A Comparative Study of Spatiotemporal Pattern and Kinematics of Human Gait between Normal Knee and Total Knee Arthroplasty

W. Chatasuwatjananon, C. Phombut, and S. Rooppakhun

School of Mechanical Engineering, Institute of Engineering, Suranaree University of Technology

Abstract

This study aims to compare the spatiotemporal pattern and kinematic data analysis of knee joint during gait between the normal knee and total knee arthroplasty (TKA) using three-dimension (3D) motion technique. A total of 10 subjects consisted of five normal knees and five total knee arthroplasty (TKA) was performed with the average body mass index (BMI) of 23.92±0.40 kg $\cdot(m^2)^{-1}$ and 23.81±0.80 kg $\cdot(m^2)^{-1}$, respectively. The 3D technical analysis using software included Qualisys Track Manager (QTM) and Visual 3D were used to create the skeleton model for the analysis of the spatiotemporal and kinematic data. The measurement data were obtained and then compared between groups using statistical mean different analyses. According to the results of the spatiotemporal pattern, there was no statistically significant difference ($P > 0.05$) between the normal knee and TKA group except the speed, step time and stance time. For the kinematic analysis, the maximum average value of the flexion-extension angle in the normal knee and the TKA were 46 deg occurred in the swing phase at 73 percent of the gait cycle. In the standing phase, the TKA group displayed a slight change of flexion-extension angle than the normal knee. In addition, the maximum average value of angular velocity in the normal knee displayed higher than TKA during standing to swing phase. The results of this study provided basic information and useful for designing and various treatment of knee joints symptoms as well as the physical treatment and sports science.

Keywords*:* Spatiotemporal, Kinematics, Gait Cycle, Total Knee Arthroplasty

INTRODUCTION

Human-life activities have motion of human body entire time such as walking, sitting, sporting or exercising, and some postures of motion effect to knee joint directly which become injured at the knee joint. Especially, a chronic injury is occurred knee joint osteoarthritis in elder by which are sophisticated-high risk more than adults [1]. The cause of the knee joint occurs from the damaged surface of bone between the distal femur and proximal tibia which are from the accident and wear aspect toward painful. In addition, solutions of treatment have different levels to treat until medication, injections, and surgery of knee joint from normal to serious injuries respectively [2]. Furthermore, this serious injury cannot recover that it has to be surgery for knee joint replacement as known as total knee arthroplasty (TKA) [3]. After surgery, it found that the motion of TKA patients distinguishes from normal knee [4]. This condition leads to the study on the kinematics of knee joint and spatiotemporal. For spatiotemporal gait parameters is explained that of speed, cycle time, step length and stride length, there are several techniques to solve these problems [5].

Nowadays, the techniques have been used by calculated photographs, video-recorded motion, and 3D-motion analysis. Particularly, the 3D-motion analysis utilized an infrared camera system and a reflective marker. Utilizing this advanced technology is in both facet sporting and medical. In addition, the advantages of this technique, are high precision, inexpensive and portable.

From mentioned, this is interesting to study walking motion of knee joint in normal knee comparing with TKA. In this study, the collected data included spatiotemporal analysis (such as step length, step time, stance time, etc.,), also kinematics, for instance, angle angular velocity and angular acceleration were performed during the gait cycle based on the 3D-motion analysis. All 10 subjects consisted of 5-normal and 5-TKA at the Suranaree University of Technology and Suranaree Hospital in Thailand was considered and then compared between among groups. Basic information of this study would lead to the application for medical treatment and physical sports science.

A. Biomechanics of Knee Joint

Biomechanics is the science of movement of a human body in which muscles, bones, tendons, and ligaments work together for the movement of the human body. The mind is to control the movements like a machine. The intrinsic mechanics of this machine gradually became clear through the work of the scientists. The knee joint is flexed and attached to the bone of the thigh. Quadricep muscles are bounded under the knee. Various forces acting on the knee and excessive pressure on the ligaments due to overload in various activities take place, which affects the functioning of the knee due to injuries such as rupture in ligaments [6].

