การพัฒนาเซ็นเซอร์แบบพกพาเพื่อวัดการเคลื่อนไหวข้อเข่าขณะเดิน และประยุกต์ใช้ในผู้ป่วยข้อเข่าเสื่อม

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DEVELOPMENT OF MOBILE SENSORS FOR MEASUREMENT OF KNEE MOTION AND APPLICATION IN PATIENTS WITH KNEE OSTEOARTHRITIS

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ทศพล เจศรีชัย : การพัฒนาเซ็นเซอร์แบบพกพาเพื่อวัดการเคลื่อนไหวข้อเข่าขณะเดินและประยุกต์ใช้ในผู้ป่วยข้อเข่าเสื่อม (DEVELOPMENT OF MOBILE SENSORS FOR MEASUREMENT OF KNEE MOTION AND APPLICATION IN PATIENTS WITH KNEE OSTEOARTHRITIS) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ศ. พญ.อารีรัตน์ สุพุทธิธาดา, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: รศ. ดร.วัชรพงษ์ โชวิฑูรกิจ, 250 หน้า.

การประยุกต์ใช้เซ็นเซอร์วัดแรงเฉื่อย (Inertial Measurement Unit ; IMU) เป็นวิธีการใหม่ที่ใช้วัดข้อมูลการเคลื่อนไหวของร่างกายทางคิเนมาติกส์ เซ็นเซอร์วัดแรงเฉื่อยที่ใช้ในครั้งนี้ประกอบด้วย triple-axis accelerometer, triple-axis gyro sensor และ triple-axis magnetometer ถูกใช้เพื่อพัฒนาอุปกรณ์แบบพกพาเพื่อใช้วัดมุมการเคลื่อนไหวของข้อเข่า ในการศึกษาครั้งนี้ผู้วิจัยพัฒนาอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อย พร้อมโปรแกรม “Knee Angle Recorder” ที่ใช้ทำงานร่วมกับอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยทั้ง 4 ชุด อุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยจะเชื่อมต่อกับคอมพิวเตอร์โดยผ่านระบบไร้สายเพื่อประโยชน์ในการใช้โดยปราศจากข้อจำกัดเรื่องระยะทางระหว่างชุดอุปกรณ์กับส่วนประมวณผล ไม่ขัดขวางการเคลื่อนไหวของขา และรายงานผลแบบทันทีทันใด และผู้วิจัยทำการพัฒนาโปรแกรม “Knee Angle Analyzer” ที่จะช่วยในการวิเคราะห์ข้อมูลการวัดที่ได้จากอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อย ในการพัฒนาอุปกรณ์ที่ใช้ในการวัดความถูกต้องของค่าที่วัดได้เป็นองค์ประกอบสำคัญประการหนึ่งในการพิจารณา ดังนั้นการตรวจสอบความถูกต้องของค่าที่วัดได้จากอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยจึงเป็นจุดประสงค์หนึ่งของการศึกษาครั้งนี้ อีกทั้งการประเมินปัญหาเมื่อนำมาใช้วัดการเคลื่อนไหวข้อเข่าก็จะทำการตรวจสอบในการศึกษาครั้งนี้ เริ่มจากการทดสอบว่าอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยมีค่าของการเอียงของเซ็นเซอร์ที่วางในชุดอุปกรณ์ในแต่ละชุดน้อยกว่า ±1 องศา จากนั้นความถูกต้องของค่าการวัดมุมการเคลื่อนไหวที่ได้จากอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยจะถูกตรวจสอบทั้งสภาวะที่อยู่นิ่งและสภาวะที่มีการเคลื่อนไหว โดยการทดสอบอุปกรณ์ดังกล่าวจะแบ่งออกเป็นสองชุดและทำการทดสอบทั้งในระนาบ sagittal และ coronal ผลการศึกษาพบว่าค่าเฉลี่ยกำลังสอง (root mean square) ของค่าความแตกต่าง มีค่าน้อยกว่า 2 องศา และค่าสัมประสิทธิ์สหสัมพันธ์ intraclass (ICC) มากกว่า 0.99 จากการเทียบกับตำแหน่งมุมอ้างอิงมาตราฐานในการทดสอบสภาวะที่อยู่นิ่งเฉพาะมุม และการทดสอบในสภาวะที่มีการเคลื่อนไหวเปรียบเทียบระหว่างระบบวัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยกับระบบกล้องสามมิติ (the Qualisys system) พบว่ามีค่าเฉลี่ยกำลังสองของค่าความแตกต่างน้อยกว่า 3 องศา (ICC มากกว่า 0.98) ทั้งในระนาบ sagittal และ coronal จากนั้นนำไปทดสอบในวัดการเคลื่อนไหวของข้อเข่าในอาสาสมัครจำนวน 10 คน ด้วยการทดสอบการเคลื่อนไหวข้อเข่า 4 ท่า (ท่างอเข่า, ท่างอสะโพกงอเข่า, ท่าการก้าวขาไปด้านหน้า และท่ากางขาออกทางด้านข้าง) และเดินทดสอบโดยเปรียบเทียบค่ามุมการเคลื่อนไหวของข้อเข่าที่ได้จากชุดอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยเทียบกับระบบกล้องสามมิติ ผลการศึกษาพบว่ามีค่าเฉลี่ยกำลังสองของค่าความแตกต่างในค่าการวัดมุมการงอ-เหยียดเข่าน้อยกว่า 6 องศา (ICC มากกว่า 0.85) ในการทดสอบการเคลื่อนไหวในท่างอเข่า ท่างอสะโพกงอเข่า และท่าการก้าวขาไปด้านหน้า ส่วนการเปรียบเทียบผลของการวัดในการเดินทดสอบพบว่ามีค่าเฉลี่ยกำลังสองของค่าความแตกต่างของมุมการงอ-เหยียดเข่าน้อยกว่า 6 องศาในหนึ่งวงรอบการเดิน (ICC มากกว่า 0.84) จากผลการทดสอบในท่าการกางขาออกทางด้านข้างพบว่าอุปกรณ์วัดมุมการเคลื่อนไหวข้อเข่าด้วย IMU ไม่สามารถวัดการกางและหุบของข้อเข่าได้ ท้ายสุดนำชุดอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยไปวัดมุมการเคลื่อนไหวของข้อเข่าขณะการเดินเพื่อดูรูปแบบการเปลี่ยนแปลงมุมการเคลื่อนไหวของข้อเข่าและค่าตัวแปรทางคิเนเมติกส์ในหนึ่งวงรอบการเดิน โดยทำการทดสอบทั้งกลุ่มหญิงสูงอายุที่มีและไม่มีอาการข้อเข่าเสื่อมจำนวน 40 คน พบว่าอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยสามารถตรวจพบความแตกต่างของค่าตัวแปรทางคิเนเมติกส์ที่เกิดขึ้นระหว่างกลุ่มผู้ที่มีและไม่มีอาการข้อเข่าเสื่อมและระหว่างขาข้างที่มีอาการข้อเข่าเสื่อมและไม่มีอาการข้อเข่าเสื่อมได้ โดยสรุปอุปกรณ์วัดมุมการเคลื่อนไหวที่ทำจากเซ็นเซอร์วัดแรงเฉื่อยพร้อมโปรแกรมที่ใช้รับข้อมูลมุมการเคลื่อนไหวและโปรแกรมที่ช่วยในการวิเคราะห์ข้อมูลมุมการเคลื่อนไหว ให้ค่าผลการวัดมุมการเคลื่อนไหวได้ดีพอสมควรและน่าจะสามารถนำไปประยุกต์ใช้ในการวัดการเคลื่อนไหวงอ-เหยียดข้อเข่าได้

สาขาวิชา วิศวกรรมชีวเวช
ปีการศึกษา 2557

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TOSSAPHON JAYSRICHAI: DEVELOPMENT OF MOBILE SENSORS FOR MEASUREMENT OF KNEE MOTION AND APPLICATION IN PATIENTS WITH KNEE OSTEOARTHRITIS. ADVISOR: PROF. AREERAT SUPUTTITADA, M.D., CO-ADVISOR: ASSOC. PROF. WATCHARAPONG KHOVIDHUNGIJ, Ph.D., 250 pp.

The Application of Inertial Measurement Unit (IMU) sensor is a new method to measure the kinematics of human movement. This IMU sensor, which consists of a triple-axis accelerometer, a triple -axis gyro sensor and a triple -axis magnetometer, is used to develop the mobile device using the knee joint angle measurement. In the present study, I developed the “IMU devices” and the “Knee Angle Recorder” software to cooperate with the four IMU devices. These IMU devices linked to a computer by the wireless connection. The benefits of the IMU devices via the wireless connection were the ambulatory devices, no restriction on the leg movement, and the real-time reporting of the knee movement. The software called the “Knee Angle Analyzer” was developed for the data analysis from the IMU measurement. However, the accurate data onto the measuring device are the awareness, hence, the accurate tests for the measuring angles by the developed “IMU devices” were this purpose. Also, any potential problems in the knee joint angle measurement were evaluated for this IMU system. All developed “IMU devices” had the inclined sensor from the zero line to be less than ±1 degrees. The accurate data onto IMU measurement were tested for the static and the dynamic conditions. The IMU devices were separated into two pairs and also were tested for the sagittal and the coronal planes. The results showed the root mean square (RMS) of different angles and the Intraclass Correlation Coefficient (ICC) values on the comparisons in the static condition between the reference angles and the IMU measurements to be less than 2 degrees (ICC≥0.99). The RMS of different angles and the ICC values when compared the measuring angles in the dynamic condition between the IMU system and the Qualisys system were less than 3 degrees (ICC≥0.98). Moreover, the “IMU devices” were tested for the accuracy on the knee joint angle measurement during the knee functional movements with ten healthy participants. The four functional knee movement tests (the knee flexion test, the hip and knee flexion test, the forward step test and the leg abduction test) and the walking test were used to compare the knee joint angles between the IMU system and the Qualisys system. The results showed the RMS of different angles and the ICC values to be less than 6 degrees (ICC≥0.85) for the knee flexion-extension movement during the knee flexion test, hip and knee flexion test and the forward step test. For the walking test, the RMS of different angles and the ICC values were less than 6 degrees (ICC≥0.84) on the knee flexion-extension movement in the gait cycle. The results from the leg abduction test revealed this IMU system to be the unable usage for measuring the knee abduction-adduction movement. Finally, the IMU system was applied to measure the pattern of knee flexion-extension movement and the kinematic variables by the forty elderly women with and without symptomatic knee osteoarthritis during the walking. The IMU system could detect some differences on the kinematic variables between the symptomatic sides and non-symptomatic sides and the differences between two groups of participants. In conclusion, these developed “IMU devices”, the “Knee Angle Recorder” software, and the “Knee Angle Analyzer” software could be used for the measurement of knee flexion-extension movement.

Field of Study: Biomedical Engineering | Student's Signature ____________

Academic Year: 2014 | Advisor's Signature ____________

Co-Advisor's Signature ____________

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CONTENTS

Page

Page

Page

Page

Page

LIST OF TABLES

PAGE

PAGE

PAGE

PAGE

LIST OF FIGURES

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

PAGE

CHAPTER 1

INTRODUCTION

1.1 Back ground

Motion analysis is a medical technique used to assess in any pathological movements. Typically, the motion analysis can be divided into two main groups; a conventional method and a motion laboratory method. A conventional method refers to an observation and/or a usage of the basic measuring tools, such as, a measuring tape, a goniometer, etc. But, the acquired data onto the conventional method are the most qualitative data that are the difficult interpretation of measurement outcomes. Also, the conventional method requires the assessment skill and the clinical experience of the therapist. Therefore, it causes the variation on the clinical reporting. While the motion laboratory method, which is the three-dimensional camera system, can give the quantitative data onto the measurement. This method refers to the standard method for the motion analysis. However, it still has some limitations; such as the required skill and the experience of device usage, the expensiveness (more than 10 million baht for a whole system in Thailand), and the applicability mostly for indoor laboratory system (Favre J, Aissaoui R, Jolles BM, de Guise JA, & Aminian K, 2009; Luinge HJ & Veltink PH, 2005; Luinge HJ, Veltink PH, & Baten CT, 1999; "LV2 Avionics System: 3D Magnetometer," ; Roetenberg D, Luinge H, & Slycke P, 2009).

Nowadays, a sensor technology is a new technique to acquire the kinematic measurement, with obvious benefits, such as mobility and inexpensiveness. The Inertial Measurement Unit (IMU) sensor is a notable senor in this decade to be used the joint angle measurement (Chardonnens J, Favre J, Cuendet F, Gremion G, & Aminian K, 2013; Chardonnens J et al., 2012; Cooper G et al., 2009; Dejnabadi H, Jolles BM, & Aminian K, 2005; Favre J et al., 2009; Favre J, Jolles BM, Aissaoui R, & Aminian K, 2008; Luinge HJ & Veltink PH, 2005; Luinge HJ et al., 1999; O'Donovan KJ, Kamnik R, O'Keeffe DT, & Lyons GM, 2007; Picerno P, Cereatti A, & Cappozzo A, 2008; Roetenberg D et al., 2009; Rouhani H, Favre J, Crevoisier X, & Aminian K, 2011; Takeda R, Tadano S, Natorigawa, Todoh M, & Yoshinari S, 2009; Takeda R, Tadano S, Todoh M, et al., 2009). Luinge HJ, Veltink PH and Baten CT (Luinge HJ et al., 1999) reported the application of the accelerometers and the gyroscopes to measure in the joint angles since 1999. They used the Kalman Filter and the Strapdown Integration algorithm to estimate angles with low noise from the sensors' output data. In 2005, Luinge HJ and Veltink PH (Luinge HJ & Veltink PH, 2005) studied continually on the application of sensors to measure the human segment orientation. They compared the joint angles from the measurements between their IMU system and the Vicon system. They also recommended that their IMU system could measure the joint angles with a bit errors. In 2009, Roetenberg D, Luinge HJ and Slycke P (Roetenberg D et al., 2009) cooperated to develop the Xsens MVN motion capture suit, which consisted of the 17 inertial sensors (a triple-axis gyroscope and a triple-axis accelerometer in each unit) and the magnetic sensor modules, for measuring the joint angles of whole body movement.

Favre J, who was the other researcher, had the several reports about the IMU measurements on the human movement (Chardonnens J et al., 2013; Chardonnens J et al., 2012; Favre J et al., 2009; Rouhani H et al., 2011). In 2008, Favre J, Jolles BM, Aissaoui R, and Aminian K (Favre J et al., 2008) used the four sets of IMU sensor that consisted of a triple-axis gyroscope and a triple-axis accelerometer and also connect to the Data-logger for the knee joint angle measurement. The knee joint angle measurement in three planes were calculated by the sensor outputs based on the fusion algorithm, which was a quaternion-based time integration of the angular velocity vector from the gyroscope outputs and to be correcting the resulting orientation by the estimated inclination from the accelerometer outputs. The joint angles from their IMU system were compared with the Liberty® magnetic tracking device. Their results revealed the low differences between the two systems. In 2009, Favre J and co-researcher improved the calibration procedure and assessed the repeatability of measurement on their IMU devices (Favre J et al., 2009). Their IMU devices revealed the high repeatability of knee joint angle measurement in all three planes. Favre J and co-researchers studied continually their IMU devices to measure the knee and the ankle movements. Also, they applied their developed devices for the sport biomechanics and the sport injury (Chardonnens J et al., 2013; Chardonnens J et al., 2012; Rouhani H et al., 2011). Other researchers (Cooper G et al., 2009; Dejnabadi H et al., 2005; O'Donovan KJ et al., 2007; Picerno P et al., 2008; Takeda R, Tadano S, Natorigawa, et al., 2009; Takeda R, Tadano S, Todoh M, et al., 2009) also approved the IMU sensor to able for measuring the joint angles in the lower limb movement.

In this study, I will apply the IMU sensors (9 Degrees of Freedom - Razor IMU - AHRS compatible; Sparkfun™ Electronics, Colorado, USA), which consists of a triple-axis accelerometer, a triple-axis gyroscope and a triple-axis magnetometer, to develop the measuring device. Four developed IMU devices will be used to measure the joint angles of the thigh, the shank and the knee on both legs. The Direction Cosine Matrix (DCM) algorithm will be used to the angle calculation in this study. It is a calculation method to recommend for the usage with these IMU sensors. The segment orientations that are estimated from the sensor outputs to be the angles in the sensor coordinate frame and also are transformed to the angles in the global coordinate frame after complete process of DCM algorithm. I plan to developed IMU devices via the wireless connection. Because I purpose to use the IMU devices without space limitation, no restriction on the leg movement and the real-time reporting. Thus, I will add the wireless connection system by the Xbee modules.

The reporting of data export from the IMU measurements is an important point. Thus, I will create software to cooperate with the four IMU devices. The software works to send a start command, to set a recording time, to receive the angular output data onto the four IMU devices, to display the measuring angles onto the line graphs of the changing angles (in degrees) versus time (in seconds), and to calculate the angles between the two segments (knee joint angles between the thigh and the shank).

According to the standards for the developmental measuring devices, the accurate data onto the devices is an important. I will test for the accurate data onto the reading angles from the IMU measurements. The reference angles and the Qualisys-Motion Capture system (the Qualisys system) will be selected to compare with the IMU system. The basic tests for the accurate data of the measuring angles will be considered on all the static and the dynamic conditions. The developed IMU devices will use to measure the knee angles. So that, the knee joint angles during the functional knee movement tests and the walking test will be tested for the accurate data onto the IMU measurements.

I will create the other software to use for the data analysis and the kinematic reporting. The software is a part of my IMU system to be a benefit for the knee kinematic assessment in a clinic.

Finally, I will bring the developed IMU system to measure the knee joint angles during a gait cycle. The elderly women with and without symptomatic knee osteoarthritis will be recruited for the test. This test will not only focus on the reporting of the knee joint angle measurement and the pattern of knee movement, but it will seek to understand the potential applications of the IMU system and any potential problems while the usage.

1.2 Research objectives

1.2.1 Main objective

This study will develop the four IMU devices by the application of the 9 Degrees of Freedom - Razor IMU - AHRS compatible (Sparkfun^{TM} Electronics, Colorado, USA) that consisted of a triple-axis accelerometer, a triple-axis gyroscope and a triple-axis magnetometer. Also, I will create the software to be used for the cooperation with the four IMU devices. The other software will be created for the data analysis and the kinematic reporting. I will test for the accurate data onto the reading angles (in degrees) from the IMU measurements. Finally, the clinical application test will be evaluated for this IMU system after the finished accuracy test.

1.2.2 Sub-objectives

1. To develop the four IMU devices by the application of the 9 Degrees of Freedom - Razor IMU - AHRS compatible (Sparkfun^{TM} Electronics, Colorado, USA). The IMU devices will be connected to a computer via the wireless connection by the Xbee modules. They will be used to measure the knee joint angles (in degrees) on both knees.

2. To create software that will be used to receive the angular output data from the four IMU devices and also will display the continuous angular output data on the monitor.

3. To evaluate the accurate data onto the reading angles (in degrees) from the IMU measurements in the static condition. The angular output data onto the IMU measurements will be compared with the reference angles and the angle measurements by the Qualisys system on both sagittal and coronal planes.

4. To evaluate the accurate data onto the reading angles (in degrees) from the IMU measurements in the dynamic condition. The angular output data onto the IMU measurements will be compared with the angle measurements by the Qualisys system on both sagittal and coronal planes.

5. To evaluate an accurate data onto the reading angles (in degrees) from the IMU measurements during the functional knee movement tests and the walking test. The knee joint angles onto the IMU measurements will be compared with the knee joint angle measurements by the Qualisys system.

6. To create software that will be used for the data analysis and the kinematic reporting on the knee movements.

7. To evaluate the knee joint angles and the knee movement pattern during a gait cycle in the elderly women with and without symptomatic knee osteoarthritis.

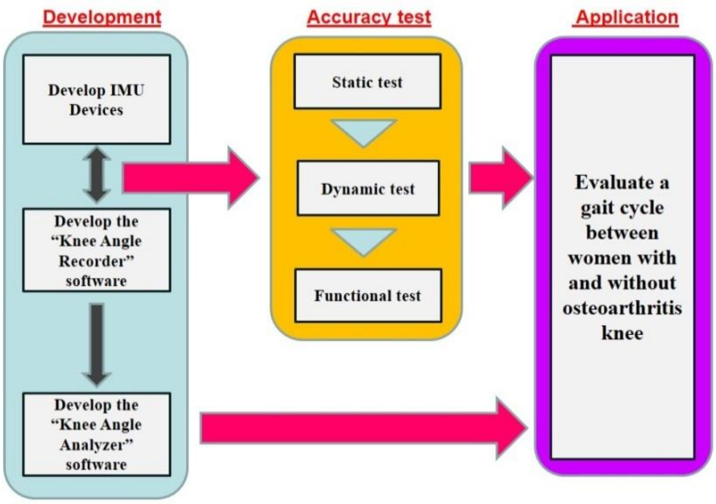
1.3 Scope of this study

This study will develop the four IMU devices and the software that will be used to cooperate between the developed IMU devices and a computer. Also, I will create the other software that will be used for the data analysis and the kinematic reporting on the knee movements. Moreover, the accurate data onto the reading angles (in degrees) from IMU measurements will be evaluated on the static condition, the dynamic condition, the functional movement tests, and the walking test. Finally, the IMU system will be applied to measure the knee joint angles and the knee movement pattern during a gait cycle in the elderly women with and without symptomatic knee osteoarthritis.

1.4 Benefits expected to be received from this study

After finishing this study, I expect to get the IMU system that can be used for measuring the knee joint angles and the knee movement pattern. Also, this IMU system can be reported the kinematic variables of knee movement depending on the selected graph area. Moreover, the developed IMU devices must be the ambulatory device (the light weight and the usage without the space limitation) and no restriction on the leg movement.

1.5 Conceptual framework of this study



CHAPTER 2

LITERATURE REVIEW

2.1 Inertial Measurement Unit

The Inertial Measurement Unit (IMU) is an electronic device that measures and reports on a craft's velocity, orientation, and gravitational forces, using a combination of accelerometers, gyroscopes, and magnetometers (Wikipedia, 2013c). In the present study, the IMU sensors have the two types; the 9 Degrees of Freedom - Razor IMU - AHRS compatible (SEN 10125) and the 9 Degrees of Freedom - Razor IMU - AHRS compatible (SEN 10736). These are the components of a triple-axis accelerometer, a triple-axis gyroscope, and a triple-axis magnetometer.

2.1.1 Accelerometer

An accelerometer is a device that measures proper acceleration. The proper acceleration measured by an accelerometer is not necessarily the coordinate acceleration (rate of change of velocity). Instead, the accelerometer sees the acceleration associated with the phenomenon of weight experienced by any test mass at rest in the frame of reference of the accelerometer device. For example, an accelerometer at rest on the surface of the earth will measure an acceleration (gravity <g> unit; 1 g = 9.81 m/s^2) straight upwards, due to its weight. By contrast, accelerometers in free fall or at rest in outer space will measure zero. Another term for the type of acceleration that accelerometers can measure is "g-force" acceleration (Wikipedia, 2013a).

In this study, the accelerometers in these IMU sensors are a triple-axis accelerometer (ADXL 345). It can measure the acceleration outputs in the X, Y and Z axis. The measurement range of the acceleration can adjust from ±2 g, ±4 g, ±8 g up to ±16 g. The measurement range of acceleration in this study is selected at ±16 g.

Table 2.1 shows the specification of a triple-axis digital accelerometer <ADXL345> (Source; SparkFun™ Electronics, Colorado, USA) (Analog devices, 2009).

Parameter	Test Conditions	Typical	Unit
Measurement range	User selectable	±2 , ±4, ±8, ±16	G
Nonlinearity	Percentage of full scale	±0.5	%
Output range resolution	Full resolution		
±2g range (10 bits)		$4/(2^{10}) = 0.00390625 \approx 0.0039$	g
±4g range (11 bits)		$8/(2^{11}) = 0.00390625 \approx 0.0039$	g
±8g range (12 bits)		$16/(2^{12}) = 0.00390625 \approx 0.0039$	g
±16g range (13 bits)		$32/(2^{13}) = 0.00390625 \approx 0.0039$	g
Sensitivity			
Sensitivity at X_{out}, Y_{out}, Z_{out}	±2g, 10-bit resolution	$256 \times [4/(2^{10})] = 1$	LSB
Scale factor at X_{out}, Y_{out}, Z_{out}	±2g, 10-bit resolution	3.9	mg/LSB
Sensitivity at X_{out}, Y_{out}, Z_{out}	±4g, 10-bit resolution	$128 \times [8/(2^{10})] = 1$	LSB
Scale factor at X_{out}, Y_{out}, Z_{out}	±4g, 10-bit resolution	7.8	mg/LSB
Sensitivity at X_{out}, Y_{out}, Z_{out}	±8g, 10-bit resolution	$64 \times [16/(2^{10})] = 1$	LSB
Scale factor at X_{out}, Y_{out}, Z_{out}	±8g, 10-bit resolution	15.6	mg/LSB
Sensitivity at X_{out}, Y_{out}, Z_{out}	±16g, 10-bit resolution	$32 \times [32/(2^{10})] = 1$	LSB
Scale factor at X_{out}, Y_{out}, Z_{out}	±16g, 10-bit resolution	31.2	mg/LSB
Operating Temperature Range		-40 to +85	°C

g is the gravity unit

mg is the millig-unit

LSB is the least significant byte unit

°C is the Celsius unit.

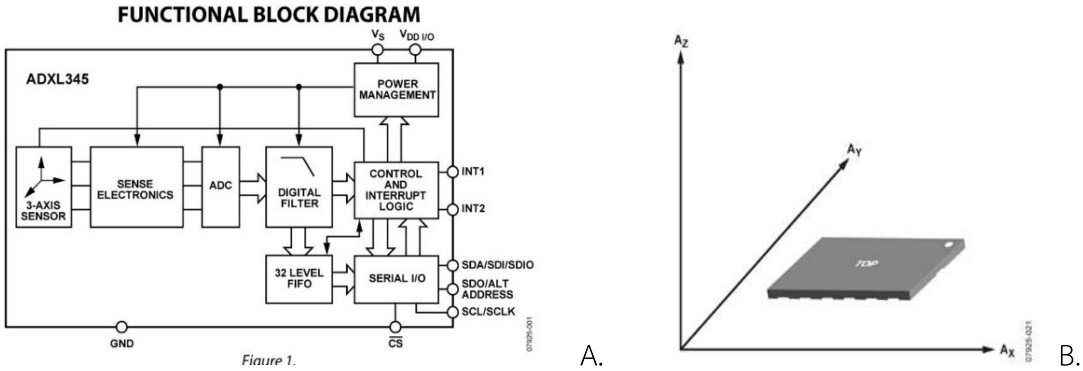


Figure 2.1 **2.1A** is the functional block diagram of a triple-axis accelerometer (ADXL345). **2.1B** shows the axes of acceleration sensitivity (Corresponding output voltage increases when accelerated along the sensitive axis) (Analog devices, 2009).

2.1.2 Gyroscope

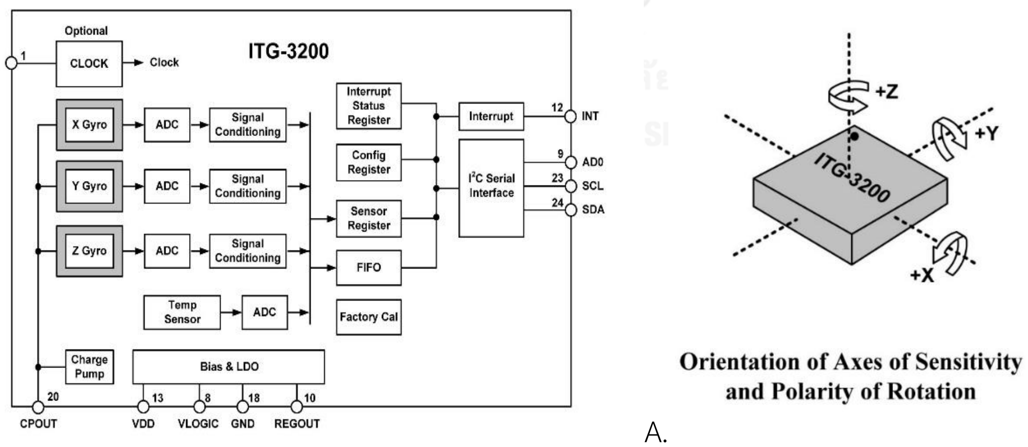
A gyroscope is a device for measuring or maintaining orientation, based on the principles of angular momentum. Mechanically, a gyroscope is a spinning wheel or disc in which the axle is free to assume any orientation. Although this orientation does not remain fixed, it changes in response to an external torque much less and in a different direction than it would without the large angular momentum associated with the disc's high rate of spin and moment of inertia. The device's orientation remains nearly fixed, regardless of the mounting platform's motion, because mounting the device in a gimbal minimizes external torque (Wikipedia, 2013b).

A triple-axis gyroscope that is used in these IMU sensors is the model ITG-3200 (SparkFun™ Electronics, Colorado, USA). It can measure the rate of angular velocity around the X, Y, and Z axis, at ±2,000 degrees per second.

Table 2.2 shows the specification of a triple-axis gyroscope <ITG-3200> (Source; SparkFun^{TM} Electronics, Colorado, USA) (InvenSense, 2010).

Parameter	Test Conditions	Typical	Unit
Measurement range	Full scale (FS)_SEL =3	±2000	°/s
Sensitivity Scale Factor	Full scale (FS)_SEL =3	14.375	LBS(°/s)
Gyro ADC Word Length		16	Bit
Resolution		4000 x [14.375/(2^{16})] = 0.87738 ≈ 0.88	°/s
Nonlinearity	Best fit straight line; 25 °C	0.2	%
GYRO mechanical frequencies			
X-axis		33	kHz
Y-axis		30	kHz
Z-axis		27	kHz
Temperature sensor			
Range		-30 to +85	°C
Sensitivity		280	LSB/°C
Linearity	Best fit straight line (-30°C to 85°C)	±1	°C
Temperature range			
Specified Temperature Range		-40 to 85	°C

°/s is the degrees per second unit.
kHz is the kilohertz unit.



A. B.

Figure 2.2 **2.2A** is the functional block diagram of a triple-axis gyroscope (ITG-3200). **2.2B** shows the orientation of the axes of sensitivity and polarity of rotation (InvenSense, 2010).

2.1.3 Magnetometer

A magnetometer (digital compass) is a measuring instrument used to measure the strength and, in some cases, the direction of magnetic fields. Magnetometers are widely used for measuring the Earth's magnetic field and in geophysical surveys to detect magnetic anomalies of various types (Wikipedia, 2013d). The Earth's magnetic field magnitude is about 0.5 to 0.6 Gauss and has a component parallel to the Earth's surface that always point toward magnetic north ("LV2 Avionics System: 3D Magnetometer,"). There are two types of magnetometers to be used in this study. Firstly, a triple-axis magnetometer in the IMU sensor number SEN 10125 is the model HMC5843 (SparkFun™ Electronics, Colorado, USA) that can measure the magnetic field at ±4 Gauss. Secondly, a triple-axis magnetometer in the IMU sensor number SEN 10736 is the model HMCL5883L (SparkFun™ Electronics, Colorado, USA) that can measure the magnetic field at ±8 Gauss

Table 2.3 shows the specification of a triple-axis magnetometer <HMC5843> (Source; Honeywell International, Inc) (Honeywell, 2010).

Parameter	Test Conditions	Typical	Unit
Measurement range	Full scale (FS) – total applied field	±4	gauss
Linearity	Full scale input range	0.1	±%FS
Resolution	AVDD=3.0V,GN	0.007	gauss
Cross-Axis Sensitivity	Cross field = 0.5 gauss, Happlied = ±3 gauss	(0.2/100) x 8 =0.016	gauss/1 gauss

gauss is the Gaussian unit of measurement of a magnetic field.

%FS is the percentage of full scale

Table 2.4 shows the specification of a triple-axis magnetometer <HMCL5883L> (Source; Honeywell International, Inc) (Honeywell, 2013).

Parameter	Test Conditions	Typical	Unit
Measurement range	Full scale (FS)	±8	Gauss
Linearity	±2.0 gauss input range	0.1	±%FS
Field resolution	VDD=3.0V, GN=0, No measurement average, Standard Deviation 100 samples	2	Gauss
Cross-Axis Sensitivity	Cross field = 0.5 gauss, Happlied = ±3 gauss	(0.2/100) x 16 =0.032	gauss/1 gauss

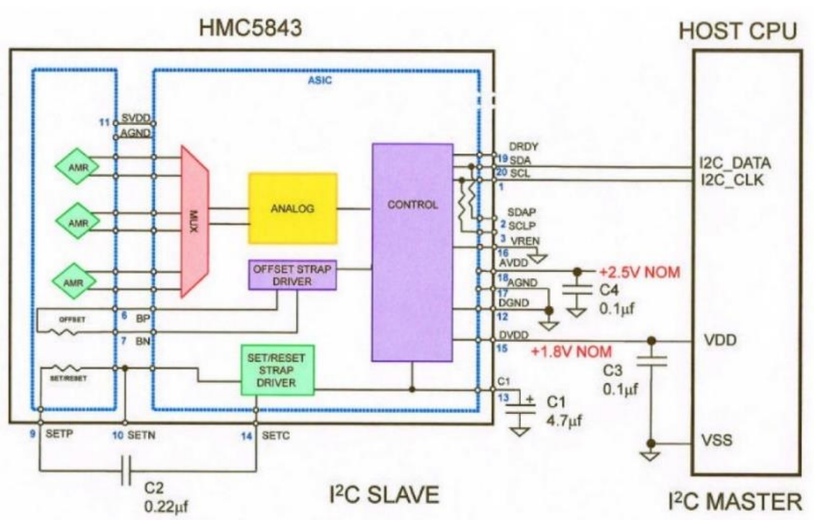


Figure 2.3 is the functional block diagram of a triple-axis magnetometer (HMC5843) (Honeywell, 2010).

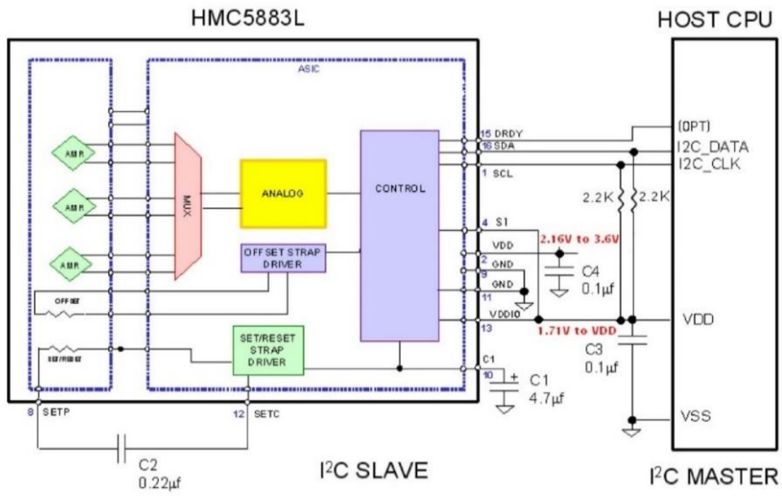


Figure 2.4 is the functional block diagram of a triple-axis magnetometer (HMCL5883L) (Honeywell, 2010).

Why does not use only the Integration of angular velocity outputs from the gyroscope? Because the estimated angles from the integration of angular velocity outputs also have the offsets and any drifts (Aminian K & B., 2004; Willemsen ATM, Van Alste JA, & Boom HBK, 1990). The two main factors that causes the offsets and any drifts are the electronic bias error (Titterton D & Weston J, 2004) and the sensor deviation from the sensor coordination axis.

2.2 Acquisition of the estimated angles by the IMU measurements

The angles from the IMU measurements are calculated by the Direction Cosine Matrix (DCM) algorithm (Premerlani W & Bizard P, 2009). The accelerometer outputs, the gyroscope outputs, and the magnetometer outputs are the components of angle calculation.

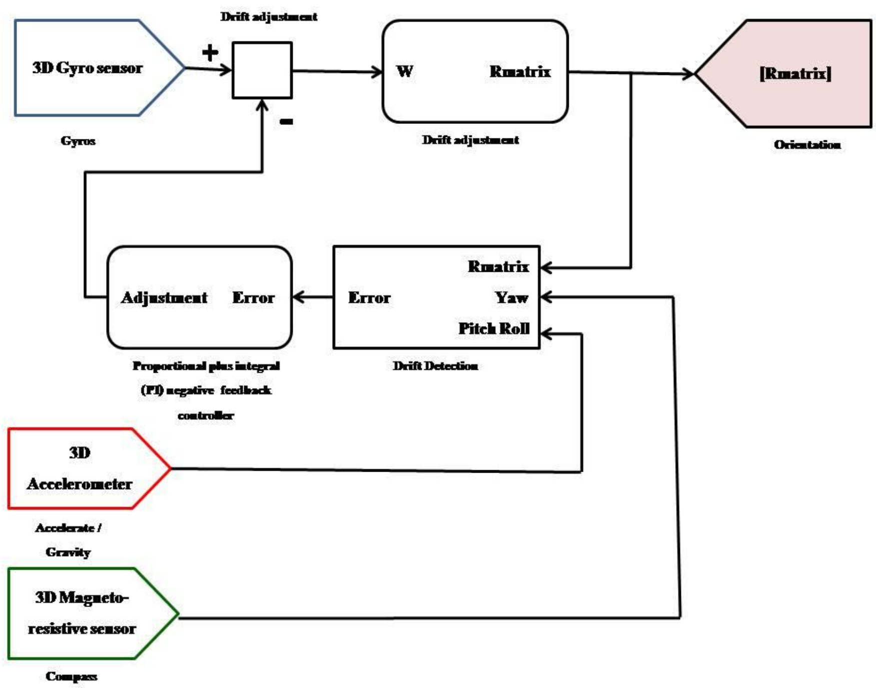


Figure 2.5 is this Block diagram of the DCM algorithm. Adapted from “Block diagram of Direction Cosine Matrix” by Premerlani W and Bizard P (Premerlani W & Bizard P, 2009).

The acceleration outputs are used to estimate the angles in pitch angle (the angular motions around the Y-axis) and the roll angle (the angular motions around the X-axis). The equations of calculated angles from the accelerometer outputs are as follows (Anil, 2012).

$$G_{Accel} = Raw_{Accel} \cdot \frac{Range}{2^{Resolution-1}} \quad (1)$$

$$pitch = \arctan\left(\frac{G_y}{\sqrt{{G_x}^2+{G_z}^2}}\right) \quad (2)$$

$$roll = \arctan\left(\frac{-G_x}{G_z}\right) \quad (3)$$

The accelerometer is the sensitivity for the force that makes changing of acceleration in the transitional axis. However, it usually occurs the signal fluctuation. In this study, the short-term of signal fluctuations from the accelerometer outputs have been removed by the 4th equation liked a low-pass filter.

$$y_t = \alpha . x_t - (1-\alpha) . y_{t-1} \quad (4)$$

y_t = Filtered signal

α = the smoothing factor

x_t = the accelerometer reading

y_{t-1} = the previous filtered signal

The gyroscope can calculate the angles from the angular velocity outputs. It uses the 5th and 6th equations to calculate the angles.

$$y_G = \left[y_{G,x} \;\; y_{G,y} \;\; y_{G,z}\right]^T \quad (5)$$

y_G = Column vector from Gyroscope

$$y_{G,t} = \omega_t + b_t + \nu_{G,t} \quad (6)$$

ω_t = the sum of angular velocity vector

b_t = a slowly varying offset vector

$v_{G,t}$ = a three element white Gaussian noise vector

The angles from the integration are in the sensor coordination frame. It also has the offsets and the Gaussian noise (Luinge HJ & Veltink PH, 2005).

The magnetometer outputs are used to define the heading of the sensor. If a magnetometer are placed parallel to a flat floor, the angles on the roll axis and the pitch axis are the “0” degrees. Also, the heading of sensor is calculated by the 7th equation.

$$\text{Heading} = \text{arcTan}\left(\frac{Y_h}{X_h}\right) \qquad (7)$$

The X_h and Y_h represent the earth's horizontal magnetic field components. As the sensor is rotated, the heading would sweep 0 to 360 degrees referenced to magnetic north. If the sensor is tilted, the tilt angles (roll and pitch) and all three magnetic field components (X,Y,Z) must be used in order to calculate heading ("LV2 Avionics System: 3D Magnetometer,").

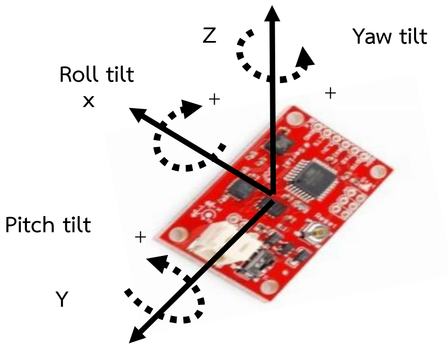


Figure 2.6 shows the definition of the rotation angles on the IMU sensors that is defined by the righted-hand coordinate system. (This image is from the SparkFun^{TM} Electronics, Colorado, USA).

The axis coordination and the rotation matrix (Rmatrix) of DCM algorithm is in order for the righted-hand coordinate system. The 8th equations is used to calculate the Rmatrix from the outputs of accelerometer, outputs from gyroscope, and outputs from magnetometer.

- To rotate sensor about its z-axis through the yaw angle (Ψ)
- To rotate sensor about its y-axis through the pitch angle (θ)
- To rotate sensor about its x-axis through the roll angle (ϕ)

$$\text{R matrix} = \begin{pmatrix} \cos\theta\cos\Psi & \sin\phi\sin\theta\cos\Psi - \cos\phi\sin\Psi & \cos\phi\sin\theta\cos\Psi - \sin\phi\sin\Psi \\ \cos\theta\sin\Psi & \sin\phi\sin\theta\sin\Psi + \cos\phi\cos\Psi & \cos\phi\sin\theta\sin\Psi - \sin\phi\cos\Psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{pmatrix} \quad (8)$$

RT = R-1 = I3x3 , det (R) = 1

$$QG = RQP \quad (9)$$

QP = A vector Q measured in the reference frame of the sensor (sensor coordination frame)

QG = A vector Q measured in the reference frame of the ground (global coordination frame)

The Rmatrix is used in the 9th equation to calculate the angles and also is used to calculate the new Rmatrix on the next sampling of DCM algorithm.

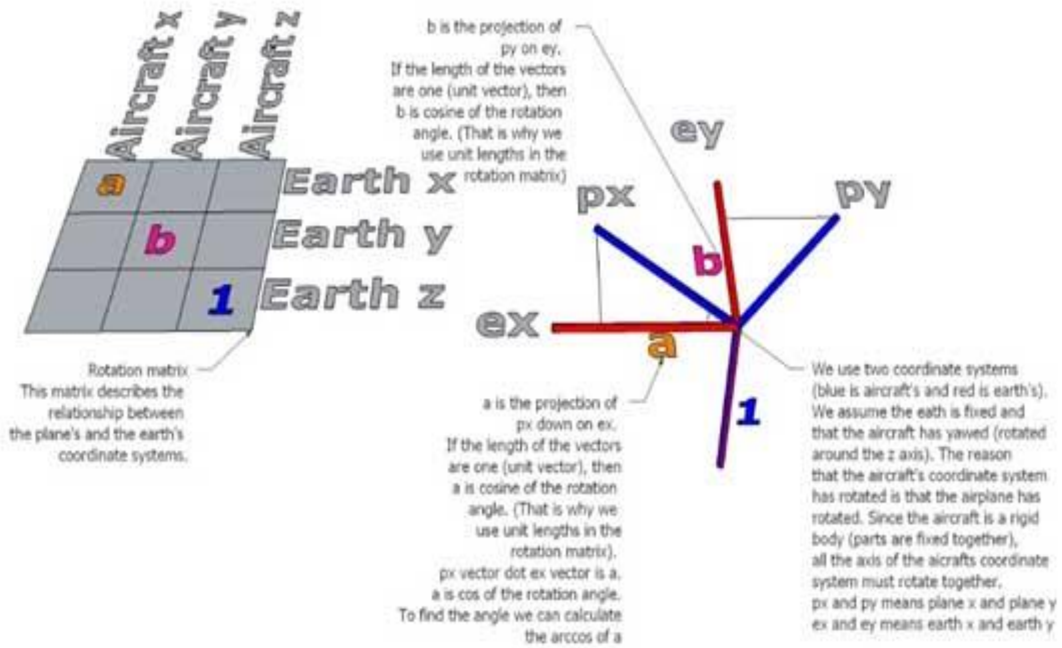


Figure 2.7 shows the DCM IMU Theory that suggested by Premerlani W (Premerlani W, 2009)

.

The vector of angular motion that are transformed in the global coordinate frame are the projection on the X, Y and Z axis. The angle projection is the cosine angle from the vector of angular motion. The "α" is the cosine angles of vector on the X-axis of the global coordination frame. The "β" is the cosine angles of vector on the Y-axis of the global coordination frame. The "γ" is the cosine angles of vector on the X-axis of the global coordination frame.

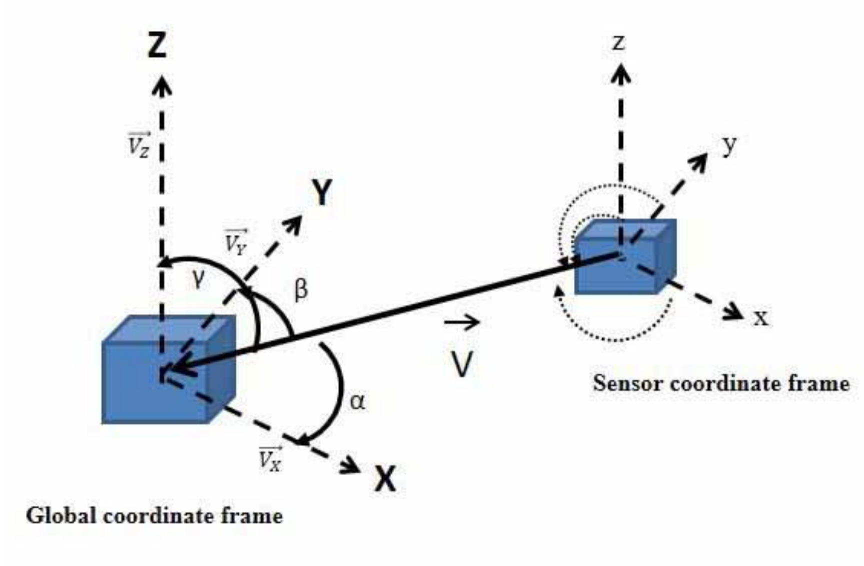


Figure 2.8 shows the vector ($\vec{V}$) from the sensor coordinate frame to the global coordinate frame. The angle projections of the vector on the X, Y, Z axis of the global coordinate frame are defined in term of α, β, and γ.

The reference global coordinate frame that is used for the angle calculation acquires from the calibration process. The developed IMU devices have the calibration process to be as follows.

- To place the developed IMU devices on a flat floor and point the heading of IMU sensors to the north.
- To turn on the developed IMU devices and wait until the finished process of sensor preparation.
- To set completely the reference global coordinate frame into the developed IMU devices.

2.3 The rate of data transfer from the IMU devices to the computer

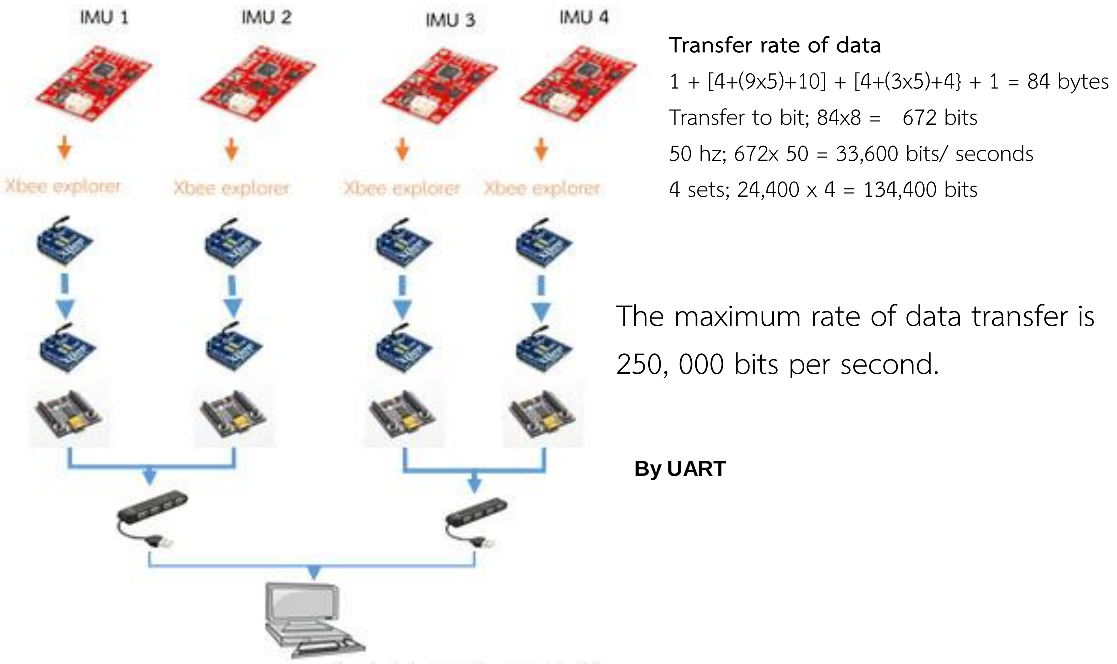


Figure 2.9 shows the pathway of data transfer between the developed IMU devices and the computer.

