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Introduction

Patients with knee osteoarthritis (KOA) have a stereotypical pattern of knee stiffness during gait.¹ Typically, KOA is an age-related degenerative disease that causes by an increased

resistance in the muscles and soft tissues during the early stance phase of knee joint movement.^{2,3} The movement of the knee joint during walking depends on joint force, ligaments, and muscles, rather than just the bony structure,⁴ and thus KOA can significantly affect the function of the knee joint in terms of joint range and mobility. In normal walking, there are slight variations in joint movement during the gait cycle, and a decrease in this normal variability may lead to joint destruction.⁵ Therefore, adequately varied joint movement may be useful for the redistribution of joint loading.⁶ A previous study reported that a softer landing during

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foot strike can improve the smoothness of a gait pattern, which in turn, helps to reduce loading on the joint.⁷

Smoothness in movement, such as during walking and running, is assumed to be attained by adulthood; however, disruptions in gait pattern due to injury or performance enhancement can alter the smoothness of the movement, and this is often quantified in terms of “jerk”.^{8,9} Jerk is defined as a change in the acceleration rate of a movement, and is the third derivative of displacement, with the smoothest movement having the lowest jerk. Several previous reports have sought to use the smoothness of joint movement to explain, coordinate, or alter joint movement.^{9–11} Newton's second law states that acceleration is proportional to force, assuming that mass is constant. Therefore, jerk, as a derivative of acceleration, can be defined as a change in force; as jerk is an index of gait smoothness, jerk is therefore linked with smoothness and force. In other words, a lower jerk value is associated with a smoother movement and a smaller change in force, whereas a higher jerk value is linked with a decrease in smoothness and a larger change in force. Several previous reports have used jerk as a measure to evaluate the smoothness of joint movements,^{9–13} however few have reported to evaluate the smoothness of the knee joint movement during walking in patients with KOA.

The purpose of the present study was to quantify the normalized angular jerk of the knee joint movement during walking in people with KOA. We hypothesized that the smoothness of the joint movement in patients with severe KOA would be altered due to a restricted range of motion in the joint angle during the stance phase, and that the instability during single leg support would cause the impaired smoothness of the knee joint movement.

Materials and methods

Subjects

The participants enrolled in the present study were orthopedic patients who visited the hospital for outpatient treatment of medial KOA. All participants underwent Rosenberg view radiography by a radiological technologist, and an orthopedic surgeon classified the severity of KOA according to the Kellgren–Lawrence (KL) radiographic osteoarthritis grading system.¹⁴ Grade 1 was defined as doubtful narrowing of joint space, possible osteophyte development, grade 2 was defined as definite osteophyte, absent or questionable narrowing of joint space, grade 3 was defined as the presence of moderate (multiple) osteophytes or a definite narrowing of the joint space, and grade 4 involved the presence of large osteophytes or marked narrowing of the joint space. Patients were then further categorized into two groups: KL grades 1 to 2 were classified as early KOA¹⁵ (in this study, 4 knees were not underwent radiography but we classified them as early group because they recognized pain and disability in daily life as walking or stair climbing), and KL grades of 3–4 were classified as severe KOA. Each group included 16 knees from eight subjects (three males, five females). The patient characteristics are presented in Table 1. The exclusion criteria were prior knee replacement surgery, rheumatoid

arthritis, unresolved injury to any lower extremity joint, prior bone injuries, and neurological problems. All participants provided written informed consent, and the study was approved by the ethical review board of our institution.

Gait analysis

Participants walked barefoot along a level, 8-m-long walkway at a self-selected, habitual speed. Kinematic data were obtained at 200 Hz using an 8-camera motion analysis system (Vicon Nexus, Oxford, UK). Two floor-mounted force plates (Kistler Instruments, Winterthur, Switzerland) were used to obtain the ground reaction forces at a rate of 1200 Hz, and the data were synchronized with the motion capture data. The global coordinate system was defined with the X-axis as anterior-posterior, the Y-axis as lateral, and the Z-axis as vertical. The average of three gait trials was collected for each subject and used for analysis.