In motion study of the knee joint, kinematics and kinetics were performed to study knee joint movement. The kinematics is the study of translation, rotation, velocity, acceleration, and inertia of knee joint during motion while kinetics consider the forces that cause them to move.

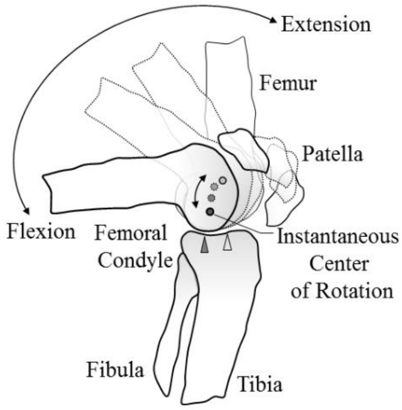

Fig. 1. Flexion – extension motion of human knee in the sagittal plane.

B. Normal Gait Cycle

The normal gait cycle is a repetitive pattern involving steps. The step time is the time between the heel strike of one leg and the heel strike of the contralateral leg. Step width can be described as the mediolateral space between the two feet. Classification of the gait cycle involves two main phases: the stance phase (ST) and the swing phase (SW). The stance phase (ST) occupies a 60 percent gait cycle while the swing phase (SW) occupies only 40 percent of it as shown in Fig. 2 [7]. According to the initial contact, heel strike is a short period that begins the moment the foot touches the ground and the first phase of double support. In the foot flat or loading response phase, the body absorbs the impact of the foot by rolling in pronation. The body is supported by one single leg. In midstance, the body begins to move from force absorption at impact to force propulsion forward. Heel off begins when the heel leaves the floor. In this phase, the bodyweight is divided over the metatarsal heads. On toe-off, the toe leaves the ground. Thus, start the swing phase. In the early swing phase, the hip extends and the hip flexes in the mid-swing phase. The late swing/declaration phase begins with hip flexion, a locked extension of the knee and a neutral position of the ankle.

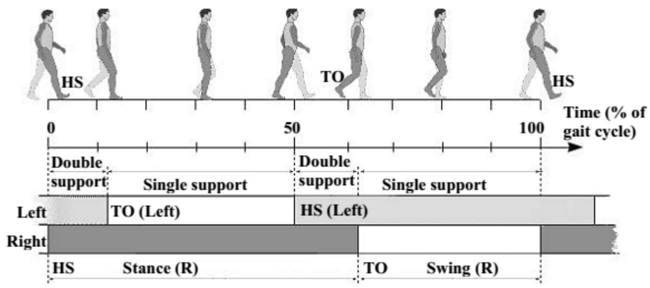

Fig. 2. Normal gait cycle.

C. Kinematics of Knee

Kinematics is a branch of classical mechanics that describes the motion of points, bodies (objects), and systems of bodies (groups of objects) without considering the forces that cause them to move. In kinematics analysis, 3-D motion capture was used to study. Walking is the most activity that was used for the kinematics study. The analytical kinematics information of walking at the stance phase found that knee has flexion approximal 0 - 6 degrees (slowly walking), 6 to 12 degrees (normal walking), and 12 - 18 degrees (quickly walking). During the flexion-extension of the knee joint at the swing phase, the range of motion approximately is 67 degrees, and increase to 83 and 90 degrees in walking and stair descent, respectively.

Furthermore, the knee joint has an extension and external rotation or flexion and internal rotation of the tibia which calls the screw home mechanism.

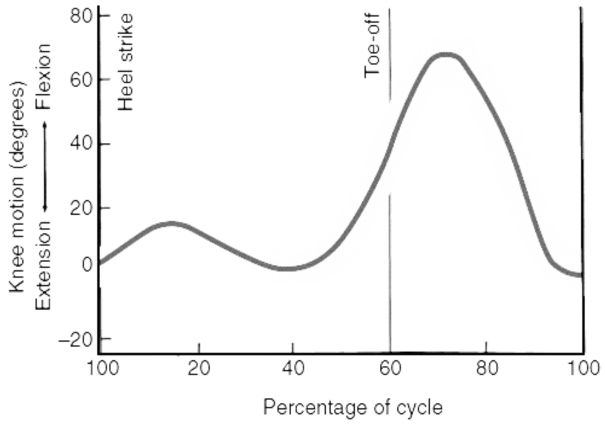

Fig. 3. Range of motion of the tibiofemoral joint in the sagittal plane during level walking in one gait cycle .