2.4 The angle estimation from the IMU measurement

The angle estimation relate to the rotated motions of IMU device. There are the pitch angle, the roll angle, and the yaw angle.

- The pitch angle (θ) starts at 90 degrees. If the IMU device rotates the backward direction around the Y-axis, the angles are reduced gradually from 90 degrees. In contrast, the IMU device rotates the forward direction around the Y-axis, the angles are increased gradually from 90 degrees. The IMU device attaches on the body segment (the thigh and the shank). Therefore, the "pitch angle" of IMU device refers to the movement of segment. The movement in the backward rotation around the Y-axis is the flexion and the movement in the forward rotation around the Y-axis is the extension.

- The roll angle (ϕ) starts at 0 degrees. If the IMU sensor rotates the lateral direction around the X-axis, the angles are increased gradually from 0 degrees (in only sensor no.1 and 2). In contrast, the IMU sensor rotates the medial direction around the X-axis, the angles are decreased gradually from 0 degrees (in only sensors no.1 and 2). The "roll angle" of IMU device refers to the movement of segment. The movement in the lateral rotation around the X-axis is the abduction and the movement in the medial rotation around the X-axis is the adduction. All of them are the movement in right leg. For the output from sensors no.3 and 4 (in the left leg) is opposition. Therefore, the angles are multiplied by (-1) before the reporting.

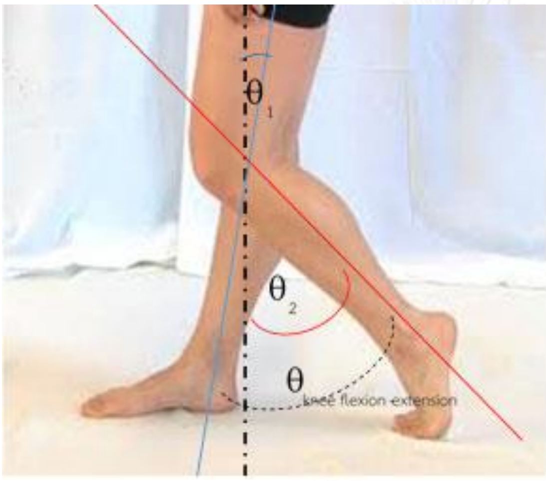
- The yaw angle (Ψ) starts at 0 degrees. If the IMU sensor rotates the lateral direction around the Z-axis, the angles are increased gradually from 0 degrees (in only sensor no.3 and 4). In contrast, the IMU sensor rotates the medial direction around the Z-axis, the angles are decreased gradually from 0 degrees (in only sensors no.3 and 4). The "yaw angle" of IMU device refers to the movement of segment. The movement in the lateral rotation around the Z-axis is the external rotation and the movement in the medial rotation around the Z-axis is the internal rotation. All of them are the movement in left leg. For the output from sensors no.1 and 2 (in the right leg) is opposition. Therefore, the angles are multiplied by (-1) before the reporting.

2.5 The estimation of knee angles

The Qualisys system estimates the knee angles by the relative angle method that is mostly used for the calculation angles between two segments. The relative angle is the included angle between the longitudinal axes of two adjacent segments. Straight fully extended position is generally defined as 0 degrees. In contrast, the IMU system estimates the knee angles from the difference between the thigh's angle and the shank's angle at the same side and the same recording time.

2.5.1 The calculation of knee flexion-extension movement from the IMU measurement

$$\text{Knee flexion-extension} = \theta_{thigh} - \theta_{shank} \quad (10)$$



- $\theta_{thigh} = 90 + (\theta_1)$, θ_1 is positive values (+) because move forward rotation.
- $\theta_{shank} = 90 + (\theta_2)$, θ_2 is negative values (-) because move backward rotation.

Figure 2.10 shows the angle estimation of knee flexion-extension movement.

2.5.2 The calculation of knee abduction-adduction movement from the IMU measurement

$$\phi_{(\text{knee abduction-adduction movement})} = \phi_{shank} - \phi_{thigh} \quad (11)$$

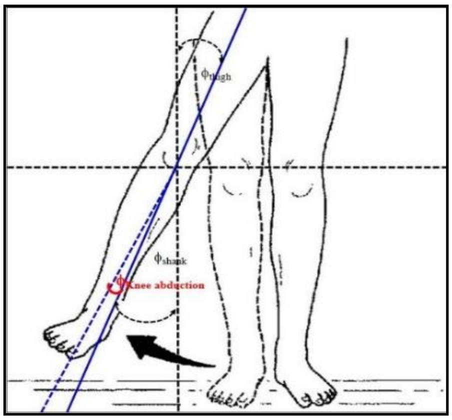


Figure 2.11 shows the angle estimation of knee abduction-adduction movement.

2.5.3 The calculation of knee external rotation-internal rotation movement from the IMU measurement

$$\Psi_{(\text{knee external rotation-internal rotation movement})} = \Psi_{shank} - \Psi_{thigh} \quad (12)$$

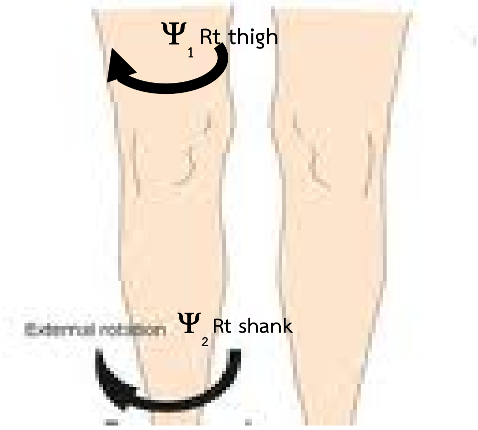


Figure 2.12 shows the angle estimation of knee external rotation-internal rotation movement.

2.6 Previous studies related to the IMU sensor

Morris JRW. (Morris JRW, 1973) was the first researcher, who applied the accelerometer for the measuring movement. He used the accelerometers to recognize the position of the beginning and the end of a gait cycle. Tong K and Granat MH. (Tong K & Granat MH, 1999) studied the inclination of the thigh and the shank, the knee angle, the speed of walk, and the cadence during the walking. They applied four uni-axial gyroscopes (ENC-05EA; Murata, Japan) and four force sensitive resistors (FSRs) to measure these parameters. The gyroscopes were attached to the skin surface at the distal part of the thighs and the shanks. The FSRs placed on the big toe, the first metatarsal, the fifth metatarsal and the heel of foot. All signals were synchronously recorded using the Vicon system at 50 Hz. The angular motion data that acquired from the drift of angular velocities is corrected by the automatic resetting the system to re-initialize the angle in each gait cycle and the high-pass filtering. Their results showed the good correlation of angular motion data between the gyroscopes and the Vicon system. They mentioned the gyroscope that placed on the shank segment to provide the segment inclination range, the cadence, the amount of steps, the estimation of stride length, and the walking speed.

Luinge HJ, Veltink PH and Baten CT. (Luinge HJ et al., 1999) reported their method to estimate an orientation (angles) by the fusion of sensor outputs. They suggested the fusion of outputs from accelerometers and gyroscopes to obtain a better estimation of orientation. Luinge HJ and Veltink PH. (Luinge HJ & Veltink PH, 2005) applied a Kalman filter and the Strapdown integration to use for the estimated orientation from the fusion of the 3-axis accelerometer outputs and three uni-axial gyroscope outputs during the ambulatory human movement. They compared the angular motion data between their IMU system and the laboratory-bound 3D human motion tracking system (Vicon). They tested for the movements of pelvis and trunk during the lifting tasks and the forearm movement during some ADL tasks. Their results revealed the problem on the integration drift around the global vertical to be continuously increased in the order of 0.5 degrees per second, and the RMS of differences on the estimated inclination was 3 degrees. The gyroscope offset could be estimated continuously during a trial. Using an initial offset error of 1 radius per second, after 2 minutes the offset error was roughly 5 percentages of the original offset error. After the using the Kalman filter, an accurate and robust system for ambulatory motion recording could be realized. Until 2009, Roetenberg D, Slycke P and Luinge HJ (Roetenberg D et al., 2009) cooperated to develop the Xsens MVN motion capture suit (XSENS TECHNOLOGIES) for measuring whole body movement by the 17 inertial sensors (a triple-axis gyroscopes, a triple-axis accelerometers, and a triple-axis magnetometer per unit).

Favre et al. (Favre J, Luthi F, et al., 2006) used the 2 miniature sensory modules (each module contained 3 uni-axis gyroscopes <ENC-03, Murata, Japan>), which were set the sampling rate at 200 Hz and recorded the data by a data logger (Physilog®, BioAGM, Switzerland), to evaluate the knee angles in the patients after anterior cruciate ligament reconstruction. They compared the angles between their system and an ultrasonic system (Zebris®, Medizintechnik, Germany) that had the sampling rate of 50 Hz and the accurate data to be less than 1 degree. The angular motion data onto their system were acquired after the finished three steps of the algorithm, which developed under the MATLAB (Mathworks, Natick, MA, USA). For the precision process, their IMU system was tested for the walking on a treadmill at 3 km/h (Marathon, Kettler, Germany) with a healthy subject. The researchers compared the angular motion data between their IMU measurements with the reference system and found the different angles to be 4.4, 2.7 and 4.2 degrees for flexion-extension, internal-external rotation and abduction-adduction, respectively. Also, the repeatability of the angular output data were 0.8, 0.7 and 1.8 degrees, respectively. Favre J, Jolles BM, Aissaoui R, and Aminian K. (Favre J et al., 2008) applied a triple-axis accelerometer (ADXL, Analog Device, range: ±5g) and a triple-axis gyroscope (ADXRS, Analog Device, range: ±600°/s) to measure the knee angles in three planes. They used a light portable data-logger (Physilog®, BioAGM, CH) to collect the data. They calculated the angle from the IMU devices by the fusion algorithm. Their fusion algorithm allowed the tracking of IMU orientation by means of a quaternion-based time integration of the angular velocity vector as measured by the gyroscope, and by correcting the resulting orientation using the inclination estimated from the accelerometer. The Liberty magnetic tracking device (Polhemus, USA) was used for a reference device in the comparison. Ten healthy young men participated and tested for the four movements. The four movements were recorded simultaneously by the inertial system and reference system: two hip AA (abduction-adduction) movement and two ground-level walks of 30 meters. Their results revealed the inertial system to be the suitable method for the knee measurement. They found the absolute knee flexion/extension angles and abduction/adduction angles with mean (SD) offset errors at -1 ° (1 °) and 0 ° (0.6 °). The mean (SD) of differences was 1.5° (0.4°) and the RMS error was 1.7° (0.5°). Their system was also the suitable method for the relative measurement of knee internal/external rotation angles (mean (SD) offset error at 3.4 (2.7 °)) with a mean (SD) RMS error at 1.6 ° (0.5 °). Favre J, Aissaoui R, Jolles BM, de Guise JA and Aminian K. (Favre J et al., 2009) improved their calibration procedure and assessed the repeatability of measurement. They placed their IMU devices at the lateral distal part of thigh and the anterior mid-shank on the right leg. The researchers also used the same devices as their previous studies. The data samplings were the 240 Hz. Eight healthy men (mean age: 26 years old, range 19-28) were recruited in their study. The subjects wore the harness to fix on their right knee. They estimated the repeatability of their system, the six alignment and calibration movements (twice hip AA in standing posture (mvt1), as well as twice knee FE (mvt2) and twice rotations of the shank in its frontal plane (mvt3) in sitting posture) were combined together, leading to eight different movement combinations. Their results showed the new procedure relying on active and passive movements and reported the high repeatability of the mean values (offset<1°) and angular patterns (SD < 0.3° and the coefficient of multiple correlation > 0.9). When comparison the angular motion data onto their system to the reference system, this functional procedure showed the high precision (SD < 2° and correlation coefficient > 0.75) and moderate accuracy (between 4.0° and 8.1°) for the knee joint angle measurement in three planes.

Mayagoitia RE, Nene AV and Veltink PH. (Mayagoitia RE, Nene AV, & Veltink PH, 2002) used the four pairs of uniaxial accelerometers (IC Sensors 3021-005-P) and the four gyroscopes (Murata ENC-05EB) attach to the shanks and the thighs in the subjects. The accelerometer signals were used to calculate the linear and the angular accelerations. The integration of gyroscope signals were to the orientation angle. The MATLAB was used for the signal proceeding. A sixth-order Butterworth low-pass filter with a cut-off frequency of 3 Hz was used to remove the noise from the raw data. A verify accuracy of the body-mounted sensor system (accelerometers and gyroscopes), optical data were gathered simultaneously by the Vicon system.

Ten participants were asked to walk two repetitions at the five speeds (very slow = 1.4 km/h, slow = 2.1 km/h, average = 2.7 km/h, fast = 3.6 km/h and very fast = 4.6 km/h) on the treadmill within 10 or 12 seconds. From the comparison, they showed the graphs of knee joint angle movement from the two systems to be close, showing the RMS errors representing <7% full range in 75% of the cases (overall mean 6.64%, SD 4.13%) and the high coefficients of multiple correlation in 100% of cases (overall mean 0.9812, SD 0.02).

Dejnabadi H, Jolles BM and Aminian K. (Dejnabadi H et al., 2005) applied the two sensor modules (a biaxial accelerometer and a gyroscope per unit) to measure the knee flexion-extension angles. Eight participants (5 men, 3 women) were recruited to test for the walking on the treadmill with 2, 3, and 4 km/h. The sampling frequency was set at 200 Hz and the Physilog [BioAGM, CH] for the ambulatory system were collected the angular output data. They compared the angles between their IMU measurements and the Zebris CMS-HS (Zebris, D) measurement that was the ultrasound-based motion measurement system. The different angles were very small (RMS = 1.3, mean = 0.2, SD = 1.1 deg.) and the correlation coefficients were excellent (0.997).

Picerno P, Cereatti A and Cappozzo A. (Picerno P et al., 2008) investigated the joint kinematics (hip, knee and ankle) in the upright position and the walking by the wearable inertial sensors and magnetic sensing modules. Their system (MTx, Xsens Motion Technologies, Enschede, Netherlands) consisted of a triple-axis linear accelerometer, a triple-axis gyroscope and a triple-axis magnetometer. They compared the angle measurements onto their four MARG with the stereo photogrammetric data (9 Vicon Mx cameras, Oxford Metrics, UK). The sampling rate of the two system were 120 samplings per second. The experiment controlled the magnetic field environment to minimize problems related to Ferro-magnetic disturbances. Their results revealed the testing for the intra- and the inter-examiner variability of the angle measurement, which is the minimal in correspondence to the flexion-extension angles (0.2^{o} - 2.9^{o}) and maximal to the internal-external rotation (1.6^{o} – 7.3^{o}). For the walking test, the RMS errors between their IMU system and the reference system varied from 2.5% to 4.8% of the ROM for the flexion-extension, whereas it ranged from 13.1% to 41.8% in correspondence of the internal-external rotation.

Cooper G et al (Cooper G et al., 2009) reported their study to estimate the knee flexion-extension angles by the IMU sensors. Their IMU system consisted of the two sets of three orthogonally aligned the single axis rate gyroscope (±1200 degrees/s) and the three-axis accelerometer (± 5 g) and a SD-micro card that integrated on each unit of the sensor for the data logging. A synchronizing pulse was sent to each unit prior to commencing measurements to provide synchronization. A Kalman filter and a process of angle estimation were used to estimate the knee angle. Seven healthy participants walked on the treadmill at 1 mile/hour and the speed was increased in five increments to 5 miles/hour over a 5 minute until the subject was running. A 10-cameras Qualysis system was used for the reference measurement. The IMU system and the camera system were recorded the data at

100 samplings per second. They found the average measurement error at the range of 0.7 degrees for slow walking (1mph) to 3.4 degrees for running (5mph).

In 2009, Takeda R, Tadano S and Todoh M had two studies about a gait analysis by the IMU sensors. Each set of their IMU devices consisted of a tri-axial acceleration sensor (H34C, Hitachi Metals, Ltd.) and three single-axis gyroscopes (ENC-03M, muRata Manufacturing Co.,Ltd), which was used to measure the acceleration and the angular velocity along three orthogonal axes. The data logger was used for the storage data. The angular velocity data onto the gyroscopes were used to estimate the translational acceleration in the gait analysis. The translational acceleration was subtracted from the acceleration sensor measurements to obtain the gravitational acceleration, and giving the orientation of the lower limb segments. The reference system was the digital camera (HDR-SR1, Sony Corp.), which was used to capture the images at 60 frames per second. The camera images were analyzed by the motion capture software (DIPP-Motion Pro, Direct Co., Ltd.). At the first study, Takeda R, Tadano S, Todoh M, Morikawa M,and Nakayasu M. (Takeda R, Tadano S, Todoh M, et al., 2009) used the seven units of IMU sensor to attach on the abdomen and on both thighs, shanks and feet. Three participants were asked to walk with controlled speed. The reports revealed their process of estimated angular motions and the filter signals. The line graph of joint motions was compared to the reference method. The angle measurements onto their IMU also were created a moving stick figure model of volunteer movement. Moreover, the movement trajectories of knee joint in the horizontal plane were reported by visual imaging on a computer. The second study, Takeda R, Tadano S, Natorigawa A, Todoh M and Yoshinari S. (Takeda

R, Tadano S, Natorigawa, et al., 2009) used the four IMU devices to measure the joint angles of the hip flexion-extension movement and the hip abduction-adduction movement and the knee flexion-extension movement. Three healthy volunteers attached the IMU devices and the reflective marker at the thighs and shanks. The participants walked for 5 meters on the flat floor with three trails. The walking velocity was fixed a cadence of 88 steps per minute by a digital metronome (TU-80, Roland Corporation). Their system showed the correlation coefficients to be above 0.88 for the hip flexion-extension movement, higher than 0.72 for the hip abduction-adduction movement, better than 0.92 for the knee flexion-extension movement.

Taylor T, Ko S, Mastrangeto C and Bamberg SJM (Taylor T, Ko S, Mastrangelo C, & Bamberg SJM, 2013) applied the IMU sensors, which consisted of a triple-axis gyroscope, a triple-axis accelerometer, and a triple-axis magnetometer in each unit, to investigate the artificial lower-limb motions. The DCM algorithm was used to create the absolute orientation from the IMU devices based on numerical integration of each gyroscope. They evaluated the hip joint movement in 3-degrees of freedom, the knee joint movement in 1-degree of freedom and the ankle joint movement in 2-degrees of freedom during the walking test. They suggested this method to be a way that could get reasonably the accurate angle measurement. Moreover, they mentioned their IMU devices to have the ability of the angle measurement in real time.

Table 2.5 shows the summary of previous studies related to the IMU sensor and the present study

Authors	Type of sensors	Method	Results

Morris JRW (1973)	Accelerometer sensor (Type?? amount??)	- To recognize the position of beginning and the end of gait cycle.	-
Tong K and Granat MH (1999)	- 4 uni-axial gyroscopes (ENC-05EA; Murata, Japan) - 4 force sensitive resistors (FSRs)	- **<u>subject</u>** 1 normal person - To compare with the Vicon system - Sampling rate 50 Hz - To measure the thigh and the shank inclination, the knee angles, the walking speed, and the cadence of walk	- The gyroscope can give an information on the segment inclination range, cadence, number of steps, and the estimation of stride length and the walking speed.
Luinge HJ and Veltink PH. (2005)	- 1 units of 3-axis accelerometer and 3 units of uni-axial gyroscopes	- To measure the movement of arms and trunk. - To use the Kalman Filter and the Strapdown integration	- They mentioned the Kalman filter to obtain a better estimated angles.
Roetenberg et. al. (2009)	- 17 inertial sensors (3-axis gyroscopes, 3-axis accelerometers and 3-axis magnetometer) - The Xbus Masters used to synchronize all sensor outputs and also send to the laptop.	- To suggest their developed their system that is called “the Xsens MVN motion capture suit (XSENS TECHNOLOGIES)” for measuring whole body movement.	-
Favre et. al. (2006)	- 2 miniature sensory modules (each module contained 3 uni-axial gyroscopes <ENC-03, Murata, Japan>) with data-logger	**<u>subject</u> a healthy men and 5 men with an isolated unilateral ACL lesion** - To compare with the ultrasonic system (Zebris®, Medizintechnik, Germany) - Sampling rate of 200 Hz - To attach the sensors on the thigh and the shank and measure the knee joint angles.	- The precision was 4.4°, 2.7° and 4.2° for the flexion- extension movement, the internal rotation-external rotation movement and the abduction-adduction movement. The repeatability was 0.8, 0.7, and 1.8 degrees - To report the measurement of knee angles in the pathologic side.
Favre et. al. (2008)	- 2 set of IMU sensor (3-axis gyroscope <ADXRS, Analog devices range ±600 °/s and a triple-axis accelerometer (ADXL, Analog devices range ±5 g) - A data logger	- **<u>subject</u> 10 healthy men.** - To compare the angles between their IMU devices and the Liberty magnetic tracking device (Polhemus, USA) - Sampling rate of 240 Hz - The fusion algorithm allowed the tracking of IMU orientation by the quaternion-based time integration of the angular velocity vector as measured using the gyroscope, and by	They recommended their system to be suitable for the knee flexion/extension measurement and the knee abduction/adduction measurement. They found the angles with mean (SD) offset errors to be -1° (1°) and 0° (0.6°)

		correcting the resulting orientation using the inclination estimated from the accelerometer. - To attach the sensors at thigh and shank and to measure the knee joint motion.	and mean (SD) was 1.5° (0.4°) and RMS error was 1.7° (0.5°). Also, the relative measurement of knee internal/external rotation was the mean (SD) offset error of 3.4 (2.7 °)) and the mean (SD) RMS error of 1.6 ° (0.5 °).
Mayagoitia RE, Nene AV and Veltink PH (2002)	- 4 pairs of uniaxial accelerometers (IC Sensors 3021-005-P) and 4 uni-axial gyroscopes (Murata ENC-05EB)	- **<u>subject</u> 10 healthy men.** - To compare with the Vicon system - Sampling rate 100 Hz - To attach the sensor on the frontal, medial aspect of shank and thigh. - To walk with two repetitions and with five speeds (very slow = 1.4 km/h, slow = 2.1 km/h, average = 2.7 km/h, fast = 3.6 km/h and very fast = 4.6 km/h) on the treadmill within 10 or 12 seconds.	The comparison of movement graph from the two systems were very close, showing RMS errors representing <7% full range in 75% of the cases (overall mean 6.64%, SD 4.13%) and high coefficients of multiple correlation in 100% of cases (overall mean 0.9812, SD 0.02).
Dejnabadi H, Jolles BM and Aminian K. (2005)	- 2 sensors (a bi-axial accelerometer and a gyroscope per a sensor) - A Physilog [BioAGM, CH]	- **<u>subject</u> 8 person (5 men, 3 women)** - Sampling rate of 200 Hz - To compare their devices with a Zebris CMS-HS (Zebris, D) ultrasound-based motion measurement system. - To measure the knee flexion-extension angles. - To walk on the treadmill with 2, 3, and 4 km/h.	Their IMU measurements are very close to the measurement from reference system, presenting very small errors (RMS = 1.3, mean = 0.2, SD = 1.1 deg.) and excellent correlation coefficients (0.997).
Cooper et. al. (2009)	2 sets (3 Uni-axial gyroscopes <±1200 degrees/s> , 3-axis accelerometer<±5>) - A SD-micro card	- **<u>subject</u> 7 persons (male 5, female 2)** - To compare with a 10 camera Qualisys system - Sampling rate of 100 Hz - To use the Kalman filter - To attach the sensors on the thigh and the shank and measure the knee joint angles during the walking on treadmill (1 to 5 mile/h in 5 min.)	They found the average measurement error ranged from 0.7 degrees for slow walking (1mph) to 3.4 degrees for running (5mph).
Takeda et. al. (2009)	- 4 sets (Each set consisted of a tri-axial accelerometer <H34C, Hitachi Metals, Ltd.> and three gyroscopes <ENC-03M, muRata	- The angular velocity data measured by the gyroscopes were used to estimate the translational acceleration in the gait analysis. The translational acceleration was then subtracted from the acceleration sensor	The correlation coefficients were above 0.88 for the hip flexion-extension movement, higher than 0.72 for the hip abduction-adduction

	Manufacturing Co.,Ltd>) - a data logger - 7 sets (Each set consisted of a tri-axial accelerometer <H34C, Hitachi Metals, Ltd.> and three gyroscopes <ENC-03M, muRata Manufacturing Co.,Ltd>) a data logger	measurements to obtain the gravitational acceleration, giving the orientation of the lower limb segments. - To compare with the Images from a digital camera (HDR-SR1, Sony Corp.) The camera images were analyzed using motion capture software (DIPP-Motion Pro, Direct Co., Ltd.). -To capture the images at 60 frames per second. - To detect the joint angles of the hip flexion-extension movement and the hip abduction-adduction movement and the knee flexion-extension movement. - **<u>subject</u> 3 persons** The volunteers walked 5 meters on the flat floor for three trails (fix velocity 88 steps per min.).	movement, better than 0.92 for the knee flexion-extension movement.
Taylor T, Ko S, Mastrangeto C and Bamberg SJM (2013)	3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer (Amount??)	- To investigate the artificial lower-limb motions. - To use the DCM algorithm - To evaluate the hip joint in 3-degrees of freedom, the knee joint in 1-degree of freedom and the ankle joint in 2-degrees of freedom during the walking.	They suggested their method to be a way that could get reasonably the accurate angle measurement. Moreover, they mentioned their IMU sensors to have the ability of the angle measurement in real time.
Tossaphon Jaysrichai (This study)	For the development of these IMU devices, I used as follows;- **- 4 IMU sensors (a triple-axis accelerometer, a triple-axis gyroscope, a triple-axis magnetometer per a sensor)** **- <u>8 units of Xbee for the wireless connection</u>** **- The other components**	- To create the "Knee Angle Recorder" software and the "Knee Angle Analyzer" software - To compare the angle measurement between this IMU system and a 6 camera (120 Hz) Qualisys system - To evaluate the accurate data onto the reading angles on both static and dynamic conditions - To evaluate the accurate data onto the reading angles (in degrees) during the functional knee movement tests and walking test **<u>in 10 normal participants</u>** - To evaluate the knee flexion-extension movement in a gait cycle within **<u>the 20 elderly women with symptomatic knee osteoarthritis</u>**	-

		and the 20 elderly women without symptomatic knee osteoarthritis	

CHAPTER 3

RESEARCH METHODOLOGY

3.1 The characteristics of participants

There were three groups of participants in this study. The criterions of characteristics and qualifications on each group were as follows:-

- **First group – The criterions for the subjects, who participated to test for the accurate data onto the IMU measurements during the four functional knee movement tests and the walking test, were as follows:-**

- The healthy participants, who had the age ranged 20 to 35 years old, did not have any problems during the walking.

- They did not complain about any pain, the abnormal muscle tightness, or/and the joint stiffness on the back and the lower extremities before the testing of 3 months.

- They did not have any neurological pathology that affected on the movement of lower extremities.

- The leg length difference between the left side and the right side, which measured from the greater trochanter to the lateral malleolus, was less than or equal to 1 centimeter.

- All participants agreed to take part in the experiment and signed the consent form.

- **Second group – The criterions of the elderly women without symptomatic knee osteoarthritis, who participated to test for the clinical application, were as follows:-**

- Twenty female participants, who had the age ranged 50 to 70 years old, had the physical characteristics (age, body mass index) similar to the elderly women with symptomatic knee osteoarthritis.

- They could walk normally on a flat floor.

- They did not exhibit the symptomatic knee osteoarthritis, which followed the clinical criterions for the classification of the idiopathic knee osteoarthritis [American College of Rheumatology; ACR] (Altman R et al., 1986).

- They did not complain about the back pain or any pain on the lower extremities during the test.

- They did not have any neurological pathology that affected on the movement of the lower extremities.

- The leg length difference between the left side and the right side, which measured from the greater trochanter to the lateral malleolus, was less than or equal to 1 centimeter.

- All participants agreed to take part in the experiment and signed the consent form.

- **Third group – The criterions for the elderly women with symptomatic knee osteoarthritis, who participated to test for the clinical application, were as follows:-**

- Twenty female participants, aged 50 -70 years old, had mild or moderate symptomatic knee osteoarthritis at least one side and were diagnosed by the physicians in department of Rehabilitation medicine, King Chulalongkorn Memorial Hospital. The criterion was defined according to the clinical criteria for the classification of the idiopathic osteoarthritis knee [ACR] (Altman R et al., 1986).

- They did not exhibit the signs of acute arthritis that included the soreness, warmth, redness, or/and swelling around the knee joint.

- They did not have any neurological pathology that affected on the movement of the lower extremities.

- All participants agreed to take part in the experiment and signed the consent form.

This study was approved by The Institutional Review Board, Faculty of Medicine, Chulalongkorn University. The Certificate of Approval was the IRB No. 485/55.

3.2 Material in this study

(1) The components of four IMU devices were as follow-

- Two units of the 9 Degrees of Freedom - Razor IMU - AHRS compatible (SEN 10125) (SparkFun^{TM} Electronics, Colorado, USA) that consist of a triple-axis accelerometer (±16 g) <ADXL 345>, a triple-axis gyroscope (±2000 degrees per second) <ITG-3200>, a triple-axis magnetometer (±4 Gauss) <HMC5843>.

- Two units of the 9 Degrees of Freedom - Razor IMU - AHRS compatible (SEN 10736) (SparkFun™ Electronics, Colorado, USA) that consist of a triple-axis accelerometer (±16 g) <ADXL 345>, a triple-axis gyroscope (±2000 degrees per second) <ITG-3200>, a triple-axis magnetometer (±8 Gauss) <HMCL5883L>.
- Eight pieces of the XBee Pro 50mW Wire Antenna - Series 2 (ZB) (SparkFun™ Electronics, Colorado, USA)
- Four pieces of the XBee Explorer Regulated (SparkFun™ Electronics, Colorado, USA)
- Four pieces of the Polymer Lithium Ion Battery–850 mAh output 3.7 (SparkFun™ Electronics, Colorado, USA)
- Four acrylic box are designed the size within 3.8 x 5.8 x 4.4 cm^3.
- Four pieces of the Mini Xbee USB Dongle (Venus Supply Co.Ltd, Bangkok, Thailand)

- Four cables of the converter mini USB to USB port
- Two pieces of USB hub

(2) The accessories of IMU devices were as follows:-

- A Lipo charger basic (SparkFun™ Electronics, Colorado, USA)
- A cable of converter micro USB to USB
- A adapter 5V.
- Four pieces of the elastic band with Velcro strap that were used for the attachment of the IMU devices to the thighs and the shanks.

(3) The computer had the “Knees Angle Recorder” software and “Knee Angle Analyzer” software, which were created by the Microsoft Visual C# 2010 Express software and the .Net framework version 4.0 (Free license software for a personal user).

(4) The Qualisys-Motion Capture system (Qualisys system) (Qualisys AB Company, Gothenburg, Sweden) with the 6 high-speed cameras (120 Hz) and the accessories were used for this study. The accessories consisted of twenty reflective markers, the markers’ sets for the thighs and the shanks, the calibration set, and the Qualisys Track Manager software and the Visual 3D software. (This instrument was placed at the Center of Excellence in Gait and Motion, King Chulalongkorn Memorial Hospital, Chulalongkorn University.)

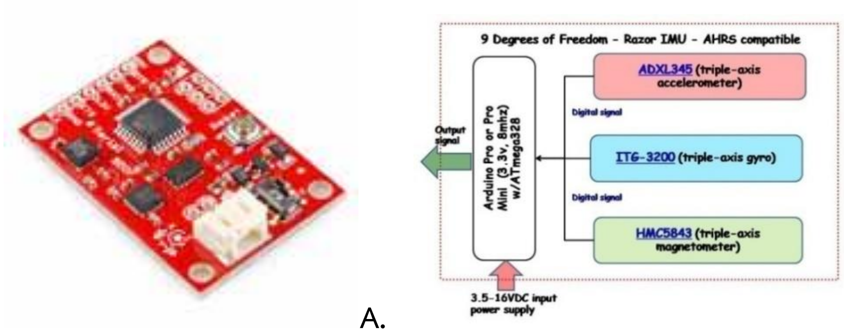
(5) A fixed angles board

(6) A Goniometer

(7) A compass

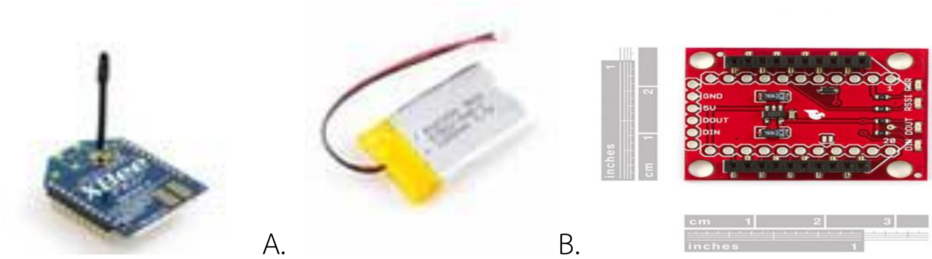
(8) A measuring tape

(9) A shorts



A. B.

Figures 3.1 show the 9 Degrees of Freedom - Razor IMU - AHRS compatible. **3.1A** shows the sensor model number SEN 10125 (Source; SparkFun™ Electronics, Colorado, USA). **3.1B** is the painting of simple circuit elements.



A. B. C.

Figures 3.2 show the components of the IMU device in the “sensor unit” part. **3.2A** shows the XBee Pro 50mW Wire Antenna - Series 2 (ZB) (Source; SparkFun™ Electronics, Colorado, USA). **3.2B** shows the Polymer Lithium Ion Battery-850mAh 3.7 V. (Source; SparkFun™ Electronics, Colorado, USA). **3.2C** shows the XBee Explorer Regulated (Source; SparkFun™ Electronics, Colorado, USA).

Figure 3.3 shows the Mini Xbee USB Dongle (Source; Venus Supply Co. Ltd, Bangkok, Thailand).

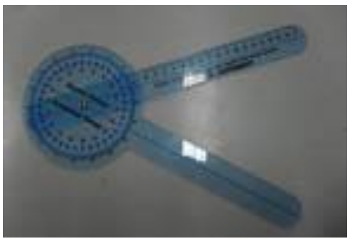


Figure 3.4 shows a goniometer.

3.3 The development of IMU devices and the software

3.3.1 The IMU devices

The researcher developed the IMU devices from the four sets of 9 Degrees of Freedom - Razor IMU - AHRS compatible. The sensor outputs from a triple-axis accelerometer, a triple-axis gyroscope and a triple-axis magnetometer were sent to the IMU board (ATmega328). The outputs were processed the DCM algorithm to define the angles into the global co-ordinate frame. The data processing of IMU sensor was operated by the Arduino code. The original Arduino code acquired from the SparkFun^{TM} Electronics. The code was added the process of data transfer by the wireless connection and set the sampling rate of 50 Hz. It was called “The amended Arduino code” and was burned into the four IMU sensors. The serial interface of IMU sensor worked to transfer the data through the link to the XBee Explorer Regulated. Then, the data were transferred continuously to the XBee Pro 50mW Wire Antenna - Series 2 (ZB). All of them, which were called “The sensor units”, were supplied the power by the Polymer Lithium Ion Battery-850mAh (Fig 3.5). The receiver units that worked to receive the angular outputs from the sensor unit, that consisted of the Xbee, the Mini Xbee USB Dongle, and the USB link (Fig 3.5). The angle measurements from the IMU devices was transferred to the computer via the USB ports. Also, the angles from IMU measurements were displayed into the fours line graphs by “Knees Angle Recorder” software. This software was created by the Microsoft Visual C# 2010 Express software. The four units of IMU devices were used to measure the knee joint angles on both legs. They were attached on the anterior mid-thighs and the anterior mid-shanks. The angles measurement from the four IMU devices represented the segment movement and also was estimated to the knee joint angles (Fig 3.6)

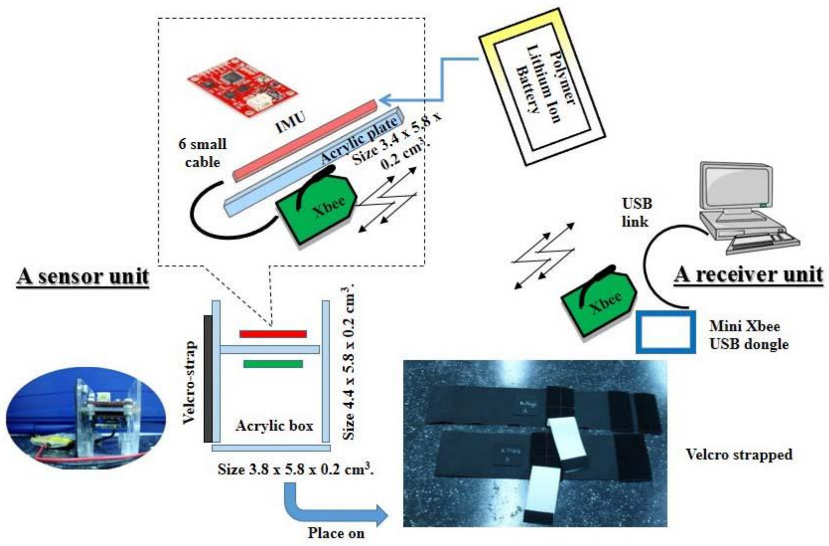


Figure 3.5 shows the developed IMU devices that consisted of the sensor unit, the receiver unit, the elastic band with Velcro strap, and a computer.

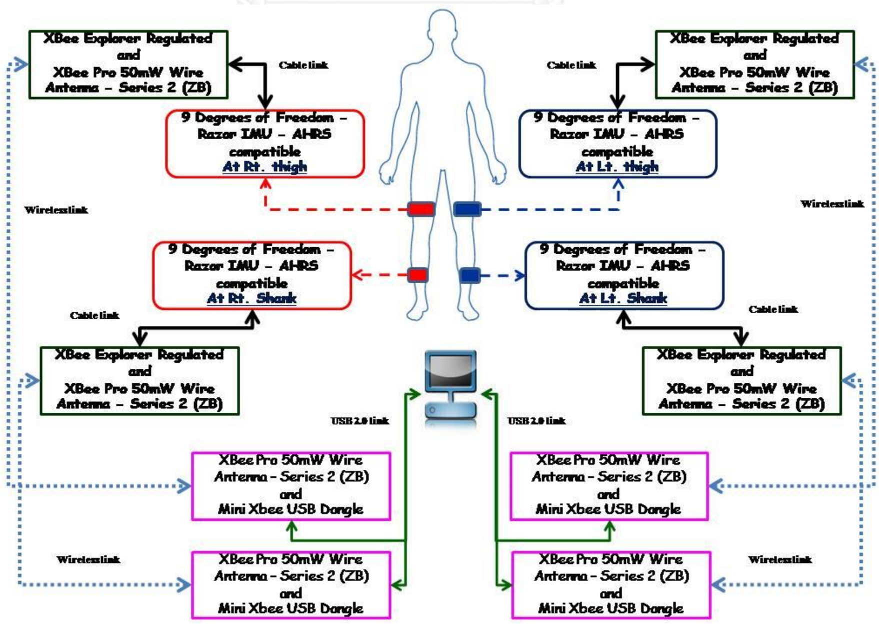


Figure 3.6 is the diagram of this IMU system.

3.3.2 The amended Arduino code

When turn on the IMU switch, the system is operated. It work to check the availability of the IMU devices and also set a calibration. A reference global coordinate frame $(\overrightarrow{\iota_G}, \overrightarrow{J_G}, \overrightarrow{k_G})$ is set to the IMU sensor. The developed IMU devices are the preparation status until the acquired "start" command from the “Knee Angle Recorder” software. When already get the "start" command, the angles from IMU measurements are sent to the computer. The samplings of IMU system are 50 Hz. The angles from the IMU measurements are calculated from the outputs of triple-axis accelerometer, triple-axis gyroscope, and triple-axis magnetometer by the DCM algorithm. The Rmatrix from the DCM algorithm are used to multiply to the angles from IMU measurements for the angle transformation. The angles are transformed from the sensor coordinate frame to the global coordinate frame. Finally, the angles are transferred through to the computer via the wireless connection in order to any given time.

3.3.3 The “Knee Ankle Recorder” software

The "Knee Ankle Recorder" software, which was created by the Microsoft Visual C# 2010 Express software, is used to corporate with the four IMU devices. This software has the many operating commands. The commands are demonstrated into the buttons. The "Yaw adjustment" command is used for the recording data (angles) for three seconds (150 samplings). The data, which are recorded by the "Yaw adjustment" command, are used for the offset adjustment in the yaw axis (the rotation around the horizontal plane). It adjusts the γ angle to be

"0 degrees" on the starting position of measurement. So that, the participant was asked to the static upright position during the "Yaw adjustment".

The "Time record" command is used to set the recording time (in seconds) that ranged from 5 seconds to 60 seconds. After the press of "Start" button, the "start" command is sent to the four IMU devices. The four IMU devices also transferred the angles to the computer at any given time. The software works to receive the angles from the IMU measurements. The angles are passed to the data processing step before the reporting. Then, the angles are displayed instantly on the line graphs, which represented the changing angles (in degrees) versus time (in seconds). In each graph, there are the three lines of changing angles. The yellow line represents the changing angles in the segment flexion-extension movement. The red line represents the changing angles in the segment abduction-adduction movement. The blue line represents the changing angles in the segment external-internal rotation movement. Moreover, the software also has the "CHECK" command to check the completion of receiving data from each IMU measurements. The "Calculation knee motion" command is used for the knee joint angle calculation that is got from the thigh angles and the shank angles at the same recording time. The knee joint angles are the movement in three planes (the knee flexion-extension movement, the knee abduction-adduction movement, the knee external-internal rotation movement). Finally, the angles can save the data into an ASCII file type.

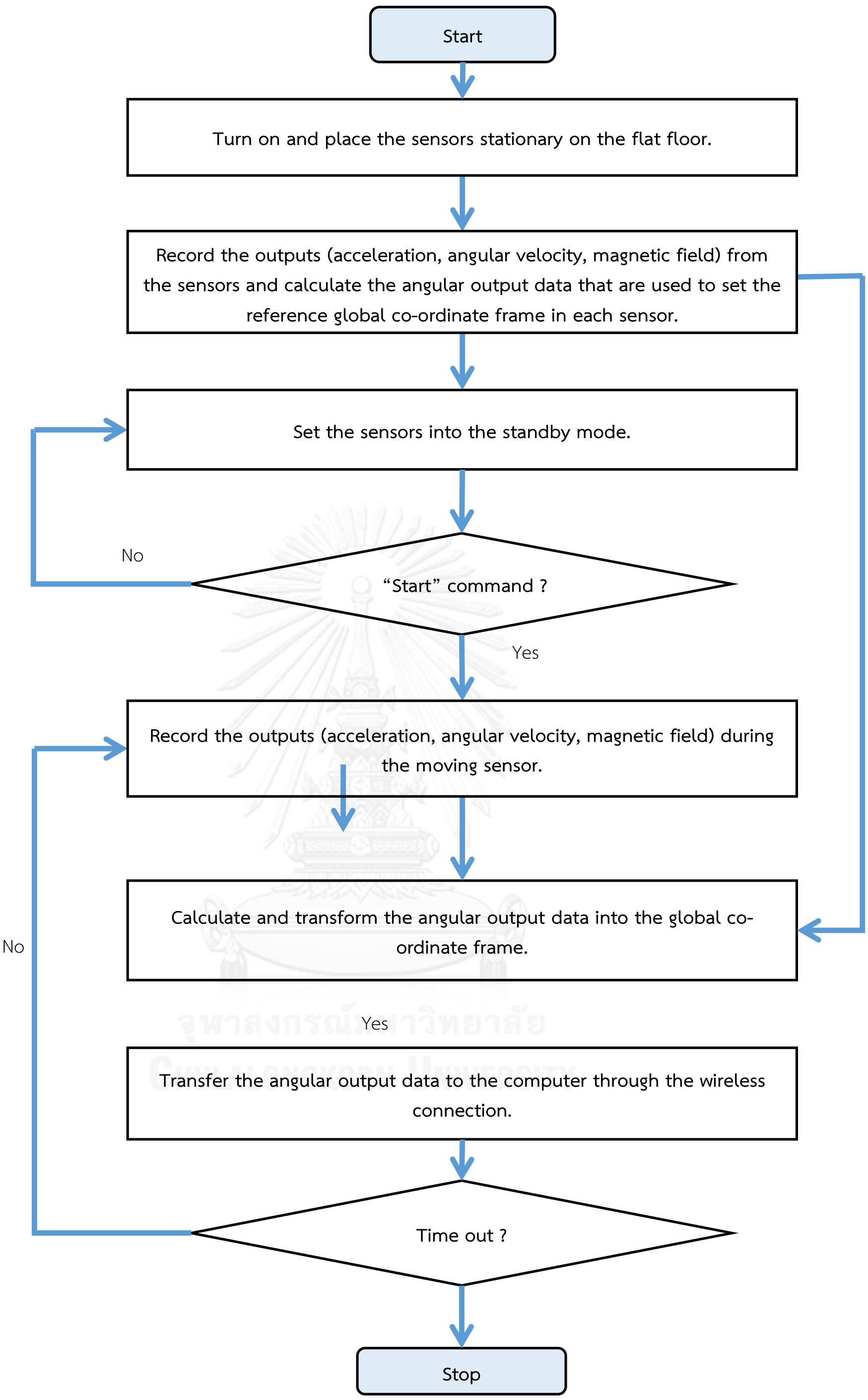


Figure 3.7 is the block diagram of the operating IMU device.

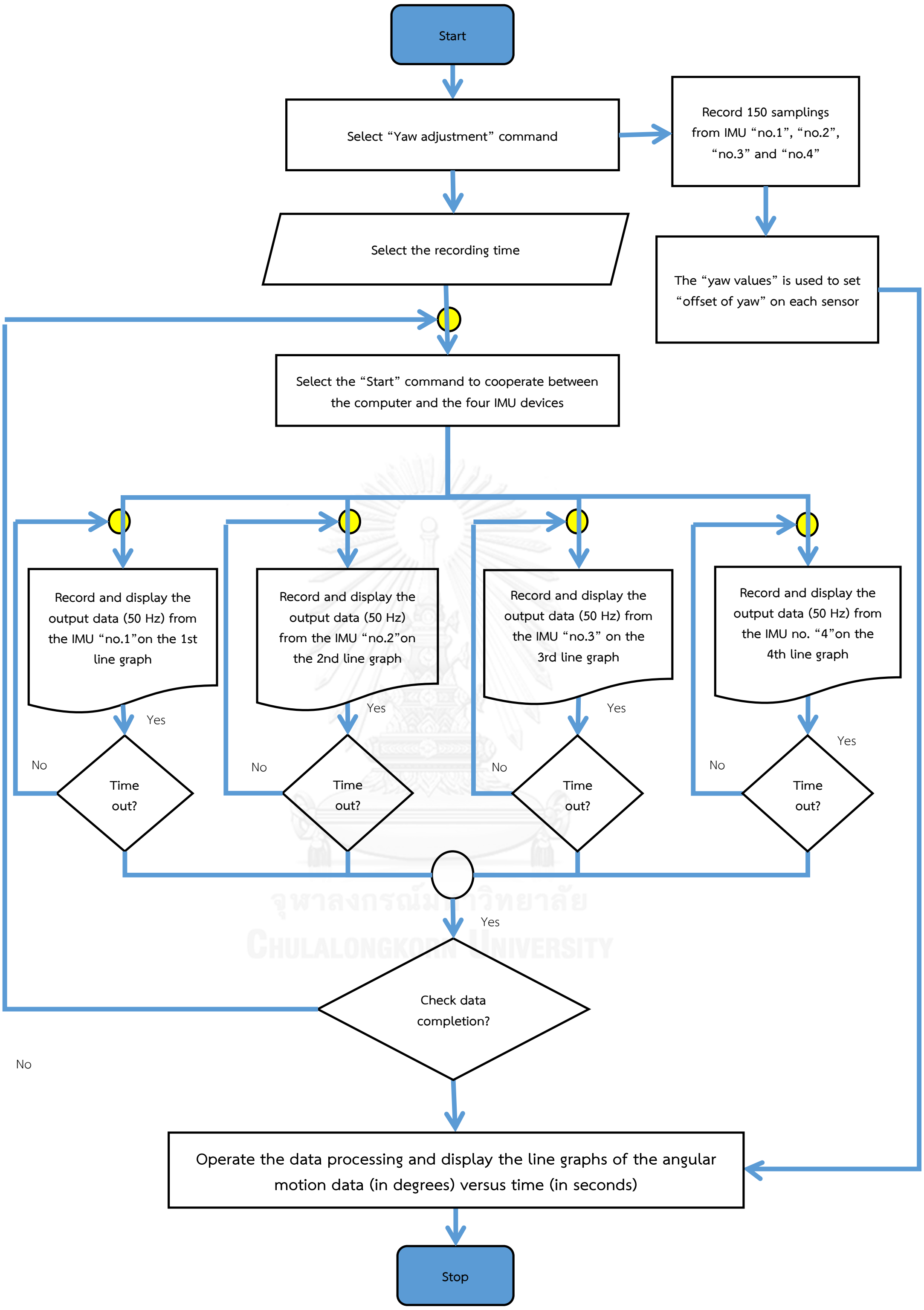


Figure 3.8 is the flowchart of "Knee Ankle Recorder" software.

