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Lower limb kinematics during the swing phase in patients with knee osteoarthritis measured using an inertial sensor

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A R T I C L E   I N F O

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A B S T R A C T

Background: During gait, the swing limb requires flexible control to adapt to ever changing environmental circumstances. However, few studies have focused on the mechanics of swing limb control in patients with knee osteoarthritis (OA). Investigating the variability of swing limb kinematics, which can be represented by variables such as the peak shank angular velocity during the swing phase obtained from an inertial sensor, provides insights into the adaptability of swing limb control. The purpose of this study was to investigate how patients with knee OA control the swing limb and whether the degree of impairment and disability due to knee OA affects swing limb control.

Methods: Twelve subjects diagnosed with knee OA and 11 healthy control subjects participated in this study. Subjects walked on a treadmill for 10 min. The mean, coefficient of variation, and fractal scaling exponent α of the peak shank angular velocity during the swing phase were calculated.

Findings: There were no significant differences between the groups for any of the kinematic parameters. The Knee Injury and Osteoarthritis Outcome Score (KOOS) activities of daily living (ADL) subsection correlated with the coefficient of variation ($r = -0.677$, $p = 0.016$) and the scaling exponent α ($r = 0.604$, $p = 0.037$) of the peak shank angular velocity.

Interpretation: Control of the swing limb was associated with the degree of impairment and disability. Larger and more random variability of peak shank angular velocity may indicate decreased ADL ability in patients with knee OA.

1. Introduction

Knee osteoarthritis (OA) is one of the most common degenerative joint diseases among the elderly. It often results in functional impairments including weakness of the quadriceps femoris muscle [1], and negatively affects the ability to perform activities of daily living (ADL) [2]. Walking is the most common mode of locomotion and is often limited by knee OA [3]. Therefore, it has been widely studied to understand pathological gait conditions such as knee OA. Previous studies of knee OA have primarily focused on the stance phase and the stance limb, while there are only a few studies on the swing phase and the swing limb control.

In the swing phase, advancement of the swing limb with safe toe clearance and preparation for ground contact with proper foot placement are required to avoid the risk of falling [4,5]. These functional tasks require flexible control to adapt to ever changing environmental circumstances. In fact, some studies have demonstrated that increased variability of swing limb kinematics may increase the risk of falling [6,7]. Patients with knee OA, who are also at risk of falling [8], have been shown to exhibit decreased knee flexion during the swing phase [9]. In addition, lower clinical knee scores have been correlated with decreased knee flexion angles during the swing phase [10]. Therefore, knee OA and/or its degree of impairment and disability may affect control of the swing limb. However, no study has focused on the variability of swing limb kinematics to understand control of the swing limb in patients with knee OA.

Stride-to-stride variability provides important information about motor control during walking [11]. In terms of magnitude of the

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variability, either too much or too little variability is associated with impaired movement patterns [12]. However, it may not be enough just to investigate magnitude of the variability to evaluate the motor flexibility and adaptability because, for instance, larger variability can be interpreted as being representative of an adaptive or an unstable movement pattern. Another aspect of variability is the temporal structure measured using non-linear analyses that capture how the movement changes over time, which represents the complexity of the movement pattern. It has been proposed that this complexity is associated with a rich behavioral state [13] and reflects the adaptability of the biological system [14,15]. One such non-linear analysis, detrended fluctuation analysis (DFA), has been applied to stride time; this has shown that the complexity of stride time in patients with knee OA does not differ from controls [16,17]. Tanimoto et al. applied DFA to swing limb kinematics in healthy adults and suggested that the movement pattern of the swing limb becomes more complex and adaptive when conscious control of the swing limb is required [18]. Therefore, DFA is useful for detecting changes in motor control and evaluating the adaptability of swing limb control.