Knee flexion-extension begins when heel strike at 0 percent gait cycle to toe-off at 62 percent gait cycle and the heel return to heel strike at 100 percent gait cycle shown in Fig. 3[8]. During flexion-extension, the tibia rotates around the femur which the external and internal rotation has approximal 10 degrees.

D. Spatiotemporal Analysis

Spatiotemporal analysis derived from the temporal and spatial occurrence of the stance and swing phases. Normal values are provided in Fig. 4 [9].

- Stride length is a distance between proximal end position of the foot at ipsilateral heel strike to the proximal end position of the foot at the next ipsilateral heel strike.
- Stride width is a mediolateral distance between proximal end position of the foot at ipsilateral heel strike to the proximal end position of the foot at the next contralateral heel strike.
- Step length is a distance between the proximal end position of the contralateral foot at the previous contralateral heel strike to the proximal end position of the ipsilateral foot at the ipsilateral heel strike.
- Speed is computed using the actual stride length / actual stride time.
- Cycle time is the actually computed time from the stride length/stride time. Computed speed uses the average of all the parts of the gait cycle which are seen and sums up the parts.

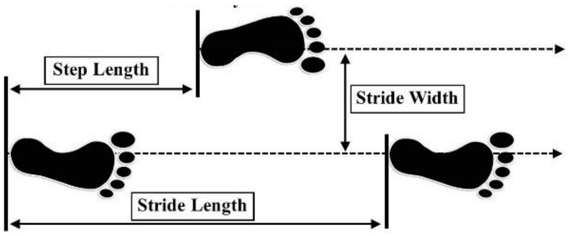

Fig. 4. Spatiotemporal gait parameters

II. Materials and Methods

A. Subject

Firstly, data records should be preserved by the Human Research Ethics Committee (HREC) follows by Suranaree University of Technology requirement that is human research and experimental (2012). After HREC accepted the proposal (EC-61-101). A total of 10 subjects consisted of five-normal knee and five-TKA in both males and females. The normal knee groups had an average BMI of 23.92 ± 0.40 kg$(m^2)^{-1}$, the average weight of 67.10 ± 4.89 kg, and an average high of 1.67 ± 0.06 m. While the TKA groups had an average BMI of 23.81 ± 0.80 kg$(m^2)^{-1}$, the average weight of 62.22 ± 9.40 kg, and an average high of 1.61 ± 0.10 m.

B. Data acquisition

In this study, the total number of 6 infrared cameras (Qualisys, Oqus 700+) were used to motion capture speed shutter of cameras was 1,000 frame rate/second. The subjects were replaced a reflective 43 markers on bodies by referred Plug-in gait markers (Vicon's) that shown in Fig. 5. Then, the subject was recorded motion during walking by cameras.

Fig. 5. Anatomical locations used reflective maker placement on the body normal knee (left) and TKA. (right)

C. 3D Modeling and Analysis

The motion data were analyzed using the Qualisys Track Manager (QTM) software. The data were exported to the c3d file format which imported to the advanced biomechanics software called Visual3D v5 professional (C-Motion, 2015) for analytical and observative movement of the knee joint. The obtained data were used to create a skeleton model by interconnected pieces link of the marker as following Fig. 6.

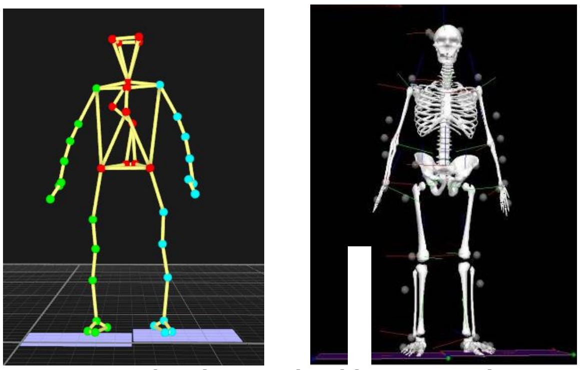

Fig. 6. Three-dimensional models in statics mode from QTM (left) and Visual3D (right) software

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After that, we have created a human skeleton model. It will analyze kinematics which consists of spatiotemporal parameters, flexion-extension angle of the knee, angular velocity and angular acceleration that relate to the frame rate. As following Fig. 7 In order to analyze the walking mode.