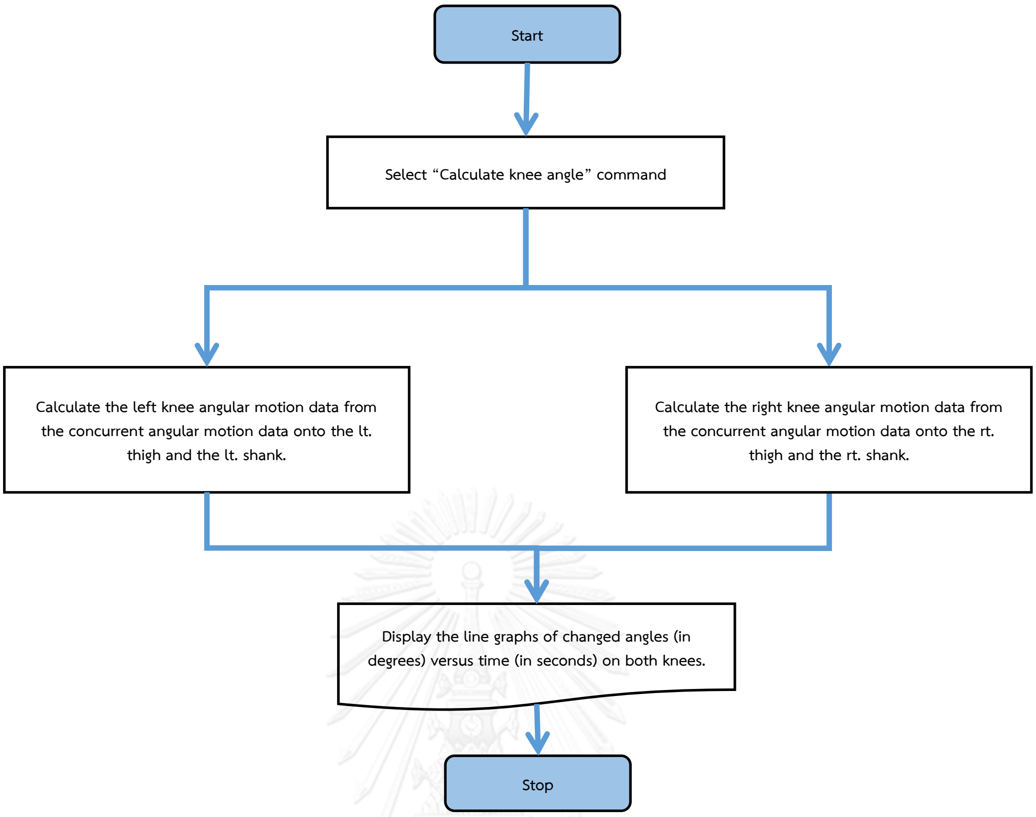


Figure 3.9 is the flowchart of "Knee Ankle Recorder" software that is a part of the knee angle calculation.

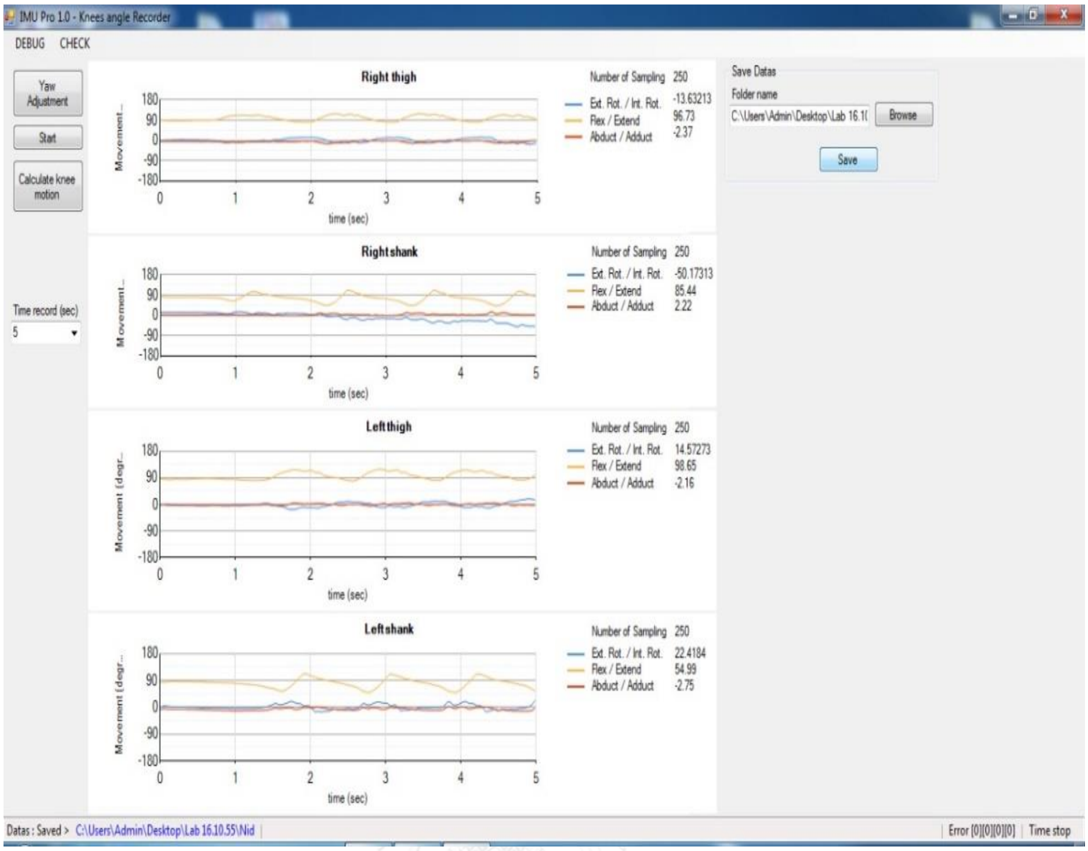


Figure 3.10 shows the screen of the “Knee Angle Recorder” software.

3.3.4. The Knee Ankle Analyzer software

The "Knee Ankle Analyzer" software, which was created by the Microsoft Visual C# 2010 Express software, is used for the kinematic analysis. The angles from IMU measurements, which was saved into the ASCII file type, are uploaded to the "Knee Ankle Analyzer" software. The “Load right knee” and “Load left knee” commands were used to upload the knees’ angles, thighs’ angles and shanks’ angles. When the complete loaded data, the line graphs of the knee flexion-extension movement on the left side and the right side are displayed on the screen. These line graphs represent the changing angles of knee flexion-extension movement (in degrees) versus time (in seconds). If the user selected the checklists of the movement on the left-hand page of software, the residual line graphs (the changing angles of knee abduction-adduction movement or the changing angles on the thigh movement and the shank movement) are displayed on the monitor.

The “Auto Detection” buttons are used to determine the turning point on the knee flexion-extension movement that are the changing points of the positive value (+) to the negative value (-) or the changing points of the negative value (-) to the positive value (+). Also, it helps to the guideline to determine as this classified periods of a gait cycle. The user can select the graph area for the kinematic analysis and the reporting.

This software can report the kinematic variables on the selected area. The kinematic variables consist of the measuring angles (in degrees) and the time of motions (in seconds) at the start point and the end point, the total movement (in degrees), the duration (in seconds), the angular velocity (in degrees/second), and the angular acceleration (in degrees/second^2). These variables are reported as the values depending on the selected area either movement in the sagittal plane or movement in the coronal plane. This software has the "Capture Report" command to be used for the reporting.

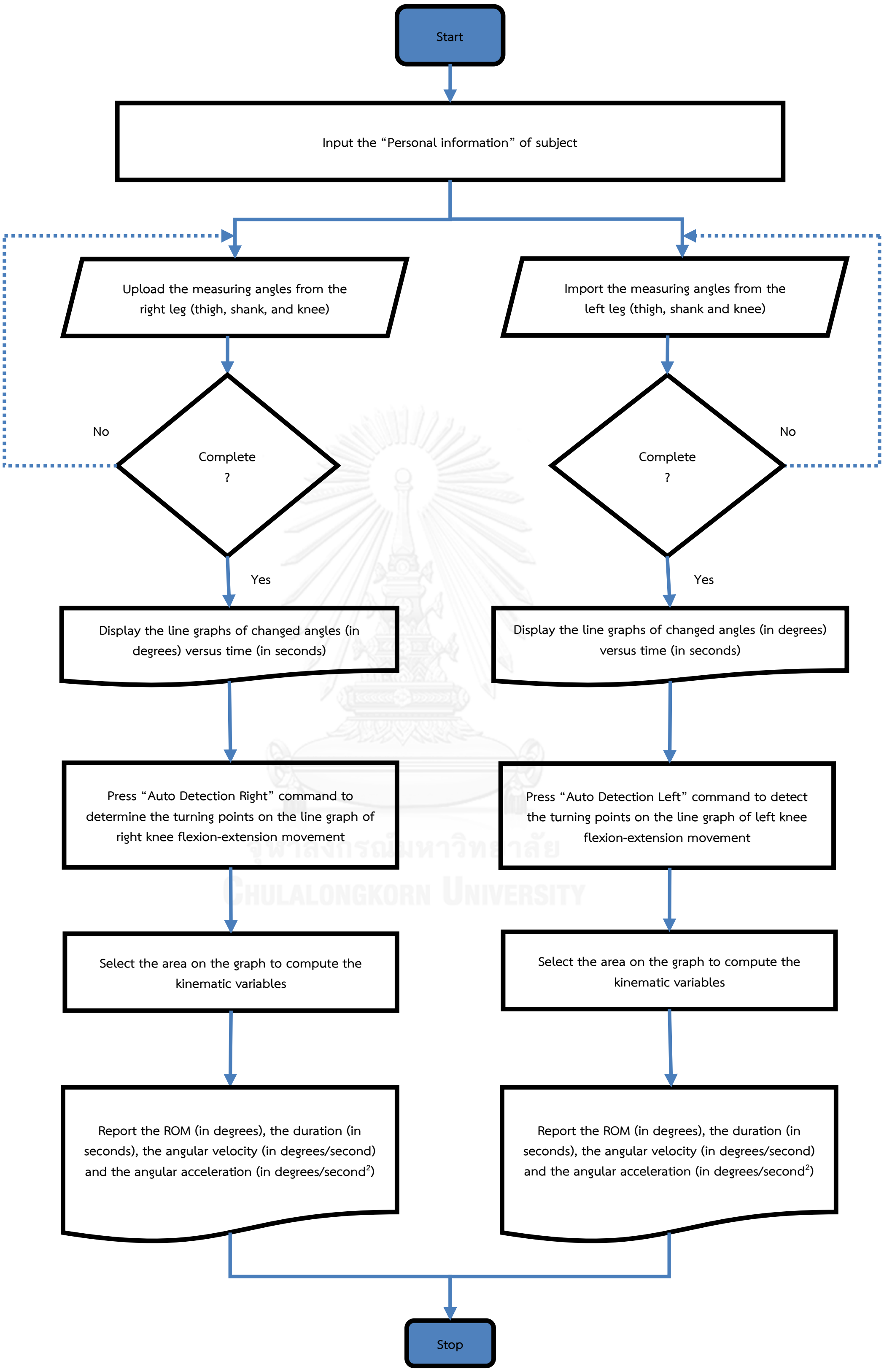


Figure 3.11 is the flowchart of the "Knee Angle Analyzer" software.

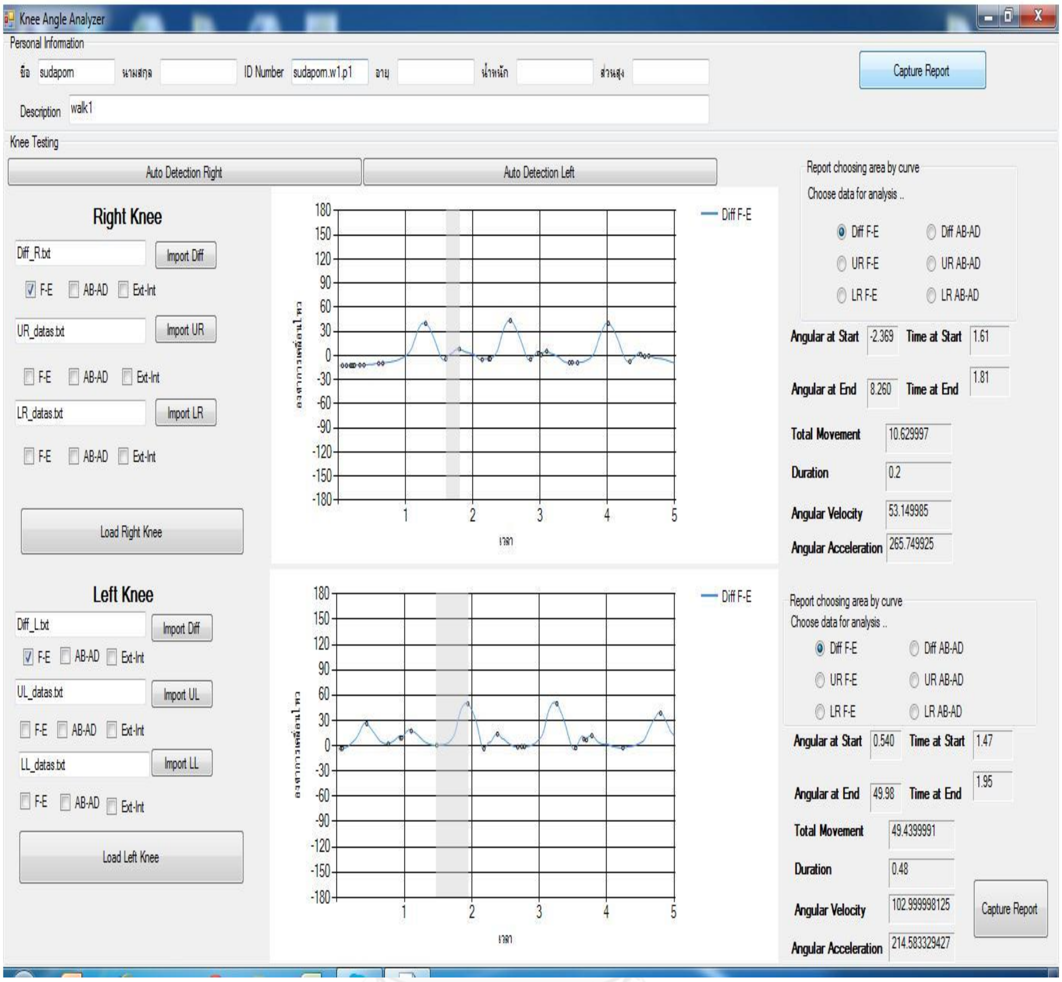


Figure 3.12 shows the screen of the "Knee Angle Analyzer" software.

3.4 How to compare the measuring angles between the Qualisys system and the IMU system

The analysis processes of the Qualisys system are as follows. Firstly, the data onto the six high-speed camera recorder are imported to the Qualisys Track Manager software. The Qualisys Track Manager software is used to identify the markers' positions and also saves the movement data into the C3D file type. Moreover, the movement data in the C3D file type are imported to the Visual 3D software. The Visual 3D software was used to mimic the skeletal model for the motion analysis.

The angles from the measurement onto thighs, shanks and knees were reported in the graphs and numeric (in degrees). The Qualisys system has the sampling rate of 120 Hz (A data sampling is 0.008333 seconds). The angles from measurement are exported the numeric data into the ASCII file type.

The IMU system, the angles from the IMU measurements are transferred to the computer and are displayed on the line graphs. The knee joint angles are estimated from the thigh's angle and the shank's angle at the same recording time. Also, all angle measurement are saved into the ASCII file type. The IMU system had the sampling rate of 50 Hz (A data sampling is 0.02 seconds).

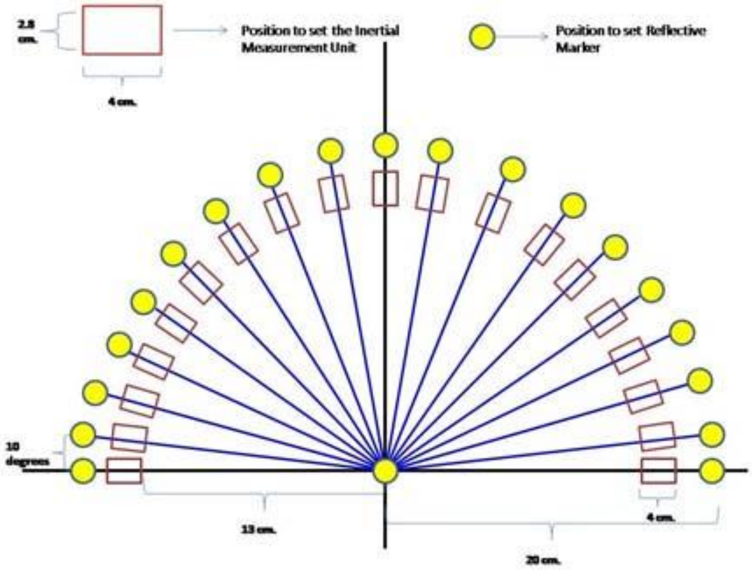
The measuring angle from the two systems into the ASCII file type were imported to the Microsoft Excel for Microsoft Windows. The starting point of movement from the measurement by the two systems were adjusted to the same starting point. Besides, the angles from the measurement were compared between the two systems at the same period. The decimal value of the angles was measured with one position.

3.5 Procedures of this study

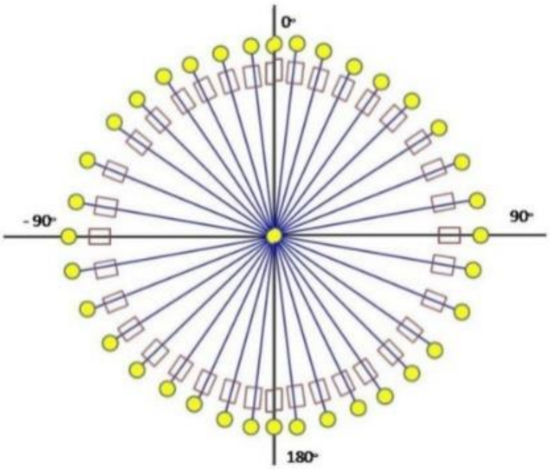
3.5.1 The accurate test for IMU measurements in the static condition

- Protocol of testing

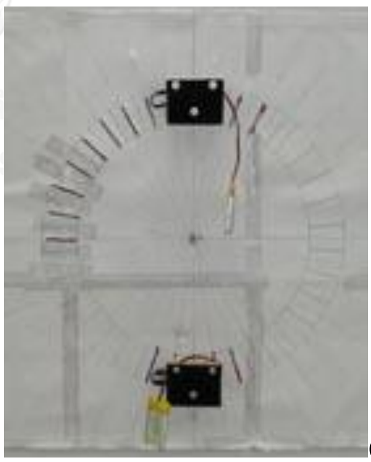
The board with the fixed angles was designed in the size 60X50 square centimeters (Fig. 3.13). The researcher placed the three reflective markers on the specific positions; at the center of the board and at each radius of 20 centimeters from the center. The IMU devices were placed at the radius 16 centimeters from the center.



A.



B.



C.


D.

Figures 3.13 show the board with reference angles that is used for the accurate test in the static condition. **3.13A and 3.13B** show the details on the board. **3.13C and 3.13D** show the placement of the IMU devices and the reflective markers on the board during the test.

The researcher compared the measuring angles among the reference angles, the Qualisys system and the IMU devices. The comparisons of measuring angles were evaluated on both sagittal and coronal planes. During the test, the four developed IMU devices were separated into two pairs. The first pair was the sensor number 1 and 2, which were used regularly for the measurement in the right leg. The second pair was the sensor number 3 and 4, which were used regularly for the measurement in the left leg. The researcher chose the sequential angles by a lottery. The selective angles for measurement in the sagittal plane were -20, -10, 0, 10, 20, 30, 40, 50, 60, 70, 80, and 90 degrees. The measurement in the coronal plane was -40, -30, -20, -10, 0, 10, 20, 30, and 40 degrees.

- The statistical comparison of measuring angles

The root mean square (RMS) of different angles and the Intraclass Correlation Coefficient (ICC) (Portney LG & Watkins MP, 1993) (Two-Way

Mixed Effects Model <Consistency Definition>) were used for the accurate test among the IMU system, the Qualisys system, and the fixed angle.

$$x_{RMS} = \sqrt{\frac{1}{n}(x^2{}_1 + x^2{}_2 + x^2{}_3 + \ldots\ldots + x^2{}_n} \qquad (13)$$

$$\text{ICC (2,1)} = \frac{\text{BMS}-\text{EMS}}{\text{BMS}+(\text{k}-1)\text{EMS}+\frac{\text{k}(\text{RMS}-\text{EMS})}{\text{n}}} \qquad (14)$$

BMS = The between-subjects mean square

EMS = The error mean square

RMS = The between-rater mean square

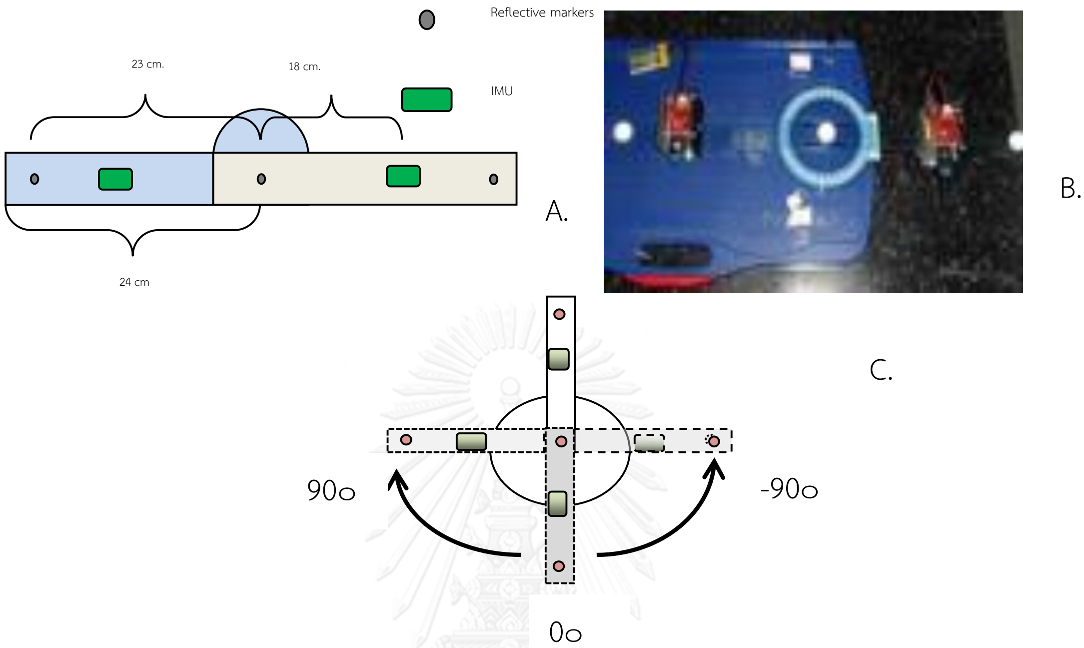
K = The number of raters

n = The number of subjects tested

3.5.2 The accurate test for IMU measurements in the dynamic condition

- <u>Protocol of testing</u>

The researcher attached three reflective markers on a goniometer. A reflective marker was attached on the center of the goniometer and the other reflective markers were attach on each ending points of the goniometer's arm. The IMU devices were attached to the goniometer's arm at 18 centimeters away from the center of the goniometer. The goniometer was placed on the stationary table and also set perpendicularly to the floor. The researcher rotated the goniometer's arm from "0" degrees (perpendicularly to the floor) to "-90" degrees (parallel to the ground). Also, the goniometer's arm was rotated from "0" degrees (perpendicularly to the floor) to "90" degrees (parallel to the ground) (Fig 3.14). This study tested for the both sagittal and the coronal planes and the two pairs of IMU devices (the sensor number 1 and 2 and the sensor number 3 and 4).



Figures 3.14 show the accurate test for IMU measurements in the dynamic condition. **3.14A and 3.14B** show the positions of the reflective markers and the IMU devices that attach on the goniometer. **3.14C** shows the movement pattern of the goniometer's arm during the testing.

- <u>The statistical comparison of measuring angles</u>

The RMS of the different angles and the ICC (Two-Way Mixed Effects Model <Consistency Definition>) were used for the accurate test between the IMU system and the Qualisys system.

3.5.3 The accurate test for IMU measurements during the functional knee movement test and the walking test

- <u>Protocol of testing</u>

The participants were explained the protocol and signed a consent form. All participants were asked about the physical characteristics such as, age, height, weight and the history of injuries on the back and on the lower limbs. The leg length of participants was measured with the measuring tape. The participants were asked to wear shorts. The researcher placed the reflective markers and the four IMU devices on the specified positions. The IMU devices were attached on the anterior mid-thigh and the anterior mid-shank on both legs by the four pieces of the elastic band with Velcro strap. The mid-thigh position is the center point between the greater trochanter and the joint line of the knee. The mid-shank is the center point between the joint line knee and the lateral malleolus. The reflective markers were placed on the bony prominences; the posterior superior iliac spine <PSIS>, the anterior superior iliac spine (ASIS), the greater trochanter, the lateral and medial epicondyle of femur, the lateral and medial malleolus of ankle, the head and base 5^{th} metatarsal and great toe on both sides. Two sets of reflective markers for the thigh segment were attached on the lateral side of mid-thigh. Two sets of reflective markers for the shank were attached on the lateral side of mid-shank. After the finished preparation, participant was asked to stand at the center walkway. The positions of reflective markers were captured by the Qualisys system (Fig. 3.15). The markers' positions that acquired from the caption were used for the process of marker identification. In addition to, the researcher removed the markers at the greater trochanter, the lateral and medial epicondyle of femur, and the lateral and medial malleolus of ankle on both legs.

The participants were asked to move their legs according to the assignments that consisted of the knee flexion test (Fig. 3.16), the hip and knee flexion test (Fig.3.17), the forward step test (Fig.3.18), and the leg abduction test (Fig.3.19). After the finished movement target, the leg will move back to the starting point. Finally, the participants were asked to walk with normal speed along the walkway (Fig. 3.20). Also, the knee flexion-extension movement during the gait cycle were selected for the comparison.

Figure 3.15 shows the IMU devices and the reflective markers that are placed on the participants.

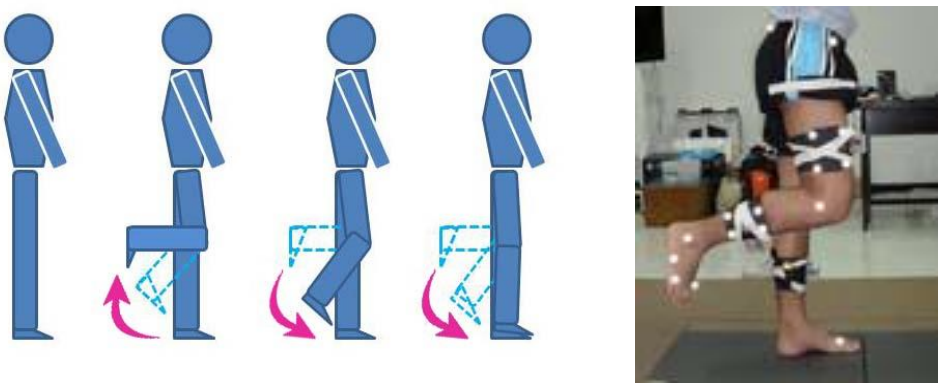


Figure 3.16 shows the movement of the knee flexion test.

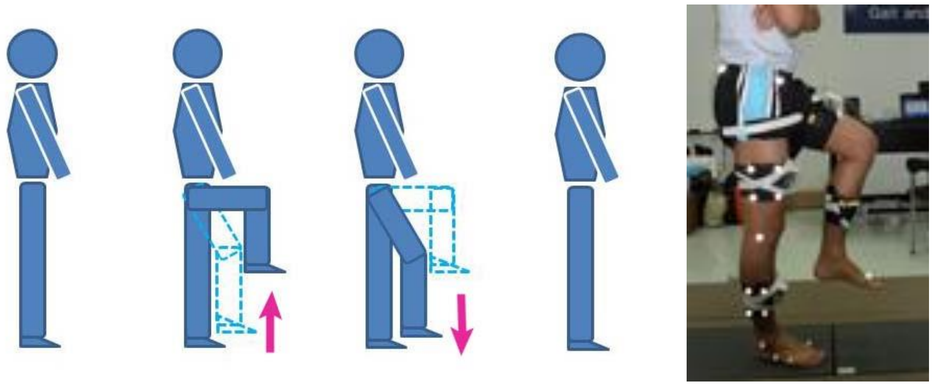


Figure 3.17 shows the movement of the hip and knee flexion test.

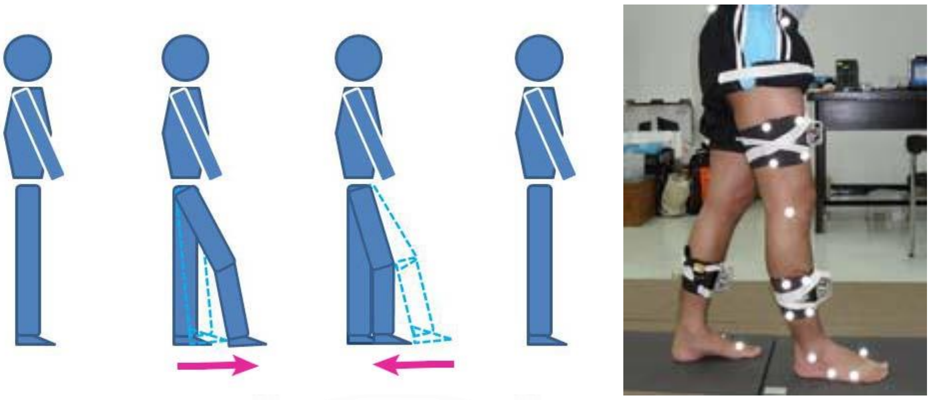


Figure 3.18 shows the movement of the forward step test.

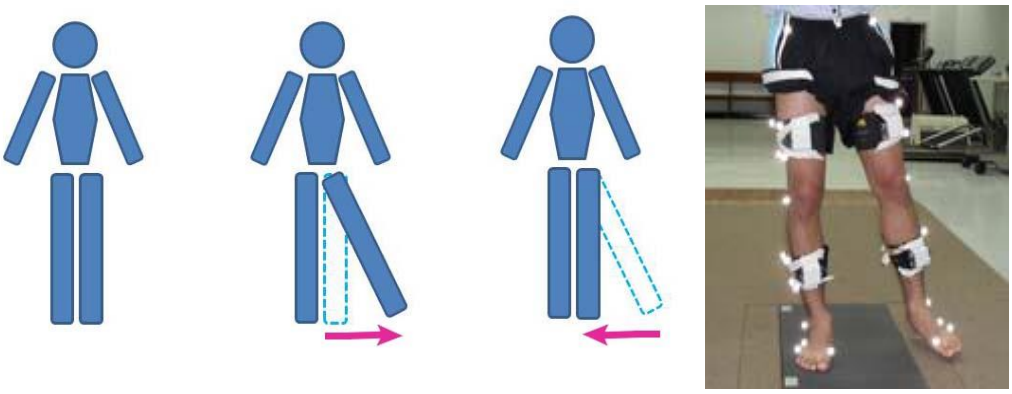


Figure 3.19 shows the movement of the leg abduction test.

Figure 3.20 shows the walking test along a walkway.

Participants were explained this protocol and signed a consent form.

↓

Participants were checked the physical characteristics and wore shorts.

↓

The IMU devices and the reflective markers were placed on the specified positions.

↓

The positions of reflective markers during the upright position of participant were captured by the Qualisys system.

↓

Participants were asked to move their legs according to the assignments and the measuring angles were recorded simultaneously by the two systems.

↓

The knee flexion-extension movement were recorded simultaneously during the walking along the walkway.

Figure 3.21 is the protocol of accurate test for the IMU measurements in the functional knee movement test and the walking test.

- <u>The statistical comparison of measuring angles</u>

The RMS of the difference angles and the ICC (Two-Way Mixed Effects Model <Consistency Definition>) were used for the comparison of the concurrent measuring angles between the IMU system and the Qualisys system.

3.5.4 The clinical application of IMU system

The elderly women with and without symptomatic knee osteoarthritis, who had the criterions according to the regulation, were recruited in this study. All participants were explained the protocol of study. Participants were examined the physical characteristics and signed a consent form. They wore a shorts and were attached the four IMU devices on the anterior mid-thigh and the anterior mid-shank on both legs. The participants were asked to walk with normal speed on the flat floor during the testing. The knee flexion-extension movement during the gait cycle were recorded and analyzed the kinematic variables by the "Knee Angle Analyzer" software. This software had the commands to determine the phases of gait cycle as the guideline. Thus, the gait cycle was divided into the four phases. The gait phase division conformed to Benedetti et. al.'s suggestion. (Benedetti MG, Catani F, Leardini A, Pignotti E, & Giannini S, 1998). The four periods were as follows:

The 1st period was the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Response (MLRS) phase.

The 2nd period was the knee movement from the MLRS phase to the Maximum Extension in Stance (MES) phase.

The 3rd period was the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period was the knee movement from the MFS phase to the FHS phase.

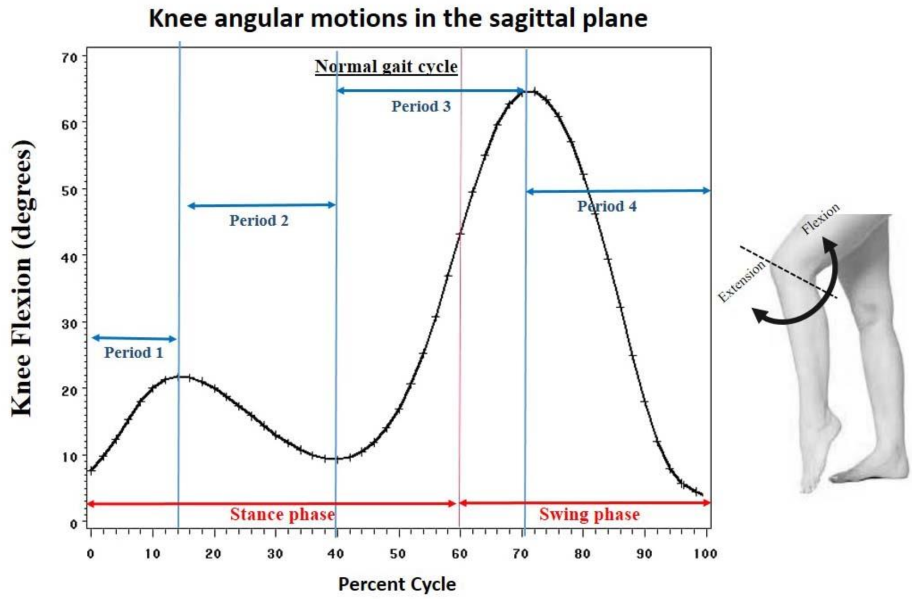


Figure 3.22 shows the classified periods of a gait cycle in the line graph of knee angular motion data in the sagittal plane.

Moreover, this study was used for the consideration of a facing problem in the clinical application of the IMU measurements.

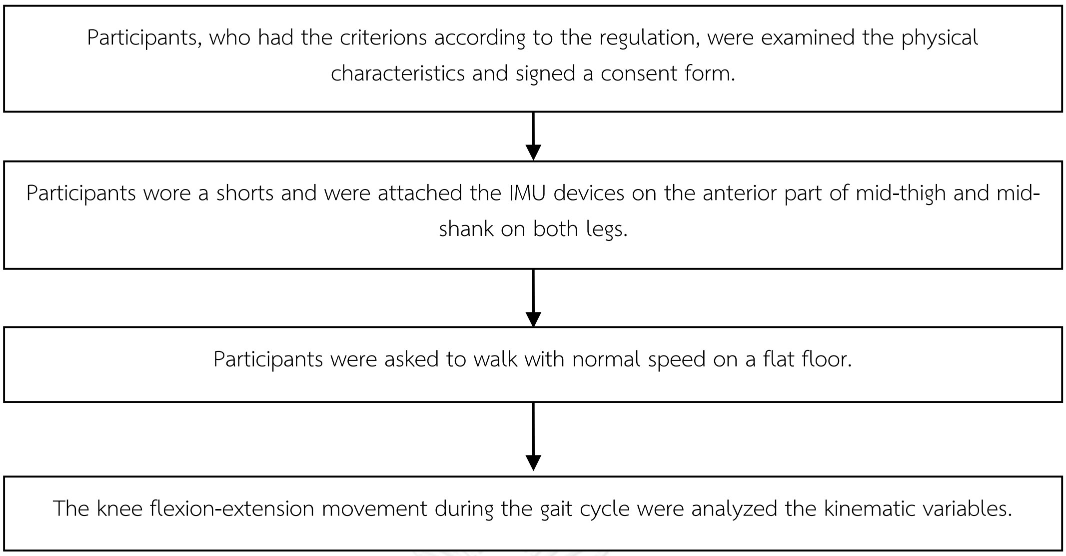


Figure 3.23 is the protocol of walking test in the clinical application.

3.6 Statistical analysis of this study

The Statistical Package for the Social Sciences **for** Microsoft Windows **version 17.0** (Copyright ©2011 Office of Information Technology, Chulalongkorn University) and the Microsoft Excel 2010 for Microsoft Windows were used in this study. The statistical analysis was as follows;

3.6.1 The descriptive statistical analysis used to calculate the RMS of different angles.

3.6.2 The ICC values were calculated by the Two-Way Mixed Effects Model (Consistency Definition) in the SPSS version 17.0 for Microsoft Windows.

3.6.3 The Independent Samples T test in the SPSS version 17.0 for Microsoft Windows was used to compare the physical characteristics and the total duration of gait cycle between the elderly women with and without symptomatic knee osteoarthritis. Also, it was used for the comparison between the symptomatic side and the non-symptomatic side in the elderly women with symptomatic knee osteoarthritis and the comparison between the left and right side in the elderly women without symptomatic knee osteoarthritis. If the data were not the normal distribution, the Mann Whitney U test was used for the analysis.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s^2\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}} \qquad (15)$$

$$S^2 = \frac{\sum_{j=1}^{n_1}\left(x_j - \bar{x}_1\right)^2 + \sum_{i=1}^{n_2}(x_i - \bar{x}_2)^2}{n_1 + n_2 - 2} \qquad (16)$$

$\bar{x}_1$ and $\bar{x}_2$ are the sample means

S^2 is the pooled sample variance

n_1 and n_2 are the sample sizes

t is a Student t quantile with $n_1 + n_2 - 2$ degrees of freedom.

3.6.4 The Dependent Samples T test in the SPSS version 17.0 for Microsoft Windows was used for the comparison of the knee kinematic variables [the angular motion (in degrees), the duration (in seconds), and the angular velocity (in degrees/second)] on each period of gait cycle between the left side and the right side. If the data were not the normal distribution, the Wilcoxon Matched-Pairs Signed-Ranks Test was used for the analysis.

$$t = \frac{\sum d}{\sqrt{\frac{n(\sum d^2) - (\sum d)^2}{n-1}}} \qquad (17)$$

d is the difference values.

n is the sample sizes.

t is a Student t quantile with n – 1 degrees of freedom.

CHAPTER 4

RESULTS

The results of this study reported the accuracy of IMU measurements (in degrees) by the developed IMU devices. There were four processes for this accurate test, such as the testing for inclined sensor in an acrylic box, the accurate test for IMU measurements in the static condition, the accurate test for IMU measurements in the dynamic condition, and the accurate test for IMU measurements in the functional knee movement tests and the walking test. Moreover, the IMU system was tested for the clinical application that measured the knee flexion-extension movement in the elderly women with and without symptomatic knee osteoarthritis during the walking.

4.1 The testing for inclined sensor in an acrylic box

This test reported the inclined IMU sensor that completely set in an acrylic box. The researcher placed the complete developed IMU devices on the flat floor. They measured the angles from the developed IMU devices on both sagittal and the coronal planes within 5 seconds (250 samplings). Each developed IMU device was tested for 3 times. These results are shown in Table 4.1.

Table 4.1 shows the average angles (in degrees) from the developed IMU devices that were placed on the flat floor during the testing.

IMU number	**The average angles** (in degrees) **from the testing in the sagittal plane***			**The average angles** (in degrees) **from the testing in the coronal plane****		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
1	90.6	90.6	90.5	-0.6	-0.6	-0.5

2	90.0	90.0	89.9	-0.3	-0.4	-0.4
3	88.5	88.5	88.4	-0.1	0.0	0.0
4	89.7	89.8	89.7	-0.2	-0.6	-0.4

*The angles (in degrees) from the developed IMU devices in the sagittal plane have been regularly 90 degrees at the zero line, when the IMU sensor placed on the flat floor.

** The angles (in degrees) from the developed IMU devices in the coronal plane have been regularly 0 degrees at the zero line, when the IMU sensor placed on the flat floor.

4.2 The accurate test for IMU measurements in the static condition

This test was the comparison of measuring angles among the IMU devices, the Qualisys system, and the reference angles. The four IMU devices were separated into two pairs. The first pair was the sensor number 1 and 2 and the second pair was the sensor number 3 and 4. This test also reported the angle measurements in the sagittal plane and in the coronal plane.

4.2.1 The testing in the sagittal plane

The angles were tested in –20°, -10°, 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90° degrees. The measuring angles were recorded within 5 seconds in each angle position. Also, the measuring angles were averaged into a value. Table 4.2 and Figure 4.1 report the results of the accurate test for IMU measurements in the static condition that were tested for the first pair of developed IMU devices.

Table 4.2 shows the measuring angles (in degrees) in the static testing, which were compared the measuring angles in the sagittal plane among the 1st pair of developed IMU devices, the Qualisys system, and the reference angles. (12 angle positions)

Reference angle (Degrees)	**The measuring angles** (in degrees) **from the Qualisys system**			**The measuring angles** (in degrees) **from the IMU system**			**The absolute different angle** (in degrees) **between the Qualisys system and the IMU system**
	Reading angle	**The different angle from the reference angle**	**The absolute different angle**	**Reading angle** (Degrees)	**Reading angle**	**The different angle from the reference angle**	
-20	-19.6	0.4	0.4	-20.2	-0.2	0.2	0.6
-10	-10.7	-0.7	0.7	-10.3	-0.3	0.3	0.5
0	-0.5	-0.5	0.5	-2.1	-2.1	2.1	1.6
10	9.9	-0.1	0.1	9.1	-0.9	0.9	0.8
20	20.6	0.6	0.6	21.6	1.6	1.6	1.0
30	31.1	1.1	1.1	28.9	-1.1	1.1	2.3
40	41.2	1.2	1.2	38.2	-1.8	1.8	3.0
50	50.3	0.3	0.3	47.5	-2.5	2.5	2.7
60	61.2	1.2	1.2	58.6	-1.4	1.4	2.6
70	70.8	0.8	0.8	68.0	-2.0	2.0	2.8
80	80.9	0.9	0.9	77.6	-2.4	2.4	3.4
90	89.7	-0.3	0.3	88.9	-1.1	1.1	0.8
RMS of different angles	-	-	0.77	-	-	1.61	2.09

RMS of different angle is the root mean square of the different angles

Single Rater ICC is the single rate of Intraclass Correlation Coefficients

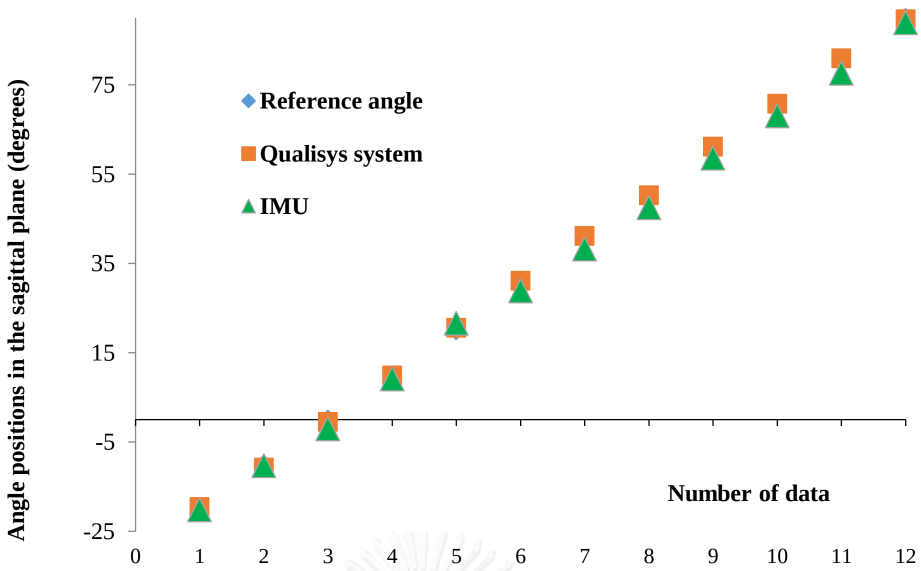


Figure 4.1 shows the scatter diagrams of measuring angles (in degrees) in the static testing, which were compared the measuring angles in the sagittal plane among the 1st pair of developed IMU devices, the Qualisys system, and the reference angles.

Table 4.3 and Figure 4.2 report the results of the accurate test in the static condition that were tested for the second pair of developed IMU devices.

Table 4.3 shows the measuring angles (in degrees) in the static testing, which were compared the measuring angles in the sagittal plane among the 2nd pair of developed IMU devices, the Qualisys system, and the reference angles. (12 angle positions)

Reference angle (Degrees)	The measuring angles (in degrees) from the Qualisys system			The measuring angles (in degrees) from the IMU system			The absolute different angle (in degrees) between the Qualisys system and the IMU system
	Reading angle	The different angle from the reference angle	The absolute different angle	Reading angle (Degrees)	Reading angle	The different angle from the reference angle	
-10	-9.4	0.6	0.6	-9.2	0.8	0.8	0.2

0	-0.4	-0.4	0.4	-0.7	-0.7	0.7	0.3
10	9.7	-0.3	0.3	10.4	0.4	0.4	0.7
20	20.6	0.6	0.6	19.5	-0.5	0.5	1.1
30	31.0	1.0	1.0	30.4	0.4	0.4	0.6
40	41.5	1.5	1.5	40.7	0.7	0.7	0.7
50	50.2	0.2	0.2	51.2	1.2	1.2	1.0
60	60.5	0.5	0.5	60.5	0.5	0.5	0.1
70	70.8	0.8	0.8	70.9	0.9	0.9	0.1
80	79.4	-0.6	0.6	79.3	-0.8	0.8	0.2
90	89.7	-0.3	0.3	89.4	-0.6	0.6	0.3
RMS of different angles	-	-	0.72	-	-	0.73	0.57
Single Rater ICC	-	-	0.9998			0.9965	0.9971

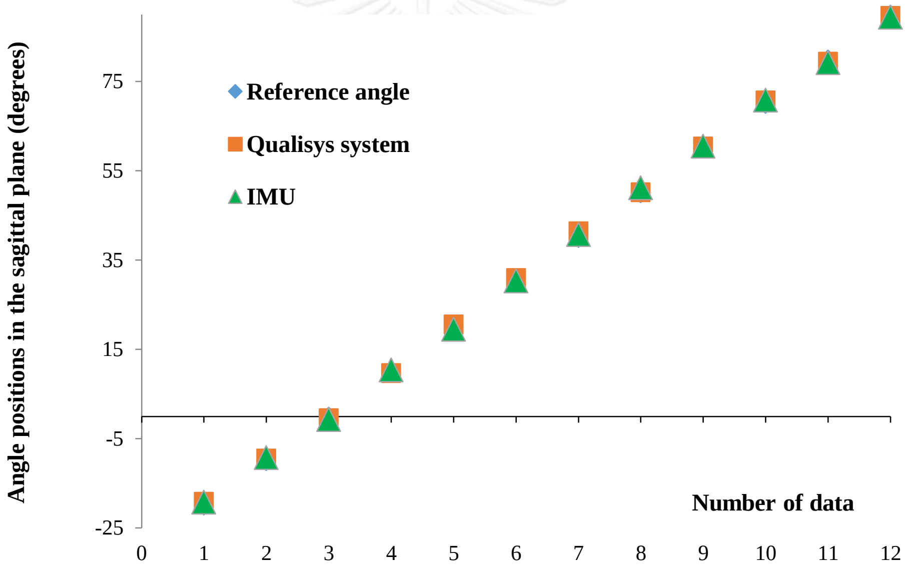


Figure 4.2 shows the scatter diagrams of measuring angles (in degrees) in the static testing, which were compared the measuring angles in the sagittal plane among the 2^{nd} pair of developed IMU devices, the Qualisys system, and the reference angles.