According to a lower extremity model of the Plug-In-Gait marker set,¹⁶ which is a widely used standardized marker arrangement for three-dimensional motion analysis, 9.5-mm-diameter reflective markers were placed directly over the following bilateral anatomical landmarks: anterior and posterior superior iliac spines, lateral thighs, lateral femoral epicondyles, lateral shanks, lateral malleoli, calcanei, and the tops of the feet at the base of the second metatarsals. After the reflective markers were attached, each subject was instructed to stand barefoot for a single static calibration in the standing position before gait analysis. After the static calibration, participants were instructed to step onto a floor-mounted force plate with their targeted lower limb for a measurement, and were allowed to perform several trial steps in preparation before the measurements were taken. From the ground reaction force data, we defined the stance phase of the gait as four periods: early stance (0–16% of the stance), mid-stance (17–50%), terminal stance (51–83%), and pre-swing (84–100%).¹⁷ Mid and terminal stance phases include the shingle leg supporting phase.¹⁸ The markers and joint angles acquired from the Plug-In-Gait model, and the ground reaction forces were low-pass filtered at 6 Hz using a second-order, dual-pass Butterworth filter. The normalized angular jerk was calculated as the knee joint smoothness in each period of the stance phase, using the following formula:^{10,11}

Normalized angular Jerk (Knee joint smoothness)

$$= \int_{t_2}^{t_1} (d^3\theta/dt^3)^2 dt \times \frac{t_f^5}{D^2}$$

where θ is the knee joint angle, t_1 and t_2 are the initial time and final time of each period of the stance phase, t_f is the time of each stance phase period, and D is the amount of change in the knee joint angle during each stance phase period. A lower value of normalized angular jerk indicates that knee joint movement is smooth, while higher values represent lack of smoothness.

Statistical analysis

Two-way ANOVA was performed to compare the smoothness of knee joint movement between groups and between each period of the stance phase; when the main effect was observed, Bonferroni post hoc testing was performed. A t -test was conducted to evaluate the differences between the two groups in range of motion during the stance phase. P -values less than 0.05 were considered statistically significant. All statistical analyses were performed using SPSS software ver. 19.0 (SPSS Inc., Tokyo, Japan).

Table 1
Characteristics of the study participants.

	Early KOA		Severe KOA	
	Mean	SD	Mean	SD
Age (years)	73.38	±9.54	75.25	±5.51
Height (m)	1.54	±0.09	1.52	±0.06
Weight (kg)	56.00	±9.77	61.81	±7.69
BMI (kg/m ²)	23.57	±3.21	26.80	±3.05

Results

Angular change and smoothness of knee joint movement in early versus severe knee osteoarthritis

The angular change in the sagittal plane of those with severe KOA was smaller than that of those with early KOA in all periods of the stance phase (Table 2). The angular change in the frontal plane of those with severe KOA was smaller than that of those with early KOA in the terminal stance period, but there were no significant differences between the groups in the other periods (Table 2). The mean and standard deviation of normalized angular jerk in each period of the stance phase is showed in Table 3. Normalized angular jerk did not significantly differ between groups in all periods (Tables 4 and 5). For references, the angular acceleration changes in the knee joint during the stance phase are shown in Fig. 1. The angular acceleration waveforms are similar, but the angular acceleration in the sagittal plane was small in the severe KOA group from the early stance to the mid-stance, and the change was large in the frontal plane.

Smoothness of knee joint movement in each period of the stance phase

Normalized angular jerk in the sagittal plane was significantly

larger in the mid-stance period and terminal stance period than in the early stance period and pre-swing period in both the early and severe KOA groups (Table 4). There was no significant change throughout the stance phase in the early KOA group in the normalized angular jerk of knee joint movement in the frontal plane; however, in the severe KOA group, there was a significantly larger jerk in the mid-stance period compared with the early stance period and the pre-swing period (Table 5).

Discussion

The present results showed that the movement range of the knee joint in the sagittal plane was restricted in severe KOA, but the smoothness of the knee joint movement in patients with severe KOA did not differ from that in patients with early KOA. The smoothness of the knee joint movement with severe KOA was thought to be impaired because of structural failure of the knee joint caused by the progressive degeneration of the joint cartilage and the presence of bone osteophytes. However, in the present study, patients with severe KOA maintained the same smoothness of joint movement as patients with early KOA by reducing the change in the angular acceleration while decreasing the range of the knee joint movement during the stance phase (especially from early stance to mid stance).

Comparisons of each period of the stance phase revealed that

Table 2

Change amount of the knee flexion-extension and adduction-abduction angle in each period of the stance phase.