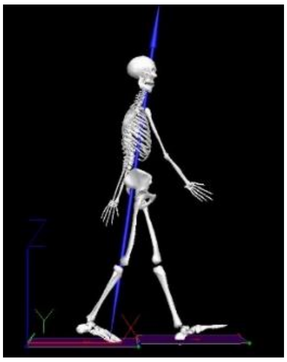


Fig. 7. Three-dimensional skeletal models during walking

D. Statistical Analysis

The statistical analysis was performed by using statistical and data analysis software package (Minitab, LLC., United Kingdom). The measurement data were expressed as mean ± standard deviation. For the comparative spatiotemporal parameter between the normal knee and TKA, the comparison of the mean (t-test) were considered statistical different at the level of p-value < 0.05.

III. Results And Discussion

According to the study of human gait, 10 volunteers have repeated the test of 3 times per person. Using the 3D motion techniques, the spatiotemporal parameters and kinematics parameter consisted of the extension-flexion angle, angular velocity, and angular acceleration the were considered. The results of the spatiotemporal gait parameter in the normal knee and TKA groups showed in Table I. Also Figure 8 to Figure 11 displayed the results of gait analysis in each group.

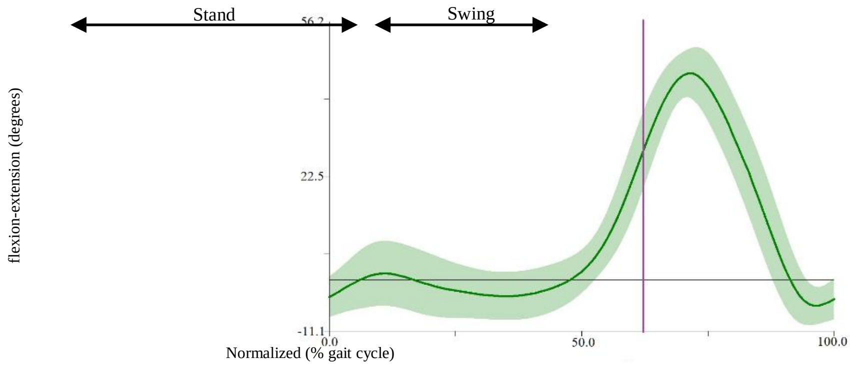
TABLE I: Comparison of Spatiotemporal Gait Parameters between Normal Human and TKA Group as MEAN (±SD)

	Normal (n=5)		***TKA (n=5)***		***P value***
Speed (m/s)*	0.815 (± 0.11)		0.602 (± 0.13)		0.023
Cycle time (s)	1.360 (± 0.11)		1.610 (± 0.19)		0.076
Stride width (cm)	12.500 (± 2.70)		14.200 (± 3.40)		0.407
Stride length (cm)	111.100 (± 9.90)		96.900 (± 10.4)		0.058
	Left	Right	Left	Right	
Step length (cm)	52.00 (±9.50)	59.10 (±3.20)	45.90 (±5.70)	51.00 (±7.50)	0.057
Step time (s)*	0.66 (±0.06)	0.70 (±0.05)	0.78 (±0.10)	0.82 (±0.10)	0.043
Stance time (s)*	0.85 (±0.09)	0.84 (±0.09)	1.02 (±0.15)	1.03 (±0.16)	0.049
Swing time (s)	0.52 (±0.04)	0.51 (±0.04)	0.60 (±0.07)	0.56 (±0.08)	0.246
Initial double Support (s)	0.19 (±0.04)	0.15 (±0.05)	0.26 (±0.06)	0.20 (±0.07)	0.230