4.2.1 The testing in the coronal plane

The angles were tested in -40°, -30°, -20°, -10°, 0°, 10°, 20°, 30°, and 40° degrees. The measuring angles were recorded within 5 seconds in each angle position. Also, the measuring angles were averaged into a value. Table 4.4 and Figure

4.3 the results of the accurate test for IMU measurements in the static condition that were tested for the first pair of developed IMU devices.

Table 4.4 shows the measuring angles (in degrees) in the static testing, which were compared the measuring angles in the coronal plane among the 1st pair of developed IMU devices, the Qualisys system, and the reference angles. (9 angle positions)

	The measuring angles (in degrees) **from the Qualisys system**			**The measuring angles** (in degrees) **from the IMU system**			
Reference angle (Degrees)	**Reading angle**	**The different angle from the reference angle**	**The absolute different angle**	**Reading angle** (Degrees)	**Reading angle**	**The different angle from the reference angle**	**The absolute different angle** (in degrees) **between the Qualisys system and the IMU system**
-40	-39.6	0.4	0.4	-40.7	-0.7	0.7	1.1
-30	-29.7	0.3	0.3	-28.2	1.8	1.8	1.5
-20	-19.6	0.4	0.4	-18.6	1.4	1.4	1.0
-10	-9.3	0.8	0.8	-10.6	-0.6	0.6	1.4
0	0.6	0.6	0.6	0.8	0.8	0.8	0.3
10	8.1	-1.9	1.9	11.9	1.9	1.9	3.8
20	18.8	-1.2	1.2	21.3	1.3	1.3	2.5
30	28.7	-1.4	1.4	31.1	1.1	1.1	2.4
40	41.1	1.1	1.1	38.9	-1.1	1.1	2.2
RMS of different angles	-	-	1.02	-	-	1.26	2.04
Single Rater ICC	-	-	0.9992			0.9991	0.9973

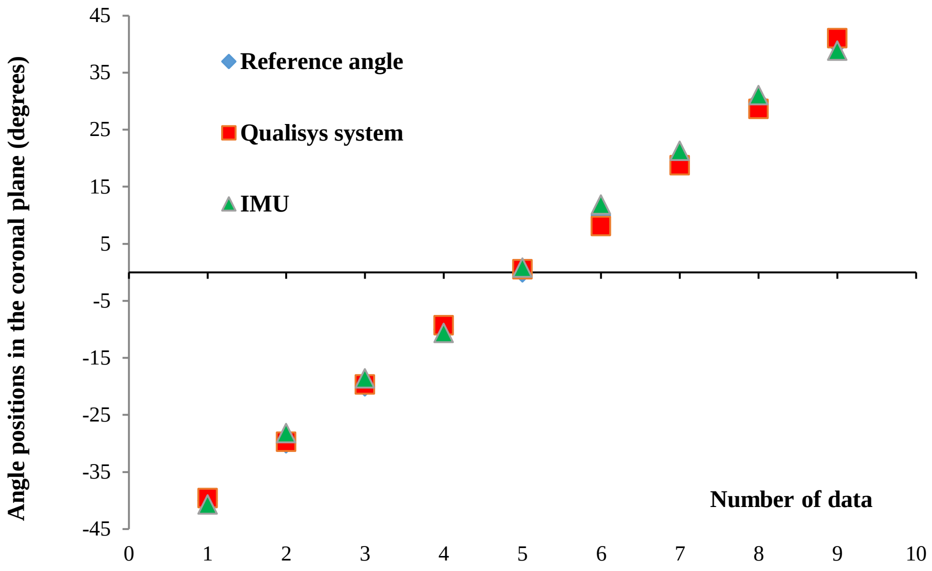


Figure 4.3 shows the scatter diagrams of measuring angles (in degrees) in the static testing, which were compared the measuring angles in the coronal plane among the 1st pair of developed IMU devices, the Qualisys system, and the reference angles.

Table 4.5 and Figure 4.4 report the results of the accurate test in the static condition that were tested for the second pair of developed IMU devices.

Table 4.5 shows the measuring angles (in degrees) in the static testing, which were compared the measuring angles in the coronal plane among the 2nd pair of developed IMU devices, the Qualisys system, and the reference angles. (9 angle positions)

Reference angle (Degrees)	The measuring angles (in degrees) from the Qualisys system			The measuring angles (in degrees) from the IMU system			The absolute different angle (in degrees) between the Qualisys system and the IMU system
	Reading angle	The different angle from the reference angle	The absolute different angle	Reading angle (Degrees)	Reading angle	The different angle from the reference angle	
-40	-38.8	1.2	1.2	-41.2	-1.2	1.2	2.4
-30	-29.5	0.5	0.5	-28.4	1.6	1.6	1.1
-20	-19.0	1.0	1.0	-18.2	1.8	1.8	0.8

-10	-10.7	-0.7	0.7	-10.9	-0.9	0.9	0.2
0	0.3	0.3	0.3	1.1	1.1	1.1	0.8
10	9.1	-0.9	0.9	8.1	-1.9	1.9	1.0
20	19.2	-0.8	0.8	18.2	-1.8	1.8	1.0
30	28.8	-1.2	1.2	28.4	-1.6	1.6	0.4
40	39.8	-0.3	0.3	37.8	-2.2	2.2	1.9
RMS of different angles	-	-	0.85	-	-	1.63	1.26
Single Rater ICC	-	-	0.9995			0.9982	0.9989

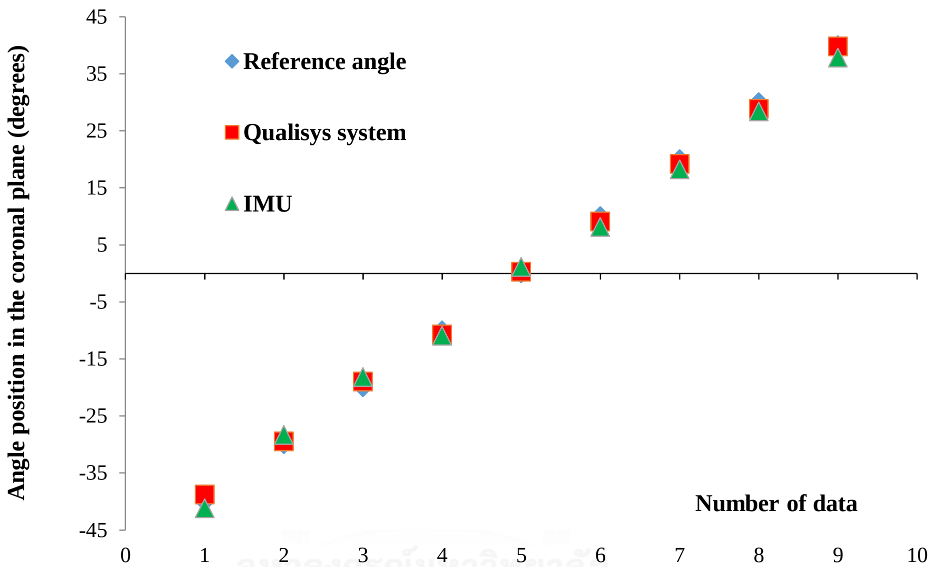


Figure 4.4 shows the scatter diagrams of measuring angles (in degrees) in the static testing, which were compared the measuring angles in the coronal plane among the 2nd pair of developed IMU devices, the Qualisys system, and the reference angles.

The angles from the IMU measurement in the horizontal plane could not report in this accurate test in the static condition.

4.3 The accurate test for IMU measurements in the dynamic condition

The accurate test for IMU measurements in the dynamic condition purposed to evaluate the measuring angles during the movement. The developed IMU devices and the reflective markers were attached on the goniometer. The movable arm of goniometer was moved in the range from 0 degrees to 90 degrees and also was moved in the range from 0 degrees to -90 degrees. The measuring angles was compared between the Qualisys system and the IMU system. This test evaluated on both the first pair (sensor number 1 and 2) and the second pair (sensor number 3 and 4) of the developed IMU devices and also evaluated on the movement on both sagittal and coronal planes.

4.3.1 The accurate test for the 1st pair of IMU measurements in the dynamic condition

4.3.1.1 The testing in the sagittal plane

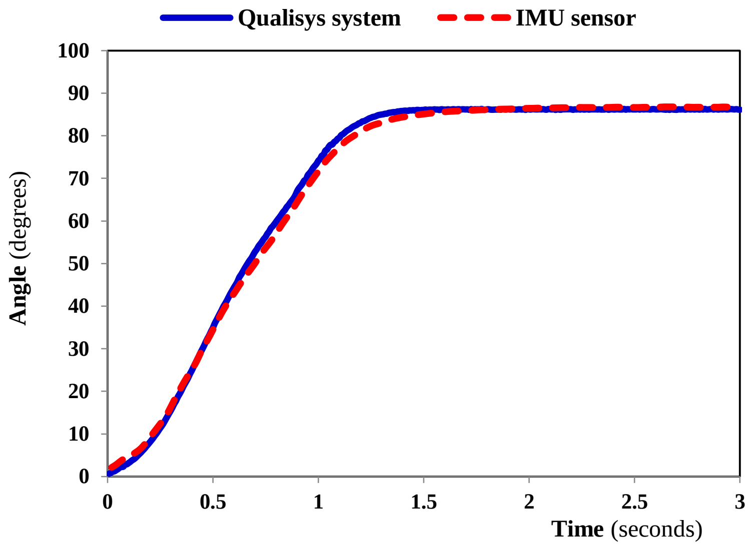


Figure 4.5 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 1st pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to 90° in the sagittal plane.

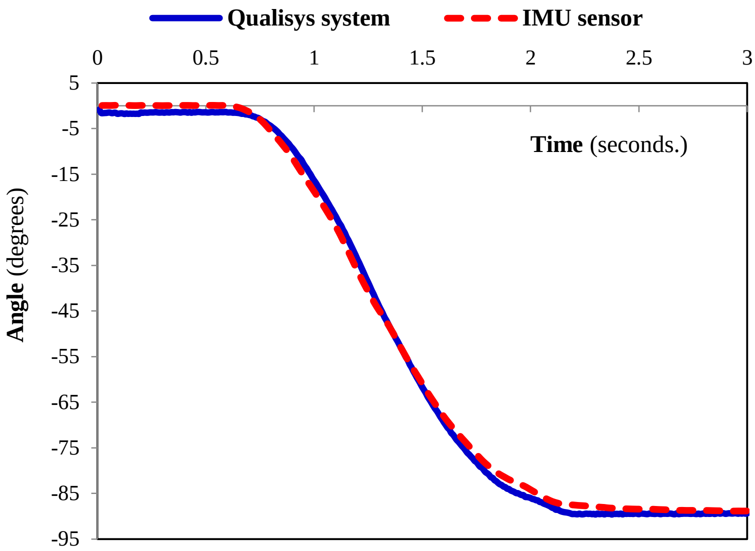


Figure 4.6 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 1st pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to -90° in the sagittal plane.

When the movable arm of goniometer was moved in the range from 0 degrees to 90 degrees in the sagittal plane, the RMS of different angles were 1.34 degrees and the single rater of ICC value was 0.9988. When the movable arm of goniometer was moved in the range from 0 degrees to -90 degrees in the sagittal plane, the RMS of different angles were 1.54 degrees and the single rater of ICC value was 0.9881.

4.3.1.2 The testing in the coronal plane

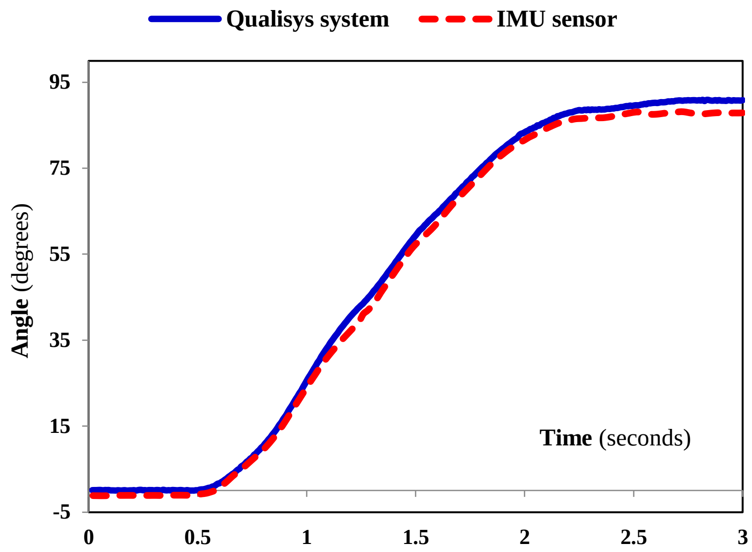


Figure 4.7 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 1st pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to 90° in the coronal plane.

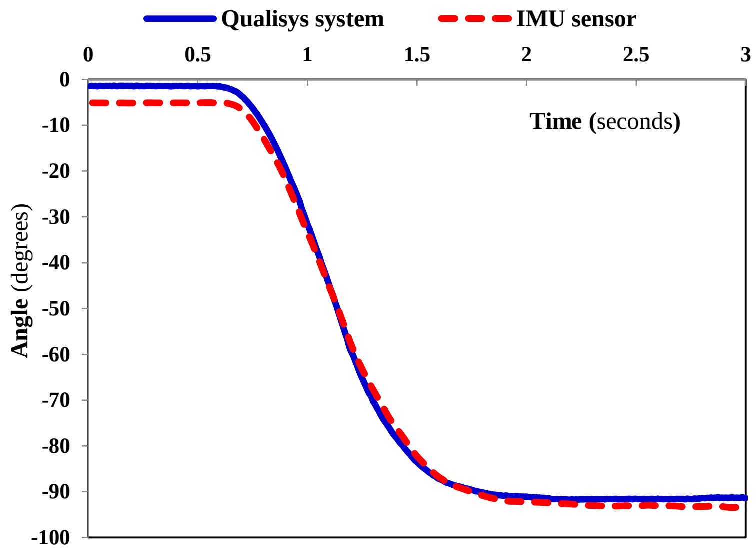


Figure 4.8 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 1st pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to -90° in the coronal plane.

When the movable arm of goniometer was moved in the range from 0 degrees to 90 degrees in the coronal plane, the RMS of different angles were 1.51 degrees and the single rater of ICC value was 0.9984. When the movable arm of goniometer was moved in the range from 0 degrees to -90 degrees in the coronal plane, the RMS of different angles were 2.24 degrees and the single rater of ICC value was 0.9863.

4.3.2 The accurate test for the 2nd pair of IMU measurements in the dynamic condition

4.3.2.1 The testing in the sagittal plane

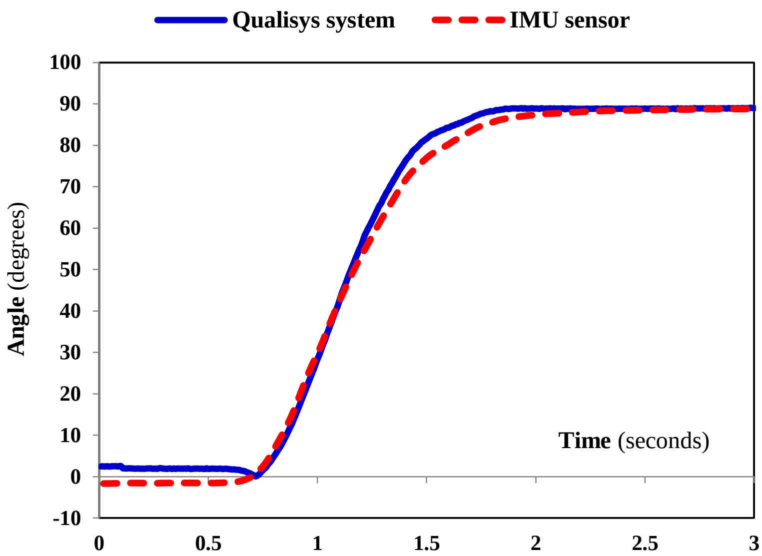


Figure 4.9 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 2nd pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to 90° in the sagittal plane.

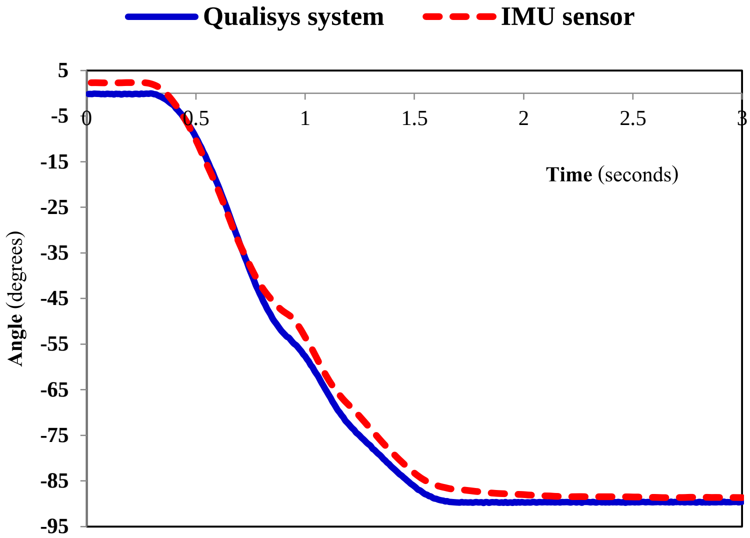


Figure 4.10 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 2nd pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to -90° in the sagittal plane.

When the movable arm of goniometer was moved in the range from 0 degrees to 90 degrees in the sagittal plane, the RMS of different angles were 2.54 degrees and the single rater of ICC value was 0.9966. When the movable arm of goniometer was moved in the range from 0 degrees to -90 degrees in the sagittal plane, the RMS of different angles were 2.19 degrees and the single rater of ICC value was 0.9934.

4.3.2.2 The testing in the coronal plane

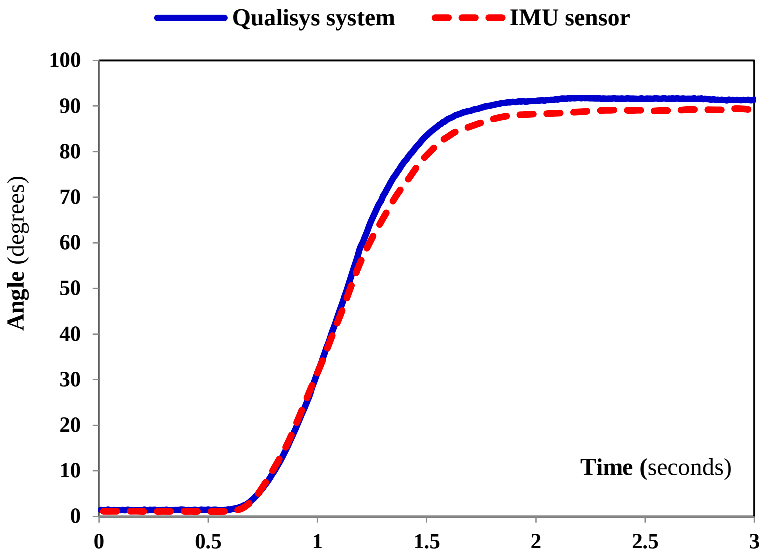


Figure 4.11 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 2nd pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to 90° in the coronal plane.

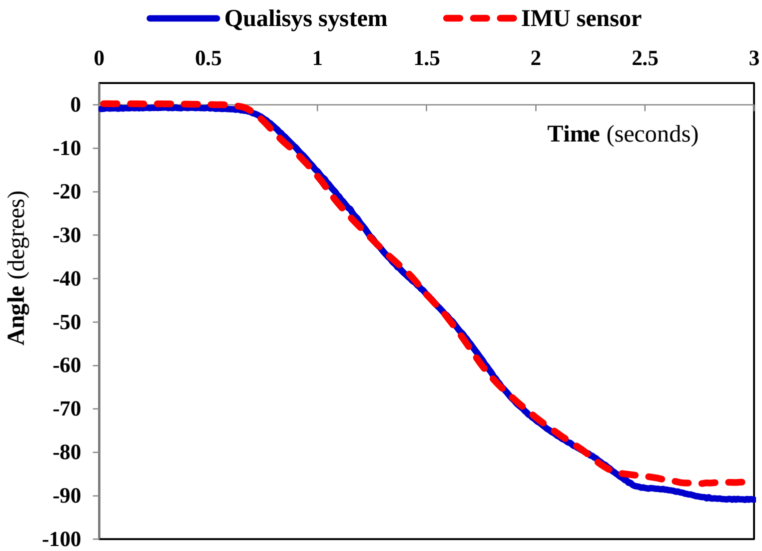


Figure 4.12 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 2nd pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to -90° in the coronal plane.

When the movable arm of goniometer was moved in the range from 0 degrees to 90 degrees in the coronal plane, the RMS of different angles were 2.42 degrees and the single rater of ICC value was 0.9985. When the movable arm of goniometer was moved in the range from 0 degrees to -90 degrees in the coronal plane, the RMS of different angles were 1.66 degrees and the single rater of ICC value was 0.9941.

The accuracy test in the dynamic condition could not test for the horizontal plane because the measuring angles from the developed IMU system were the divergence and gradually decreased while the stop-motion.

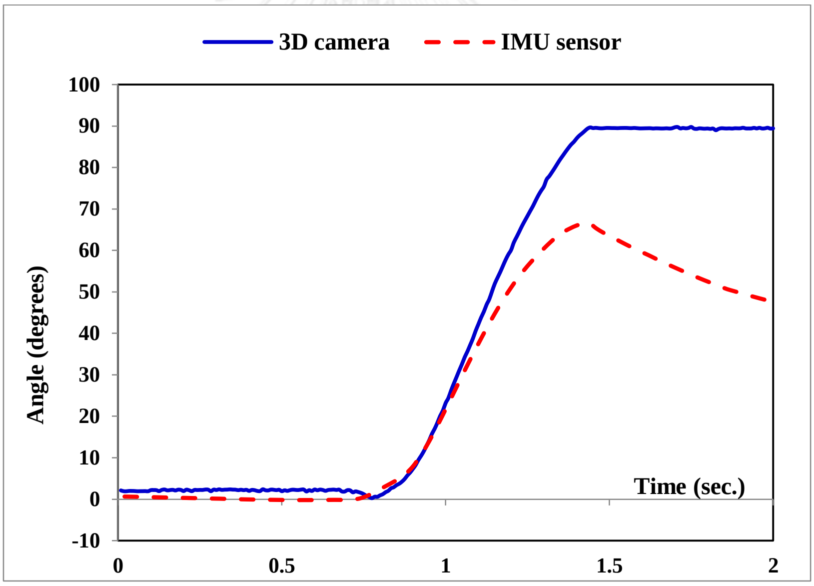


Figure 4.13 shows the line graphs of changing angles (in degrees) versus time (in seconds) on the comparison of measuring angles between the 1st pair of the developed IMU devices and the Qualisys system. The measuring angles were collected when the moving goniometer from 0° to 90° in the horizontal plane.

4.4 The accurate test for IMU measurements in the functional knee movement tests and the walking test.

This test compared the measuring angles between the IMU system (in degrees) and the Qualisys system. The four functional knee movement tests and the walking test were used for the comparison. The four functional knee movement tests consisted of the knee flexion test, the hip and knee flexion test, the forward step test, and the leg abduction test. Also, the walking test was the walking with normal speed along the walkway.

4.4.1 Physical characteristics of the participants

Ten healthy participants took a part in this test. The physical characteristics of the participants are reported in Table 4.6.

Table 4.6 shows the physical characteristics of ten participants.

No.	Sex	Age (yrs.)	Weight (kg.)	Height (cm.)	Thigh Length (cm.)		Shank Length (cm.)	
					Lt. Side	Rt. Side	Lt. Side	Rt. Side
1	F	30	47	162	39	39	38	38
2	M	27	70	173	44	44	44	43.5
3	M	23	57	163	35	35	39	39
4	M	24	71	170	40	40	41	41
5	M	30	57	170	42	42	40	40
6	M	34	76	168	40	40	42	41
7	F	23	63	156	36	36	38	38
8	F	28	48	156	44	44	38	38
9	M	24	66	169	40	40	42	42
10	M	25	60	167	44	44	40	40

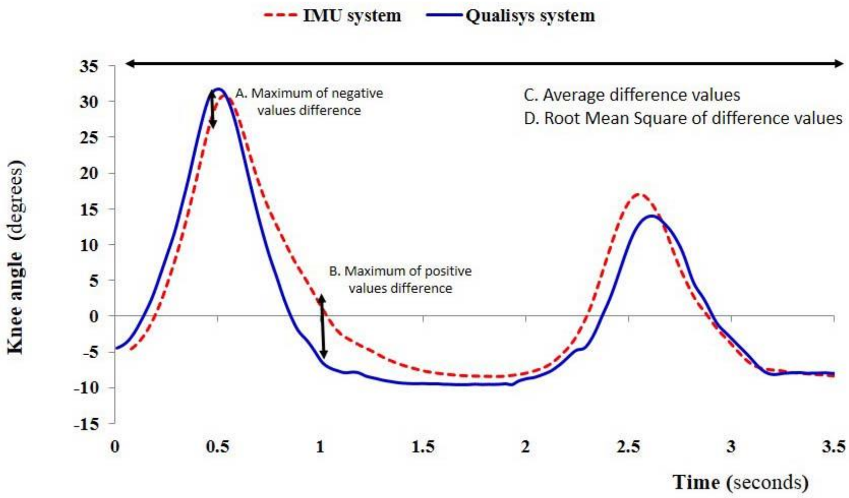


Figure 4.14 shows the guideline figure and the variables to be used for the graph analysis.

A. **The maximum negative value of different angles** is the peak of the negative value in the different angles that the knee joint angles from the IMU system are less than the knee joint angles from the Qualisys system at the same period.

B. **The maximum positive value of different angles** is the peak of the positive value in the different angles that the knee joint angles from the IMU system are more than the knee joint angles from the Qualisys system at the same period.

C. **The average different angles** is the average of the differences in the knee joint angle measurement between the IMU system and the Qualisys system.

D. The root mean square (RMS) of the different angles is the RMS of the differences in the knee joint angle measurement between the IMU system and the Qualisys system.

4.4.2 The knee flexion test

The accurate test for the IMU measurement was evaluated during the knee flexion movement. The knee flexion test was the main movement of the shank segment. The participants were measured the knee flexion-extension movement on both legs by the knee flexion test. The line graphs of knee flexion movement (in degrees) versus time (in seconds) from the IMU system and the Qualisys system, which were evaluated on the knee flexion test with ten participants, are reported in the Appendix E and F.

Table 4.7 shows the comparison of knee flexion measurement (in degrees) between the Qualisys system and the IMU system, which were tested on the left legs during the knee flexion test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	min	Max.Neg	Max.Pos	Average	RMS	
1	123.6	-2.5	124.2	-1.5	-7.4	5.5	-1.6	3.6	0.999
2	112.3	-7.6	112.9	-8.6	-11.1	3.2	-2.4	3.9	0.997
3	106.3	-6.7	106.4	-6.7	-6.6	6.0	-0.1	2.8	0.978
4	103.6	-4.6	105.4	-7.0	-5.7	5.5	0.4	2.5	0.998
5	105.9	-5.2	109.8	-5.2	-5.4	3.1	-1.2	2.6	0.999
6	101.6	-0.3	108.7	-0.3	-8.2	3.3	-2.1	3.9	0.998
7	97.6	-11.8	93.1	-11.8	-3.0	13.4	2.7	4.7	0.998
8	113.5	-11.6	107.5	-11.6	-4.4	6.8	2.6	3.5	1.000
9	111.5	-14.7	111.7	-14.7	-8.9	4.7	-2.2	3.8	0.995
10	110.1	-14.2	117.9	-14.2	-7.9	4.4	-2.4	3.8	0.997

ROM is the range of motion.

Max means the maximum of reading angles.

Min means the minimum of reading angles.

Max. Neg is the peak of the negative values in the different angles.

Max. Pos is the peak of the positive values in the different angles.

Average is the average different angles.

RMS is the root means square of the different angles.

Table 4.8 shows the comparison of knee flexion measurement (in degrees) between the Qualisys system and the IMU system, which were tested on the right legs during the knee flexion test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	min	Max.Neg	Max.Pos	Average	RMS	
1	125.1	-0.9	122.5	-0.9	-3.6	9.3	1.3	3.4	0.999
2	126.6	0.5	124.2	0.5	-6.9	10.6	-0.2	3.6	0.999
3	82.7	-3.3	84.9	-3.3	-10.6	1.4	-2.2	3.4	0.999
4	115.5	5.7	116.3	5.7	-6.9	2.1	-2.1	3.2	0.999
5	114.5	-0.6	112.9	-0.6	-4.6	4.5	-0.3	2.3	0.999
6	106.7	-0.6	107.5	-0.6	-7.7	-0.8	-2.9	3.4	0.993
7	134.4	-4.0	133.5	-4.0	-6.1	2.0	-2.0	2.7	0.999
8	123.6	-6.2	122.2	-6.2	-7.5	4.6	-0.8	2.7	0.998
9	128.2	-4.7	124.2	-4.7	-10.4	6.3	-0.2	3.4	0.998
10	112.0	4.8	114.0	4.8	-2.8	2.7	-0.7	1.5	1.000

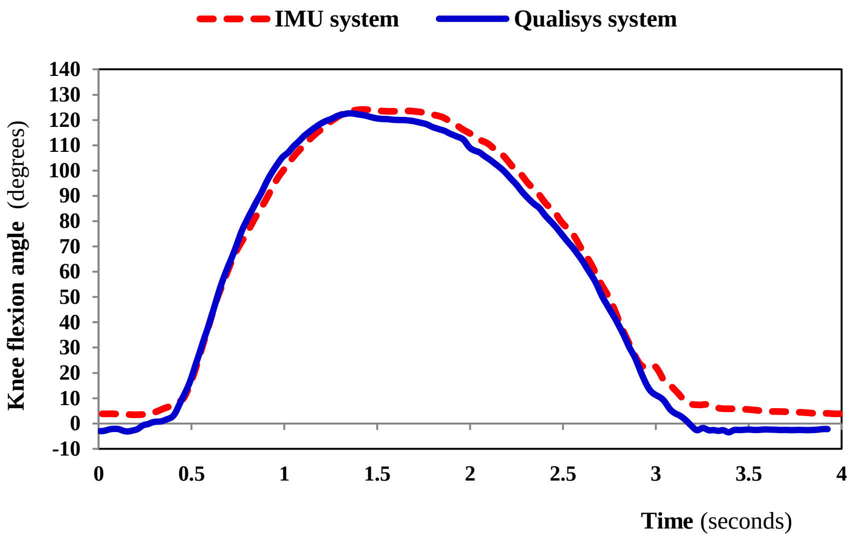


Figure 4.15 shows the line graphs of knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no.1 on the left leg).

4.4.3 The hip and knee flexion test

The accurate test for the IMU measurement was evaluated during the hip and knee flexion movement. The hip and knee flexion test was the movement of the thigh and the shank together until the bend hip 90 degrees and the bend knee 90 degrees. The participants were measured the knee flexion-extension movement on both legs by the hip and knee flexion test. The line graphs of knee flexion movement (in degrees) versus time (in seconds) from the IMU system and the Qualisys system, which were evaluated on the hip and knee flexion test with ten participants, are reported in the Appendix G and H.

Table 4.9 shows the comparison of knee flexion measurement (in degrees) between the Qualisys system and the IMU system, which were tested on the left legs during the hip and knee flexion test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	Min	Max.Neg	Max.Pos	Average	RMS	
1	123.6	-2.5	124.2	-2.5	-8.4	4.5	-3.1	4.4	0.999
2	96.4	0.4	97.8	0.4	-6.2	2.2	-2.0	3.1	0.972
3	100.3	-7.3	112.6	-7.3	-11.6	8.3	0.5	4.6	0.988
4	97.8	-4.1	106.0	-4.1	-8.7	7.0	0.1	5.4	0.990
5	97.8	-4.1	105.9	-4.1	-8.7	7.8	0.1	4.8	0.958
6	89.9	-5.4	97.2	-5.4	-7.3	1.8	-1.9	3.3	0.991
7	90.0	-2.2	96.4	-2.2	-6.4	0.7	-2.0	2.6	0.993
8	86.2	-7.5	93.4	-7.5	-8.6	4.8	-2.7	4.6	0.994
9	116.5	-11.4	126.0	-11.4	-10.0	5.6	-0.1	3.9	0.986
10	62.3	-1.0	62.0	-1.0	-1.5	4.6	2.2	3.0	0.974

Table 4.10 shows the comparison of knee flexion measurement (in degrees) between the Qualisys system and the IMU system, which were tested on the right legs during the hip and knee flexion test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	Min	Max.Neg	Max.Pos	Average	RMS	
1	98.5	2.3	98.9	2.3	-3.1	11.2	1.4	3.6	0.998
2	114.1	2.5	112.5	2.5	-1.6	8.0	2.2	3.7	0.997
3	110.3	6.2	115.8	6.2	-5.9	4.6	-0.3	2.7	0.995
4	107.4	-0.2	113.2	-0.2	-5.8	5.2	0.3	3.0	0.996
5	90.1	2.1	93.4	2.1	-3.9	4.8	0.2	2.3	0.993
6	112.0	-2.6	117.3	-2.6	-5.3	5.8	-0.1	2.7	0.996
7	114.2	-2.2	119.2	-2.2	-4.2	4.5	-0.2	1.6	0.998
8	122.4	-6.1	133.0	-6.1	-11.1	0.9	-2.3	3.9	0.995
9	125.5	-2.3	135.3	-2.3	-10.7	10.7	-0.9	3.8	0.996
10	63.1	-1.8	68.4	-1.8	-12.5	4.6	-1.7	3.9	0.998

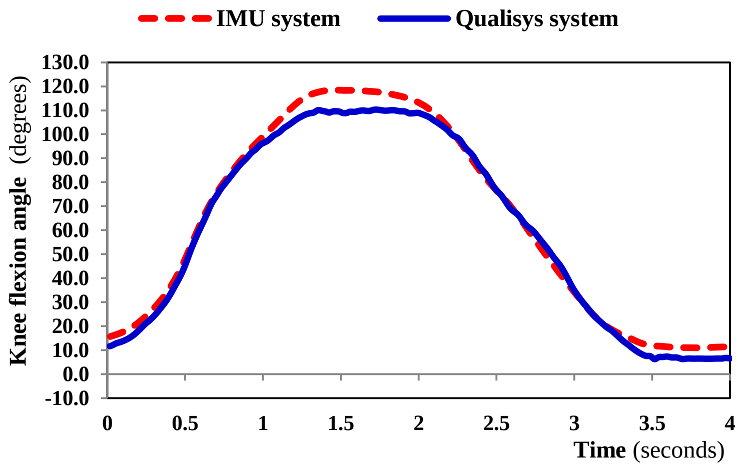


Figure 4.16 shows the line graphs of knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.4 on the right leg).

4.4.4 The forward step test

The accurate test for the IMU measurement was evaluated during the forward step movement. The forward step test was the concurrency movement towards the thigh and the shank to touch on a floor in the forward direction. The participants were measured the knee flexion-extension movement on both legs by the forward step test. The line graphs of knee flexion movement (in degrees) versus time (in seconds) from the IMU system and the Qualisys system, which were evaluated on the forward step test with ten participants, are reported in the Appendix I and J.

Table 4.11 shows the comparison of knee flexion measurement (in degrees) between the Qualisys system and the IMU system, which were tested on the left legs during the forward step test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The angle different between the two systems				Single rater ICC value
	Max	Min	Max	Min	Max.Neg	Max.Pos	Average	RMS	
1	43.9	-3.9	46.0	-3.9	-40.8	6.8	-0.4	4.5	0.959
2	31.4	-3.5	33.5	-3.5	-14.1	2.7	-0.7	3.7	0.955
3	37.8	-3.6	40.4	-3.6	-11.9	2.3	-3.5	4.9	0.978
4	24.84	-3.60	22.13	-3.60	-6.50	3.76	0.35	1.89	0.950
5	28.2	0.0	25.7	0.0	-7.0	6.1	-3.1	4.1	0.856
6	22.3	-5.9	21.6	-5.9	-7.1	3.4	-1.8	3.0	0.952
7	38.1	-2.1	44.7	-2.1	-10.6	0.2	-4.6	5.2	0.946
8	41.2	-4.4	40.9	-4.4	-12.5	4.6	-1.7	3.9	0.869
9	38.1	-2.1	44.7	-2.1	-10.6	0.2	-4.6	5.2	0.989
10	38.5	-4.7	42.1	-4.7	-10.2	2.2	-3.4	4.2	0.996

Table 4.12 shows the comparison of knee flexion measurement (in degrees) between the Qualisys system and the IMU system, which were tested on the right legs during the forward step test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	Min	Max.Neg	Max.Pos	Average	RMS	
1	38.4	1.1	31.3	1.1	-3.1	11.1	1.4	3.2	0.882
2	38.4	1.1	31.3	1.1	-3.1	11.1	1.4	3.2	0.910
3	26.2	-2.1	24.6	-2.1	-6.5	2.5	-0.9	2.5	0.938
4	30.8	-2.2	29.9	-2.2	-10.1	2.2	-2.1	3.8	0.950
5	40.2	-5.3	39.4	-5.3	-9.9	9.2	0.6	4.0	0.921

6	32.2	2.6	30.5	2.6	-7.2	9.6	0.0	3.2	0.960
7	35.2	-1.8	33.0	-1.8	-6.2	7.7	0.3	2.4	0.951
8	37.5	0.1	36.9	0.1	-10.9	3.6	-1.9	4.0	0.963
9	37.8	-0.5	37.8	-0.5	-14.8	1.0	-2.6	4.2	0.938
10	18.5	-0.5	21.1	-0.5	-8.0	6.3	-0.7	2.8	0.900

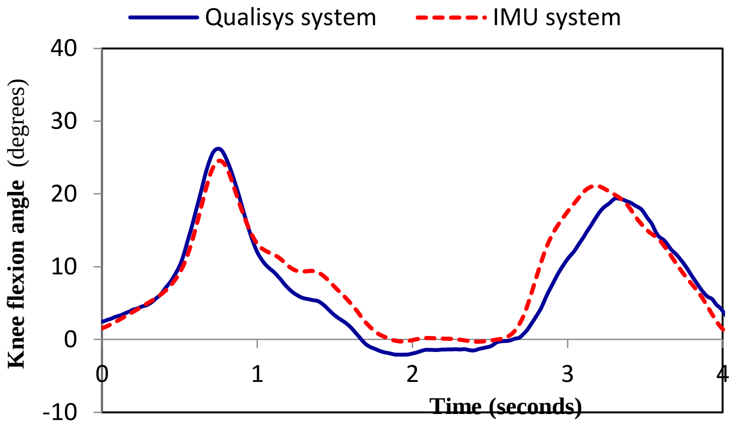


Figure 4.17 shows the line graphs of knee flexion measurement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.4 on the right leg)

4.4.5 The leg abduction test

The accurate test for the IMU measurement was evaluated during the leg abduction movement. The leg abduction test was the process to step the leg to the side. The participants were measured the knee abduction-adduction movement on both legs by the leg abduction test. The line graphs of knee abduction movement (in degrees) versus time (in seconds) from the IMU system and the Qualisys system, which were evaluated on the leg abduction test with ten participants, are reported in the Appendix K and L.

Table 4.13 shows the comparison of knee abduction measurement (in degrees) between the Qualisys system and the IMU system, which were tested on the left legs during the leg abduction test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	min	Max.Neg	Max.Pos	Average	RMS	
1	1.6	-2.1	4.5	-2.1	-3.9	2.6	0.1	1.4	0.324
2	3.8	-0.5	6.5	-0.5	-3.9	1.1	-0.7	1.4	0.580
3	5.7	-1.7	5.0	-1.7	-5.6	3.8	-0.7	1.8	0.251
4	7.9	-3.1	8.3	-3.1	-2.7	3.8	0.3	1.3	0.562
5	1.5	-0.8	5.2	-0.8	-4.9	2.0	-1.0	1.6	0.400
6	1.1	-1.4	4.5	-1.4	-4.6	1.6	-1.3	2.1	-0.049
7	6.2	-3.5	5.1	-3.5	-4.2	4.2	0.6	2.1	-0.271
8	3.8	-0.7	5.3	-0.7	-3.9	3.7	-0.3	1.4	0.441
9	4.2	-0.6	10.0	-0.6	-6.5	3.8	0.4	1.9	0.871
10	1.4	-2.6	4.5	-2.6	-3.4	2.5	-0.9	1.5	0.750

Table 4.14 shows the comparison of knee abduction measurement (in degrees) between the Qualisys system and the IMU system, which were tested on the right legs during the leg abduction test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	min	Max.Neg	Max.Pos	Average	RMS	
1	4.8	-2.6	3.9	-2.6	-3.6	2.3	-0.8	1.8	0.071
2	1.3	-2.1	4.6	-2.1	-12.5	4.6	-1.7	3.9	0.685
3	5.0	-1.1	10.8	-1.1	-5.6	4.7	0.0	1.7	0.829
4	2.7	-2.6	3.9	-2.6	-3.0	3.7	-0.5	1.8	-0.264
5	6.6	0.2	5.4	0.2	-1.5	2.8	0.2	0.9	0.826
6	1.1	-2.5	2.7	-2.5	-2.3	2.4	-0.3	1.1	0.561
7	5.0	-1.1	9.3	-1.1	-5.5	2.0	-0.4	1.7	0.547
8	5.0	0.0	6.9	1.1	-13.1	0.0	-1.6	4.0	0.868
9	1.5	-0.8	5.2	-0.8	-4.9	2.0	-1.0	1.6	0.400
10	5.7	-0.2	5.0	-0.2	-2.7	3.0	-0.8	1.8	0.417

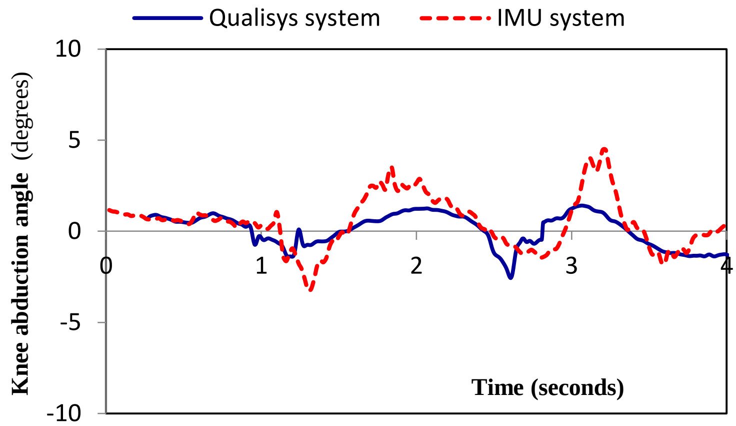


Figure 4.18 shows the line graphs of knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.10 on the left leg.)

4.4.6 The walking test along the walkway

The accurate test for the IMU measurement was evaluated during the walking test. The knee flexion movement in a gait cycle by the IMU measurement were compared with the Qualisys system. The line graphs of knee flexion movement (in degrees) versus time (in seconds) from the IMU system and the Qualisys system, s, which were evaluated on the walking test along a walkway with ten participants, are reported in the Appendix M and N.

Table 4.15 shows the comparison of knee flexion measurement in the gait cycle (in degrees) between the Qualisys system and the IMU system, which were tested on the left legs during the walking test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	Min	Max.Neg	Max.Pos	Average	RMS	
1	28.2	0.0	25.7	0.0	-7.0	6.1	-3.1	4.1	0.880
2	45.7	20.6	-0.4	25.7	0.8	0.4	-6.4	2.3	0.924

3	61.07	-6.7	57.2	-6.7	-11.2	11.7	-0.3	4.0	0.935
4	51.9	-4.4	43.4	-4.4	-7.4	11.6	0.8	3.2	0.982
5	55.0	-10.3	43.4	-10.3	-8.8	13.1	0.6	4.3	0.912
6	64.6	-3.3	59.0	-3.3	-12.8	15.5	-0.3	5.1	0.941
7	52.0	0.1	46.4	0.1	-12.3	6.8	-0.6	3.7	0.943
8	60.9	-7.7	60.9	-7.7	-15.4	11.4	-2.6	6.0	0.846
9	63.3	1.0	61.9	1.0	-12.1	5.6	-2.0	4.6	0.963
10	62.8	-0.3	60.3	-0.3	-12.9	5.1	-1.6	3.9	0.974

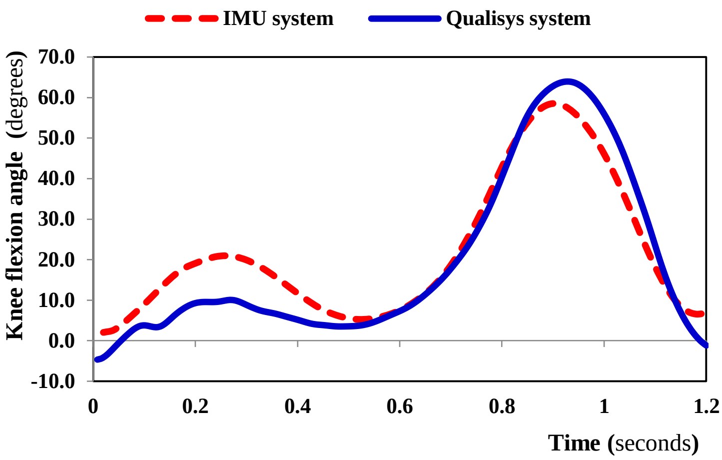


Figure 4.19 shows the line graphs of knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.8 on the left leg.)

Table 4.16 shows the comparison of knee flexion measurement in the gait cycle (in degrees) between the Qualisys system and the IMU system, which were tested on the right legs during the walking test (10 participants).

Subject	ROM from the Qualisys system		ROM from the IMU system		The different angles between the two systems				Single rater ICC value
	Max	Min	Max	min	Max.Neg	Max.Pos	Average	RMS	
1	54.6	2.9	44.8	2.9	-14.3	14.5	0.0	4.6	0.841
2	51.0	3.3	46.4	3.3	-18.9	8.3	-1.7	5.3	0.856
3	5.1	0.1	11.4	0.1	-12.9	5.5	-1.9	4.6	0.933
4	56.8	0.7	48.4	0.7	-8.5	13.9	0.4	4.2	0.909
5	58.6	-6.8	52.9	-6.8	-12.6	11.0	-0.6	4.8	0.944
6	65.7	4.7	55.0	4.7	-7.8	18.6	1.9	5.2	0.967
7	5.7	0.7	59.0	0.7	-13.1	5.2	-1.1	3.8	0.939

8	60.2	4.2	56.5	4.2	-10.0	8.5	-1.2	4.3	0.961
9	61.7	2.1	61.5	2.1	-7.7	9.1	0.1	2.8	0.985
10	62.4	2.6	64.0	2.6	-7.6	7.8	-0.3	2.7	0.975

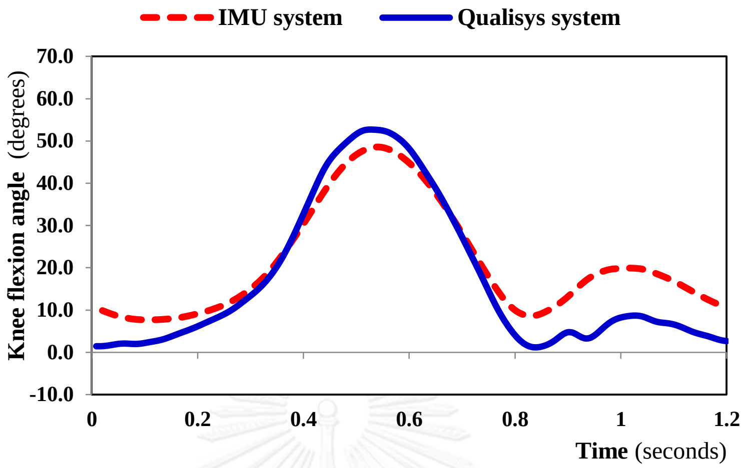


Figure 4.20 shows the line graphs of knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.8 on the right leg)

4.5 The clinical application test for the IMU system

This IMU system was tested for the clinical application. Forty elderly women with and without symptomatic knee osteoarthritis were measured the knee flexion movement in a gait cycle during the walking. Twenty elderly women with symptomatic knee osteoarthritis were the patients in the King Chulalongkorn Memorial Hospital. Also, twenty elderly women without symptomatic knee osteoarthritis, who had the age between 50 to 70 years old and had the physical characteristics (age, body mass index) similar to the elderly women with symptomatic knee osteoarthritis, were the volunteers. Moreover, this study seeks to understand the potential applications of the devices and any potential problems. The physical characteristics of participants are shown in the Tables 4.17 and 4.18.