Inertial sensing is useful technology for evaluation of this variability because it allows large amounts of continuous gait data to be collected [19]. Angular velocity of the shank measured by an inertial sensor can provide useful information on swing limb kinematics. In fact, peak angular velocity of the shank during the swing phase has been used to detect abnormal gait mechanics in patients with a reconstructed anterior cruciate ligament and people at risk of falling [20,21]. In addition, during the swing phase, neuromuscular control of muscles around the knee joint, such as the quadriceps femoris and hamstrings, that are often impaired by knee OA affects movement of the shank. Therefore, there is evidence to suggest that peak angular velocity of the shank may be a useful parameter for assessments of gait mechanics during the swing phase in patients with knee OA.

The purpose of this study was to investigate peak shank angular velocity during the swing phase of the affected limb to clarify how control of the swing limb is affected by knee OA. We analyzed mean, variability and complexity of the peak shank angular velocity to understand the movement pattern of the swing limb in knee OA in more detail and compared them to control participants with healthy knees. Furthermore, we also investigated the relationships between the degree of impairment (pain, symptoms and weakness of quadriceps femoris) and ADL disability and parameters of peak shank angular velocity to clarify the clinical significance of the movement pattern of the swing limb. We hypothesized that peak shank angular velocity would differ between groups and would be correlated to the degree of impairment and disability. Additionally, we hypothesized that knee OA and the resultant impairment and disability is associated with decreased peak shank angular velocity and larger and more random variability of peak shank angular velocity.

2. Methods

2.1. Subjects

Twelve subjects (10 females and 2 males) diagnosed with unilateral or bilateral knee OA by an orthopedist and 11 healthy control subjects (9 females and 2 males) participated in this study (Table 1). The severity of knee OA was assessed using the Kellgren-Lawrence grading scale [22]. Patients with a history of musculoskeletal disorders other than that at the knee joint, which affected gait, were excluded. The control group did not fulfill the American College of Rheumatology classification criteria for knee OA [23] and had no pain in the other lower extremity. Exclusion criteria for both groups included a history of neurological disease that affected their gait, a history of rheumatoid arthritis, and difficulty walking on a treadmill without a handrail. Because lower limb kinematics is similar in unilateral and bilateral knee OA [24], the knee OA group included both unilateral and bilateral knee OA patients. The studied limb was the most symptomatic side for patients with bilateral knee OA and the affected limb for unilateral knee OA. In the control group, the studied limb was selected randomly in accordance with the left/right ratio of the study limb in the knee OA group. All subjects provided informed consent and the study was approved by the Institutional Ethics Committee.

Table 1
Characteristics of the knee OA and control groups.

	Knee OA (n = 12)	Control (n = 11)	p value
Age (years)	73.0 (71.5–73.0)	66.0 (62.5–73.5)	0.154
Body height (cm)	152.2 ± 5.8	153.2 ± 8.7	0.744
Body weight (kg)	54.3 ± 7.0	51.3 ± 10.5	0.423
BMI (kg/m^2)	23.4 ± 2.5	21.6 ± 2.5	0.099
Unilateral/bilateral	3/9		
K-L grade	I: 4, II: 0, III: 6, IV: 2		
KOOS pain	78.9 ± 13.3		
KOOS symptoms	83.9 ± 9.1		
KOOS ADL	89.3 ± 8.1		

Value: mean ± standard deviation or median (interquartile range).
Abbreviations: BMI, body mass index; K-L grade, Kellgren-Lawrence grade; KOOS, Knee Injury and Osteoarthritis Outcome Score; ADL, activities of daily living

2.2. Clinical assessments

To evaluate the degree of impairment and disability due to knee OA, we measured the self-reported clinical score and the strength of the quadriceps femoris muscle. To assess the self-reported impairment and disability for the knee OA group, the Knee Injury and Osteoarthritis Outcome Score (KOOS) for the Japanese population [25] was used. The KOOS consists of five subscales: pain, symptoms, ADL, sport and recreation, and knee-related quality of life. We focused on the pain and symptoms subscales to assess the signs or symptoms of each subject, and on the ADL subscale to assess the physical performance of each subject [26]. The possible scores on each subscale range from 0 to 100. Higher scores represent better conditions.