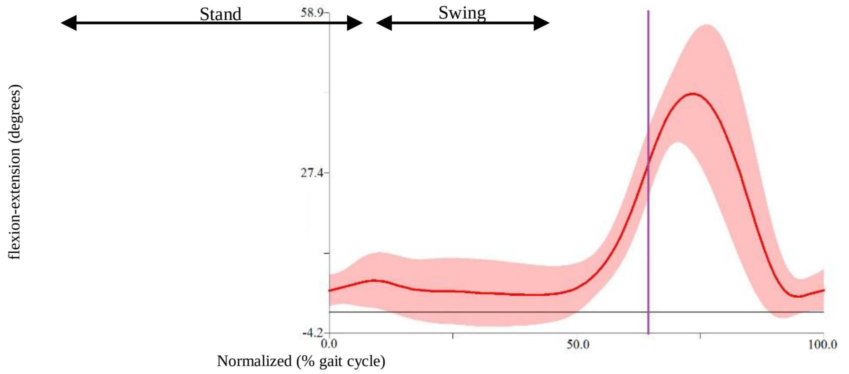
*Significant difference between normal and TKA ($P < 0.05$).

Table I showed the comparison results of spatiotemporal parameters between the normal knee and the TKA group. There was no statistically significant difference ($p < 0.05$) between two groups except speed, step time, and stance time. During the gait cycle, the average speed of normal knee was faster than the TKA group, while the step time and the stance time in the normal knee were less than the TKA group. However, the mean value of cycle time in the TKA group was higher than the normal knee. From the previous study, the standard range of a gait cycle was 1.0 seconds to 1.4 seconds (60 percent of the gait cycle) [10]. In addition, there was no statistically significant difference between spatiotemporal parameters of the left and right sides.

The results of the flexion-extension angle in each percent of the gait cycle in the normal knee and TKA group displayed in Fig. 8(a) and Fig. 8(b), respectively. The vertical lines described from stand to swing phase (62 percent gait cycle). Clearly, the maximum flexion-extension angle of the normal knee and TKA group exhibited an average value of 46.06 deg and 45.19 deg at the swing phase of the gait cycle, respectively. Generally, the maximum angle was proximal of 67 deg during walking [8].



(a)



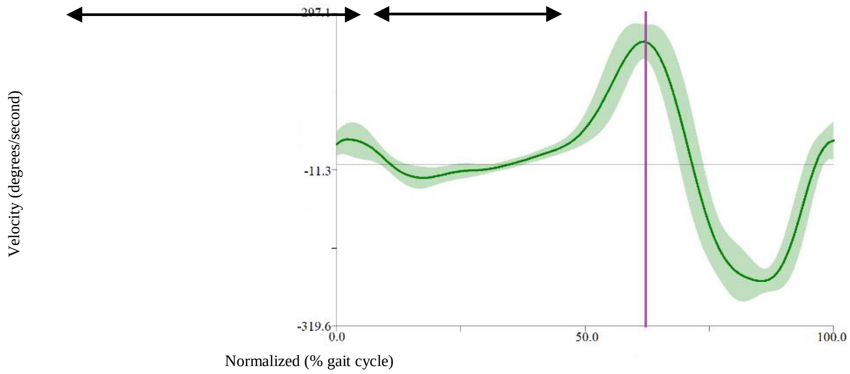
(b)

Fig. 8. Relationship between the flexion-extension angle and gait cycle
(a) Normal knee (b) TKA.

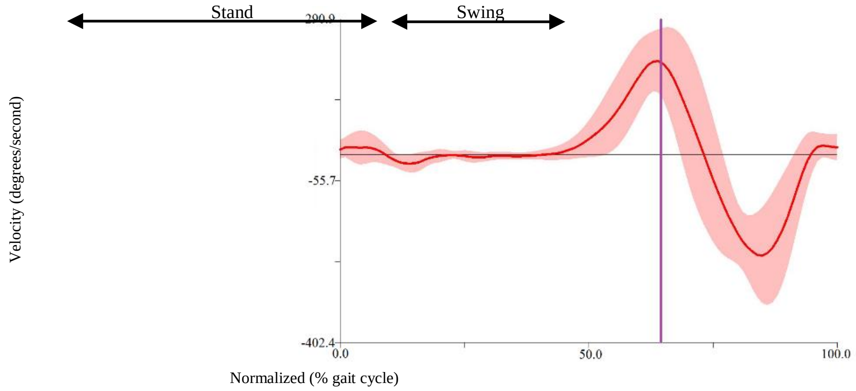
Fig. 9(a), the results of maximum average angular velocity in the normal knee was displayed 249.03deg.(s)$^{-1}$ of the gait cycle (stand to swing phase), while in TKA group revealed the maximum average angular velocity of 211.97 deg.(s)$^{-1}$ of gait cycle (swing phase) as shown in Fig 9 (b). This was similar to the experiment of Diane L. [11] who studied the gait cycle with the maximum angular velocity in a range of 190 deg.(s)$^{-1}$ to 420 deg.(s)$^{-1}$.