Table 4.17 shows the physical characteristics of the twenty elderly women without symptomatic knee osteoarthritis.

No	Age (yrs.)	Weight (kg.)	Height (cm.)	BMI (kg/m^2)	Thigh Length (cm.)		Shank Length (cm.)	
					Lt. Side	Rt. Side	Lt. Side	Rt. Side
1	53	58	160	22.66	39	39	37	37
2	50	54	157	21.91	36.5	36	33.5	34
3	58	68	155	28.30	33	33	33	34
4	62	70	159	27.69	33	34	36	35
5	58	53	163	19.95	40	40.5	39	39.5
6	65	64	158	25.64	36	35	36	36.5
7	50	62	160	24.22	36	36	41	41
8	58	62	161	23.92	34	34	40	41
9	58	50	153	21.36	33	33	37	38
10	60	56	153	23.92	32	32.5	35.5	36
11	64	58	158	23.23	36	36	41	42
12	65	57	160	22.27	36	36	43	43
13	63	55	159	21.76	37	38	45	44
14	65	53	154	22.35	35	34.5	39	38
15	56	58	147	26.84	31	31	35	36.5
16	60	60	147	27.77	30	30	33	34.5
17	55	80	165	29.38	32	33	33	34
18	56	75	163	28.23	32	33	33	34
19	54	60	160	23.44	39	39	37	37
20	67	66	153	28.19	32	32.5	36	36.5
Average	**58.85**	**60.95**	**157.25**	**24.65**				
SD	**5.05**	**7.70**	**4.91**	**2.85**				

Table 4.18 shows the physical characteristics of the twenty elderly women with symptomatic knee osteoarthritis.

No	Age (yrs.)	Weight (kg.)	Height (cm.)	BMI (kg/m^2)	Thigh Length (cm.)		Shank Length (cm.)		Medical Diagnosis
					Lt. Side	Rt. Side	Lt. Side	Rt. Side	
1	67	63	160	24.61	40	39	39	41	Rt. OA
2	62	68	157	27.59	38	38	39	38	Rt. OA
3	65	62	160	24.22	36	37	36	35.5	Lt. OA

4	62	55	158	22.03	35.5	36	37	36	Rt. OA
5	61	71	158	28.44	36	36	40	41	Rt. OA
6	62	60	159	23.73	35.5	36	40	41	Rt. OA
7	67	58	149	26.12	33	32.5	36	35	Lt. OA
8	69	59	148	26.94	34	33	36	34	Lt. OA
9	63	68	154	28.67	35	33	38	36.5	Lt. OA
10	56	58	147	26.84	31	31	35	36.5	Rt. OA
11	53	64	152	27.70	33	33.5	37	37	Rt. OA
12	70	53	155	22.06	35	35	36	35	Rt. OA
13	68	56	155	23.31	36	36	36	35	Rt. OA
14	58	59	154	24.88	33	35	38	38	Rt. OA
15	64	64	154	26.99	33	35	38	38	Rt. OA
16	70	53	148	24.20	30.5	30	34	34	Lt. OA
17	67	60	149	27.03	32	31	35	34	Lt. OA
18	57	70	154	29.52	34	33	34	36	Both (Lt>Rt)
19	56	51	164	18.96	36	36	39	39	Both (Rt>Lt)
20	55	52	148	23.74	33	33	32	33	Both (Lt>Rt)
Average	**62.60**	**60.20**	**154.15**	**25.38**					
SD	**5.33**	**6.01**	**4.87**	**2.66**					

There was not the difference in the physical characteristics between two groups of participants (p value > 0.05; The Dependent Samples T test in the SPSS version 17.0 for Microsoft Windows). Figures 4.21 shows the line graphs of knee flexion movement on the left side of the twenty elderly women without symptomatic knee osteoarthritis, which were collected by the walking test. Figure 4.22 shows the line graphs of knee flexion movement on the right side of the twenty elderly women without symptomatic knee osteoarthritis, which were collected by the walking test. For a group of elderly women with symptomatic knee osteoarthritis, the line graphs of knee flexion movement in the gait cycle, which were collected by the walking test, are shown Figures 4.23 and 4.24. Figure 4.23 shows the line graphs of knee flexion movement in the symptomatic side and Figure 4.24 shows the line graphs of knee flexion movement in the non-symptomatic side. Also, all the line graphs of knee flexion movement in the gait cycle with the forty participants are reported in the Appendix O and P.

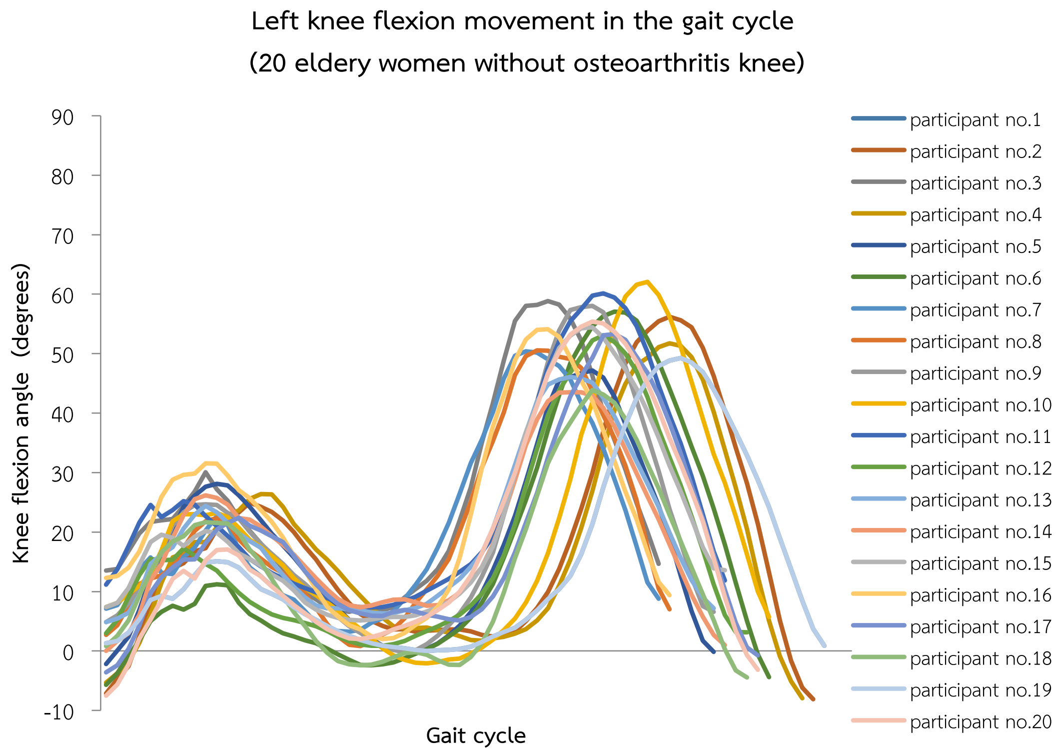


Figure 4.21 shows the line graphs of left knee flexion movement (in degrees) in the gait cycle that were tested by the twenty elderly women without symptomatic knee osteoarthritis.

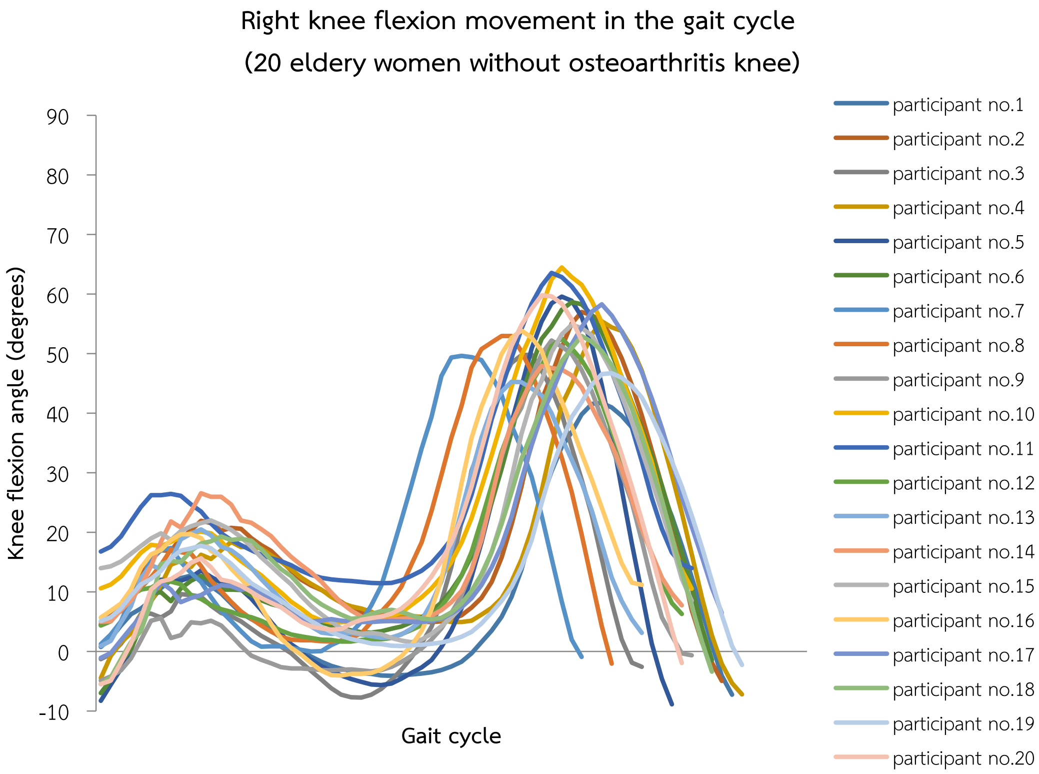


Figure 4.22 shows the line graphs of right knee flexion movement (in degrees) in the gait cycle that were tested by the twenty elderly women without symptomatic knee osteoarthritis.

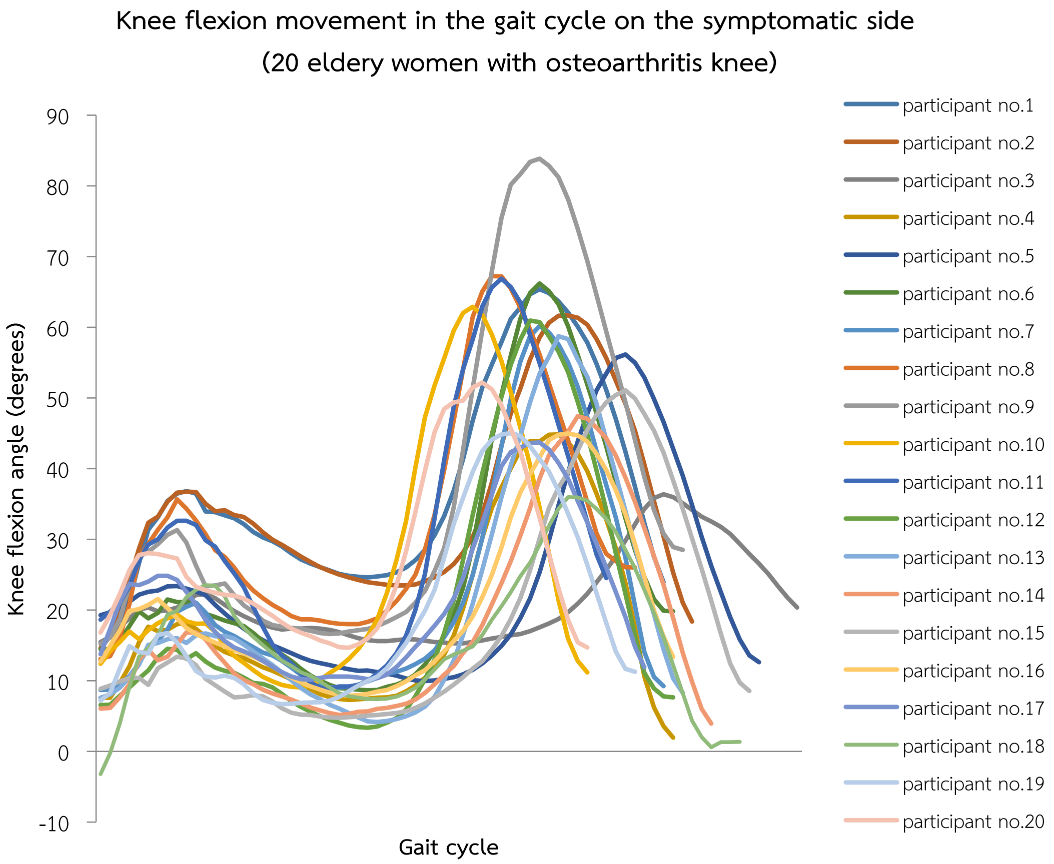


Figure 4.23 shows the line graphs of knee flexion movement (in degrees) in the gait cycle that were tested on the symptomatic side by the twenty elderly women with symptomatic knee osteoarthritis

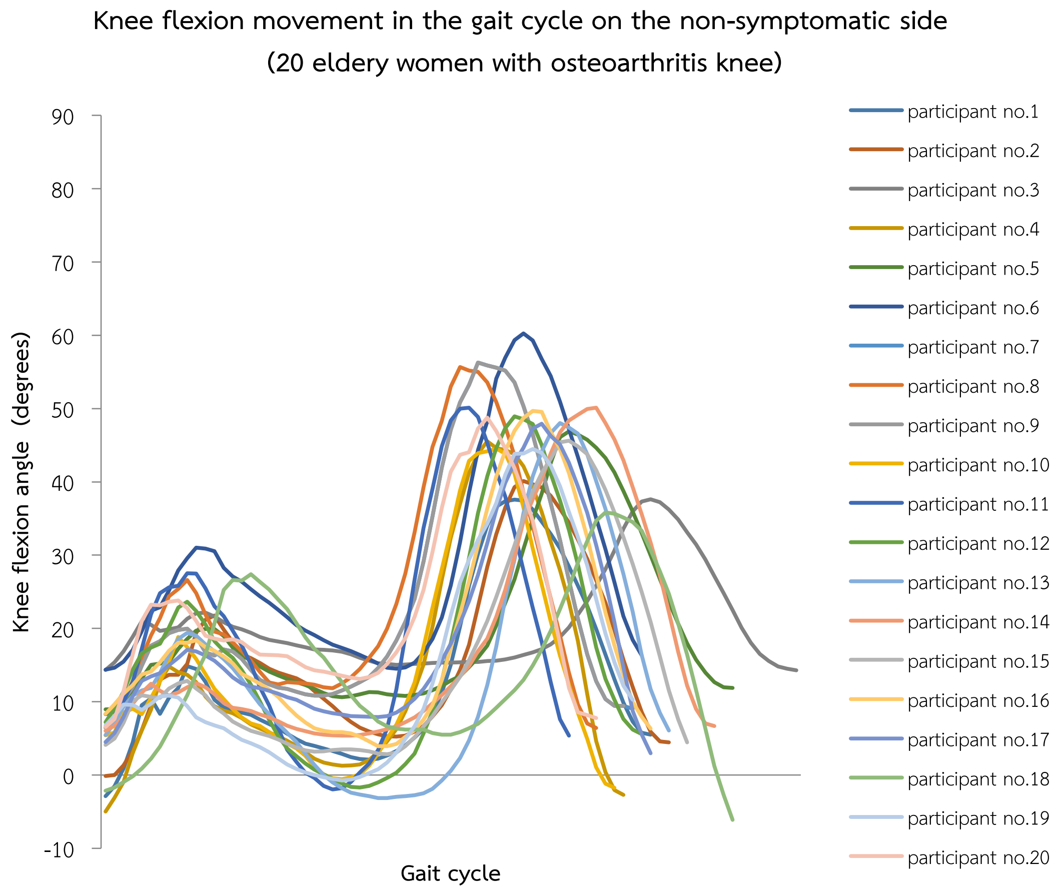


Figure 4.24 shows the line graphs of knee flexion movement (in degrees) in the gait cycle that were tested on the non-symptomatic side by the twenty elderly women with symptomatic knee osteoarthritis.

Table 4.19 shows the knee flexion measurement (in degrees) and time of motions (in seconds) in each period of the gait cycle and the total duration (in seconds) that were tested by the twenty elderly women without symptomatic knee osteoarthritis.

No.	Knee side	Kinematics of knee flexion movement in the gait cycle								Total duration (seconds)
		Period 1 FHS to MFLR		Period 2 MFLR to MES		Period 3 MES to MFS		Period 4 MFS to FHS		
		ROM (degrees)	Duration (seconds)	ROM (degrees)	Duration (seconds)	ROM (degrees)	Duration (seconds)	ROM (degrees)	Duration (seconds)	
1	Rt.	12.0	0.18	-16.8	0.4	45.9	0.42	-49.0	0.26	1.26
	Lt	13.7	0.2	-15.0	0.38	48.3	0.46	-47.4	0.26	1.30
2	Rt.	14.1	0.22	-14.9	0.46	51.7	0.28	-61.6	0.28	1.24
	Lt	29.0	0.26	-21.5	0.4	57.1	0.36	-65.7	0.28	1.30

3	**Rt.**	10.9	0.16	-17.4	0.36	57.6	0.34	-52.5	0.22	1.08
	Lt	16.5	0.18	-23.4	0.26	52.3	0.36	-45.5	0.22	1.02
4	**Rt.**	22.8	0.26	-13.4	0.46	50.5	0.28	-62.7	0.28	1.28
	Lt	31.7	0.28	-24.7	0.4	50.0	0.34	-59.7	0.24	1.26
5	**Rt.**	21.9	0.2	-19.3	0.36	65.2	0.36	-71.2	0.24	1.16
	Lt	30.3	0.2	-28.1	0.34	47.2	0.34	-47.6	0.24	1.12
6	**Rt.**	19.7	0.2	-9.5	0.34	55.5	0.4	-63.2	0.3	1.24
	Lt	16.9	0.2	-13.5	0.26	59.4	0.46	-61.5	0.28	1.20
7	**Rt.**	16.2	0.14	-17.4	0.28	49.6	0.3	-50.6	0.26	0.98
	Lt	15.5	0.2	-19.4	0.24	47.1	0.32	-41.6	0.24	1.00
8	**Rt.**	12.3	0.16	-15.0	0.3	51.3	0.36	-55.0	0.2	1.02
	Lt	19.6	0.2	-21.5	0.26	49.7	0.32	-43.5	0.24	1.02
9	**Rt.**	10.0	0.2	-8.5	0.34	55.6	0.36	-58.9	0.28	1.18
	Lt	19.8	0.18	-24.9	0.36	58.3	0.34	-51.5	0.22	1.10
10	**Rt.**	9.5	0.2	-15.3	0.26	59.7	0.46	-56.0	0.28	1.20
	Lt	15.8	0.2	-25.3	0.38	64.1	0.4	-56.9	0.24	1.22
11	**Rt.**	9.7	0.14	-15.0	0.42	52.1	0.32	-49.6	0.3	1.18
	Lt	14.1	0.14	-17.9	0.34	52.8	0.42	-50.0	0.24	1.14
12	**Rt.**	7.1	0.14	-16.1	0.44	49.4	0.34	-46.1	0.26	1.18
	Lt	10.8	0.14	-14.9	0.36	50.8	0.4	-44.5	0.28	1.18
13	**Rt.**	17.8	0.2	-16.7	0.38	41.4	0.26	-38.2	0.26	1.10
	Lt	17.8	0.18	-16.9	0.32	38.7	0.36	-37.7	0.26	1.12
14	**Rt.**	19.7	0.24	-19.2	0.38	41.8	0.28	-38.4	0.28	1.18
	Lt	22.8	0.16	-17.2	0.42	34.3	0.30	-39.7	0.26	1.14
15	**Rt.**	8.0	0.22	-20.4	0.4	53.3	0.32	-46.6	0.26	1.20
	Lt	13.9	0.2	-15.1	0.28	49.3	0.42	-40.9	0.24	1.14
16	**Rt.**	14.0	0.16	-23.7	0.32	58.0	0.36	-42.7	0.24	1.08
	Lt	19.2	0.18	-29.5	0.32	52.1	0.3	-44.7	0.22	1.02
17	**Rt.**	8.5	0.24	-5.2	0.38	51.3	0.36	-51.3	0.28	1.26
	Lt	21.7	0.28	-12.2	0.38	42.4	0.28	-36.5	0.26	1.20
18	**Rt.**	24.8	0.24	-14.0	0.42	47.6	0.3	-58.3	0.28	1.24
	Lt	21.3	0.2	-24.0	0.46	46.2	0.24	-48.3	0.28	1.18
19	**Rt.**	10.2	0.22	-14.8	0.4	45.6	0.38	-48.6	0.3	1.30
	Lt	13.6	0.2	-13.8	0.38	48.4	0.44	-45.7	0.3	1.32
20	**Rt.**	19.0	0.2	-9.5	0.28	55.0	0.4	-63.2	0.3	1.18
	Lt	21.7	0.22	-13.2	0.26	52.2	0.4	-56.4	0.32	1.20

ROM is the range of motion
FHS is the Flexion Heel Strike
MFLR is Maximum Flexion at Loading Response

MES is Maximum Extension in Stance
MFS is Maximum Flexion in Swing
Positive value (+) means the movement in flexion direction.
Negative value (-) means the movement in extension direction.

Table 4.20 shows the knee flexion measurement (in degrees) and time of motions (in seconds) in each period of the gait cycle and the total duration (in seconds) that were tested by the twenty elderly women with symptomatic knee osteoarthritis.

No.	Knee side	Kinematics of knee flexion movement in the gait cycle								Total duration (seconds)
		Period 1 FHS to MFLR		Period 2 MFLR to MES		Period 3 MES to MFS		Period 4 MFS to FHS		
		ROM (degrees)	Duration (seconds)	ROM (degrees)	Duration (seconds)	ROM (degrees)	Duration (seconds)	ROM (degrees)	Duration (seconds)	
1	sym	22.7	0.24	-11.7	0.32	38.9	0.38	-43.0	0.28	1.22
	non-sym	16.0	0.18	-12.3	0.4	34.0	0.34	-29.7	0.3	1.22
2	sym	18.4	0.18	-12.6	0.48	37.3	0.32	-40.4	0.28	1.26
	non-sym	19.8	0.24	-13.9	0.42	33.7	0.26	-34.8	0.34	1.26
3	sym	6.2	0.22	-6.5	0.44	21.1	0.56	-20.7	0.32	1.54
	non-sym	8.7	0.26	-9.3	0.58	27.2	0.46	-24.5	0.3	1.60
4	sym	9.7	0.18	-9.8	0.36	37.4	0.4	-42.4	0.26	1.20
	non-sym	16.8	0.16	-12.3	0.38	43.2	0.3	-43.1	0.32	1.16
5	sym	4.1	0.16	-13.1	0.52	42.6	0.42	-39.3	0.28	1.38
	non-sym	7.5	0.24	-6.3	0.42	34.6	0.36	-32.5	0.36	1.38
6	sym	7.0	0.14	-12.9	0.42	57.6	0.36	-46.4	0.28	1.20
	non-sym	16.6	0.2	-16.5	0.44	45.8	0.28	-43.9	0.26	1.18
7	sym	12.3	0.2	-12.0	0.3	51.1	0.42	-51.0	0.26	1.18
	non-sym	13.5	0.18	-9.1	0.28	45.4	0.36	-47.2	0.34	1.16
8	sym	13.4	0.14	-18.8	0.3	46.4	0.38	-45.1	0.24	1.06
	non-sym	20.1	0.18	-14.7	0.32	43.8	0.28	-49.3	0.3	1.08
9	sym	16.1	0.16	-14.7	0.32	67.2	0.46	-54.0	0.3	1.24
	non-sym	12.4	0.2	-8.0	0.26	45.4	0.36	-46.8	0.32	1.14
10	sym	7.0	0.16	-10.3	0.26	53.8	0.36	-51.7	0.24	1.02
	non-	13.4	0.16	-19.4	0.36	45.1	0.34	-46.3	0.26	1.12

	sym									
11	sym	14.0	0.16	-23.7	0.32	58.0	0.36	-42.4	0.22	1.06
	non-sym	19.2	0.18	-29.5	0.32	52.1	0.3	-44.7	0.22	1.02
12	sym	8.0	0.14	-11.2	0.42	57.4	0.34	-53.1	0.3	1.20
	non-sym	16.4	0.18	-25.3	0.38	50.7	0.34	-43.4	0.28	1.18
13	sym	9.1	0.22	-12.6	0.36	54.6	0.38	-50.5	0.26	1.22
	non-sym	14.0	0.18	-22.6	0.42	50.6	0.42	-42.5	0.24	1.26
14	sym	10.8	0.2	-11.7	0.3	42.3	0.5	-43.5	0.28	1.28
	non-sym	6.5	0.2	-7.2	0.32	44.6	0.54	-43.3	0.28	1.34
15	sym	4.5	0.16	-8.6	0.34	46.3	0.6	-42.5	0.26	1.36
	non-sym	8.7	0.18	-9.9	0.42	42.7	0.42	-41.2	0.26	1.28
16	sym	8.9	0.12	-13.7	0.4	37.1	0.46	-31.6	0.22	1.20
	non-sym	10.1	0.2	-14.5	0.4	45.8	0.34	-43.4	0.26	1.20
17	sym	11.1	0.12	-14.7	0.44	33.6	0.36	-31.8	0.22	1.14
	non-sym	12.6	0.18	-9.2	0.42	40.0	0.36	-45.0	0.24	1.20
18	sym	26.7	0.22	-16.2	0.36	28.6	0.4	-35.4	0.3	1.28
	non-sym	29.6	0.32	-21.9	0.42	30.3	0.36	-41.9	0.28	1.38
19	sym	9.6	0.14	-8.2	0.38	36.5	0.34	-33.8	0.26	1.12
	non-sym	4.1	0.14	-11.5	0.4	45.1	0.4	-34.2	0.22	1.16
20	sym	8.3	0.12	-12.4	0.4	33.8	0.3	-31.9	0.22	1.04
	non-sym	17.1	0.14	-10.3	0.44	33.6	0.28	-35.9	0.24	1.10

Sym is the symptomatic side of knee osteoarthritis.

Non- sym is the non-symptomatic side of knee osteoarthritis.

Table 4.21 shows the comparison of the range of knee flexion movement (in degrees), time of motions (in seconds) and the total duration of the gait cycle between the left knee and the right knee, which were tested by the twenty elderly women without symptomatic knee osteoarthritis.

Parameters	Periods of a gait cycle	Left side ($\bar{X} \pm SD$)	Right side ($\bar{X} \pm SD$)	Sig. (2-tailed) (α = 0.05)
Range of knee angular motion (in degrees)	1st period (FHS to MFLR)	19.29 ± 5.77	14.41 ± 5.43	0.001*
	2nd period (MFLR to MES)	-19.60 ± 5.35	-15.11 ± 4.37	0.01*
	3rd period (MES to MFS)	50.04 ± 6.87	51.91 ± 5.92	0.147
	4th period (MFS to FHS)	-48.27 ± 8.12	-53.19 ± 8.78	0.004*
Time of motions (in seconds)	1st period (FHS to MFLR)	0.20 ± 0.04	0.20 ± 0.04	0.585
	2nd period (MFLR to MES)	0.34 ± 0.06	0.37 ± 0.06	0.033*
	3rd period (MES to MFS)	0.36 ± 0.06	0.34 ± ± 0.05	0.166
	4th period (MFS to FHS)	0.26 ± 0.03	0.27 ± 0.03	0.049*
Total duration in the gait cycle		1.16 ± 0.10	1.18 ± 0.09	0.064

Positive value (+) means the knee movement in flexion direction.
Negative value (-) means the knee movement in extension direction
* Significant difference p< 0.05

From the Table 4.21, the result found the range of knee flexion movement had the significant difference in the 1st, 2nd, and 4th periods (p = 0.001, 0.01 and 0.004, respectively). The time of motion had the significant difference in 2nd and 4th periods (p = 0.033, 0.049) (The Paired Samples T test in the SPSS version 17.0 for Microsoft Windows).

Table 4.22 shows the comparison of the range of knee flexion movement (in degrees), time of motions (in seconds) and the total duration of the gait cycle between the symptomatic side and the non-symptomatic side, which were tested by the twenty elderly women with symptomatic knee osteoarthritis.

Parameters	Periods of a gait cycle	Symptomatic side ($\bar{X} \pm SD$)	Non-symptomatic side ($\bar{X} \pm SD$)	Sig. (2-tailed) (α = 0.05)
Range of knee angular motion (in degrees)	1st period (FHS to MFLR)	11.40 ± 5.85	14.16 ± 5.84	0.018*
	2nd period (MFLR to MES)	-12.77 ± 3.80	-14.19 ± 6.46	0.282
	3rd period (MES to MFS)	44.08 ± 11.62	41.69 ± 7.08	0.174
	4th period (MFS to FHS)	-41.53 ± 8.68	-40.68 ± 6.54	0.592

Time of motions (in seconds)	1st period (FHS to MFLR)	0.17 ± 0.04	0.20 ± 0.04	0.012*
	2nd period (MFLR to MES)	0.37 ± 0.07	0.39 ± 0.07	0.189
	3rd period (MES to MFS)	0.41 ± 0.08	0.36 ± 0.07	0.001*
	4th period (MFS to FHS)	0.26 ± 0.03	0.28 ± 0.04	0.05*
Total duration in the gait cycle		1.21 ± 0.13	1.22 ± 0.13	0.378

From the Table 4.22, the result found the range of knee flexion movement had the significant difference in the 1st periods of the gait cycle ($p = 0.018$). The time of motion had the significant difference in 1st, 3rd, and 4th periods of the gait cycle ($p = 0.012, 0.001$ and 0.05, respectively) (The Paired Samples T test in the SPSS version 17.0 for Microsoft Windows).

Table 4.23 shows the significant differences on the comparison between the twenty elderly women with symptomatic knee osteoarthritis (on the symptomatic sides) and the twenty elderly women without symptomatic knee osteoarthritis (on both sides).

Symptomatic side in 20 elderly women with symptomatic knee osteoarthritis.	20 elderly women without symptomatic knee osteoarthritis.							
	Left sides (20 sides)				Right side (20 side)			
	1st period	2nd Period	3rd period	4th period	1st period	2nd Period	3rd period	4th period
Range of knee motions	0.001*	0.001*	0.056	0.015*	0.100	0.079	0.011*	0.001*
Time of motions	0.013*	0.129	0.065	0.384	0.026*	0.882	0.006*	0.661
Total duration	0.157				0.338			

Table 4.24 shows the significant differences on the comparison between the twenty elderly women with symptomatic knee osteoarthritis (on the non-symptomatic sides) and the twenty elderly women without symptomatic knee osteoarthritis (on both sides).

Non-symptomatic side in 20 elderly women with symptomatic knee osteoarthritis.	**20 elderly women without symptomatic knee osteoarthritis.**							
	Left sides (20 sides)				Right side (20 side)			
	1st period	2nd Period	3rd period	4th period	1st period	2nd Period	3rd period	4th period
Range of knee motions	0.008*	0.006*	0.001*	0.002*	0.887	0.601	0.001*	0.001*
Time of motions	0.696	0.022*	0.698	0.028*	0.937	0.310	0.572	0.242
Total duration	0.095				0.215			

CHAPTER 5

DISCUSSION

This study purposed to develop the IMU devices via the wireless connection to be used for the knee joint angle measurement. This study was separated into three parts. The first part was the development process of the IMU devices and the software. The second part was the accurate test for the IMU measurement (in degrees). The third part was the clinical application test.

5.1 The developed IMU devices

The IMU sensors (9-Degrees of Freedom - Razor IMU - AHRS compatible) were used to develop these IMU devices because they could apply to measure the angles, with obvious benefits, such as low cost (less than 1,600 USD for this IMU system) and ambulatory device (estimate 120 grams per unit and without cable). In previous studies, the researchers used only the accelerometers or the gyroscopes to estimate the angles (Luinge HJ & Veltink PH, 2004; Morris JRW, 1973; Tong K & Granat MH, 1999). The estimated angles by the accelerometer might find an error from the signal fluctuations. The estimated angles by the gyroscope that was integrated the angular velocity also found the distortion. The distortion caused the offset or any drift in the data (Aminian K & B., 2004; Willemsen ATM et al., 1990). Nowadays, the IMU sensor is a notable sensor to measure the kinematics of movement (Chardonnens J et al., 2013; Chardonnens J et al., 2012; Cooper G et al., 2009; Dejnabadi H et al., 2005; Favre J et al., 2009; Favre J et al., 2008; Luinge HJ & Veltink PH, 2005; Luinge HJ et al., 1999; O'Donovan KJ et al., 2007; Roetenberg D et al., 2009;

Rouhani H et al., 2011; Takeda R, Tadano S, Natorigawa, et al., 2009; Takeda R, Tadano S, Todoh M, et al., 2009).

Previous studies employed the several angle calculation methods to estimate the angles from the outputs of accelerometer and gyroscope. There were the Quaternion-based fusion method (Chardonnens J et al., 2013; Chardonnens J et al., 2012; Favre J et al., 2008; Favre J, Jolles BM, Siegris O, & Aminian K, 2006; Favre J, Luthi F, et al., 2006; Rouhani H et al., 2011), the Kalman filter and the Euler angle method (Cooper G et al., 2009; Luinge HJ & Veltink PH, 2005), the estimated orientation of segments using the gravitational acceleration (Takeda R, Tadano S, Natorigawa, et al., 2009; Takeda R, Tadano S, Todoh M, et al., 2009), and the DCM method (Taylor T et al., 2013). Most studies (Cooper G et al., 2009; Luinge HJ & Veltink PH, 2005; Takeda R, Tadano S, Natorigawa, et al., 2009; Takeda R, Tadano S, Todoh M, et al., 2009) reported only the knee flexion-extension movement, although, some studies (Takeda R, Tadano S, Natorigawa, et al., 2009; Takeda R, Tadano S, Todoh M, et al., 2009) reported the knee abduction-adduction movement. However, they also had some restriction on the estimated angles on external rotation-internal rotation movement. Until the studies by Favre and co-researchers (Favre J et al., 2008; Favre J, Jolles BM, et al., 2006; Favre J, Luthi F, et al., 2006), they suggested the Quaternion-based fusion method to estimate the angles in three planes. It also did not have a Gimbals lock (pitch $<\theta>$ to close at 90 degrees $\tan\theta \rightarrow \infty$) on the angle calculation, however, it was too hard calculation method. The DCM algorithm was a method to apply for the estimated angles in three planes without a Gimbals lock (กฤษฎา แสงเพ็ชร์ส่อง, 2549). So that, the DCM algorithm was used for the angle calculation in this study. It also was recommended to use with these IMU sensors (9 Degrees of Freedom - Razor IMU - AHRS compatible). The amended Arduino code that had the process of angle calculation by DCM algorithm was burned into the IMU sensors. According to this purpose, the device for measuring the knee movement did not restrict the leg movement and without space limitation. Therefore, the wireless connection by the eight sets of XBee Pro 50mW Wire Antenna were added to these developed IMU devices. The developed IMU devices were set the sampling rate of 50 Hz. I created the software, which is called the “Knee Angle Recorder” software, to cooperate with the four IMU devices. This software works to receive and display the angles from the IMU measurement. Consequently, the angles were displayed in the line graphs of changing angles (in degrees) versus time (in seconds). Moreover, this software had the command to check the completion data before the calculation of knee joint angles. The knee joint angles were calculated from the thigh’s angles and the shank’s angles. The highlights of this IMU system were the differences from the previous studies as follows. These IMU devices developed by the 4 sets of 9-Degrees of Freedom - Razor IMU - AHRS compatible (a triple-axis accelerometer, a triple-axis gyroscope, a triple-axis magnetometer) and added the wireless connection by Xbee modules. Thus, the IMU sensors could give the nine parameters to calculate the angles by the DCM algorithm. Also, this system could reported immediately the angles while the leg movements into the line graphs of changing angles (in degrees) versus time (in seconds). Moreover, I developed the other software that is called the “Knee Angle Analyzer” software to use for the kinematic analysis and the reporting data by the IMU measurement. This software was a benefit for therapists to assess specifically on each period of movement. It could report the measuring angles (in degrees) and the time of motions (in seconds) at the start point and the end point, the total movement (in degrees), the duration (in seconds), the angular velocity (in degrees/second), and the angular acceleration (in degrees/second^2) upon the selective area of movement graph .

5.2 The accurate test for the IMU measurement

According to the standards for a developmental measuring device, the accurate data from the measurement are the important consideration. The angles from IMU measurement have the six positions of decimal, however, they also have the fluctuation of values in the third to sixth positions of decimal. Thus, I rounded a number to one decimal in the IMU measurements.

Firstly, the four IMU devices were evaluated the inclined sensors in the acrylic box after the complete development because the inclination of IMU sensor had the influence for the angle calculation. The results showed the steady measuring angles from the IMU measurements on the sagittal and the coronal planes. All developed IMU devices had the inclination position from the zero line to be less than ±1 degrees.

Secondly, the accurate data onto the IMU measurements (in degrees) were tested for the static and dynamic conditions and also were tested for the sagittal and the coronal planes. The four sets of developed IMU devices were separated into two pairs. The first pair was the IMU devices number 1 and 2 that was used to measure the angles on the right leg. The second pair was the IMU devices number 3 and 4 that was used to measure the angles on the left leg. The testing in the static condition were reported in the RMS of different angles and the single rater of ICC values. The first pair of IMU devices had the RMS of different angles, which compared with the reference angles in the sagittal plane, to be 1.61 degrees. The RMS of different angles was 1.26 degrees in the coronal plane. The second pair of IMU devices had the RMS of different angles to be 0.73 degrees and 1.63 degrees, respectively. The single rater ICC values were to 0.996 to 0.999. These ICC values referred to the good correlation on the measuring angles between the developed IMU devices and the reference angles.

The angle positions in the sagittal plane were -20, -10, 0, 10, 20, 30, 40, 50, 60, 70, 80, and 90 degrees. The angle positions in the coronal plane were -40, -30, -20, -10, 0, 10, 20, 30, and 40 degrees. These angle positions were selected for the comparison because they covered the range of knee movement in this test. The testing in the horizontal plane could not evaluate in the static condition because these developed IMU devices did not report the accurate data on this plane. What are the causes? The gyroscope output were absolute “0” degrees per second because of the static placement. The gyroscope is used to measure the changing angular velocity of object. So, the IMU devices with the static position did not have any changing angular velocity. The magnetic field magnitude from magnetometer that were used to calculate the heading of sensor were not estimate accurately the angle positions. Therefore, the estimated angles in the static position from the IMU devices (the sagittal plane and the coronal plane) were mainly from the accelerometer. However, the acceleration outputs that were used to estimate the angles in the static position were the vector of gravitational acceleration outputs. Hence, the testing in horizontal plane did not report by the IMU measurement.

By the accurate test in the dynamic condition, the measuring angles were compared between the IMU system and the Qualisys system. The testing in the first pair of IMU measurement on both sagittal and coronal planes showed the RMS of different angles to be 2.24 degrees and the single rater ICC values were in the range from 0.986 to 0.998. For the second pair of IMU devices, the RMS of different angles was 2.54 degrees and the single rater ICC values were in the range from 0.993 to 0.998. The results indicated the good correlation onto angle measurement between the Qualisys system and the IMU system. For the horizontal plane, the line graph in the Figure 4.13 revealed the low accuracy during the testing as a result of the restriction in this study. According to the previous mention, the angular outputs from the calculation by IMU device acquired from the outputs of accelerometer, gyroscope, and magnetometer. The measuring angles in earliest stage of movement likely showed a good relationship between the IMU system and the Qualisys system. After that, the measuring angles from the IMU system revealed the divergence from the measurement by the Qualisys system. Because the transitional acceleration outputs from accelerometer were decrease in the late stage of movement and the gravitational acceleration outputs did not the effect of inclined IMU device. Also, the changed angular velocity from the gyroscope were decrease in the late stage of movement and then gradually returned to the steady state. Besides, the magnetometer outputs were not estimate accurately the angle positions. Therefore, the measuring angles between the two systems were divergence in the horizontal plane movement.

Thirdly, the IMU devices were tested for the accurate data onto IMU measurements during the knee functional movements and the walking test. The knee joint angle movements using the IMU measurement were compared to the measuring angles by the Qualisys system. The four functional movement tests were as follows. Firstly, the knee flexion test, the shank moved backward until 90 degrees of knee flexion during the standing. I needed to evaluate the knee flexion-extension movement when moved only the shank segment. Secondly, the hip and knee flexion test was the movement of the thigh and the shank together until the bend hip 90 degrees and bend knee 90 degrees. The knee flexion-extension movement were evaluated by the movement of thigh segment and shank segment together. Thirdly, the forward step movement was the concurrency movement towards the thigh and the shank to touch on a floor in the forward direction. The knee flexion-extension movement were evaluated in the condition that had the effects on the extrinsic force (the ground reaction force, etc.). Fourthly, the leg abduction test was the process to step the leg to the side. I needed to evaluate the knee abduction-adduction movement. After the finished movement target, the leg will move back to the starting point. Finally, the walking test, the participants were asked to walk with normal speed along the walkway.

The results from the IMU measurement revealed the RMS of different angles and the single rater ICC values from the measurement by the Qualisys system to be as follows. The RMS of different angles by the knee flexion test was 4.7 degrees and the single rater ICC values were in the range of 0.997 to 1.000. The RMS of different angles by the hip and knee flexion test were 5.4 degrees and the single rater ICC values were in the range of 0.972 to 0.999. The RMS of different angles by the forward step test was 5.2 degrees and the single rater ICC values were in the range of 0.856 to 0.996. The RMS of different angles by the leg abduction test were 4.0 degrees and the single rater ICC values revealed the no correlation between the two systems. The RMS of different angles in a gait cycle by the walking test were 6 degrees and ICC values were in the range of 0.841 to 0.982.

In the previous studies, Favre J and Co-researchers (Favre J et al., 2008) tested the accuracy of IMU measurement by the walking with 30 meters. They found the average root mean square errors (RMSE) to be less than 2 degrees in three planes of motion. Dejnabadi H, Jolles BM and Aminian K (Dejnabadi H et al., 2005) evaluated the accuracy of their IMU measurement during the walking on the treadmill with vary speeds. They found the very small errors (RMS = 1.3, mean = 0.2, SD = 1.1 degrees.) and excellent correlation coefficients (0.997), when compared the measuring angles between their IMU system and the ultrasound-based motion measurement system. Moreover, the other researchers also found the good accuracy of their IMU measurement. Their testing revealed the RMS in the range of 0.2 to 7 degrees and the good correlation between their IMU system and the reference system (Cooper G et al., 2009; Picerno P et al., 2008; Takeda R, Tadano S, Natorigawa, et al., 2009). However, the results in this study were too hard comparison with the previous studies because of the different factors, such as, the types of IMU sensors, the sampling rates, the standard reference system, and the methods of testing.

In this study, the two systems had the different sampling rates. The Qualisys system had the samplings of 120 Hz, but the IMU system had the samplings of 50 Hz. Besides, the two systems could not set the simultaneous starting record. Therefore, I solved this problem with an adjustment of starting offset. I exported measuring angles from the two systems into the Microsoft Excel for Microsoft Windows and also specified the starting point of the movement (Fig. 5.1). The RMS of different angles and the single rater ICC values were got from the calculation at the same recording time.

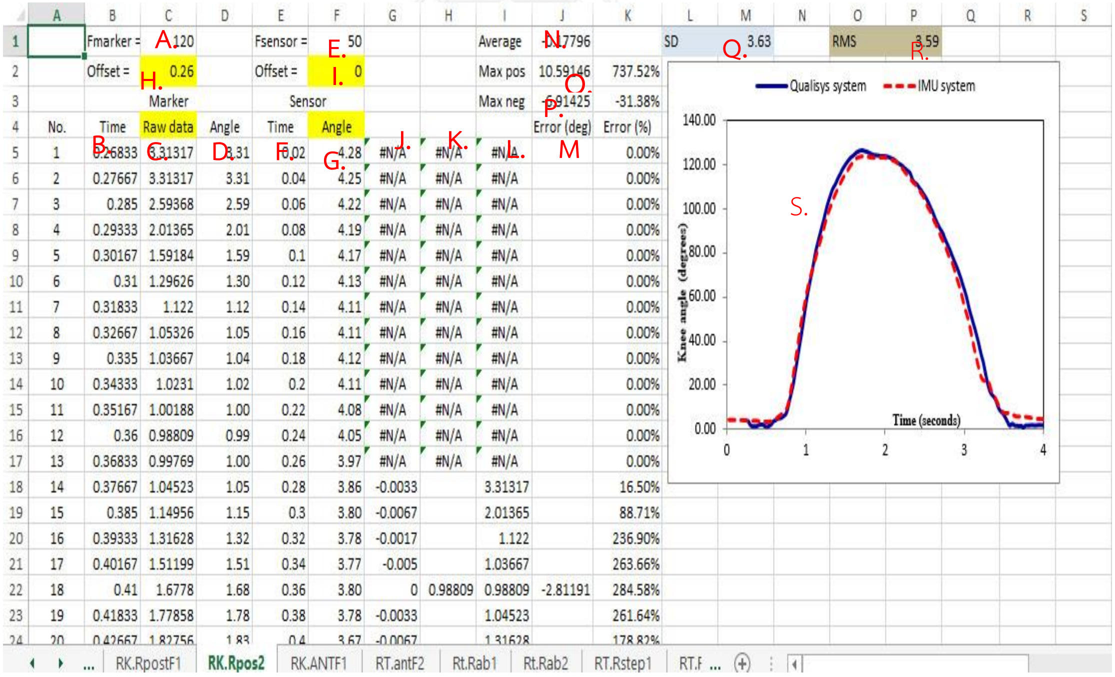


Figure 5.1 shows a page on the Microsoft Excel for Microsoft Windows that was used to compare the knee angular motion data between the Qualisys system and the IMU system.

A. is a sampling rate of the Qualisys system (120 Hz).

B. is the time of samplings from the Qualisys system (in seconds). A data are 0.008333 second.

C. and D. are the measuring angles by the Qualisys system.

E. is a sampling rate of the IMU system (50 Hz).

F. is the time of samplings from the IMU system (in seconds). A data are 0.02 second.

G. is the measuring angles by the IMU system.

H. is the adjusted time offset from the Qualisys system (in the column B).

I. is the adjusted time offset from the IMU system (in the column F).

J. is the function "VLOOKUP(E18,$B$5:$D$876,1)-E18" to find the position of the close estimated time between the Qualisys system and IMU system. Example, the point of time on the IMU system in column E18 to compare with the closest point of time from the Qualisys system in the column B2. And then, the close point of time from the Qualisys system in column B2 is subtracted with the point of time on the IMU system in the column E18. After that, the difference value is reported in the column J18.

K. is the function IF(G5=0,VLOOKUP(E5,$B$5:$D$876,3),""). The "IF" function is to report the measuring angles by the Qualisys in column D at the closest point of time (D6) when the difference value in E5 was to zero.

L is the function "VLOOKUP(E5,$B$5:$D$876,3)" to find the position of the close estimated time between the Qualisys system and IMU system.

M. is the different angles between column K (Angles from the Qualisys system) and column G (Angles from the IMU system) at the same point of time.

N. is the average different angles in the column J.

O. is the peak positive values of different angles in the column J.

P. is the peak negative values of different angles in the column J.

Q. is the standard deviation of different angles in the column J.

R. is the root mean square (RMS) of different angles in the column J.

S. is the line graphs of knee joint angle movement (in degrees) versus time (in seconds) between the Qualisys system and the IMU system

The factors caused the different angles of knee joint angle measurement between the Qualisys system and the IMU system to be as follows. The first factor was the acquirement of measuring angles by the IMU measurements, which were calculated from the outputs from a triple-axis accelerometer, a triple-axis gyroscope, a triple-axis magnetometer. Therefore, the force was the main effect on the outputs from the IMU measurements. The force consisted of the intrinsic force (muscle force, resistance of tissue, etc.), which was to generate or to stop the movement, and the extrinsic force (ground reaction force, friction, etc.). For the example, the knee joint angles occurred on the measurement by the forward step test and the walking test. The area of line graphs at the foot to contact a floor or the area of line graphs at the turning point of movement, they were increased the different angles on the knee joint angle measurement. It might be the effects from the forces (both the intrinsic force and the extrinsic force). Although, this equation that was used to calculate the outputs from the accelerometer and the gyroscope also had an elimination of noises or errors. Besides, the knee joint angles by the IMU measurement were calculated by the difference of segments' angle. In contrast, the knee joint angles by the Qualysis system acquired from the detection of reflective marker's position and to calculate the angles by the relative angle method.