The strength of the quadriceps femoris muscle, which has been suggested to correlate with knee pain and disability in ADL [27], was measured using a dynamometer (μTas MT-1; Anima, Chofu, Japan). The subjects were seated on a clinical bed with the hip and knee flexed to 90°. The sensor was attached to the front of the shank, and the shank was strapped to the bedpost. The subjects were instructed to perform maximal isometric voluntary knee extension for five seconds, and maximum force was recorded. The muscle strength test was performed twice, and the largest value was adopted in the analysis. Muscle strength was measured in Newtons as the magnitude of the force output and was normalized to body weight (N/kg).

2.3. Gait analysis

2.3.1. Apparatus

Subjects walked on a motorized treadmill (T616; SportsArt, Tainan, Taiwan). One inertial sensor with a tri-axial accelerometer and gyroscope (MVP-RF8-GC-500; MicroStone, Saku, Japan) was placed on the anterior aspect of the shank at a position halfway between the proximal and the distal ends. The sensor was attached to a plastic plate, and then the plastic plate was fixed to the shank using medical tape. The measurement range of the accelerometer was ± 20 m/s^2. The measurement range of the gyroscope was ± 500 °/s. The acceleration and angular velocity data were measured with a sampling rate of 100 Hz.

2.3.2. Procedures

Before data collection, subjects walked for about 10 min on the treadmill to become habituated to treadmill walking. The speed of the treadmill was increased or decreased incrementally to determine each

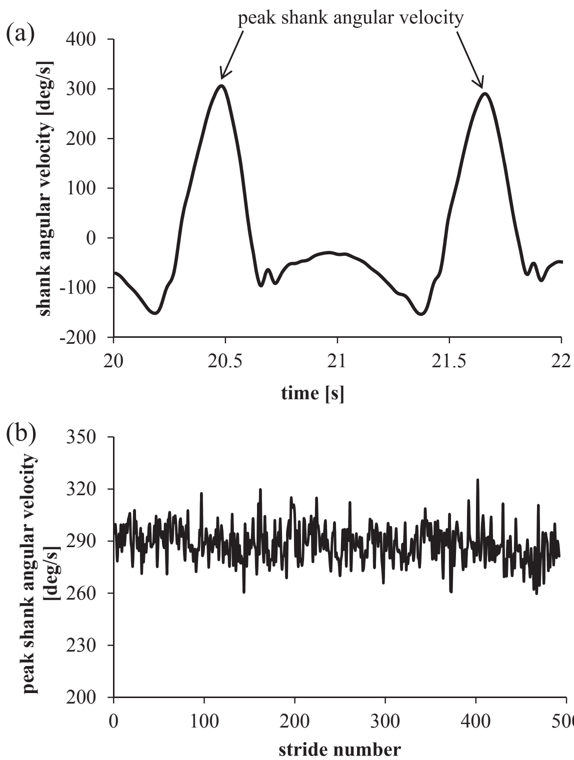

Fig. 1. (a) Typical shank angular velocity signal at a particular time for a subject. The peaks during the swing phase at every stride were extracted to generate a time series. (b) Typical time series of the peak shank angular velocity during the swing phase for a subject.

subject's self-selected gait speed. The self-selected gait speed was selected according to each subject's most comfortable speed within the habituation trial. The period of habituation to the self-selected speed was at least 3 min. In a measurement trial, subjects walked for 11 min at the self-selected speed. The first minute was for habituation to the speed, and the following 10 min were used as the measurement period.

2.4. Data processing

Data were processed using Matlab 2014a (MathWorks, Natick, USA). The angular velocity signal in the sagittal plane was filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 20 Hz. This cut-off frequency was selected to remove the higher-frequency components and noise of the data [28]. Angular velocity peaks during the swing phase (peak shank angular velocity) were extracted to generate a time series (Fig. 1). Peak shank angular velocity is a useful parameter for detecting altered movement patterns of the lower limb during the swing phase when stride time and gait speed are not altered [18,20,21]. Heel contact points were identified from acceleration peaks to generate a time series of stride times (Fig. 2). Stride time is defined as the duration between two consecutive heel contacts on the same side. We analyzed the time series of these gait parameters obtained from each subject. The number of data points in time series ranged from 395 to 663 for all subjects.