Fig. 10(a) and Fig. 10(b) showed the result of an average maximum value of angular acceleration in the normal knee and TKA groups as 2,817.84 deg.(s)$^{-2}$ and 2,200.97 deg.(s)$^{-2}$ of the gait cycle, respectively.

Stand Swing

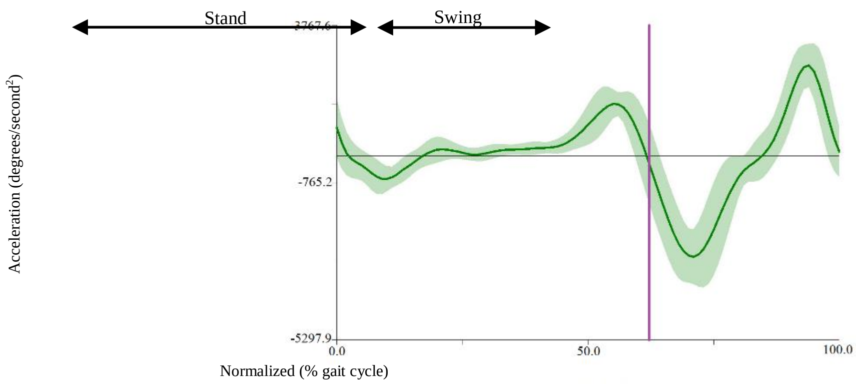


(a)

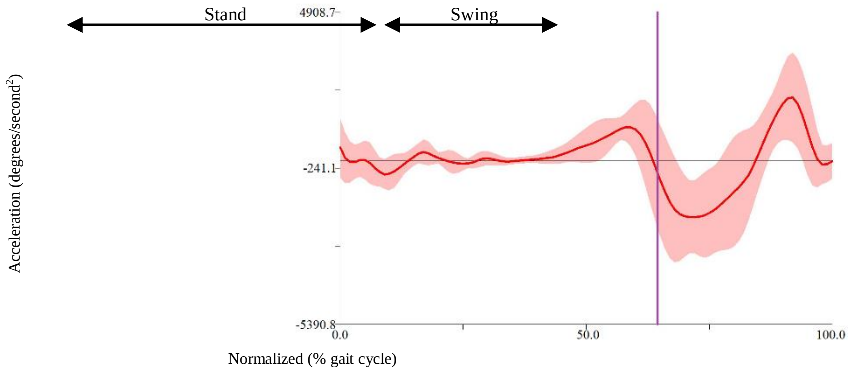


(b)

Fig. 9. Relationship between angular velocity and the gait cycle
(A) Normal knee (B) TKA.



(a)

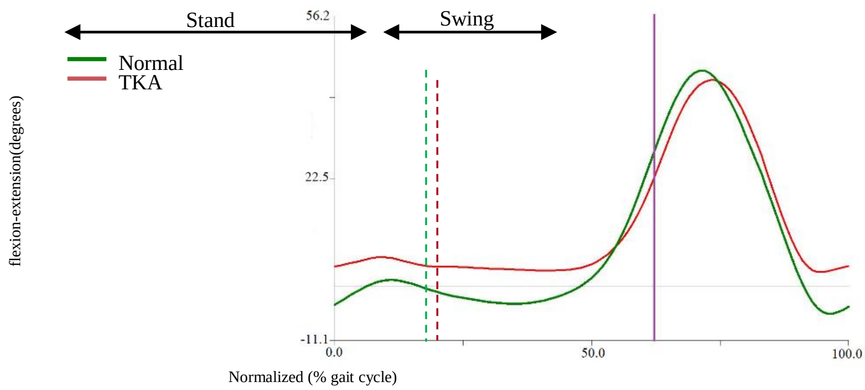


(b)