The second factor was the placement position of the IMU devices. Some previous studies placed the IMU devices to close the distal end of the segment, example the Cooper et. al. 's study (Cooper G et al., 2009). These placement positions of IMU devices were attached to the anterior mid-thigh and anterior mid-shank on the both legs by the elastic band with Velcro strap as same the placement positions by Favre et. al.'s study (Favre J et al., 2008). I selected these placement positions because I did not need the IMU placement to interfere to the standard reflective marker's positions by the Qualysis system. However, the placement area had some effects to the knee abduction-adduction movement because the anterior mid-shank was likely to the prominence area. It made the unstable attachment for the IMU devices, although, I applied the elastic band with Velcro strap for the fixation. Moreover, the knee abduction-adduction movement were very short range and also had the effects of forces. All of them made the high differences on the RMS of different angles and to be no correlation of measuring angles between the two systems during the leg abduction test.

However, this IMU system is a good method to measure the movement pattern of knee flexion-extension movement that is the essential movement towards the knee joint. Also, the IMU system can report immediately the quantitative knee joint angle measurement that is a benefit for therapists to interpret the knee kinematics.

5.3 The clinical application of IMU system

The main purpose was to understand the potential applications of IMU measurement and potential problems during the knee joint angle measurement. These participants were a group of elderly women without symptomatic knee osteoarthritis and a group of elderly women with symptomatic knee osteoarthritis. The knee osteoarthritis pathology mainly caused the knee pain and the abnormal knee movement in the elderly persons. The IMU system were used to report the pattern of knee flexion-extension movement and report the knee kinematic variables on a gait cycle.

The results from the group of elderly women without symptomatic knee osteoarthritis found the range of knee flexion movement and the time of motion at the same periods to be the significant differences between the left legs and the right legs (the range of knee flexion movement at 1^{st}, 2^{nd} and 4^{th} periods of the gait cycle <p = 0.001, 0.01 and 0.004> and the time of motion at 2^{nd} and 4^{th} periods of the gait cycle <p = 0.033 and p = 0.049>). The left legs were the large range of knee flexion movement at 1^{st} and 2^{nd} periods of the gait cycle and the 3^{rd} and 4^{th} periods of the gait cycle had the large range of knee flexion movement in the right legs. Form the time of motions, I found that the right legs used the long time more than the left legs at the 2^{nd} period of the gait cycle. In the 3^{rd} period of the gait cycle, the left legs used the long time more than the right legs. The results reveal the pattern of knee flexion movement and body balance keeping during the walking. The short range of knee flexion movement and the long time of motion at 2^{nd} period of the gait cycle referred to the main leg to keep the body stability.

While the testing for a group of elderly women with symptomatic knee osteoarthritis, the results revealed the range of knee flexion movement to be shorter than the group of elderly women without symptomatic knee osteoarthritis. Also, the range of knee flexion movement in the symptomatic sides had the shorter than the non-symptomatic sides at the 1^{st} and 2^{nd} periods of the gait cycle. The time of motions in the symptomatic sides also had the shorter than the non-symptomatic at 1^{st} and 2^{nd} periods of the gait cycle. The time of motions in the symptomatic sides was the long at the 3^{rd} period of the gait cycle and was the short at the 4^{th} periods of the gait cycle when compared with the non-symptomatic sides. From the results, the symptomatic sides kept to move the short range of knee flexion movement and to use the short time of motion at the 1^{st} periods of the gait cycle. They referred the patients with the knee osteoarthritis to avoid the contact floor with the pain or severe sides. Moreover, the elderly women with symptomatic knee osteoarthritis preferred to keep the short range of knee flexion movement and to move slowly on the knee movement during the walking. They was the advantage to keep the stability of knee movement and helped to reduce the angular momentum that impacted to the painful sides.

The potential problem was the signal disturbance from a machine with magnetic radiation such as short-wave diathermy, micro-wave diathermy that made to the uncompleted measuring angles at any given time.

5.4 The notices in this study

The developed IMU devices always calibrate automatically when the opening sensors. A stationary placing of IMU devices on the flat floor and the heading sensors to point at the north must do during the opening sensors.

5.5 The Limitations in this study

- Firstly, these IMU devices had the restriction to measure the angles in the horizontal plane.
- Secondly, A placing of sensors near an electromagnetic device should be avoided because the signal wireless outputs were disturbed by it.

- Third, the heading sensor point to the north while testing should be avoided that caused an error on the estimated angles. So that, I avoided having the right-hand side of the participants pointing to the north while the tests.

5.6 The benefits of this study

The developed IMU devices, the "Knee Angle Recorder" software and the "Knee Angle Analyzer" software were a new method to measure the knee flexion-extension movement pattern and to report immediately the measuring angles. These IMU system were inexpensive, ambulatory device, and usage for the knee flexion measurement with an outdoor laboratory.

Table 5.1 shows the comparison of the qualifications among the IMU system, the conventional method, and the three-dimensional camera system.

Parameters	Conventional method	This IMU system	Three-dimensional camera system
Price	Very low price	Inexpensiveness (≈ 1,600 USD)	Expensiveness (> 320,000 USD)
Required skill / experience	Yes	A bit	Yes
Type of data output	Most qualitative data	Quantitative data	Quantitative data
Real situation usage	Can	Can	Most indoor laboratory
Accurate data	Up to skilled examiner (most low accuracy)	Moderate accuracy	High accuracy

Table 5.2 shows the comparison of the qualifications among the IMU system, the video recorder method, and the electro- goniometer.

Parameter	Video Record	This IMU system	Electro goniometer
Price	Cheap for a video camera but the software for the data analysis is expensiveness	Inexpensiveness (≈1,600 USD)	Expensiveness (≈ 32,000 USD) and the accessory deceives (> 1,600 baht per unit)
Friendly user	No. It required the skills to data recorder and to analysis the	A bit	A bit

	movement		
Sampling rates	25 – 30 Hz (up to video camera)	**50 Hz**	25 – 50 Hz
Interpretation results from the devices	Required the skill to analysis	**Easy**	Easy
Plane of movement	One plane	**Available for the flexion-extension measurement and the abduction-adduction measurement**	One or two Up to accessory device
Accurate data	Up to skilled examiner	**Moderate accuracy**	-

5.7 The plan for the further development

I plan to increase the rate of data samplings in the IMU measurement. Also, I plan to add the video recorder to the IMU system.

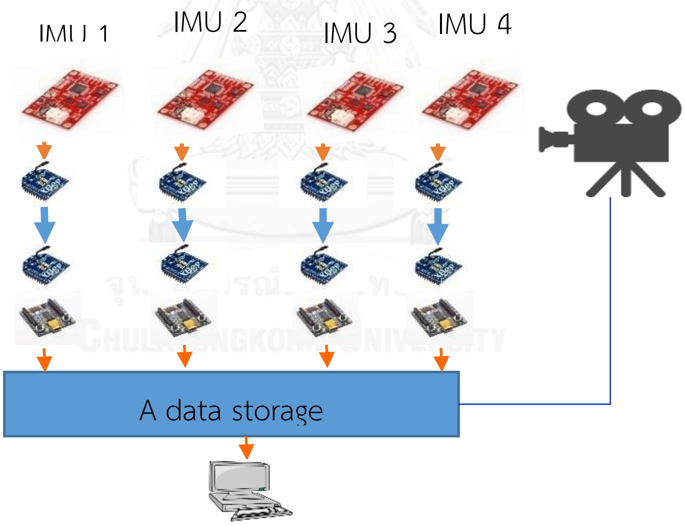


Figure 5.2 shows my idea plan to improve the IMU devices

CHAPTER 6

CONCLUSION

This IMU system was an ongoing development project, which consists of the four sets of IMU devices, the “Knee Angle Recorder” software, and the “Knee Angle Analyzer” software. The IMU devices were developed from the 9 Degrees of Freedom - Razor IMU - AHRS compatible that consist of a triple-axis accelerometer, a triple-axis gyroscope, a triple-axis magnetometer (SparkFun^{TM} Electronics, Colorado, USA). The IMU system was a tool to be used for the measurement of knee flexion-extension movement pattern and to report immediately the measuring angles. This IMU system were used the DCM algorithm to calculate the angles. By the DCM algorithm, the outputs from the accelerometer, the gyroscope, and the magnetometer were calculated for the rotation matrix. After that, the rotation matrix was multiplied to the angles in the sensor coordination frame to transform into the angles in the global coordination frame. The measuring angles by the IMU devices were transferred to the computer via the wireless connection that was used the eight sets of Xbee Pro 5o mW Attenna – series 2. The “Knee Angle Recorder” software worked to cooperate with the four IMU devices. The software worked to transfer the “start” command and receive the measuring angles in order to any given time. Also, the measuring angles were displayed in the four line graphs of the changing angle (in degrees) versus time (in seconds) on the monitor. The measuring angles from the thigh segment and the shank segment on the same side and the same recording time were calculated to the knee joint angles in three planes. The “Knee Angle Analyzer” software worked to analyze and report the kinematic movement. The kinematic variables consisted of the measuring angles (in degrees), the time of motion (in seconds), the total duration (in seconds), the angular velocity (in degrees per second) and the angular acceleration (in degrees per second^2). It was a benefit for therapists to assess the movement.

The accurate tests for the IMU measurement were as follows. Firstly, the inclined IMU sensors after the placement in the acrylic boxes were investigated. All developed "IMU devices" had the inclined sensor from the zero line to be less than ±1 degrees. Secondly, these IMU system were compared the measuring angles with the reference angles and the Qualisys system. This test was in the static condition and also was the both sagittal and coronal planes. The root mean square (RMS) of different angles and the single rater Intraclass Correlation Coefficient (ICC) values between the reference angles and the measuring angles by the IMU system was less than 2 degrees (ICC≥0.99). Thirdly, these IMU system were tested the accuracy in the dynamic condition on both sagittal and the coronal planes. These results of measuring angles from the IMU measurement were compared with the Qualisys system. The RMS of different angles were less than 3 degrees (ICC≥0.98). Finally, the accurate test for the IMU measurement was evaluated by the four functional knee movements (the knee flexion test, the hip and knee flexion test, the forward step test, and the leg abduction test) and the walking test. The results showed the single rater ICC values of measuring angles on the knee flexion-extension movement to be the good correlation between the Qualisys system and the IMU system (ICC values ≥0.84). The RMS of different angles on the knee flexion-extension movement were less than 6 degrees. But, the testing on the knee abduction-adduction movement (the leg abduction test) reveled the no correlation between the Qualisys system and the IMU system. Therefore, the IMU system was not used to measure the knee abduction-adduction movement.

The clinical application test of the IMU system was tested in two groups; a group of elderly women without symptomatic knee osteoarthritis and a group of elderly women with symptomatic knee osteoarthritis. The IMU system was used to measure the knee flexion movement patterns on the gait cycle on both legs. Also the kinematics of knee flexion movement was selected for the reporting on each period of the gait cycle. The results showed the symptomatic side and non-symptomatic side in the elderly women with symptomatic knee osteoarthritis tended to be decreased the range of knee flexion movement on the gait cycle when compared to the elderly women without symptomatic knee osteoarthritis. Also, the gait cycle in the elderly women with symptomatic knee osteoarthritis tended to spend the time of motion more than the elderly women without symptomatic knee osteoarthritis. The results from the 1st period of a gait cycle referred the patients with the knee osteoarthritis to avoid the contact floor with the pain or severe sides.

In conclusion, this IMU system is an alternative tool to measure accurately the knee joint angles and pattern of knee flexion movement. It also apply for measuring the knee flexion movement during the daily activities.

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APPENDIX

APPENDIX A

เอกสารแสดงความยินยอมเข้าร่วมในโครงการวิจัย

การวิจัยเรื่อง "การพัฒนาเซ็นเซอร์แบบพกพาเพื่อวัดการเคลื่อนไหวข้อเข่าและประยุกต์ใช้ในผู้ป่วยข้อเข่าเสื่อม"

(Development of Mobile Sensors for Measurement of Knee Motion and Application for Patients with Knee Osteoarthritis)

วันให้คำยินยอม วันที่.............เดือน.......................................พ.ศ.......... ....

ข้าพเจ้า นาย/นาง/นางสาว...

ที่อยู่...

ได้อ่านรายละเอียดจากเอกสารข้อมูลสำหรับผู้เข้าร่วมโครงการวิจัยวิจัยที่แนบมาฉบับวันที่ .... และข้าพเจ้ายินยอมเข้าร่วมโครงการวิจัยโดยสมัครใจ

ข้าพเจ้าได้รับสำเนาเอกสารแสดงความยินยอมเข้าร่วมในโครงการวิจัยที่ข้าพเจ้าได้ลงนาม และ วันที่ พร้อมด้วยเอกสารข้อมูลสำหรับผู้เข้าร่วมโครงการวิจัย ทั้งนี้ก่อนที่จะลงนามในใบยินยอมให้ทำการวิจัยนี้ ข้าพเจ้าได้รับการอธิบายจากผู้วิจัยถึงวัตถุประสงค์ของการวิจัย ระยะเวลาของการทำวิจัย วิธีการวิจัย อันตราย หรืออาการที่อาจเกิดขึ้นจากการวิจัย รวมทั้งประโยชน์ที่จะเกิดขึ้นจากการวิจัย และแนวทางรักษาโดยวิธีอื่นอย่างละเอียด ข้าพเจ้ามีเวลาและโอกาสเพียงพอในการซักถามข้อสงสัยจนมีความเข้าใจอย่างดีแล้ว โดยผู้วิจัยได้ตอบคำถามต่าง ๆ ด้วยความเต็มใจไม่ปิดบังซ่อนเร้นจนข้าพเจ้าพอใจ

ข้าพเจ้ารับทราบจากผู้วิจัยว่าหากเกิดอันตรายใด ๆ จากการวิจัยดังกล่าว ข้าพเจ้าจะได้รับการรักษาพยาบาลโดยไม่เสียค่าใช้จ่าย

ข้าพเจ้ามีสิทธิที่จะบอกเลิกเข้าร่วมในโครงการวิจัยเมื่อใดก็ได้ โดยไม่จำเป็นต้องแจ้งเหตุผล และการบอกเลิกการเข้าร่วมการวิจัยนี้ จะไม่มีผลต่อการรักษาโรคหรือสิทธิอื่น ๆ ที่ข้าพเจ้าจะพึงได้รับต่อไป

ผู้วิจัยรับรองว่าจะเก็บข้อมูลส่วนตัวของข้าพเจ้าเป็นความลับ และจะเปิดเผยได้เฉพาะเมื่อได้รับการยินยอมจากข้าพเจ้าเท่านั้น บุคคลอื่นในนามของบริษัทผู้สนับสนุนการวิจัย คณะกรรมการพิจารณาจริยธรรมการวิจัยในคน สำนักงานคณะกรรมการอาหารและยาอาจได้รับอนุญาตให้เข้ามาตรวจและประมวลข้อมูลของข้าพเจ้า ทั้งนี้จะต้องกระทำไปเพื่อวัตถุประสงค์เพื่อตรวจสอบความถูกต้องของข้อมูลเท่านั้น โดยการตกลงที่จะเข้าร่วมการศึกษานี้ข้าพเจ้าได้ให้คำยินยอมที่จะให้มีการตรวจสอบข้อมูลประวัติทางการแพทย์ของข้าพเจ้าได้

ผู้วิจัยรับรองว่าจะไม่มีการเก็บข้อมูลใด ๆ ของข้าพเจ้า เพิ่มเติม หลังจากที่ข้าพเจ้าขอยกเลิกการเข้าร่วมโครงการวิจัยและต้องการให้ทำลายเอกสารและ/หรือ ตัวอย่างที่ใช้ตรวจสอบทั้งหมดที่สามารถสืบค้นถึงตัวข้าพเจ้าได้

ข้าพเจ้าเข้าใจว่า ข้าพเจ้ามีสิทธิ์ที่จะตรวจสอบหรือแก้ไขข้อมูลส่วนตัวของข้าพเจ้าและสามารถยกเลิกการให้สิทธิในการใช้ข้อมูลส่วนตัวของข้าพเจ้าได้ โดยต้องแจ้งให้ผู้วิจัยรับทราบ

ข้าพเจ้าได้ตระหนักว่าข้อมูลในการวิจัยรวมถึงข้อมูลทางการแพทย์ของข้าพเจ้าที่ไม่มีการเปิดเผยชื่อ จะผ่านกระบวนการต่าง ๆ เช่น การเก็บข้อมูล การบันทึกข้อมูลในแบบบันทึกและในคอมพิวเตอร์ การตรวจสอบ การวิเคราะห์ และการรายงานข้อมูลเพื่อวัตถุประสงค์ทางวิชาการ รวมทั้งการใช้ข้อมูลทางการแพทย์ในอนาคต เท่านั้น

ข้าพเจ้าได้อ่านข้อความข้างต้นและมีความเข้าใจดีทุกประการแล้ว ยินดีเข้าร่วมในการวิจัยด้วยความเต็มใจ จึงได้ลงนามในเอกสารแสดงความยินยอมนี้

....ลงนามผู้ให้ความยินยอม

(..) ชื่อผู้ยินยอมตัวบรรจง

วันที่ ....เดือน...................................พ.ศ............................

ข้าพเจ้าได้อธิบายถึงวัตถุประสงค์ของการวิจัย วิธีการวิจัย อันตราย หรืออาการไม่พึงประสงค์หรือความเสี่ยงที่อาจเกิดขึ้นจากการวิจัย รวมทั้งประโยชน์ที่จะเกิดขึ้นจากการวิจัยอย่างละเอียด ให้ผู้เข้าร่วมในโครงการวิจัยตามนามข้างต้นได้ทราบและมีความเข้าใจดีแล้ว พร้อมลงนามลงในเอกสารแสดงความยินยอมด้วยความเต็มใจ

....ลงนามผู้ทำวิจัย

(...) ชื่อผู้ทำวิจัย ตัวบรรจง

วันที่ ....เดือน..................................พ.ศ............................

....ลงนามพยาน

(...) ชื่อพยาน ตัวบรรจง

วันที่ ....เดือน..................................พ.ศ............................

APPENDIX B1

เอกสารข้อมูลคำอธิบายสำหรับผู้เข้าร่วมวิจัยในการทดสอบความเชื่อถือได้ของชุดเครื่องมือ

ชื่อโครงการวิจัย เรื่อง “การพัฒนาเซ็นเซอร์แบบพกพาเพื่อวัดการเคลื่อนไหวข้อเข่าและประยุกต์ใช้ในผู้ป่วยข้อเข่าเสื่อม” (Development of Mobile Sensors for Measurement of Knee Motion and Application for Patients with Knee Osteoarthritis)

ผู้สนับสนุนการวิจัย ไม่มี

<u>ผู้ทำวิจัย</u>

ชื่อ นายทศพล เจศรีชัย

นักกายภาพบำบัดและนิสิตระดับดุษฎีบัณฑิต หลักสูตรวิศวกรรมชีวเวช

คณะวิศวกรรมศาสตร์

ที่อยู่ หลักสูตรวิศวกรรมชีวเวช คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

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เรียน ผู้เข้าร่วมโครงการวิจัยทุกท่าน

ท่านได้รับเชิญให้เข้าร่วมในโครงการวิจัยนี้เนื่องจากท่านเป็นผู้ที่มีคุณสมบัติตามที่งานวิจัยกำหนด คือ เป็นอาสาสมัครที่มีสุขภาพดีไม่มีปัญหาด้านการเดิน เพื่อเข้าร่วมการทดสอบความเชื่อถือได้ของชุดเครื่องมือวัดองศาการเคลื่อนไหวข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อย (Inertial Measurement Unit) ก่อนที่ท่านจะตัดสินใจเข้าร่วมในการศึกษาวิจัยดังกล่าว ขอให้ท่านอ่านเอกสารฉบับนี้อย่างถี่

ถ้วน เพื่อให้ท่านได้ทราบถึงเหตุผลและรายละเอียดของการศึกษาวิจัยในครั้งนี้ หากท่านมีข้อสงสัยใดๆ เพิ่มเติม กรุณาซักถามจากทีมงานของผู้ทำวิจัย ซึ่งจะเป็นผู้สามารถตอบคำถามและให้ความกระจ่างแก่ท่านได้

ท่านสามารถขอคำแนะนำในการเข้าร่วมโครงการวิจัยนี้จากครอบครัว เพื่อน หรือแพทย์ประจำตัวของท่านได้ ท่านมีเวลาอย่างเพียงพอในการตัดสินใจโดยอิสระ ถ้าท่านตัดสินใจแล้วว่าจะเข้าร่วมในโครงการวิจัยนี้ ขอให้ท่านลงนามในเอกสารแสดงความยินยอมของโครงการวิจัยนี้

<u>เหตุผลความเป็นมา</u>

โรคข้อเข่าเสื่อม (Osteoarthritis Knee) เป็นโรคข้อที่พบมากและเป็นสาเหตุที่ทำให้เกิดอาการเจ็บ ไม่สามารถเคลื่อนไหว (เดินพื้นราบ ขึ้น-ลงบันได)หรือทำงานได้ตามปกติ เกิดจากภาวะการเสื่อมของกระดูกที่ข้อเข่า การวิเคราะห์การเดินเป็นกระบวนการทางชีวกลศาสตร์ที่นำมาใช้ตรวจประเมินผู้ป่วยข้อเข่าเสื่อมทั้งในทางคลินิกและทางห้องปฏิบัติการ ในการตรวจประเมินการเดินทางคลินิกที่ทำในปัจจุบัน เป็นการประเมินขั้นพื้นฐานที่ใช้สายตาพิจารณาการเดินของผู้ป่วยจึงเป็นข้อจำกัดในการเปรียบเทียบผลการรักษาอีกทั้งประสบการณ์ของผู้ทำการประเมินที่แตกต่างกันทำให้เป็นการยากที่นำผลการประเมินของบุคคลหนึ่งเทียบกับอีกบุคคล ส่วนการประเมินระดับสูงที่มีความละเอียดของข้อมูลและมีค่ามาตรฐานนั้นเป็นการประเมินทางห้องปฏิบัติการทางชีวกลศาสตร์ซึ่งจะให้ข้อมูลที่เป็นเชิงปริมาณที่น่าเชื่อถือและเป็นมาตรฐานทั้งข้อมูลองศาการเคลื่อนไหวของข้อต่อต่างๆของร่างกายในทั้งสามมิติ แต่ก็มีข้อจำกัดถึงความยุ่งยากในขั้นตอนการเก็บสถานที่และรูปแบบที่สามารถเก็บข้อมูลได้ และมีค่าใช้จ่ายที่ค่อนข้างสูงในการเก็บข้อมูลเนื่องจากเครื่องมือและอุปกรณ์มีราคาแพง

ด้วยเทคโนโลยีด้านเซ็นเซอร์ที่มีการพัฒนาและประดิษฐ์ขึ้นในปัจจุบัน ทำให้เป็นแนวทางเลือกอีกแนวทางในการนำมาใช้วิเคราะห์การเคลื่อนไหวขณะเดิน โดยอาจสามารถลดข้อจำกัด

เรื่องสถานที่ในการเก็บข้อมูล และค่าใช้จ่ายที่ค่อนข้างสูงที่ใช้ในการเก็บข้อมูล และนำไปใช้ช่วยวิเคราะห์ได้ในทางคลินิก ซึ่งได้มีการนำเซ็นเซอร์วัดแรงเฉื่อย (IMU) มาใช้วัดข้อมูลด้านกลศาสตร์การเคลื่อนที่ (kinematics) ของร่างกาย มีนักวิจัยหลายท่านการพยายามนำค่าที่วัดได้จากเซ็นเซอร์เซ็นเซอร์วัดแรงเฉื่อย มาหาสมการเพื่อคำนวณมุม จากการที่มีการศึกษาต่อเนื่องทำให้ผู้วิจัยสนใจการนำ เซ็นเซอร์วัดแรงเฉื่อย (รุ่น 9 Degrees of Freedom - Razor IMU - AHRS compatible) ซึ่งประกอบด้วยเซ็นเซอร์วัดความเร่งทั้ง 3 ระนาบ, เซ็นเซอร์วัดความเร็วเชิงมุม ทั้ง 3 แกนหมุน, เซ็นเซอร์วัดสนามแม่เหล็ก (magnetometer) ทั้ง 3 แกน เพื่อนำมาประยุกต์ใช้วัดองศาการเคลื่อนไหวข้อเข่า ด้วยการติดเซ็นเซอร์วัดแรงเฉื่อย 4 ตำแหน่ง คือ ที่กึ่งกลางต้นขาและกึ่งกลางหน้าแข้งทั้งสองข้าง โดยนำค่าความเร็วเชิงมุม ความเร่งแกนระนาบ และตำแหน่งทิศทางจากเข็มทิศผ่านกระบวนการคำนวณเมตริกซ์โคไซน์แสดงทิศทาง (Direction cosine matrix) ที่เป็นอีกวีธีการหนึ่งที่สามารถนำมาปรับใช้เพื่อทำการลดค่าความคลาดเคลื่อนที่เกิดขึ้น การคำนวณหาค่าพิกัดมุมที่เซ็นเซอร์วัดแรงเฉื่อยสามารถหาได้จากการหาค่าโคไซน์ของ เวกเตอร์ลัพท์ (เวกเตอร์ที่ชี้ไปที่พิกัดของอุปกรณ์เซ็นเซอร์วัดแรงเฉื่อย) โดยค่ามุมที่ได้นี้ขึ้นกับค่าพิกัดที่ได้จากการสุ่มเก็บข้อมูล (sampling) ในแต่ละครั้ง และส่งข้อมูลผ่านสัญญาณแบบไร้สาย (wireless) มาคำนวณเป็นมุมการเคลื่อนไหว (องศา) ในระนาบแบ่งซ้าย-ขวา (sagittal), ระนาบแบ่งหน้า-หลัง (coronal) และระนาบแบ่งบน-ล่าง (horizontal) ของต้นขาและหน้าแข้ง และหามุมการงอและเหยียดเข่า มุมการกางและหุบข้อเข่า และมุมการหมุนเข้าหรือหมุนออกจากแนวกลางของข้อเข่า แสดงผลเป็นกราฟมุมการเคลื่อนไหวของข้อเข่าบนคอมพิวเตอร์ ด้วยวิธีการดังกล่าวจะสามารถช่วยให้ได้ผลมุมการเคลื่อนไหวแบบทันทีที่เกิดขึ้น

ผู้วิจัยทำการทดสอบเปรียบเทียบความถูกต้องและแม่นยำของเครื่องมือที่วัดได้จากเซ็นเซอร์วัดแรงเฉื่อยเทียบกับการวัดการเคลื่อนไหวสามมิติด้วยระบบกล้อง (Qualisys-Motion Capture System) ด้วยการนำเปรียบเทียบกับค่ามุมองศาในขณะอยู่นิ่ง (static test) และเปรียบเทียบการวัดมุมขณะมีการเคลื่อนไหว (dynamic test) ทั้งการเคลื่อนไหวในอุปกรณ์ที่รู้ค่าช่วงองศาการ

เคลื่อนไหว และในการทดสอบเคลื่อนไหวขาและการเดินในคนปกติ โดยผู้วิจัยจะขอความอนุมัติการดำเนินการวิจัยจากคณะกรรมการจริยธรรมการวิจัยในคนก่อนเริ่มดำเนินการทดสอบ และผู้วิจัยจะให้ข้อมูลคำอธิบายวัตถุประสงค์ วิธีการปฏิบัติต่อผู้เข้าร่วมวิจัย ประโยชน์ และความเสี่ยง ฯลฯ ตอบข้อสงสัยจนผู้เข้าร่วมวิจัยเข้าใจ และให้เวลาตัดสินใจโดยอิสระก่อนเข้าร่วมการทดสอบ

จากนั้นนำไปเครื่องมือวัดมุมการเคลื่อนไหวข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อยไปทดสอบเปรียบเทียบระหว่างการเคลื่อนไหวข้อเข่าในหญิงสูงอายุที่มีและไม่มีอาการข้อเข่าเสื่อมขณะเดินตรงพื้นราบในระยะ 10 เมตร, เดินขึ้น-ลงบันได ซึ่งเป็นกิจกรรมพื้นฐานที่ทำในชีวิตประจำวัน

<u>วัตถุประสงค์ของการศึกษา</u>

วัตถุประสงค์หลัก

เพื่อประยุกต์ใช้เซ็นเซอร์วัดแรงเฉื่อยที่เชื่อมต่อแบบไร้สายกับคอมพิวเตอร์ พร้อมพัฒนาโปรแกรมวัดองศาการเคลื่อนไหวของข้อเข่าเพื่อประยุกต์ใช้ประเมินการเดินในผู้ป่วยที่มีอาการข้อเข่าเสื่อม

วัตถุประสงค์ย่อยในการศึกษาครั้งนี้

เพื่อเปรียบเทียบค่าองศาการเคลื่อนไหวข้อเข่า (องศา) จากอุปกรณ์วัดองศาการเคลื่อนไหวของข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อย กับอุปกรณ์วัดการเคลื่อนไหวแบบสามมิติด้วยระบบกล้อง (Qualisys-Motion Capture System) ในการเคลื่อนไหวขาและข้อเข่า และเดินพื้นราบความเร็วการเดินปกติ

<u>วิธีการที่เกี่ยวข้องกับการวิจัย</u>

การทดสอบความเชื่อถือได้ของชุดเครื่องมือวัดองศาการเคลื่อนไหวข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อย

อาสาสมัครที่เข้าร่วมการวิจัยจำนวน 10 คน จะได้รับการสอบถามประวัติ เก็บข้อมูลด้านคุณลักษณะร่างกาย (ส่วนสูง น้ำหนัก ความยาวขา) ในการทดสอบจะให้อาสาสมัครทำการเคลื่อนไหวขาด้วยการงอสะโพกงอเข่า เหยียดขาไปด้านหลัง กางขาออกและหุบขา ก้าวไปด้านหน้าและก้าวขาไปด้านหลัง และเดินบนแนวทางเดิน

ขั้นตอนและรายละเอียดที่อาสาสมัครต้องทำ

อาสาสมัครตอบข้อมูลเกี่ยวกับประวัติ และคุณลักษณะร่างกาย จากนั้นเซ็นใบยินยอมเข้าร่วมการวิจัย

↓

อาสาสมัครเปลี่ยนกางเกงเป็นขาสั้น ติดเครื่องหมายสะท้อนแสงและ ชุดอุปกรณ์เซ็นเซอร์วัดแรงเฉื่อย

↓

ทำการทดสอบเคลื่อนไหวขาทั้งสองข้างในลักษณะต่างๆขณะยืนอยู่นิ่ง

↓

ทำการทดสอบด้วยการเดินบนแนวทางเดิน

* ใช้เวลาในการเก็บข้อมูลจากอาสาสมัครแต่ละคนไม่เกิน คนละ 1 ชั่วโมง

<u>ความรับผิดชอบของอาสาสมัครผู้เข้าร่วมในโครงการวิจัย</u>

เพื่อให้งานวิจัยนี้ประสบความสำเร็จ ผู้ทำวิจัยใคร่ขอความความร่วมมือจากท่าน โดยจะขอให้ท่านปฏิบัติตามคำแนะนำของผู้ทำวิจัยอย่างเคร่งครัด รวมทั้งแจ้งอาการผิดปกติต่าง ๆ ที่เกิดขึ้นกับท่านระหว่างที่ท่านเข้าร่วมในโครงการวิจัยให้ผู้ทำวิจัยได้รับทราบ

<u>ความเสี่ยงที่อาจได้รับ</u>

ระหว่างการเก็บข้อมูลผู้วิจัยจะอยู่กับท่านตลอดเวลา เพื่อคอยระมัดระวังป้องกันอันตรายหรืออุบัติเหตุ ที่อาจเกิดขึ้นกับท่านได้ ท่านจึงแทบไม่มีความเสี่ยงเพิ่มขึ้นจากการร่วมโครงการแต่อย่างใด ที่สำคัญอุปกรณ์วัดองศาด้วยเซ็นเซอร์วัดแรงเฉื่อย เป็นอุปกรณ์ที่ใช้ติดบนสายรัดที่รัดไว้บริเวณต้น

ขาและหน้าแข้งเท่านั้น ในขณะทำการวัดองศาการเคลื่อนไหวข้อเข่า จะไม่มีการ ฝังอุปกรณ์ใดๆ เข้าสู่ร่างกายของอาสาสมัคร และอุปกรณ์วัดองศาด้วยเซ็นเซอร์วัดแรงเฉื่อย มีความปลอดภัยเพราะใช้แบตเตอรี่ที่มีกำลังต่ำ ทั้งบรรจุภัณฑ์เป็นฉนวนไฟฟ้า จึงไม่มีปัญหากระแสไฟฟ้ารั่วที่เป็นอันตรายต่อผู้ใช้

กรุณาแจ้งผู้ทำวิจัยในกรณีที่พบอาการผิดปกติ ระหว่างที่อยู่ในโครงการวิจัย หรือถ้ามีการเปลี่ยนแปลงเกี่ยวกับสุขภาพของท่าน ขอให้ท่านรายงานให้ผู้ทำวิจัยทราบโดยเร็ว

ประโยชน์ที่อาจได้รับ

ท่านจะไม่ได้รับประโยชน์ใดๆจากการเข้าร่วมในการวิจัยครั้งนี้ แต่ผลการศึกษาที่ได้จะทำให้ได้อุปกรณ์วิเคราะห์แบบง่ายเพื่อสามารถนำไปตรวจวัดการเคลื่อนไหวข้อเข่าในขณะมีการเคลื่อนไหวเพื่อใช้ในการประเมินทางคลินิกได้อย่างมีประสิทธิภาพ

วิธีการและรูปแบบการรักษาอื่น ๆ ซึ่งมีอยู่สำหรับอาสาสมัคร

ท่านไม่จำเป็นต้องเข้าร่วมโครงการวิจัยนี้เพื่อประโยชน์ในการรักษาโรคที่ท่านเป็นอยู่ เนื่องจากมีแนวทางการรักษาอื่น ๆ หลายแบบสำหรับรักษาโรคของท่านได้ ดังนั้นจึงควรปรึกษาแนวทางการรักษาวิธีอื่นๆ กับแพทย์ผู้ให้การรักษาท่านก่อนตัดสินใจเข้าร่วมในการวิจัย

ข้อปฏิบัติของท่านขณะที่ร่วมในโครงการวิจัย

ขอให้ท่านปฏิบัติดังนี้

- ขอให้ท่านให้ข้อมูลทางการแพทย์ของท่านทั้งในอดีต และปัจจุบัน แก่ผู้ทำวิจัยด้วยความสัตย์จริง
- ขอให้ท่านแจ้งให้ผู้ทำวิจัยทราบความผิดปกติที่เกิดขึ้นระหว่างที่ท่านร่วมในโครงการวิจัย

อันตรายที่อาจเกิดขึ้นจากการเข้าร่วมในโครงการวิจัยและความรับผิดชอบของผู้ทำวิจัย/ผู้สนับสนุนการวิจัย

หากพบอันตรายที่เกิดขึ้นจากการวิจัย ท่านจะได้รับการรักษาอย่างเหมาะสมทันที และท่านปฏิบัติตามคำแนะนำของทีมผู้ทำวิจัยแล้ว ผู้ทำวิจัย/ผู้สนับสนุนการวิจัยยินดีจะรับผิดชอบค่าใช้จ่ายในการรักษาพยาบาลของท่าน และการลงนามในเอกสารให้ความยินยอม ไม่ได้หมายความว่าท่านได้สละสิทธิ์ทางกฎหมายตามปกติที่ท่านพึงมี

ในกรณีที่ท่านได้รับอันตรายใด ๆ หรือต้องการข้อมูลเพิ่มเติมที่เกี่ยวข้องกับโครงการวิจัย ท่านสามารถ

ติดต่อกับผู้ทำวิจัยคือ นายทศพล เจศรีชัย ได้ที่หมายเลขโทรศัพท์ 086 – 533-3860 ได้ตลอด 24 ชั่วโมง

ค่าใช้จ่ายของท่านในการเข้าร่วมการวิจัย

ท่านจะได้รับการตรวจวัดมุมการเคลื่อนไหวของข้อเข่าโดยไม่ต้องเสียค่าใช้จ่ายใดๆ ทั้งสิ้น

ค่าตอบแทนสำหรับผู้เข้าร่วมวิจัย (ถ้ามี)

ท่านจะไม่ได้รับเงินค่าตอบแทนในการเข้าร่วมการวิจัย แต่ท่านจะได้รับค่าเดินทาง ค่าเสียเวลา และ ค่าชดเชยการสูญเสียรายได้ ครั้งละ 200 บาท รวมทั้งหมด 1 ครั้ง

<u>การเข้าร่วมและการสิ้นสุดการเข้าร่วมโครงการวิจัย</u>

การเข้าร่วมในโครงการวิจัยครั้งนี้เป็นไปโดยความสมัครใจ หากท่านไม่สมัครใจจะเข้าร่วมการศึกษาแล้ว ท่านสามารถถอนตัวได้ตลอดเวลา การขอถอนตัวออกจากโครงการวิจัยจะไม่มีผลต่อการดูแลรักษาโรคของท่านแต่อย่างใด

ผู้ทำวิจัยอาจถอนท่านออกจากการเข้าร่วมการวิจัย เพื่อเหตุผลด้านความปลอดภัยของท่าน หรือเมื่อผู้สนับสนุนการวิจัยยุติการดำเนินงานวิจัย หรือ ในกรณีดังต่อไปนี้

- ท่านไม่สามารถปฏิบัติตามคำแนะนำของผู้ทำวิจัย

<u>การปกป้องรักษาข้อมูลความลับของอาสาสมัคร</u>

ข้อมูลที่อาจนำไปสู่การเปิดเผยตัวท่าน จะได้รับการปกปิดและจะไม่เปิดเผยแก่สาธารณชน ในกรณีที่ผลการวิจัยได้รับการตีพิมพ์ ชื่อและที่อยู่ของท่านจะต้องได้รับการปกปิดอยู่เสมอ โดยจะใช้เฉพาะรหัสประจำโครงการวิจัยของท่าน

จากการลงนามยินยอมของท่านผู้ทำวิจัย และผู้สนับสนุนการวิจัยสามารถเข้าไปตรวจสอบบันทึกข้อมูลทางการแพทย์ของท่านได้แม้จะสิ้นสุดโครงการวิจัยแล้วก็ตาม หากท่านต้องการยกเลิกการให้สิทธิ์ดังกล่าว ท่านสามารถแจ้ง หรือเขียนบันทึกขอยกเลิกการให้คำยินยอม โดยส่งไปที่ นายทศพล เจศรีชัย หลักสูตรวิศวกรรมชีวเวช คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ถนนพญาไท แขวงวังใหม่ ปทุมวัน กรุงเทพฯ 10330

หากท่านขอยกเลิกการให้คำยินยอมหลังจากที่ท่านได้เข้าร่วมโครงการวิจัยแล้ว ข้อมูลส่วนตัวของท่านจะไม่ถูกบันทึกเพิ่มเติม อย่างไรก็ตามข้อมูลอื่น ๆ ของท่านอาจถูกนำมาใช้เพื่อประเมิน

ผลการวิจัย และท่านจะไม่สามารถกลับมาเข้าร่วมในโครงการนี้ได้อีก ทั้งนี้เนื่องจากข้อมูลของท่านที่จำเป็นสำหรับใช้เพื่อการวิจัยไม่ได้ถูกบันทึก

จากการลงนามยินยอมของท่านแพทย์ผู้ทำวิจัยสามารถบอกรายละเอียดของท่านที่เกี่ยวกับการเข้าร่วมโครงการวิจัยนี้ให้แก่แพทย์ผู้รักษาท่านได้

<u>สิทธิ์ของผู้เข้าร่วมในโครงการวิจัย</u>

ในฐานะที่ท่านเป็นผู้เข้าร่วมในโครงการวิจัย ท่านจะมีสิทธิ์ดังต่อไปนี้

1. ท่านจะได้รับทราบถึงลักษณะและวัตถุประสงค์ของการวิจัยในครั้งนี้
2. ท่านจะได้รับการอธิบายเกี่ยวกับระเบียบวิธีการของการวิจัยทางการแพทย์ และอุปกรณ์ที่ใช้ในการวิจัยครั้งนี้
3. ท่านจะได้รับการอธิบายถึงความเสี่ยงและความไม่สบายที่จะได้รับจากการวิจัย
4. ท่านจะได้รับการอธิบายถึงประโยชน์ที่ท่านอาจจะได้รับจากการวิจัย
5. ท่านจะมีโอกาสได้ซักถามเกี่ยวกับงานวิจัยหรือขั้นตอนที่เกี่ยวข้องกับงานวิจัย
6. ท่านจะได้รับทราบว่าการยินยอมเข้าร่วมในโครงการวิจัยนี้ ท่านสามารถขอถอนตัวจากโครงการเมื่อไรก็ได้ โดยผู้เข้าร่วมในโครงการวิจัยสามารถขอถอนตัวจากโครงการโดยไม่ได้รับผลกระทบใด ๆ ทั้งสิ้น
7. ท่านจะได้รับสำเนาเอกสารใบยินยอมที่มีทั้งลายเซ็นและวันที่
8. ท่านมีสิทธิ์ในการตัดสินใจว่าจะเข้าร่วมในโครงการวิจัยหรือไม่ก็ได้ โดยปราศจากการใช้อิทธิพลบังคับข่มขู่ หรือการหลอกลวง

หากท่านไม่ได้รับการชดเชยอันควรต่อการบาดเจ็บหรือเจ็บป่วยที่เกิดขึ้นโดยตรงจากการวิจัย หรือท่านไม่ได้รับการปฏิบัติตามที่ปรากฏในเอกสารข้อมูลคำอธิบายสำหรับผู้เข้าร่วมในการวิจัย ท่านสามารถร้องเรียนได้ที่ คณะกรรมการจริยธรรมการวิจัย คณะแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

ตึกอานันทมหิดลชั้น 3 โรงพยาบาลจุฬาลงกรณ์ ถนนพระราม 4 ปทุมวัน กรุงเทพฯ 10330 โทร 0-2256-4455 ต่อ 14, 15 ในเวลาราชการ

ขอขอบคุณในการร่วมมือของท่านมา ณ ที่นี้

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APPENDIX B2

เอกสารข้อมูลคำอธิบายสำหรับผู้เข้าร่วมวิจัยสำหรับการทดสอบในผู้เข้าร่วมวิจัยสูงอายุที่ไม่มีและมีอาการข้อเข่าเสื่อม

ชื่อโครงการวิจัย เรื่อง "การพัฒนาเซ็นเซอร์แบบพกพาเพื่อวัดการเคลื่อนไหวข้อเข่าและประยุกต์ใช้ในผู้ป่วยข้อเข่าเสื่อม" (Development of Mobile Sensors for Measurement of Knee Motion and Application for Patients with Knee Osteoarthritis)

ผู้สนับสนุนการวิจัย -

<u>ผู้ทำวิจัย</u>

ชื่อ นายทศพล เจศรีชัย

นักกายภาพบำบัดและนิสิตระดับดุษฎีบัณฑิต หลักสูตรวิศวกรรมชีวเวช คณะวิศวกรรมศาสตร์

ที่อยู่ หลักสูตรวิศวกรรมชีวเวช คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

เบอร์โทรศัพท์ 086-533-3860

<u>ผู้วิจัยร่วม</u> ศ.พญ.อารีรัตน์ สุพุทธิธาดา ภาควิชาเวชศาสตร์ฟื้นฟู คณะแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย เบอร์โทรศัพท์ 081 – 488-8549

รศ.ดร.วัชรพงษ์ โขวิฑูรกิจ ภาควิชาวิศวกรรมไฟฟ้า คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย เบอร์โทรศัพท์ 089-487-9020

เรียน ผู้เข้าร่วมโครงการวิจัยทุกท่าน

ท่านได้รับเชิญให้เข้าร่วมในโครงการวิจัยนี้เนื่องจาก

1. เป็นผู้สูงอายุที่มีการเสื่อมของข้อเข่า อายุระหว่าง 50-70 ปี จำนวน 20 คน เป็นผู้ที่มีคุณสมบัติตามที่งานวิจัยกำหนดเพื่อทดสอบเปรียบเทียบผลการวัดองศาการเคลื่อนไหวข้อเข่าในผู้ป่วยข้อเข่าเสื่อม

2. เป็นผู้สูงอายุที่ไม่มีอาการเสื่อมของข้อเข่า อายุระหว่าง 50-70 ปี จำนวน 20 คน เป็นผู้ที่มีคุณสมบัติตามที่งานวิจัยกำหนดเพื่อทดสอบเปรียบเทียบผลการวัดองศาการเคลื่อนไหวข้อเข่าในผู้ป่วยข้อเข่าเสื่อม

ก่อนที่ท่านจะตัดสินใจเข้าร่วมในการศึกษาวิจัยดังกล่าว ขอให้ท่านอ่านเอกสารฉบับนี้อย่างถี่ถ้วน เพื่อให้ท่านได้ทราบถึงเหตุผลและรายละเอียดของการศึกษาวิจัยในครั้งนี้ หากท่านมีข้อสงสัยใดๆ เพิ่มเติม กรุณาซักถามจากทีมงานของผู้ทำวิจัย ซึ่งจะเป็นผู้สามารถตอบคำถามและให้ความกระจ่างแก่ท่านได้

ท่านสามารถขอคำแนะนำในการเข้าร่วมโครงการวิจัยนี้จากครอบครัว เพื่อน หรือแพทย์ประจำตัวของท่านได้ ท่านมีเวลาอย่างเพียงพอในการตัดสินใจโดยอิสระ ถ้าท่านตัดสินใจแล้วว่าจะเข้าร่วมในโครงการวิจัยนี้ ขอให้ท่านลงนามในเอกสารแสดงความยินยอมของโครงการวิจัยนี้

<u>เหตุผลความเป็นมา</u>

โรคข้อเข่าเสื่อม (Osteoarthritis Knee) เป็นโรคข้อที่พบมากและเป็นสาเหตุที่ทำให้เกิดอาการเจ็บ ไม่สามารถเคลื่อนไหว (เดินพื้นราบ ขึ้น-ลงบันได)หรือทำงานได้ตามปกติ เกิดจากภาวะการเสื่อมของกระดูกที่ข้อเข่า การวิเคราะห์การเดินเป็นกระบวนการทางชีวกลศาสตร์ที่นำมาใช้ตรวจประเมินผู้ป่วยข้อเข่าเสื่อมทั้งในทางคลินิกและทางห้องปฏิบัติการ ในการตรวจประเมินการเดินทางคลินิกที่ทำในปัจจุบัน เป็นการประเมินขั้นพื้นฐานที่ใช้สายตาพิจารณาการเดินของผู้ป่วยจึงเป็นข้อจำกัดในการเปรียบเทียบผลการรักษาอีกทั้งประสบการณ์ของผู้ทำการประเมินที่แตกต่างกันทำให้เป็นการยากที่นำผลการประเมินของบุคคลหนึ่งเทียบกับอีกบุคคล ส่วนการประเมินระดับสูงที่มีความละเอียดของข้อมูลและมีค่ามาตรฐานนั้นเป็นการประเมินทางห้องปฏิบัติการทางชีวกลศาสตร์ซึ่งจะให้ข้อมูลที่เป็นเชิงปริมาณที่น่าเชื่อถือและเป็นมาตรฐานทั้งข้อมูลองศาการเคลื่อนไหวของข้อต่อต่างๆของร่างกายในทั้งสามมิติ แต่ก็มีข้อจำกัดถึงความยุ่งยากในขั้นตอนการเก็บสถานที่และรูปแบบที่สามารถเก็บข้อมูลได้ และมีค่าใช้จ่ายที่ค่อนข้างสูงในการเก็บข้อมูลเนื่องจากเครื่องมือและอุปกรณ์มีราคาแพง