	Stance phase	Early KOA		Severe KOA		p-values
		Mean	SD	Mean	SD	
Sagittal plane (flexion-extension)	Early stance phase	10.24°	±2.95°	6.55°	±3.61°	p < 0.01
	Mid stance phase	9.2°	±4.05°	5.39°	±3.33°	p < 0.01
	Terminal stance phase	6.07°	±2.49°	3.74°	±2.41°	p = 0.011
	Pre-swing phase	65.06°	±7.56°	48.36°	±11.78°	p < 0.01
Frontal plane (adduction-abduction)	Early stance phase	2.93°	±1.83°	3.76°	±2.15°	p = 0.249
	Mid stance phase	4.36°	±2.46°	3.86°	±2.74°	p = 0.593
	Terminal stance phase	2.4°	±1.07°	1.49°	±0.51°	p < 0.01
	Pre-swing phase	16.89°	±7.44°	12.36°	±7.33°	p = 0.093

p < 0.05 for the comparison between groups in each period of the stance phase.

Table 3

The mean and standard deviation of knee joint smoothness in each period of the stance phase.

	Stance phase	Early KOA		Severe KOA	
		Mean	SD	Mean	SD
Sagittal plane (flexion-extension)	Early stance phase	1.32×10^2	$\pm 2.94 \times 10^2$	1.14×10^2	$\pm 1.74 \times 10^3$
	Mid stance phase	1.88×10^3	$\pm 2.10 \times 10^3$	2.21×10^3	$\pm 1.50 \times 10^3$
	Terminal stance phase	2.19×10^3	$\pm 1.89 \times 10^3$	3.27×10^3	$\pm 1.64 \times 10^4$
	Pre-swing phase	9.75	±7.42	4.56×10	$\pm 7.68 \times 10^2$
Frontal plane (adduction-abduction)	Early stance phase	5.80×10^2	$\pm 9.34 \times 10$	1.16×10^2	$\pm 2.31 \times 10^2$
	Mid stance phase	1.49×10^3	$\pm 2.20 \times 10^3$	2.30×10^3	$\pm 2.59 \times 10^3$
	Terminal stance phase	7.88×10^3	$\pm 3.69 \times 10^3$	2.40×10^3	$\pm 3.48 \times 10^3$
	Pre-swing phase	3.24×10^2	$\pm 1.25 \times 10^2$	3.19×10^2	$\pm 7.10 \times 10^2$

Table 4

Results of the two-way ANOVA of knee joint smoothness in the sagittal plane.

	Type III sum of squares	Degree of freedom	Mean Square	F	p-value	Bonferroni's post hoc-test in each phase		
						Early KOA	Severe KOA	
Group	4.09×10^6	1	4.09×10^6	0.903	0.350	early vs mid	p = 0.016	p < 0.01
Stance phase	1.79×10^8	1.822	9.81×10^7	20.494	0.000	early vs terminal	p = 0.049	p < 0.01
Group × Stance phase	6.25×10^6	1.822	3.43×10^6	0.716	0.481	mid vs pre-swing	p < 0.01	p < 0.01
Error	2.62×10^8	54.651	4.79×10^6			terminal vs pre-swing	p = 0.034	p < 0.01

p < 0.05 for the comparison between each period of the stance phase within the group.

Table 5
Result of the two-way ANOVA of knee joint smoothness in the frontal plane.

	Type III sum of squares	Degree of freedom	Mean Square	F	p-value	Bonferroni's post hoc-test in each stance phase severe KOA	
Group	5.28×10^7	1	5.28×10^7	1.077	0.308	early vs mid	$p < 0.01$
Stance phase	4.92×10^8	1.067	4.61×10^8	5.009	0.030	mid vs pre-swing	$p < 0.01$
Group \times Stance phase	1.95×10^8	1.067	1.82×10^8	1.981	0.169		
Error	2.95×10^9	32.016	9.21×10^7				

$p < 0.05$ for the comparison between each period of the stance phase within the group.