Movement patterns were evaluated using the mean, coefficient of variation (CV), and fractal scaling exponent α. The mean and CV were calculated for each time series. CV (standard deviation/mean × 100%) represents the magnitude of the variability in the time series. In addition, the fractal scaling exponent α was calculated for each time series to quantify the strength of the long-range correlations using DFA [29]. DFA has previously been used to investigate the complexity of physiological system [15], which reflects the adaptability of the system [14,15]. We used DFA introduced by Peng et al. [29]. The calculation of the average fluctuation size $F(n)$ was repeated with box size n ranging

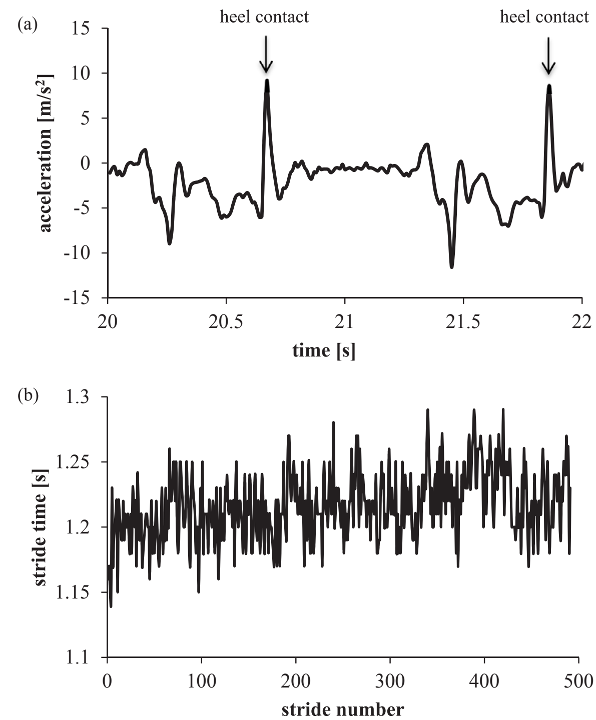

Fig. 2. (a) Typical acceleration signal at a particular time for a subject. Acceleration was used to identify heel contact points, which were used to calculate stride times. (b) Typical time series of the stride time for a subject.

from 4 to $N/4$, where N represents the number of data points in the time series. The slope of the relation between log $F(n)$ and log n is the scaling exponent α. An α value of 0.5 indicates that the time series was random noise. An α value greater than 0.5 and less than 1.0 indicates that the time series had a long-range correlation [30].

2.5. Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics ver. 22.0 (IBM Japan, Tokyo, Japan). The Shapiro-Wilk test was used to determine whether the data followed a normal distribution. If they followed a normal distribution, the unpaired t-test was used under homoscedasticity and a Welch test was used under heteroscedasticity for comparison of the demographic data and gait parameters between the groups. If the data did not follow a normal distribution, a Mann-Whitney U test was used. The relationship between the parameters of peak shank angular velocity and clinical assessments (KOOS and strength of the quadriceps femoris muscle) was investigated using Pearson's correlation coefficients. The significance level was set at 0.05.

3. Results

There was no significant difference in the demographic data between the groups (Table 1). Their self-selected gait speed was not significantly different, nor was the difference in mean, CV, and scaling exponent α of peak shank angular velocity and stride time (Table 2).

The correlations between the parameters of peak shank angular velocity and clinical assessments for the knee OA group are shown in Table 3. The KOOS pain score correlated positively with mean of the peak shank angular velocity ($r = 0.616$, $p < 0.05$). The KOOS ADL score correlated negatively with CV of the peak shank angular velocity ($r = -0.677$, $p < 0.05$). In addition, the KOOS ADL score was positively correlated with mean ($r = 0.741$, $p < 0.01$) and scaling exponent α ($r = 0.604$, $p < 0.05$) of the peak shank angular velocity. Quadriceps femoris muscle strength correlated positively with scaling exponent α ($r = 0.655$, $p < 0.05$). In addition, quadriceps femoris

Table 2
Gait parameters in the knee OA and control groups.