ด้วยเทคโนโลยีด้านเซ็นเซอร์ที่มีการพัฒนาและประดิษฐ์ขึ้นในปัจจุบัน ทำให้เป็นแนวทางเลือกอีกแนวทางในการนำมาใช้วิเคราะห์การเคลื่อนไหวขณะเดิน โดยอาจสามารถลดข้อจำกัดเรื่องสถานที่ในการเก็บข้อมูล และค่าใช้จ่ายที่ค่อนข้างสูงที่ใช้ในการเก็บข้อมูล และนำไปใช้ช่วยวิเคราะห์ได้ในทางคลินิก ซึ่งได้มีการนำเซ็นเซอร์วัดแรงเฉื่อย (IMU) มาใช้วัดข้อมูลด้านกลศาสตร์การเคลื่อนที่ (kinematics) ของร่างกาย มีนักวิจัยหลายท่านการพยายามนำค่าที่วัดได้จากเซ็นเซอร์เซ็นเซอร์วัดแรงเฉื่อย มาหาสมการเพื่อคำนวณมุม จากการที่มีการศึกษาต่อเนื่องทำให้ผู้วิจัยสนใจการนำ เซ็นเซอร์วัดแรงเฉื่อย รุ่น 9 Degrees of Freedom - Razor IMU - AHRS compatible ซึ่งประกอบด้วยเซ็นเซอร์วัดความเร่งทั้ง 3 ระนาบ, เซ็นเซอร์วัดความเร็วเชิงมุม ทั้ง 3 แกนหมุน, เซ็นเซอร์วัดสนามแม่เหล็ก (magnetometer) ทั้ง 3 แกน เพื่อนำมาประยุกต์ใช้วัดองศาการเคลื่อนไหวข้อเข่า ด้วยการติดเซ็นเซอร์วัดแรงเฉื่อย 4 ตำแหน่ง คือ ที่กึ่งกลางต้นขาและกึ่งกลางหน้าแข้งทั้งสองข้าง โดยนำค่าความเร็วเชิงมุม ความเร่งแกนระนาบ และตำแหน่งทิศทางจากเข็มทิศผ่านกระบวนการคำนวณเมตริกซ์โคไซน์แสดงทิศทาง (Direction cosine matrix) ที่เป็นอีกวิธีการหนึ่งที่สามารถนำมาปรับใช้เพื่อทำการลดค่าความคลาดเคลื่อนที่เกิดขึ้น การคำนวณหาค่าพิกัดมุมที่เซ็นเซอร์วัดแรงเฉื่อยสามารถหาได้จากการหาค่าโคไซน์ของ เวกเตอร์ลัพท์ (เวกเตอร์ที่ชี้ไปที่พิกัดของอุปกรณ์เซ็นเซอร์วัดแรงเฉื่อย) โดยค่ามุมที่ได้นี้ขึ้นกับค่าพิกัดที่ได้จากการสุ่มเก็บข้อมูล (sampling) ในแต่ละครั้ง และส่งข้อมูลผ่านสัญญาณแบบไร้สาย (wireless) มาคำนวณเป็นมุมการเคลื่อนไหว (องศา) ในระนาบแบ่งซ้าย-ขวา (sagittal), ระนาบแบ่งหน้า-หลัง (coronal) และระนาบแบ่งบน-ล่าง (horizontal) ของต้นขาและหน้าแข้ง และหามุมการงอและเหยียดเข่า มุมการกางและหุบข้อเข่าและมุมการหมุนเข้าหรือหมุนออกจากแนวกลางของข้อเข่า แสดงผลเป็นกราฟมุมการเคลื่อนไหวของข้อเข่าบนคอมพิวเตอร์ ด้วยวิธีการดังกล่าวจะสามารถช่วยให้ได้ผลมุมการเคลื่อนไหวแบบทันทีที่เกิดขึ้น

ผู้วิจัยทำการทดสอบเปรียบเทียบความถูกต้องและแม่นยำของเครื่องมือที่วัดได้จากเซ็นเซอร์วัดแรงเฉื่อยเทียบกับการวัดการเคลื่อนไหวสามมิติด้วยระบบกล้อง (Qualisys-Motion Capture System) ด้วยการนำเปรียบเทียบกับค่ามุมองศาในขณะอยู่นิ่ง (static test) และเปรียบเทียบการวัดมุมขณะมีการเคลื่อนไหว (dynamic test) ทั้งการเคลื่อนไหวในอุปกรณ์ที่รู้ค่าช่วงองศาการเคลื่อนไหว และในการทดสอบเคลื่อนไหวขาและการเดินในคนปกติ โดยผู้วิจัยจะขอความอนุมัติการดำเนินการวิจัยจากคณะกรรมการจริยธรรมการวิจัยในคนก่อนเริ่มดำเนินการทดสอบ และผู้วิจัยจะให้ข้อมูลคำอธิบายวัตถุประสงค์ วิธีการปฏิบัติต่อผู้เข้าร่วมวิจัย ประโยชน์ และความเสี่ยง ฯลฯ ตอบข้อสงสัยจนผู้เข้าร่วมวิจัยเข้าใจ และให้เวลาตัดสินใจโดยอิสระก่อนเข้าร่วมการทดสอบ

จากนั้นนำไปเครื่องมือวัดมุมการเคลื่อนไหวข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อยไปทดสอบเปรียบเทียบระหว่างการเคลื่อนไหวข้อเข่าในหญิงสูงอายุที่มีและไม่มีอาการข้อเข่าเสื่อมขณะเดินตรงพื้นราบในระยะ 10 เมตร, เดินขึ้น-ลงบันได ซึ่งเป็นกิจกรรมพื้นฐานที่ทำในชีวิตประจำวัน

<u>วัตถุประสงค์ของการศึกษา</u>

วัตถุประสงค์หลัก

เพื่อประยุกต์ใช้เซ็นเซอร์วัดแรงเฉื่อยที่เชื่อมต่อแบบไร้สายกับคอมพิวเตอร์ พร้อมพัฒนาโปรแกรมวัดองศาการเคลื่อนไหวของข้อเข่าเพื่อประยุกต์ใช้ประเมินการเดินในผู้ป่วยที่มีอาการข้อเข่าเสื่อม

วัตถุประสงค์ย่อยในการศึกษาครั้งนี้

นำอุปกรณ์วัดองศาการเคลื่อนไหวของข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อย มาวัดการเคลื่อนไหวข้อเข่าขณะเดินพื้นราบด้วยความเร็วปกติ และขณะก้าวขึ้น-ลงบันได เปรียบเทียบระหว่างผู้ที่ไม่มีปัญหาการเดินกับผู้ที่มีอาการข้อเข่าเสื่อม

<u>วิธีการที่เกี่ยวข้องกับการวิจัย</u>

การทดสอบอุปกรณ์วัดองศาการเคลื่อนไหวของข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อย เปรียบเทียบระหว่างผู้ที่ไม่มีปัญหาการเดินกับผู้ที่มีอาการข้อเข่าเสื่อม

ผู้เข้าร่วมวิจัยสูงอายุที่ไม่มีและมีอาการข้อเข่าเสื่อมกลุ่มละ 20 คน ผู้วิจัยจะขอสอบถามประวัติ ตรวจประเมินอาการ การเคลื่อนไหวข้อเข่า กำลังกล้ามเนื้อรอบข้อเข่า และการยืนและการเดินพื้นราบ และขึ้นลงบันได เพื่อคัดกรองว่าท่านมีคุณสมบัติที่เหมาะสมที่จะเข้าร่วมในการวิจัย

หากท่านมีคุณสมบัติตามเกณฑ์คัดเข้า ท่านจะได้รับเชิญให้มาพบแพทย์ตามวันเวลาที่ผู้ทำวิจัยนัดหมาย และอยู่ในงานวิจัยไม่เกินชั่วโมง เพื่อทดสอบการเดินด้วยการเดินบนพื้นราบระยะทาง 10 เมตร และขึ้นลงบันได 3 ขั้น โดยตลอดระยะเวลาที่ท่านอยู่ในโครงการวิจัย คือ ไม่เกิน 1 ชั่วโมงและมาพบผู้วิจัยหรือผู้ร่วมทำวิจัยทั้งสิ้น 1 ครั้ง

ขั้นตอนและรายละเอียดที่อาสาสมัครต้องทำ

ผู้เข้าร่วมการวิจัยตอบข้อมูลในแบบสอบถามเกี่ยวกับอาการและความสามารถในการเคลื่อนไหวขา

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ผู้เข้าร่วมการวิจัยเปลี่ยนกางเกงขาสั้นและติดอุปกรณ์วัดการเคลื่อนไหวข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อยที่ต้นขาและหน้าแข้ง

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ผู้เข้าร่วมการวิจัยเดินตรงบนทางราบ ในระยะทาง 10 เมตร

* ใช้เวลาในการเก็บข้อมูลจากอาสาสมัครแต่ละคนไม่เกิน คนละ 1 ชั่วโมง

<u>ความรับผิดชอบของอาสาสมัครผู้เข้าร่วมในโครงการวิจัย</u>

เพื่อให้งานวิจัยนี้ประสบความสำเร็จ ผู้ทำวิจัยใคร่ขอความความร่วมมือจากท่าน โดยจะขอให้ท่านปฏิบัติตามคำแนะนำของผู้ทำวิจัยอย่างเคร่งครัด รวมทั้งแจ้งอาการผิดปกติต่าง ๆ ที่เกิดขึ้นกับท่านระหว่างที่ท่านเข้าร่วมในโครงการวิจัยให้ผู้ทำวิจัยได้รับทราบ

<u>ความเสี่ยงที่อาจได้รับ</u>

ระหว่างการเก็บข้อมูลผู้วิจัยจะอยู่กับท่านตลอดเวลา เพื่อคอยระมัดระวังป้องกันอันตรายหรืออุบัติเหตุ ที่อาจเกิดขึ้นกับท่านได้ ท่านจึงแทบไม่มีความเสี่ยงเพิ่มขึ้นจากการร่วมโครงการแต่อย่างใด ที่สำคัญอุปกรณ์วัดองศาด้วยเซ็นเซอร์วัดแรงเฉื่อย เป็นอุปกรณ์ที่ใช้ติดบนสายรัดที่รัดไว้บริเวณต้นขาและหน้าแข้งเท่านั้น ในขณะทำการวัดองศาการเคลื่อนไหวข้อเข่า จะไม่มีการ ฝังอุปกรณ์ใดๆ เข้าสู่ร่างกายของอาสาสมัคร และอุปกรณ์วัดองศาด้วยเซ็นเซอร์วัดแรงเฉื่อย มีความปลอดภัยเพราะใช้แบตเตอรี่ที่มีกำลังต่ำ ทั้งบรรจุภัณฑ์เป็นฉนวนไฟฟ้า จึงไม่มีปัญหากระแสไฟฟ้ารั่วที่เป็นอันตรายต่อผู้ใช้

กรุณาแจ้งผู้ทำวิจัยในกรณีที่พบอาการผิดปกติ ระหว่างที่อยู่ในโครงการวิจัย หรือถ้ามีการเปลี่ยนแปลงเกี่ยวกับสุขภาพของท่าน ขอให้ท่านรายงานให้ผู้ทำวิจัยทราบโดยเร็ว

<u>ประโยชน์ที่อาจได้รับ</u>

ท่านจะไม่ได้รับประโยชน์ใดๆจากการเข้าร่วมในการวิจัยครั้งนี้ แต่ผลการศึกษาที่ได้จะ

1 ได้อุปกรณ์วิเคราะห์แบบง่ายเพื่อสามารถนำไปตรวจวัดการเคลื่อนไหวข้อเข่าในขณะมีการเคลื่อนไหวเพื่อใช้ในการประเมินทางคลินิกได้อย่างมีประสิทธิภาพ

2 ทำให้ทราบข้อมูลความแตกต่างที่พบระหว่างหญิงสูงอายุที่ไม่มีปัญหาการเดินกับหญิงสูงอายุที่มีอาการข้อเข่าเสื่อม

<u>วิธีการและรูปแบบการรักษาอื่น ๆ ซึ่งมีอยู่สำหรับอาสาสมัคร</u>

ท่านไม่จำเป็นต้องเข้าร่วมโครงการวิจัยนี้เพื่อประโยชน์ในการรักษาโรคที่ท่านเป็นอยู่ เนื่องจากมีแนวทางการรักษาอื่น ๆ หลายแบบสำหรับรักษาโรคของท่านได้ ดังนั้นจึงควรปรึกษาแนวทางการรักษาวิธีอื่นๆ กับแพทย์ผู้ให้การรักษาท่านก่อนตัดสินใจเข้าร่วมในการวิจัย

ข้อปฏิบัติของท่านขณะที่ร่วมในโครงการวิจัย

ขอให้ท่านปฏิบัติดังนี้

- ขอให้ท่านให้ข้อมูลทางการแพทย์ของท่านทั้งในอดีต และปัจจุบัน แก่ผู้ทำวิจัยด้วยความสัตย์จริง
- ขอให้ท่านแจ้งให้ผู้ทำวิจัยทราบความผิดปกติที่เกิดขึ้นระหว่างที่ท่านร่วมในโครงการวิจัย

อันตรายที่อาจเกิดขึ้นจากการเข้าร่วมในโครงการวิจัยและความรับผิดชอบของผู้ทำวิจัย/ผู้สนับสนุนการวิจัย

หากพบอันตรายที่เกิดขึ้นจากการวิจัย ท่านจะได้รับการรักษาอย่างเหมาะสมทันที และท่านปฏิบัติตามคำแนะนำของทีมผู้ทำวิจัยแล้ว ผู้ทำวิจัย/ผู้สนับสนุนการวิจัยยินดีจะรับผิดชอบค่าใช้จ่ายในการรักษาพยาบาลของท่าน และการลงนามในเอกสารให้ความยินยอม ไม่ได้หมายความว่าท่านได้สละสิทธิ์ทางกฎหมายตามปกติที่ท่านพึงมี

ในกรณีที่ท่านได้รับอันตรายใด ๆ หรือต้องการข้อมูลเพิ่มเติมที่เกี่ยวข้องกับโครงการวิจัย ท่านสามารถติดต่อกับผู้ทำวิจัยคือ นายทศพล เจศรีชัย ได้ที่หมายเลขโทรศัพท์ 086 – 533-3860 ได้ตลอด 24 ชั่วโมง

ค่าใช้จ่ายของท่านในการเข้าร่วมการวิจัย

ท่านจะได้รับการตรวจวัดมุมการเคลื่อนไหวของข้อเข่าโดยไม่ต้องเสียค่าใช้จ่ายใดๆ ทั้งสิ้น

ค่าตอบแทนสำหรับผู้เข้าร่วมวิจัย (ถ้ามี)

ท่านจะไม่ได้รับเงินค่าตอบแทนในการเข้าร่วมการวิจัย แต่ท่านจะได้รับค่าเดินทาง ค่าเสียเวลา และ ค่าชดเชยการสูญเสียรายได้ ครั้งละ 200 บาท รวมทั้งหมด 1 ครั้ง

การเข้าร่วมและการสิ้นสุดการเข้าร่วมโครงการวิจัย

การเข้าร่วมในโครงการวิจัยครั้งนี้เป็นไปโดยความสมัครใจ หากท่านไม่สมัครใจจะเข้าร่วมการศึกษาแล้ว ท่านสามารถถอนตัวได้ตลอดเวลา การขอถอนตัวออกจากโครงการวิจัยจะไม่มีผลต่อการดูแลรักษาโรคของท่านแต่อย่างใด

ผู้ทำวิจัยอาจถอนท่านออกจากการเข้าร่วมการวิจัย เพื่อเหตุผลด้านความปลอดภัยของท่าน หรือเมื่อผู้สนับสนุนการวิจัยยุติการดำเนินงานวิจัย หรือ ในกรณีดังต่อไปนี้

- ท่านไม่สามารถปฏิบัติตามคำแนะนำของผู้ทำวิจัย
- พบว่าท่านมีปัญหาไม่สามารถเดินพื้นราบและเดินขึ้น-ลงบันได 3 ขั้นได้

<u>การปกป้องรักษาข้อมูลความลับของอาสาสมัคร</u>

ข้อมูลที่อาจนำไปสู่การเปิดเผยตัวท่าน จะได้รับการปกปิดและจะไม่เปิดเผยแก่สาธารณชน ในกรณีที่ผลการวิจัยได้รับการตีพิมพ์ ชื่อและที่อยู่ของท่านจะต้องได้รับการปกปิดอยู่เสมอ โดยจะใช้เฉพาะรหัสประจำโครงการวิจัยของท่าน

จากการลงนามยินยอมของท่านผู้ทำวิจัย และผู้สนับสนุนการวิจัยสามารถเข้าไปตรวจสอบบันทึกข้อมูลทางการแพทย์ของท่านได้แม้จะสิ้นสุดโครงการวิจัยแล้วก็ตาม หากท่านต้องการยกเลิกการให้สิทธิ์ดังกล่าว ท่านสามารถแจ้ง หรือเขียนบันทึกขอยกเลิกการให้คำยินยอม โดยส่งไปที่ นายทศพล เจศรีชัย หลักสูตรวิศวกรรมชีวเวช คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ถนนพญาไท แขวงวังใหม่ ปทุมวัน กรุงเทพฯ 10330

หากท่านขอยกเลิกการให้คำยินยอมหลังจากที่ท่านได้เข้าร่วมโครงการวิจัยแล้ว ข้อมูลส่วนตัวของท่านจะไม่ถูกบันทึกเพิ่มเติม อย่างไรก็ตามข้อมูลอื่น ๆ ของท่านอาจถูกนำมาใช้เพื่อประเมินผลการวิจัย และท่านจะไม่สามารถกลับมาเข้าร่วมในโครงการนี้ได้อีก ทั้งนี้เนื่องจากข้อมูลของท่านที่จำเป็นสำหรับใช้เพื่อการวิจัยไม่ได้ถูกบันทึก

จากการลงนามยินยอมของท่านแพทย์ผู้ทำวิจัยสามารถบอกรายละเอียดของท่านที่เกี่ยวกับการเข้าร่วมโครงการวิจัยนี้ให้แก่แพทย์ผู้รักษาท่านได้

<u>สิทธิ์ของผู้เข้าร่วมในโครงการวิจัย</u>

ในฐานะที่ท่านเป็นผู้เข้าร่วมในโครงการวิจัย ท่านจะมีสิทธิ์ดังต่อไปนี้

1. ท่านจะได้รับทราบถึงลักษณะและวัตถุประสงค์ของการวิจัยในครั้งนี้
2. ท่านจะได้รับการอธิบายเกี่ยวกับระเบียบวิธีการของการวิจัยทางการแพทย์ และอุปกรณ์ที่ใช้ในการวิจัยครั้งนี้
3. ท่านจะได้รับการอธิบายถึงความเสี่ยงและความไม่สบายที่จะได้รับจากการวิจัย
4. ท่านจะได้รับการอธิบายถึงประโยชน์ที่ท่านอาจจะได้รับจากการวิจัย
5. ท่านจะมีโอกาสได้ซักถามเกี่ยวกับงานวิจัยหรือขั้นตอนที่เกี่ยวข้องกับงานวิจัย
6. ท่านจะได้รับทราบว่าการยินยอมเข้าร่วมในโครงการวิจัยนี้ ท่านสามารถขอถอนตัวจากโครงการเมื่อไรก็ได้ โดยผู้เข้าร่วมในโครงการวิจัยสามารถขอถอนตัวจากโครงการโดยไม่ได้รับผลกระทบใด ๆ ทั้งสิ้น
7. ท่านจะได้รับสำเนาเอกสารใบยินยอมที่มีทั้งลายเซ็นและวันที่
8. ท่านมีสิทธิ์ในการตัดสินใจว่าจะเข้าร่วมในโครงการวิจัยหรือไม่ก็ได้ โดยปราศจากการใช้อิทธิพลบังคับข่มขู่ หรือการหลอกลวง

หากท่านไม่ได้รับการชดเชยอันควรต่อการบาดเจ็บหรือเจ็บป่วยที่เกิดขึ้นโดยตรงจากการวิจัย หรือท่านไม่ได้รับการปฏิบัติตามที่ปรากฏในเอกสารข้อมูลคำอธิบายสำหรับผู้เข้าร่วมในการวิจัย ท่านสามารถร้องเรียนได้ที่ คณะกรรมการจริยธรรมการวิจัย คณะแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ตึกอานันทมหิดลชั้น 3 โรงพยาบาลจุฬาลงกรณ์ ถนนพระราม 4 ปทุมวัน กรุงเทพฯ 10330 โทร 0-2256-4455 ต่อ 14, 15 ในเวลาราชการ

ขอขอบคุณในการร่วมมือของท่านมา ณ ที่นี้

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APPENDIX C1

RECORD FORM

โครงการวิจัย : การพัฒนาเซ็นเซอร์แบบพกพาเพื่อวัดการเคลื่อนไหวข้อเข่าและประยุกต์ใช้ในผู้ป่วยข้อเข่าเสื่อม
(Development of Mobile Sensors for Measurement of Knee Motion and Application for Patients with Knee Osteoarthritis)

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สำหรับอาสาสมัครที่มีสุขภาพดีไม่มีปัญหาด้านการเดิน เพื่อเข้าร่วมการทดสอบความเชื่อถือได้ของชุดเครื่องมือวัดองศาการเคลื่อนไหวข้อเข่าด้วย IMU

ลำดับที่ผู้เข้าร่วมวิจัย .... วันที่ .... / .... / ....

สถานที่ที่ทำการเก็บข้อมูล ....

ข้อมูลส่วนบุคคล

เพศ ○ ชาย ○ หญิง อายุ .... ปี

น้ำหนัก .... กิโลกรัม ส่วนสูง .... เซนติเมตร

ความยาวขา (วัดจาก Anterior Superior Iliac Spine ;ASIS ถึง medial malleolus)

ขาซ้าย....................ซม. ขาขวา.............ซม.

ความยาวต้นขา (วัดจาก Greater trochanter ถึง lateral joint line of knee)

ขาซ้าย....................ซม. ขาขวา................ซม

เส้นรอบวงของต้นขา วัดที่จุดกึ่งกลางของส่วนต้นขา

ขาซ้าย....................ซม. ขาขวา................ซม

ความยาวขาท่อนปลาย (วัดจาก lateral joint line of knee ถึง lateral malleolus)

ขาซ้าย....................ซม. ขาขวา..............ซม

เส้นรอบวงของขาท่อนปลาย วัดที่จุดกึ่งกลางของขาท่อนปลาย

ขาซ้าย....................ซม. ขาขวา................ซม

ข้อมูลเกี่ยวกับสุขภาพ

1. มีสุขภาพแข็งแรง ไม่มีโรคประจำตัว ○ ใช่ ○ไม่ใช่..........
2. ไม่มีโรคหรือความผิดปกติที่ส่วนขาและข้อเข่า ○ ใช่ ○ไม่ใช่.........
3. สามารถเดินได้เป็นปกติ ○ ใช่ ○ไม่ใช่.........
4. ไม่มีความผิดปกติของการทรงตัวหรือการควบคุมการเคลื่อนไหว ○ ใช่ ○ไม่ใช่.........

แบบบันทึกผลการทดลอง

การเคลื่อนไหวที่ทดสอบ	**ขาข้าง**	**ช่วงองศาการเคลื่อนไหวข้อเข่าที่วัดได้จากระบบกล้อง 3 มิติ**	**ช่วงองศาการเคลื่อนไหวข้อเข่าที่วัดได้จาก IMU**	**ช่วงผลต่างขององศาที่เปรียบเทียบระหว่าง 2 ระบบ**	Comment
การงอเข่าไปด้านหน้า	ขาซ้าย				
	ขาขวา				
การงอเข่าไปด้านหลัง	ขาซ้าย				
	ขาขวา				
การกางและหุบข้อสะโพก	ขาซ้าย				
	ขาขวา				
การก้าวไปข้างหน้า-กลับที่เดิม	ขาซ้าย				
	ขาขวา				
การเดินใน 1 วงรอบการเดิน					

APPENDIX C2

CASE RECORD FORM

โครงการวิจัย : การพัฒนาเซ็นเซอร์แบบพกพาเพื่อวัดการเคลื่อนไหวข้อเข่าและประยุกต์ใช้ใน ผู้ป่วยข้อเข่าเสื่อม

(Development of Mobile Sensors for Measurement of Knee Motion and Application for Patients with Knee Osteoarthritis)

****

สำหรับอาสาสมัครที่เข้าร่วมการทดสอบเปรียบเทียบผลการวัดองศาการเคลื่อนไหวข้อเข่าใน ผู้ป่วยข้อเข่าเสื่อม

ลำดับที่ผู้เข้าร่วมวิจัย .... วันที่ .... / .... / ....

สถานที่ที่ทำการเก็บข้อมูล ....

ข้อมูลส่วนบุคคล

เพศ ○ ชาย ○ หญิง อายุ .... ปี

น้ำหนัก .... กิโลกรัม ส่วนสูง .... เซนติเมตร

ความยาวขา (วัดจาก Anterior Superior Iliac Spine ;ASIS ถึง medial malleolus)

ขาซ้าย...................ซม. ขาขวา...............ซม.

ความยาวต้นขา (วัดจาก Greater trochanter ถึง lateral joint line of knee)

ขาซ้าย...................ซม. ขาขวา...............ซม

เส้นรอบวงของต้นขา วัดที่จุดกึ่งกลางของส่วนต้นขา

ขาซ้าย................ซม. ขาขวา...............ซม

ความยาวขาท่อนปลาย (วัดจาก lateral joint line of knee ถึง lateral malleolus)

ขาซ้าย...................ซม. ขาขวา...............ซม

เส้นรอบวงของขาท่อนปลาย วัดที่จุดกึ่งกลางของขาท่อนปลาย

ขาซ้าย...................ซม.   ขาขวา...............ซม

ข้อมูลเกี่ยวกับสุขภาพ

5. มีอาการของโรคข้อเข่าเสื่อม	◯ ใช่	◯ไม่ใช่
6. มีอาการเสื่อมของข้อเข่า	◯ 1 ข้าง ข้าง.........	◯ทั้ง 2 ข้าง (ข้าง...........มีอาการมากกว่า)
7. สามารถเดินพื้นราบในระยะ 10 เมตร	◯ ใช่	◯ไม่ใช่
8. สามารถเดินขึ้น-ลงบันได 3 ขั้นได้	◯ ใช่	◯ไม่ใช่

แบบบันทึกผลการทดลอง

<u>การเดินระยะ 10 เมตร</u>

จำนวนก้าวที่เดิน   ขาซ้าย............................ก้าว   ขาขวา...........................ก้าว

เวลาทั้งหมดที่ใช้ในการเดิน.............................วินาที

จำนวนวงรอบการเดินที่สามารถนำมาเปรียบเทียบทดสอบ...............................วงรอบ

มีอาการเจ็บเกิดขึ้นหรือไม่   ◯ ไม่มี   ◯ มี จำนวน..........ครั้ง ที่ขาข้าง................

***<u>หมายเหตุ</u>**   ข้อมูลองศาการเคลื่อนไหวข้อเข่าจะถูกบันทึกและวิเคราะห์ในโปรแกรมคอมพิวเตอร์

APPENDIX D

CERTIFICATE OF APPROVAL

COA No. 039/2013

IRB No. 485/55

INSTITUTIONAL REVIEW BOARD

Faculty of Medicine, Chulalongkorn University

1873 Rama 4 Road, Patumwan, Bangkok 10330, Thailand, Tel 662-256-4455 ext 14, 15

Certificate of Approval

The Institutional Review Board of the Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand, has approved the following study which is to be carried out in compliance with the International guidelines for human research protection as Declaration of Helsinki, The Belmont Report, CIOMS Guideline and International Conference on Harmonization in Good Clinical Practice (ICH-GCP)

Study Title : Development of Mobile Sensors for Measurement of Knee Motion

Study Code : -

Principal Investigator : Mr.Tossaphon Jaysrichai

Study Center : Biomedical Engineering program, Faculty of engineering, Chulalongkorn University.

Review Method : Full board

Continuing Report : At least once annually or submit the final report if finished.

Document Reviewed :

1. Protocol Version 2.0 Dated 27 Dec. 2012
2. Protocol Synopsis Version 2.0 Dated 27 Dec 2012
3. Information sheet research for participants to test the validity of measuring degrees of knee motion with inertial sensors Version 3.0 Dated 11 Jan 2013
4. Information sheet research for a comparison test between the knee and the elderly who have no symptoms of osteoarthritis Version 3.0 Dated 11 Jan 2013
5. Informed Consent Form Version 2.0 Dated 27 Dec 2012
6. Invited to join the project Version 3.0 Dated 11 Jan 2013
7. Case Record Form Version 1.0 Dated 5 Nov 2012
8. Principle Investigator's Curriculum Vitae

Signature: Tada Sueblinvong
(Emeritus Professor Tada Sueblinvong MD)
Chairperson
The Institutional Review Board

Signature: Supeecha Wittayalertpanya
(Associate Professor Supeecha Wittayalertpanya)
Member and Assistant Secretary, Acting
Secretary The Institutional Review Board

Date of Approval : January 22, 2013

Approval Expire Date : January 21, 2014

Approval granted is subject to the following conditions: (see back of this Certificate)

All approved investigators must comply with the following conditions:

1. Strictly conduct the research as required by the protocol;
2. Use only the information sheet, consent form (and recruitment materials, if any), interview outlines and/or questionnaires bearing the Institutional Review Board's seal of approval ; and return one copy of such documents of the first subject recruited to the Institutional Review Board (IRB) for the record;
3. Report to the Institutional Review Board any serious adverse event or any changes in the research activity within five working days;
4. Provide reports to the Institutional Review Board concerning the progress of the research upon the specified period of time or when requested;
5. If the study cannot be finished within the expire date of the approval certificate, the investigator is obliged to reapply for approval at least one month before the date of expiration.
6. If the research project is completed, the researcher must be form the Faculty of Medicine, Chulalongkorn University.

* A list of the Institutional Review Board members (names and positions) present at the meeting of Institutional Review Board on the date of approval of this study has been attached. All approved documents will be forwarded to the principal investigator.

COA No. 039/2013

IRB No. 485/55

คณะกรรมการจริยธรรมการวิจัยในคน

คณะแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

1873 ถ.พระราม 4 เขตปทุมวัน กรุงเทพฯ 10330 โทร. 0-2256-4455 ต่อ 14, 15

เอกสารรับรองโครงการวิจัย

คณะกรรมการจริยธรรมการวิจัยในคน คณะแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ดำเนินการให้การรับรองโครงการวิจัยตามแนวทางหลักจริยธรรมการวิจัยในคนที่เป็นมาตรฐานสากลได้แก่ Declaration of Helsinki, The Belmont Report, CIOMS Guideline และ International Conference on Harmonization in Good Clinical Practice หรือ ICH-GCP

ชื่อโครงการ : การพัฒนาเซ็นเซอร์แบบพกพาเพื่อวัดการเคลื่อนไหวข้อเข่าและประยุกต์ใช้ในผู้ป่วยข้อเข่าเสื่อม

เลขที่โครงการวิจัย : -

ผู้วิจัยหลัก : นายทศพล เจศรีชัย

สังกัดหน่วยงาน : Biomedical Engineering program, Faculty of engineering, Chulalongkorn University.

วิธีทบทวน : คณะกรรมการเต็มชุด

รายงานความก้าวหน้า : ส่งรายงานความก้าวหน้าอย่างน้อย 1 ครั้ง/ปี หรือส่งรายงานฉบับสมบูรณ์หากดำเนินโครงการเสร็จสิ้นก่อน 1 ปี

เอกสารรับรอง :

1. โครงการวิจัย Version 2.0 Dated 27 Dec. 2012
2. โครงการวิจัยฉบับย่อ Version 2.0 Dated 27 Dec 2012
3. เอกสารข้อมูลคำอธิบายสำหรับผู้เข้าร่วมในโครงการวิจัย สำหรับผู้เข้าร่วมโครงการวิจัยส่วนการทดสอบความถูกต้องของเครื่องมือวัดองศาการเคลื่อนไหวของข้อเข่าด้วยเซ็นเซอร์วัดแรงเฉื่อย Version 3.0 Dated 11 Jan 2013
4. เอกสารข้อมูลคำอธิบายสำหรับผู้เข้าร่วมในโครงการวิจัย สำหรับผู้เข้าร่วมการทดสอบเปรียบเทียบการเคลื่อนไหวข้อเข่าระหว่างผู้สูงอายุที่มีและไม่มีอาการข้อเข่าเสื่อม Version 3.0 Dated 11 Jan 2013
5. เอกสารแสดงความยินยอมเข้าร่วมในโครงการวิจัย Version 2.0 Dated 27 Dec 2012
6. เอกสารเชิญชวนเข้าร่วมโครงการ Version 3.0 Dated 11 Jan 2013
7. Case Record Form Version 1.0 Dated 5 Nov 2012
8. Principle Investigator's Curriculum Vitae

ลงนาม .... ลงนาม..

(ศาสตราจารย์กิตติคุณแพทย์หญิงธาดา สืบหลินวงศ์) (รองศาสตราจารย์สุพีชา วิทยเลิศปัญญา)

ประธาน — กรรมการและผู้ช่วยเลขานุการปฏิบัติหน้าที่แทนเลขานุการ

คณะกรรมการจริยธรรมการวิจัยในคน — คณะกรรมการจริยธรรมการวิจัยในคน

วันที่รับรอง : 22 มกราคม 2556

วันหมดอายุ : 21 มกราคม 2557

ทั้งนี้ การรับรองนี้มีเงื่อนไขดังที่ระบุไว้ด้านหลังทุกข้อ (ดูด้านหลังของเอกสารรับรองโครงการวิจัย)

นักวิจัยทุกท่านที่ผ่านการรับรองจริยธรรมการวิจัยต้องปฏิบัติดังต่อไปนี้

1. ดำเนินการวิจัยตามที่ระบุไว้ในโครงร่างการวิจัยอย่างเคร่งครัด
2. ใช้เอกสารแนะนำอาสาสมัคร ใบยินยอม (และเอกสารเชิญเข้าร่วมวิจัยหรือใบโฆษณาถ้ามี) แบบสัมภาษณ์ และหรือ แบบสอบถาม เฉพาะที่มีตราประทับของคณะกรรมการพิจารณาจริยธรรมเท่านั้น และส่งสำเนาเอกสารดังกล่าวที่ใช้กับผู้เข้าร่วมวิจัยจริงรายแรกมาที่ฝ่ายวิจัย คณะแพทยศาสตร์ เพื่อเก็บไว้เป็นหลักฐาน
3. รายงานเหตุการณ์ไม่พึงประสงค์ร้ายแรงที่เกิดขึ้นหรือการเปลี่ยนแปลงกิจกรรมวิจัยใดๆ ต่อคณะกรรมการพิจารณาจริยธรรมการวิจัย ภายใน 5 วันทำการ
4. ส่งรายงานความก้าวหน้าต่อคณะกรรมการพิจารณาจริยธรรมการวิจัย ตามเวลาที่กำหนดหรือเมื่อได้รับการร้องขอ
5. หากการวิจัยไม่สามารถดำเนินการเสร็จสิ้นภายในกำหนด ผู้วิจัยต้องยื่นขออนุมัติใหม่ก่อนอย่างน้อย 1 เดือน
6. หากการวิจัยเสร็จสมบูรณ์ผู้วิจัยต้องแจ้งปิดโครงการตามแบบฟอร์มของคณะแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

* รายชื่อของคณะกรรมการจริยธรรมการวิจัยในคน (ชื่อและตำแหน่ง) ที่อยู่ในที่ประชุมวันที่รับรองโครงการวิจัยได้แนบมาด้วย เอกสารที่รับรองทั้งหมดจะถูกส่งไปยังผู้วิจัยหลัก

APPENDIX E

THE KNEE FLEXION TEST ON THE LEFT LEG

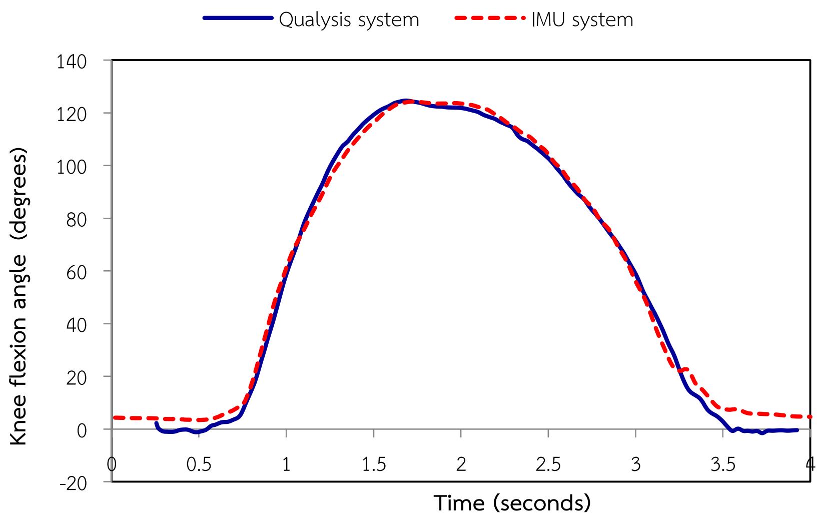

Figure E1 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 1).

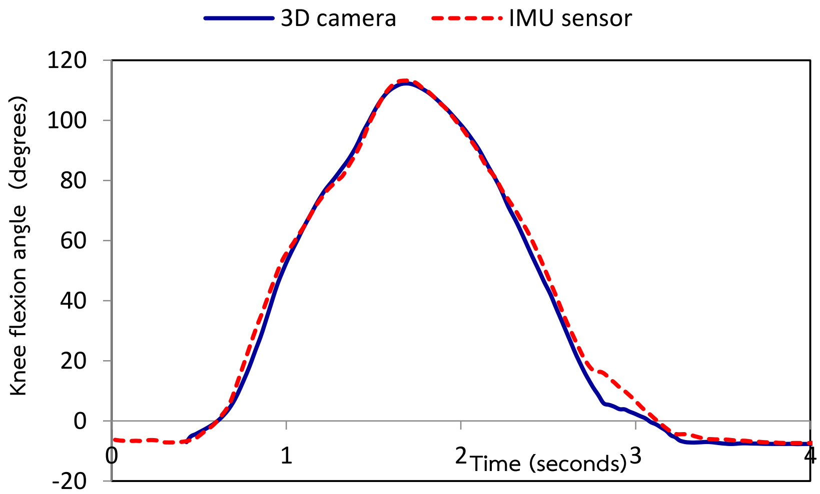

Figure E2 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test (The data are from the participant no. 2).

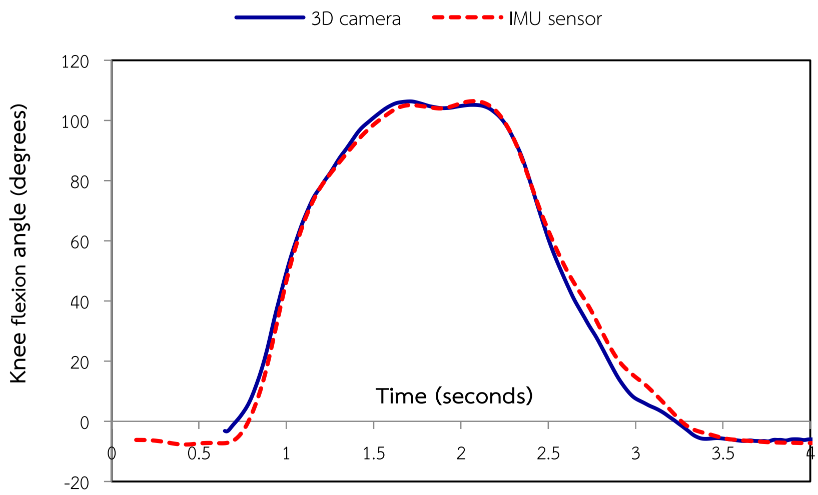

Figure E3 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 3).

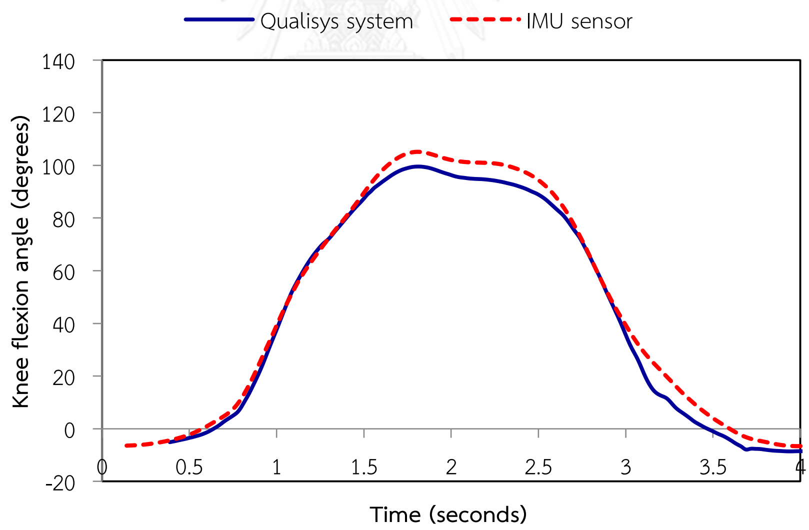

Figure E4 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 4).

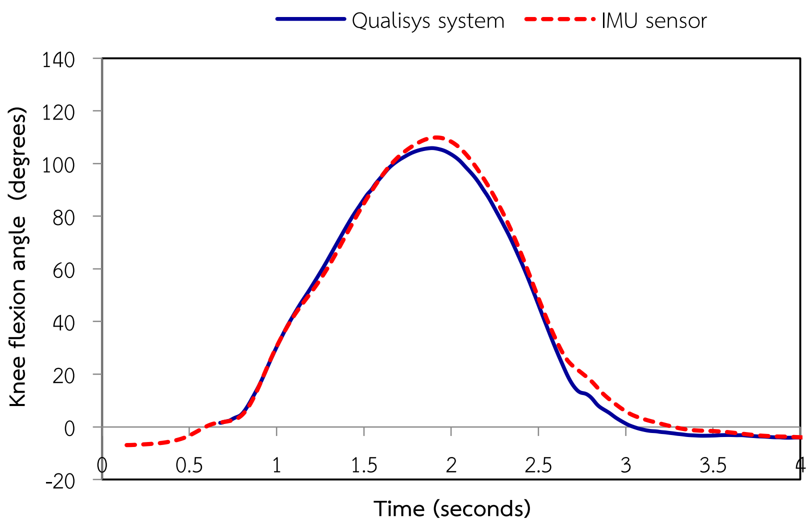

Figure E5 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 5).

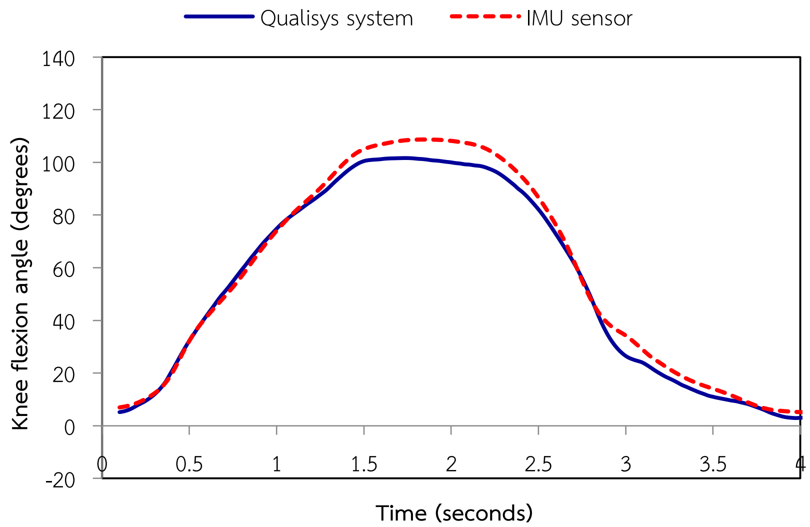

Figure E6 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 6).

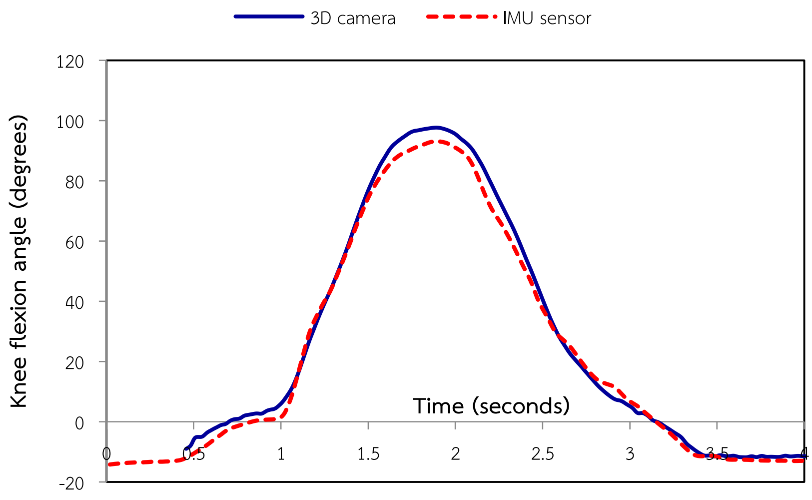

Figure E7 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 7).

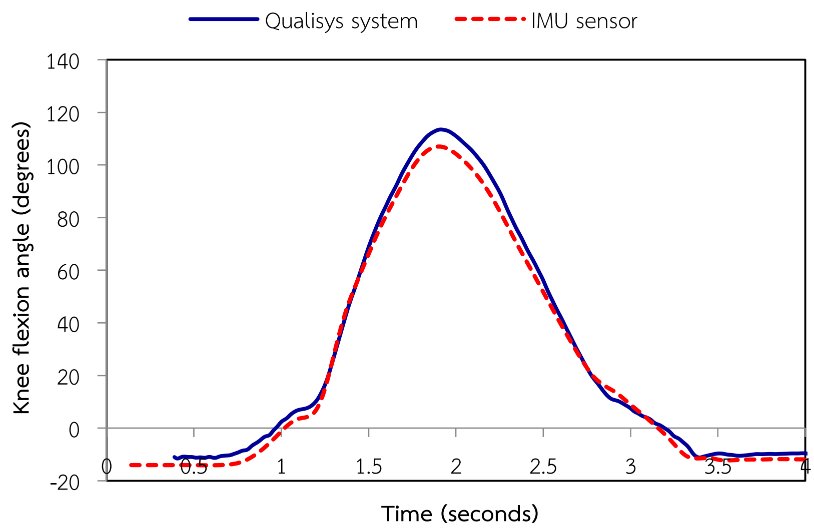

Figure E8 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 8).

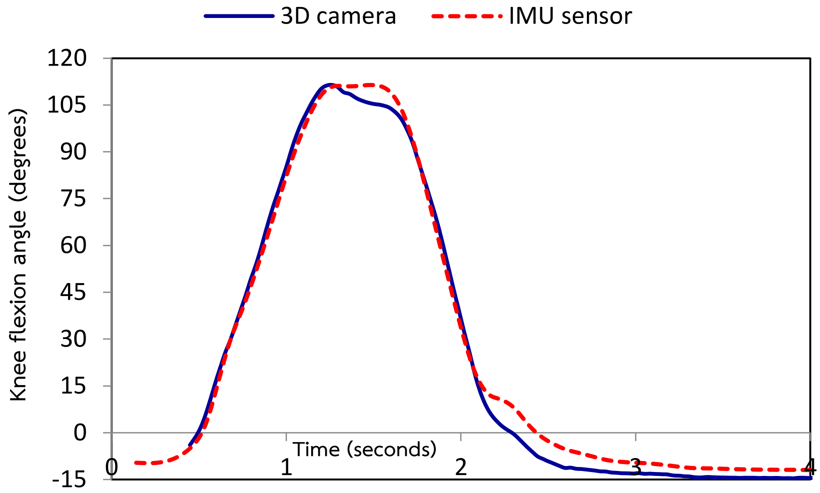

Figure E9 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 9).

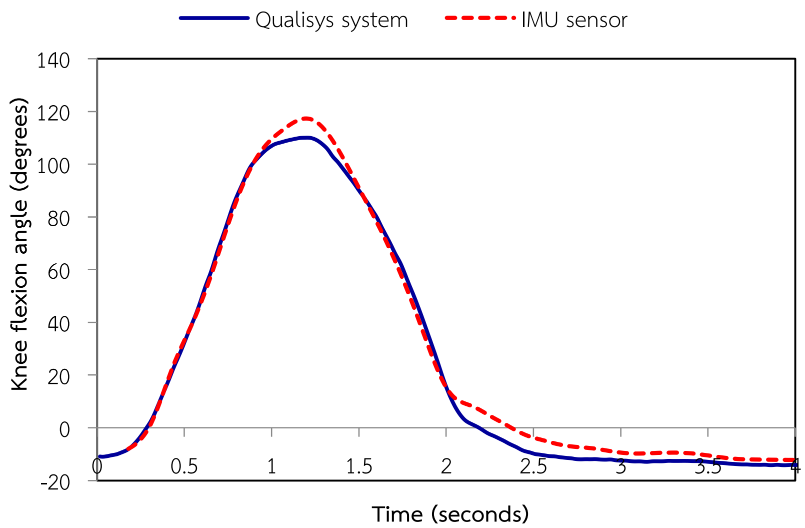

Figure E10 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 10).

APPENDIX F

THE KNEE FLEXION TEST ON THE RIGHT LEG

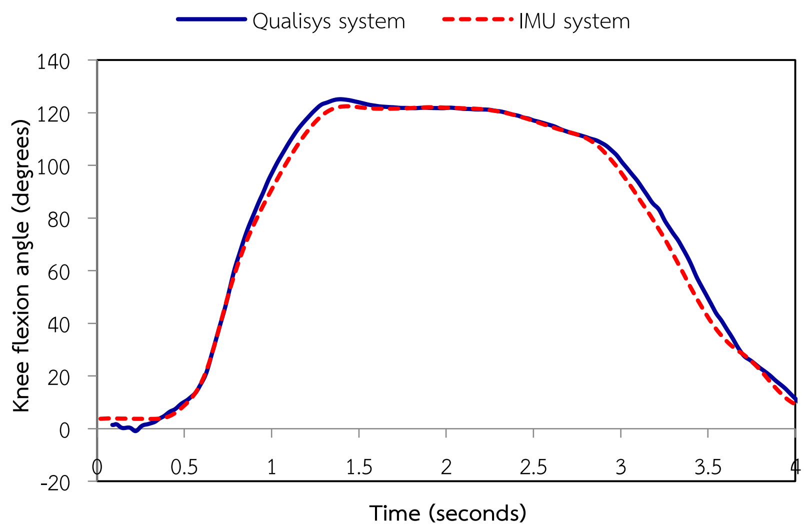

Figure F1 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 1).