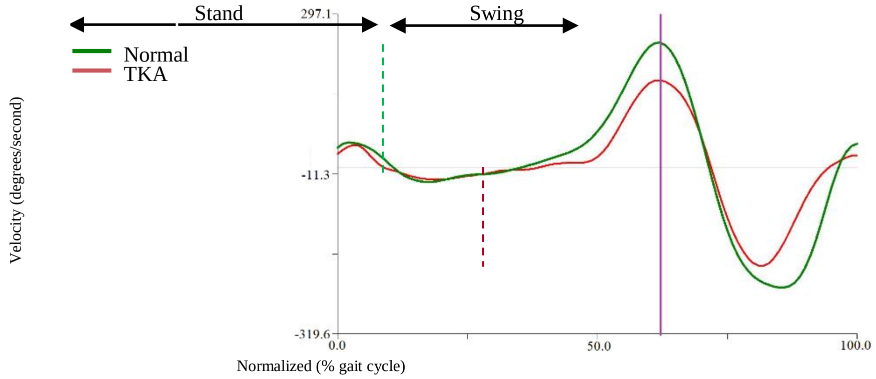
Fig. 10. Relationship between angular acceleration and gait cycle
(a) Normal knee (b) TKA.

In the standing phase as in Fig. 11 (a), TKA had a flexion-extension angle lower than the normal knee. During the swing phase, the flexion-extension angle of normal knee and TKA was similar. From Fig. 11 (b), the results showed the maximum angular velocity of the normal knee that occurred in the swing phase (62 percent of the gait cycle), while TKA had maximum angular velocity in the swing phase.

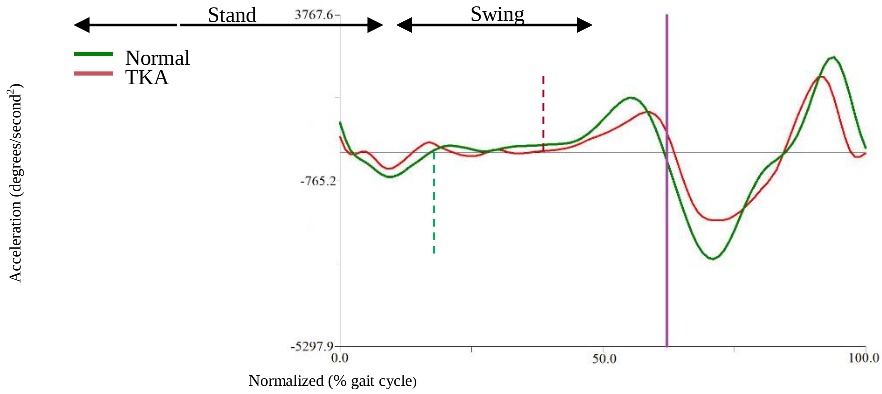
Angular acceleration as in Fig. 11 (c) had a similar value to both of the normal knee and TKA in the standing phase. In the swing phase, the maximum angular acceleration of normal knee difference from TKA. In addition, angular acceleration also changed the value from negative to positive.



(a)



(b)



(c)

Fig. 11. Comparative kinematics values between the normal knee and TKA group: (a) flexion-extension angle, (b) angular velocity, and (c) angular acceleration.

IV. Conclusion

In this study, the spatiotemporal patterns and kinematics analysis of the gait cycle in the normal knee and TKA using 3D motion analysis were presented. The results revealed that the average speed, step time, and stance time was statistically significantly different between the normal knee and TKA. The magnitude of average speed in the normal knee was higher than the TKA group, while the step time and stance timeless than TKA. For the kinematics study, the flexion-extension angle including the angular acceleration was no significantly different between the normal knee and TKA, while there was significantly different in the angular velocity. This study provides useful for various treatment of knee joints symptoms in order to develop physical treatment and sports science.

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