	Knee OA (n = 12)	Control (n = 11)	p value
Peak shank angular velocity			
Mean (deg/s)	281.0 ± 63.6	323.7 ± 62.3	0.119
CV (%)	7.00 ± 2.48	5.61 ± 1.39	0.116
Scaling exponent α	0.68 ± 0.11	0.69 ± 0.09	0.872
Stride time			
Mean (s)	1.11 ± 0.13	1.12 ± 0.17	0.879
CV (%)	2.84 ± 1.18	2.58 ± 0.93	0.574
Scaling exponent α	0.86 ± 0.13	0.84 ± 0.11	0.739
Gait speed (km/h)	2.78 ± 0.88	3.35 ± 0.93	0.146

Value: mean ± standard deviation.
Abbreviation: CV, coefficient of variation.

muscle strength correlated positively with the KOOS ADL score ($r = 0.587$, $p < 0.05$).

4. Discussion

The purpose of this study was to compare peak shank angular velocity during the swing phase in patients with knee OA to that of control subjects using an inertial sensor and to investigate relationships between the degree of impairment and disability and parameters of peak shank angular velocity. However, there were no statistical differences between the two groups for any parameter of the peak shank angular velocity, and this finding did not support our hypothesis. In this study, participants in the knee OA group had relatively high walking ability because the stride time and self-selected gait speed in the knee OA group did not differ from those in the control group and the KOOS score was relatively high. The reason the difference was not significant may be the unexpectedly high level of walking ability in the knee OA group. However, the mean of the peak shank angular velocity exhibited a tendency to decrease, and CV of the peak shank angular velocity exhibited a tendency to increase in the knee OA group. Post-hoc power analysis indicated a statistical power of 0.34 for mean and 0.35 for CV of the peak shank angular velocity, which were relatively low. Therefore, there might be a type II error in these parameters. Similarly, gait speed did not differ significantly between the groups, although the knee OA group tended to be slower; the statistical power was 0.30. Future studies, with larger cohorts, may find significant differences in these parameters. In agreement with the mean and CV of the peak shank angular velocity, there was no significant difference between the groups in the complexity of lower limb kinematics during the swing phase evaluated using DFA. Alkjaer et al. previously suggested that the complexity in patients with knee OA evaluated using the Lyapunov exponent of continuous knee joint angle for the entire gait cycle is not different from that in healthy control subjects [16], and this result may be due to patients in this study having relatively mild knee OA symptoms. Therefore, the complexity of swing limb kinematics may still be influenced in patients with more severe knee OA.

Conversely, several correlations between parameters of peak shank angular velocity and clinical assessments were significant in the knee OA group. Specifically, there were significant correlations between mean of the peak shank angular velocity and the KOOS pain and ADL scores, CV of the peak shank angular velocity and the KOOS ADL score, the scaling exponent α of the peak shank angular velocity and the KOOS ADL score and quadriceps femoris muscle strength. These findings partially support our hypothesis. It has been reported that angular parameters of the knee during walking correlate with several subjective clinical scores [10,31]. The present study is the first to show that parameters of peak shank angular velocity obtained from an inertial sensor are related to the severity of knee pain and ADL disability; this could imply that these parameters are useful for understanding the relationship between swing phase kinematics and clinical symptoms and ADL disability. Mean of the peak shank angular velocity correlated positively with the KOOS pain score and KOOS ADL score, suggesting that higher peak shank angular velocity is associated with lower severity of clinical symptoms and ADL disability. It has been shown that knee extension angle at initial contact is decreased in patients with knee OA [32]. This pathognomonic angular movement may relate to our result that patients with knee OA who had more severe pain and higher ADL disability exhibited lower peak shank angular velocity. Consequently, it is possible that insufficient knee extension during initial contact might be caused by lower angular velocity of the shank during the swing phase.