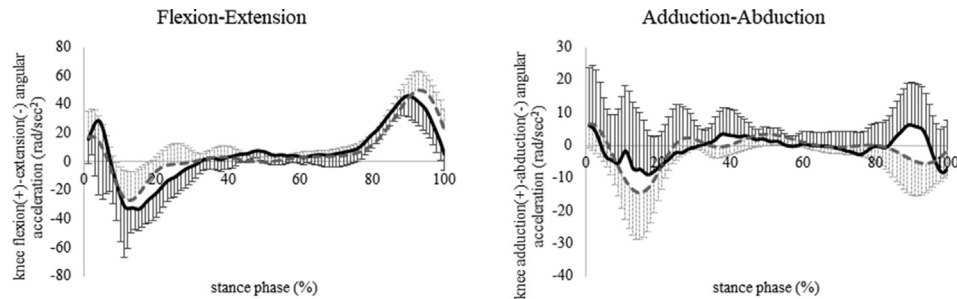


Fig. 1. Longitudinal data on the knee joint angular acceleration during the stance phase. The left image represents the knee flexion-extension angular acceleration, and the right represents the knee adduction-abduction angular acceleration. The black line is the early KOA group, and the gray dotted line is the severe KOA group. The vertical lines indicate the standard deviations.

the normalized angular jerk increased in the mid-stance and terminal stance periods in the sagittal plane, resulting in impaired smoothness of knee joint movement compared with the other two periods. On the other hand, patients with KOA also experience many problems in the frontal plane. In particular, the varus thrust seen in the early stance period of the stance phase is a mechanical risk factor for progression of medial KOA.¹⁹ Varus thrust may represent dynamic instability and malalignment in the frontal plane of the knee joint.²⁰ In the present study, the early and severe KOA groups both showed varus movement in the early period of the stance phase, with no significant differences between groups; this result was similar to past reports.²¹ In addition, the movement smoothness in the frontal plane of the mid-stance period in severe KOA was decreased in the early and pre-swing periods, but there was no difference between the smoothness of the periods of the stance phase in the early KOA group. The mid-stance and terminal stance periods involve single leg support. Although the joint movement in these periods was small in both groups, it was presumed that the smoothness of joint movement was decreased because the need to maintain the bodyweight with a single leg meant that the load on the knee joint increased; this was especially pronounced in the frontal plane movement of patients with severe KOA.

The mobility of knee flexion-extension reportedly decreases in the stance phase in patients with KOA.²² The present study also showed that patients with severe KOA had decreased mobility. The pain with patients of KOA restricts activities of daily living, which is the most common complaint of KOA.^{23,24} However, the correlation between radiographic KOA severity and knee pain is not as strong as would be expected.²⁵ It has been suggested that weak quadriceps muscles may contribute to the pain experienced by patients with KOA, as the quadriceps muscle is the principal dynamic stabilizer of the knee.²⁶ This quadriceps muscle weakness compromises the joint movement during the stance phase, which in turn can cause changes in knee movement and the activation patterns of other muscles.^{27,28} This may cause a loss of coordination of the knee

joint movement during the stance phase in patients with KOA. In past reports, the strategy used by those with KOA to maintain the smoothness of joint movement was to reduce the ground reaction force.²⁹ Therefore, this may reduce the load on the joint while reducing the change in angular acceleration and maintaining the smoothness of the joint movement in the KOA group.

There are several limitations in the present study. First, the control group was composed of patients with early KOA, rather than patients with normal knees. A comparison of subjects with age-matched healthy knee joints is needed. But, because elderly people almost exclusively had knee pain, and radiographic changes are possible even if patients are asymptomatic, it is difficult to choose age matched healthy subjects. Second, the present study was cross-sectional, and the number of subjects was small.

The present study verified the effect on the knee joint of movement smoothness (evaluated as angular jerk during the stance phase) in patients with severe KOA. Although there was no difference in the smoothness of joint movement according to the severity of KOA, it was found that the smoothness of joint movement in the single leg supporting phase decreased. The present results suggest that it is important to acquire stability of the knee joint during single leg standing for KOA therapy.

Conclusion

The present results revealed that the smoothness of joint movement decreases in the single leg supporting phase of the stance phase, although there is no difference in smoothness of joint movement according to the severity of KOA. The instability during single leg support due to increase of the knee joint load and destruction cause the impaired smoothness of the knee joint movement. Evaluating the smoothness of joint movement using the angular jerk as well as variables such as the range of motion and joint moment in the stance phase in patients with KOA may help in KOA treatment.

Conflicts of interest

The authors have no conflicts of interest relevant to this article.

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