In terms of variability, greater CV of the peak shank angular velocity correlated with the lower KOOS ADL score. CV represents the magnitude of the variability; a high value of CV can be interpreted as an adaptive or as an unstable movement pattern. Therefore, it is inferred from our results that patients with knee OA who have more severe ADL disability demonstrate more unstable movement patterns during the swing phase. In addition, the scaling exponent α, which provides the temporal structure of the variability, is helpful in understanding the nature of the long-range correlations in the movement pattern. The lower KOOS ADL scores correlated with a decreased scaling exponent α of the peak shank angular velocity. Scaling exponent α generally ranges from 0.5 to 1.0 and scores closer to 0.5 indicate higher randomness (white noise) in the time series. Therefore, our results suggest that patients with knee OA who have lower ADL ability exhibit a larger variability and more randomness of their swing limb movement patterns, which can be interpreted as an unstable and less organized movement pattern that is less adaptable to environmental circumstances [12,13]. In addition, the scaling exponent α displayed a significant positive correlation with quadriceps femoris muscle strength, suggesting that more randomness of swing limb movement patterns is associated with lower strength of quadriceps femoris muscle. Quadriceps femoris muscle strength is important for ADL ability in patients with knee OA [27]. In this study, a similar correlation between quadriceps femoris muscle strength and KOOS ADL score was observed. Therefore, the knee extensor strength may be an important factor for higher complexity and adaptability of lower limb movement patterns during the swing phase and for ADL ability as well. The aforementioned

Table 3
The correlations between parameters of peak shank angular velocity and clinical assessments for the knee OA group (n = 12).

	KOOS pain		KOOS symptoms		KOOS ADL		Quadriceps strength	
	r value	p value	r value	p value	r value	p value	r value	p value
Peak shank angular velocity								
Mean	0.616[a]	0.033	0.470	0.123	0.741[b]	0.006	0.570	0.053
CV	−0.492	0.105	−0.567	0.065	−0.677[a]	0.016	−0.359	0.252
Scaling exponent α	0.269	0.397	0.366	0.242	0.604[a]	0.037	0.655[a]	0.021

Abbreviations: CV, Coefficient of variation; KOOS, Knee Injury and Osteoarthritis Outcome Score; ADL, Activities of daily living.
[a] Significant correlation at the 0.05 level.
[b] Significant correlation at the 0.01 level.

results suggest that greater and more random variability of peak shank angular velocity during the swing phase is associated with decreased ADL ability in patients with knee OA.

In relation to the results, it is important to note that this study had several limitations. To begin, a treadmill was used to assess the gait parameters. Long records of steady-state walking behavior are needed to assess variability in gait parameters accurately [33]; Moraiti et al. used a treadmill to eliminate any confounding effects of walking speed within a trial on variability [34]. Therefore, we used a treadmill to collect a large number of continuous data at constant speed. However, natural gait may be affected by the controlled pace on a treadmill. Thus, the generalizability of our results to over-ground walking could be limited. Secondly, the sample size was relatively small for finding significant differences, and the sample population was limited to patients with mild knee OA who could walk at a gait speed similar to control subjects. Therefore, further studies should be performed with a larger number of subjects with varying degrees of severity and incidence of symptoms (i.e., bilateral vs. unilateral), during over-ground walking, to confirm the effects of knee OA on movement patterns during the swing phase in natural gait.

5. Conclusions

Parameters of peak shank angular velocity during the swing phase in the knee OA group measured with an inertial sensor did not differ compared to control participants without knee OA, but were significantly correlated with the degree of impairment and disability in knee OA. The correlation results suggest that patients who are more strongly affected by knee OA swing their lower limb more slowly and with larger and more random variability. Consequently, our findings provide new insight into the relationship between several accepted measures of clinical impairment and the variability of swing limb kinematics in patients with knee OA.

Conflict of interest

The authors have no conflict of interest associated with this study.

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