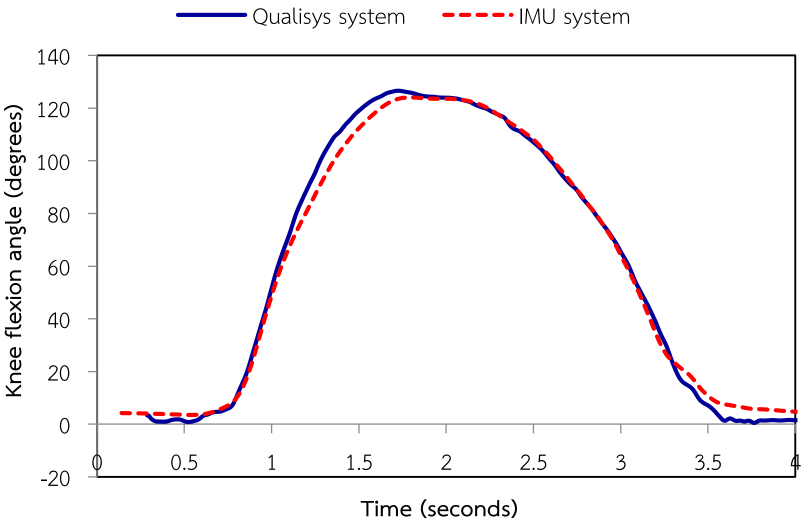

Figure F2 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 2).

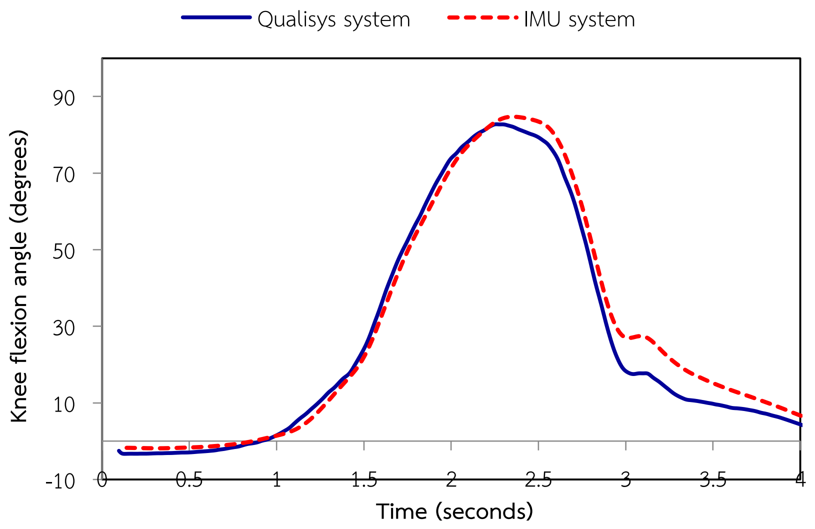

Figure F3 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 3).

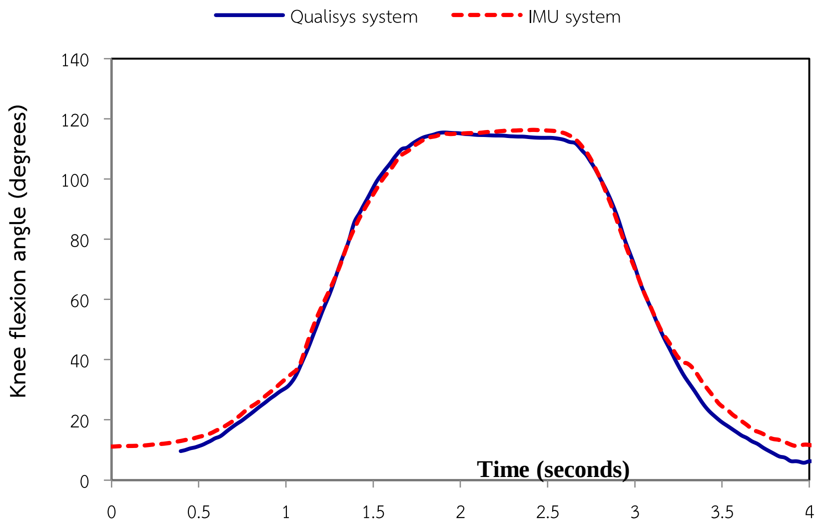

Figure F4 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 4).

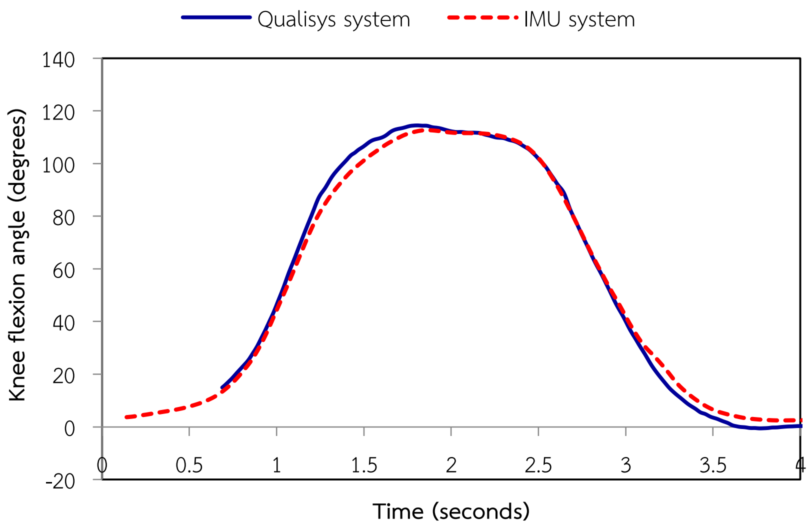

Figure F5 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 5).

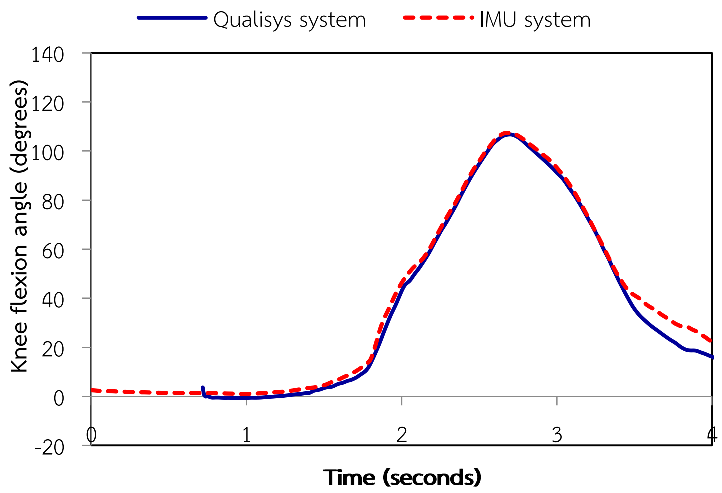

Figure F6 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 6).

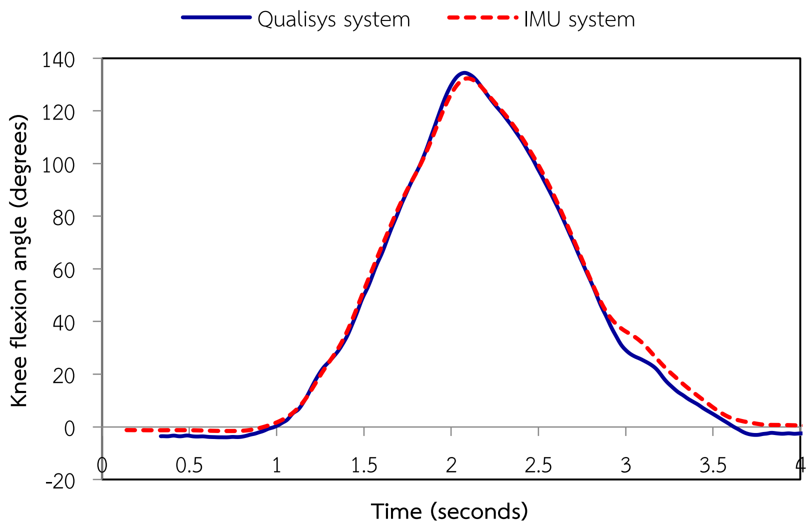

Figure F7 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 7).

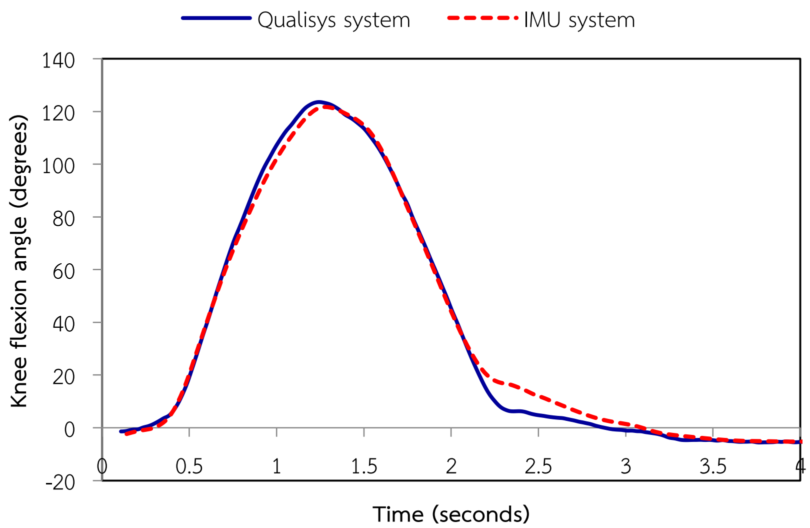

Figure F8 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 8).

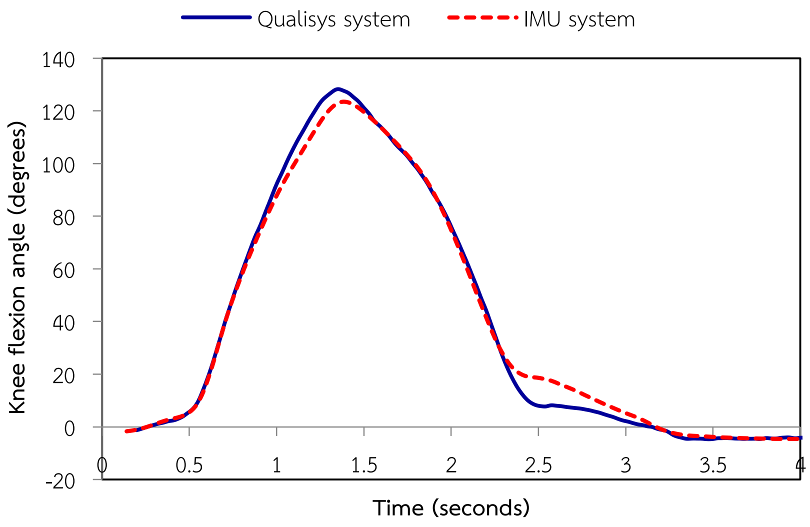

Figure F9 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 9).

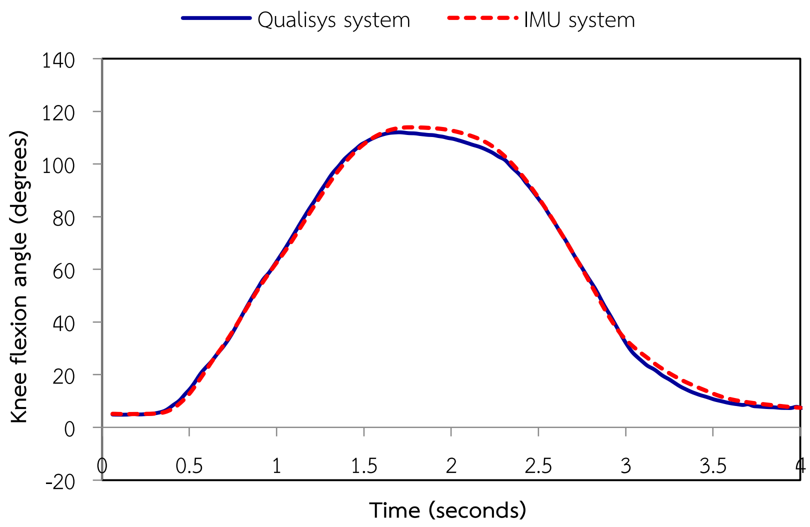

Figure F10 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the knee flexion test. (The data are from the participant no. 10).

APPENDIX G

THE HIP AND KNEE FLEXION TEST ON THE LEFT LEG

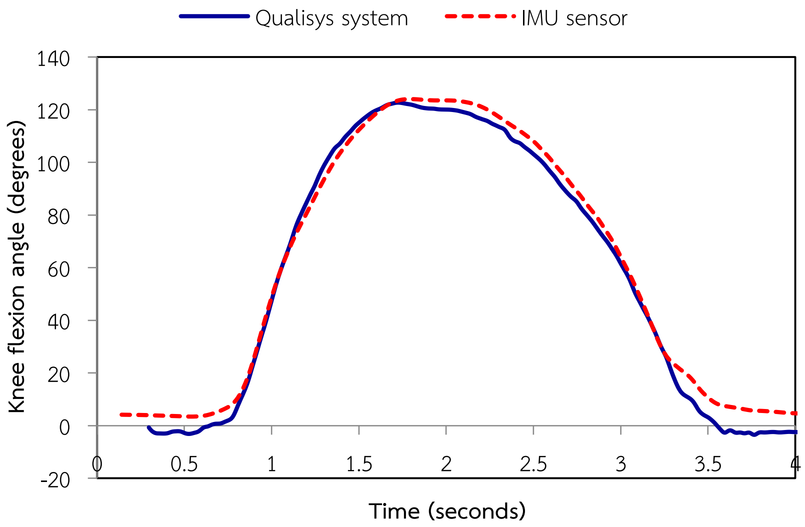

Figure G1 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.1).

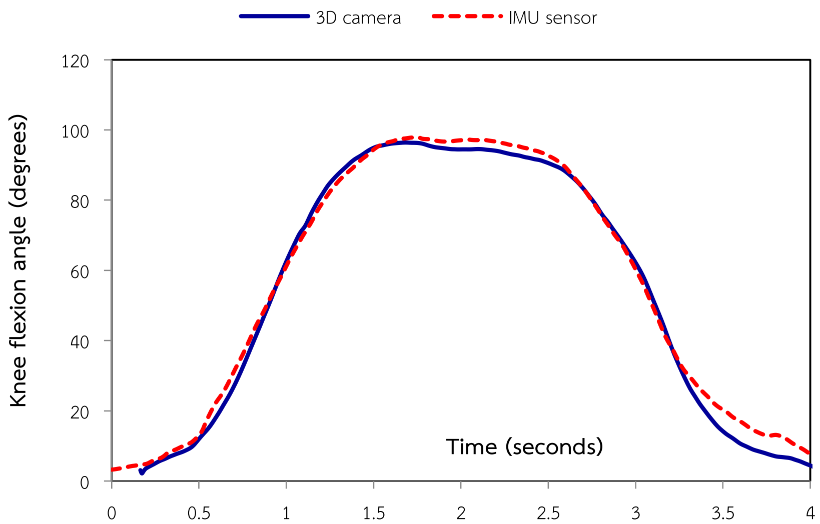

Figure G2 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the

Qualisys system, during the hip and knee flexion test. (The data are from the participant no.2).

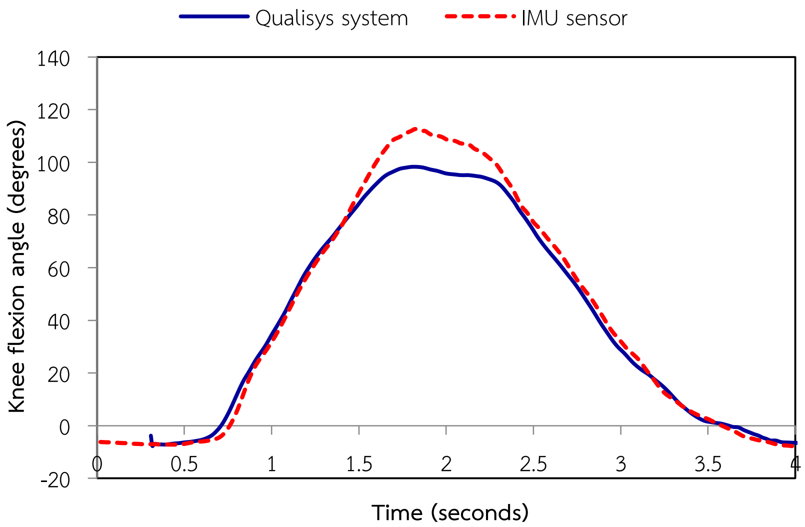

Figure G3 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.3).

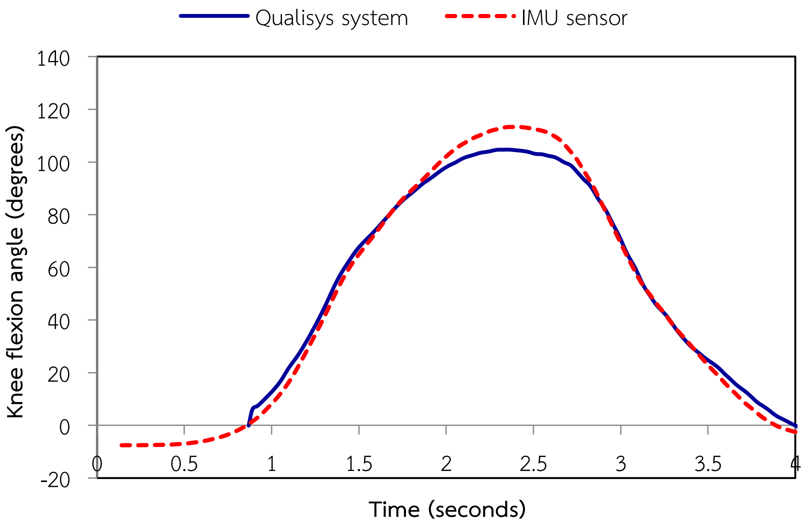

Figure G4 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the

Qualisys system, during the hip and knee flexion test. (The data are from the participant no.4).

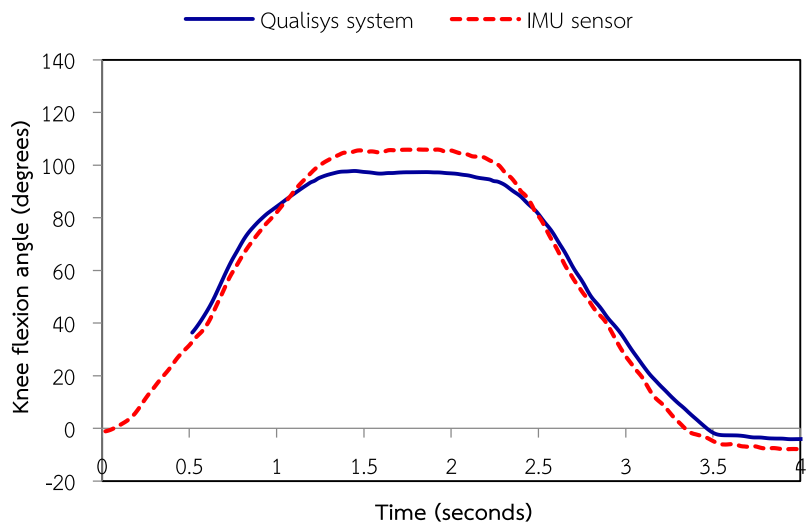

Figure G5 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.5).

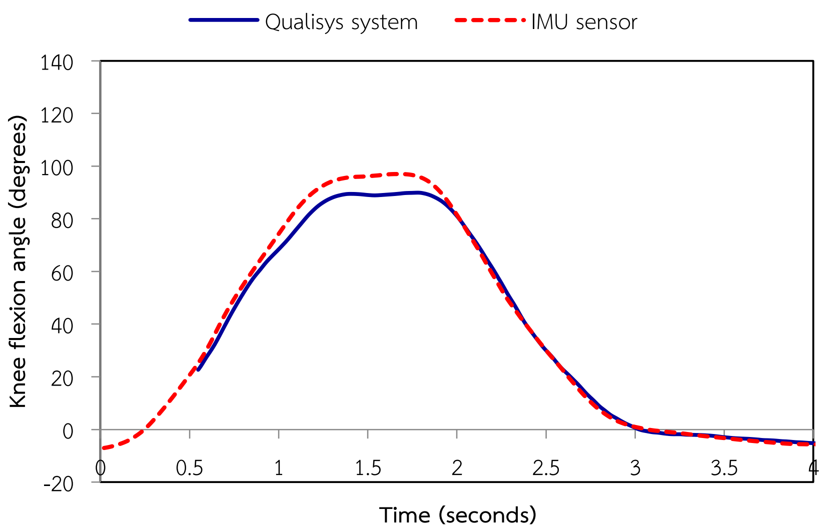

Figure G6 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the

Qualisys system, during the hip and knee flexion test. (The data are from the participant no.6).

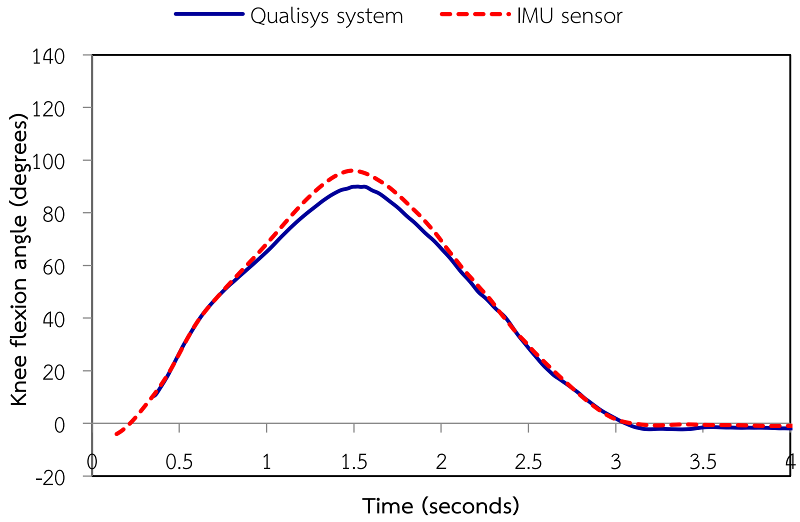

Figure G7 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.7).

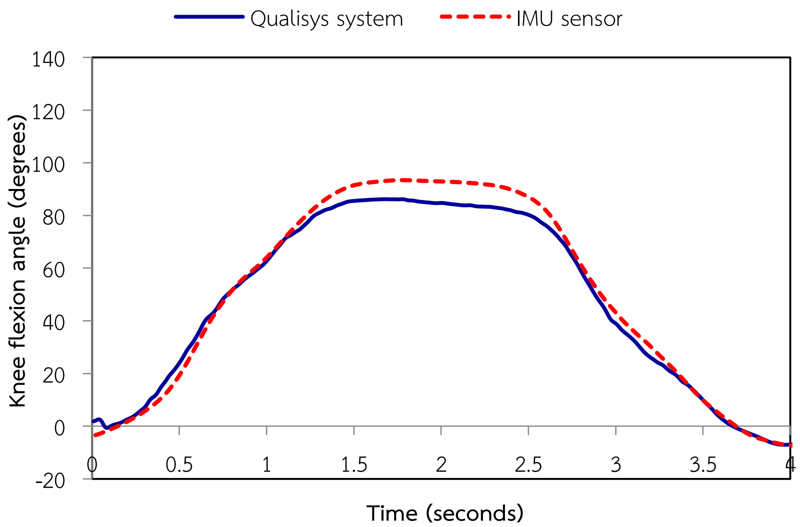

Figure G8 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the

Qualisys system, during the hip and knee flexion test. (The data are from the participant no.8).

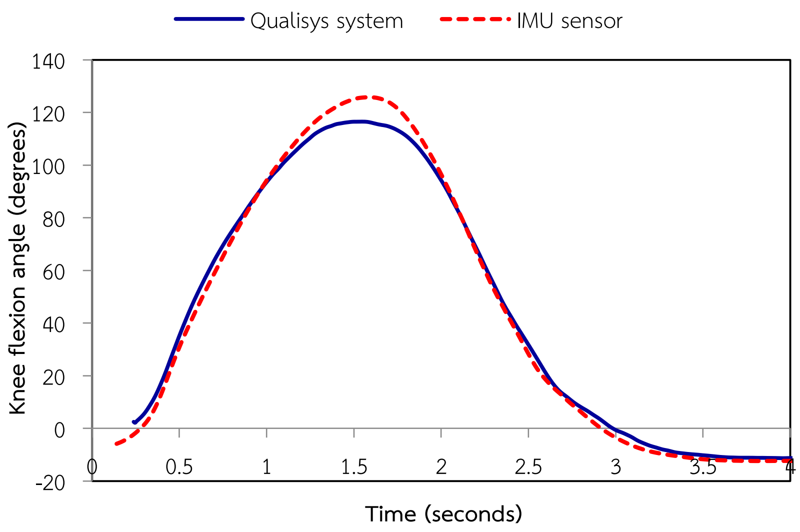

Figure G9 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.9).

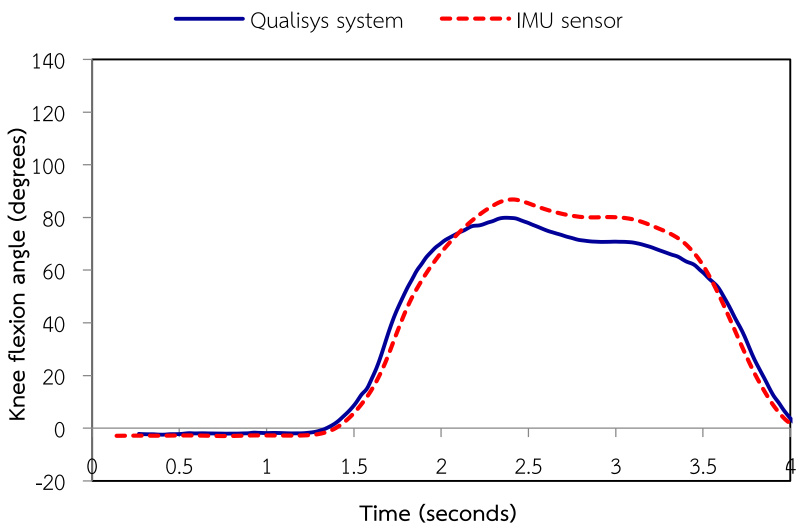

Figure G10 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.10).

APPENDIX H

THE HIP AND KNEE FLEXION TEST ON THE RIGHT LEG

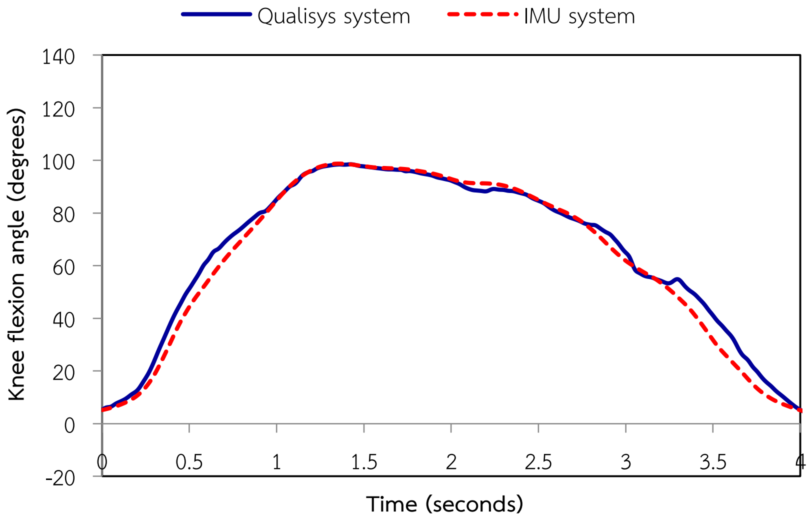

Figure H1 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.1).

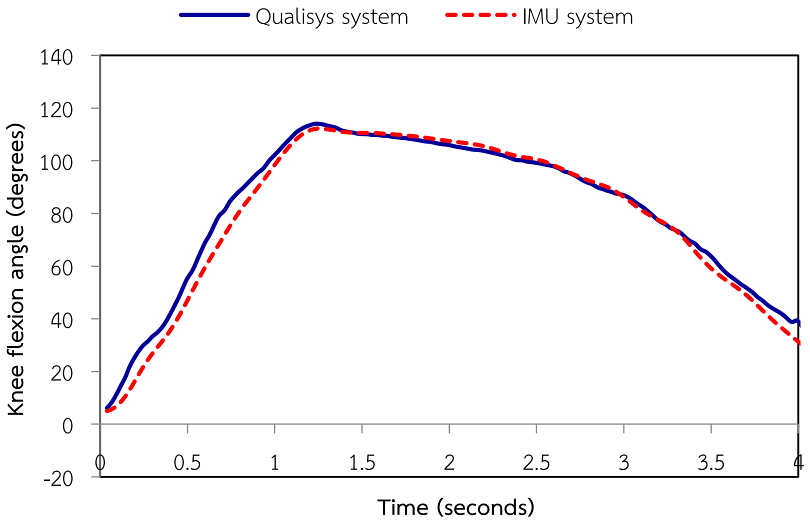

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Figure H2 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.1).

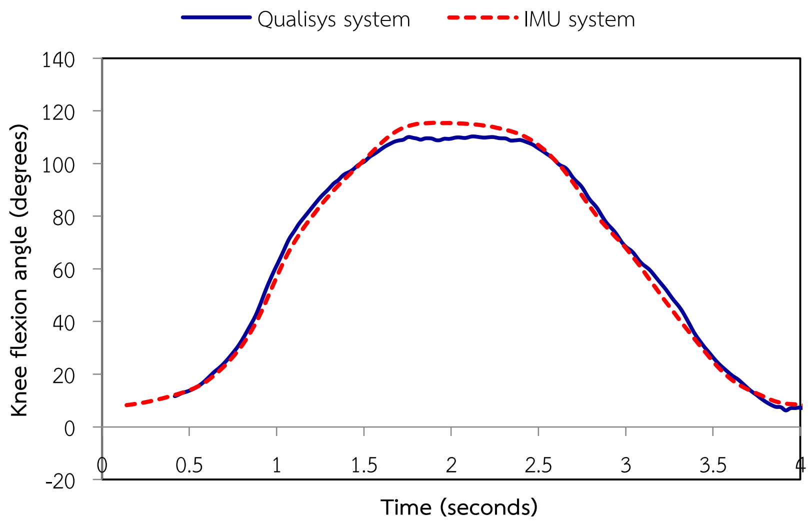


Figure H3 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.3).

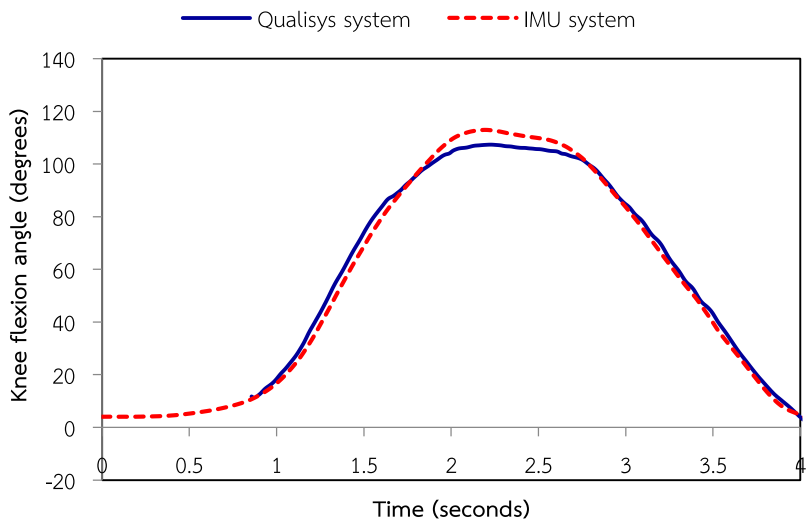


Figure H4 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.4).

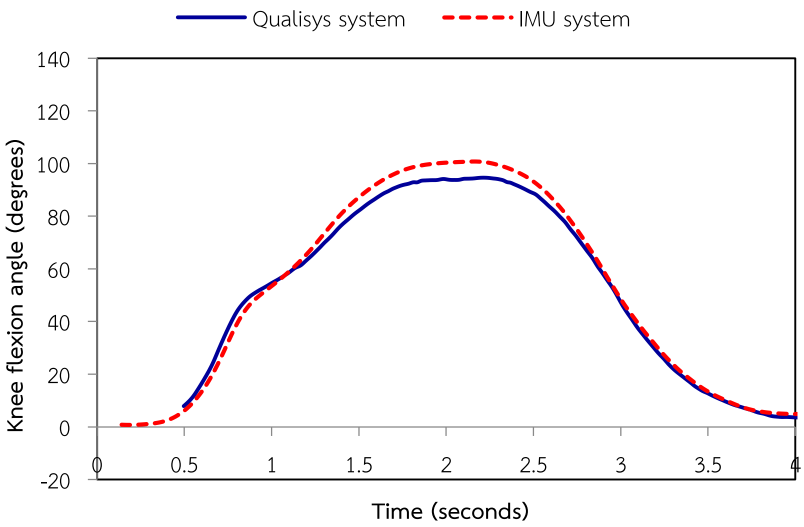


Figure H5 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.5).

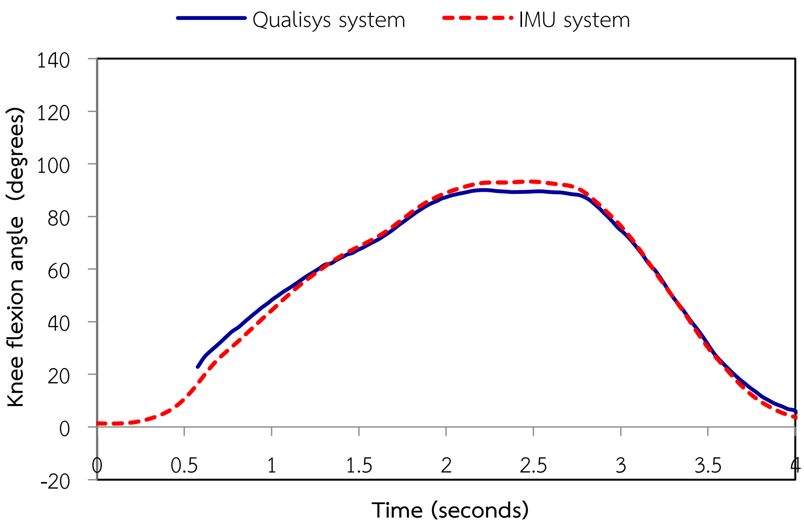


Figure H6 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.6).

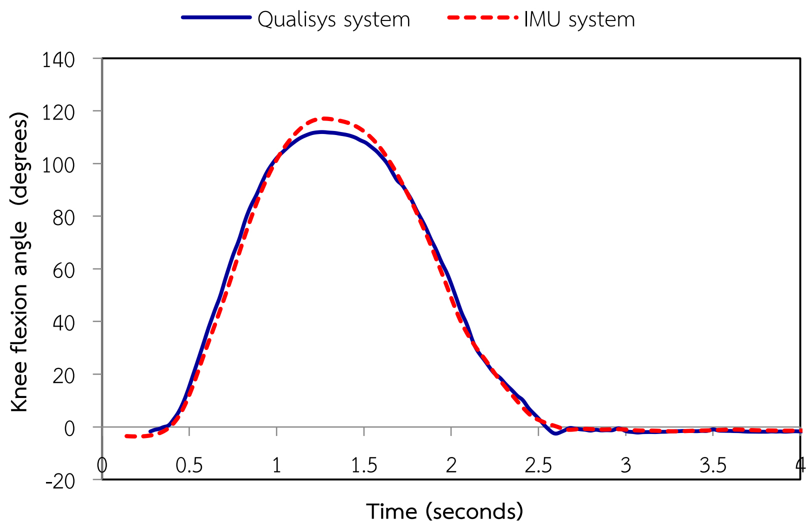


Figure H7 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.7).

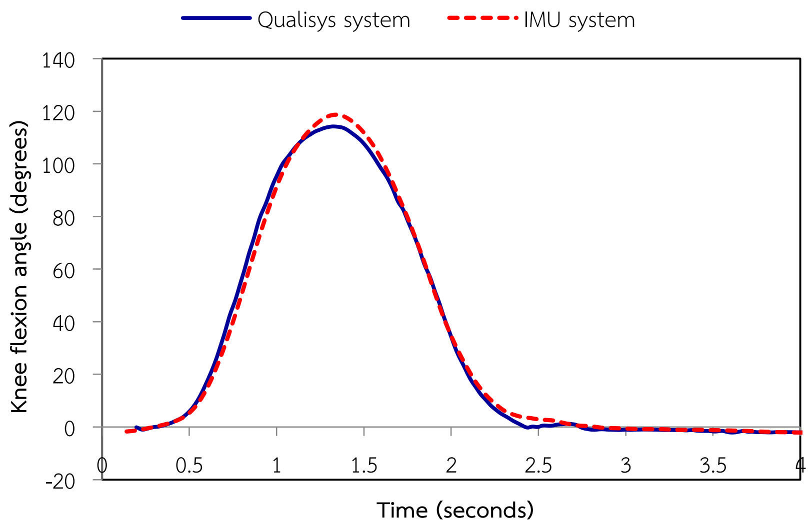


Figure H8 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.8).

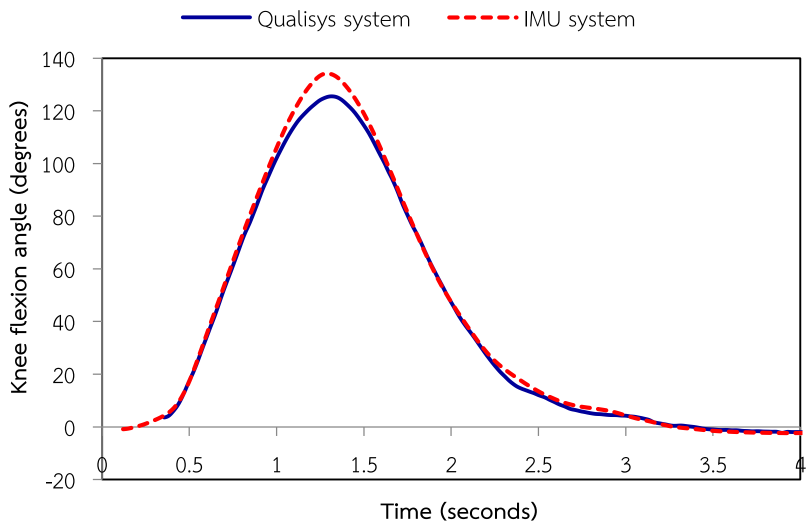


Figure H9 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.9).

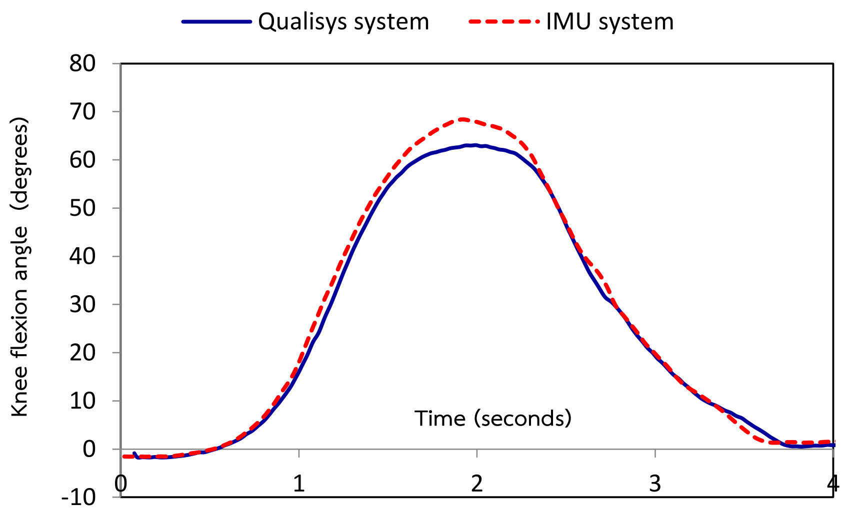


Figure H10 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the hip and knee flexion test. (The data are from the participant no.10).

APPENDIX I

THE FORWARD STEP TEST ON THE LEFT LEG

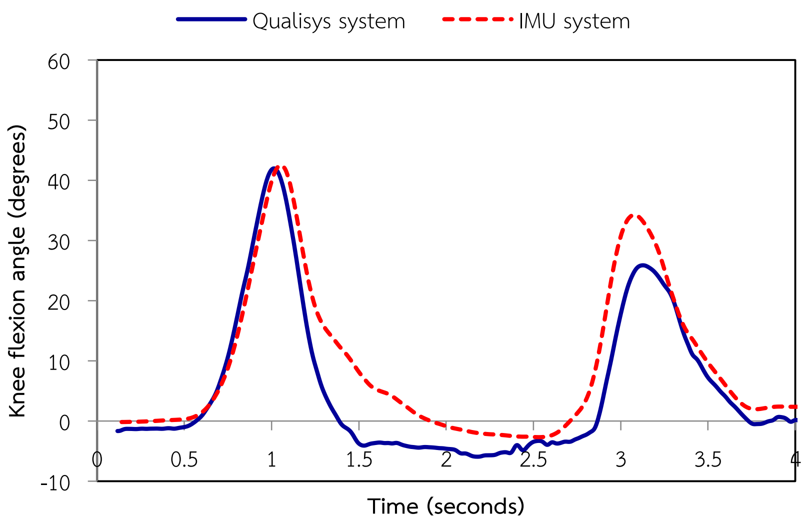


Figure I1 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.1).

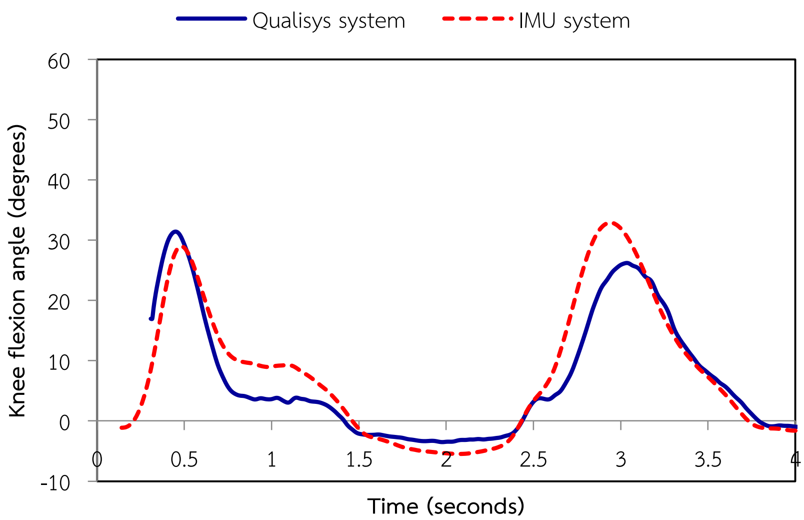


Figure I2 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.2).

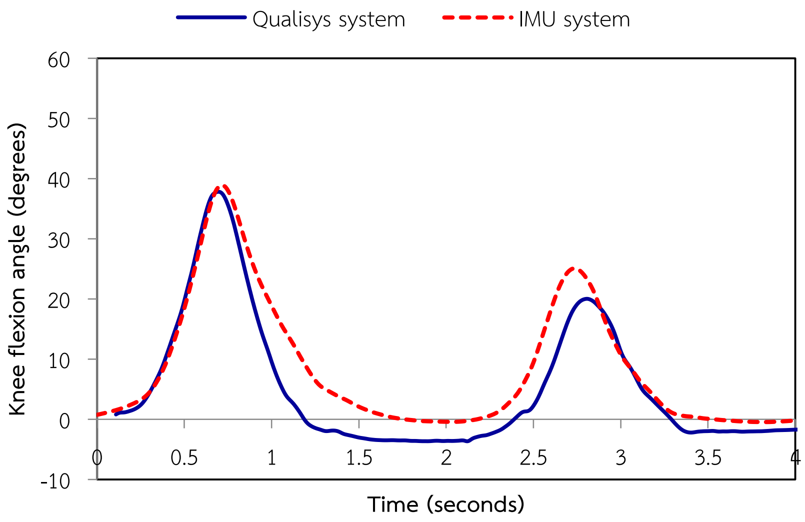


Figure 13 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.3).

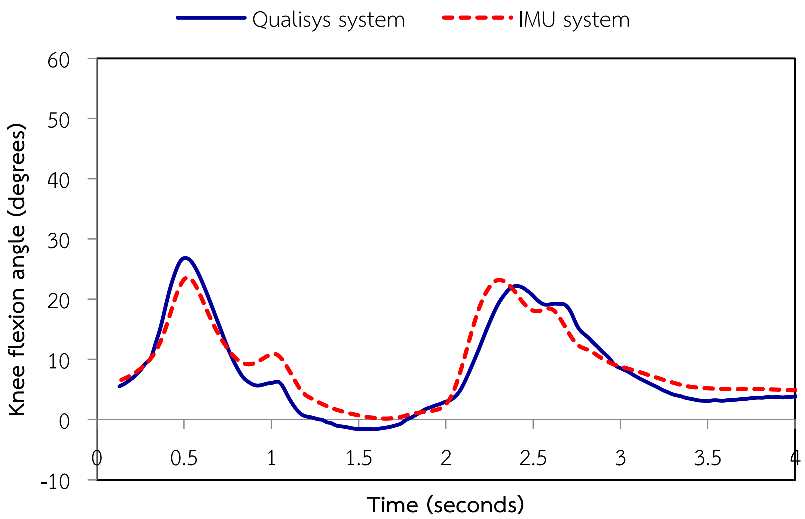


Figure 14 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.4)

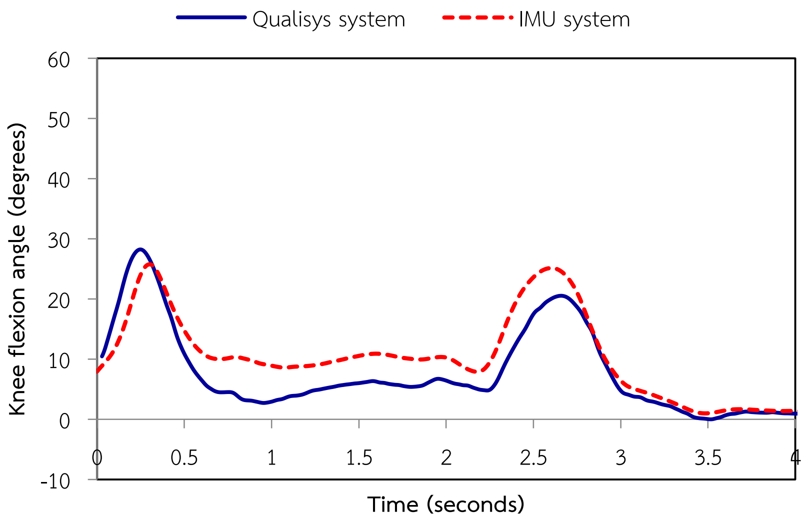


Figure I5 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.5).

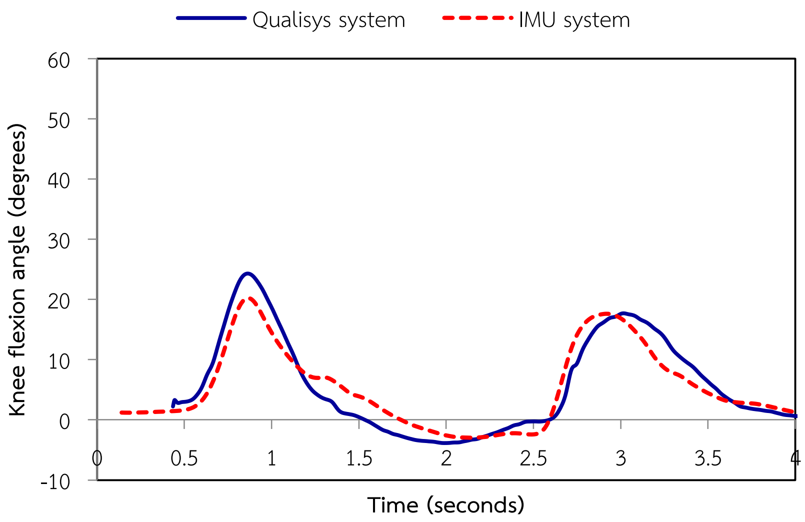


Figure I6 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.6)

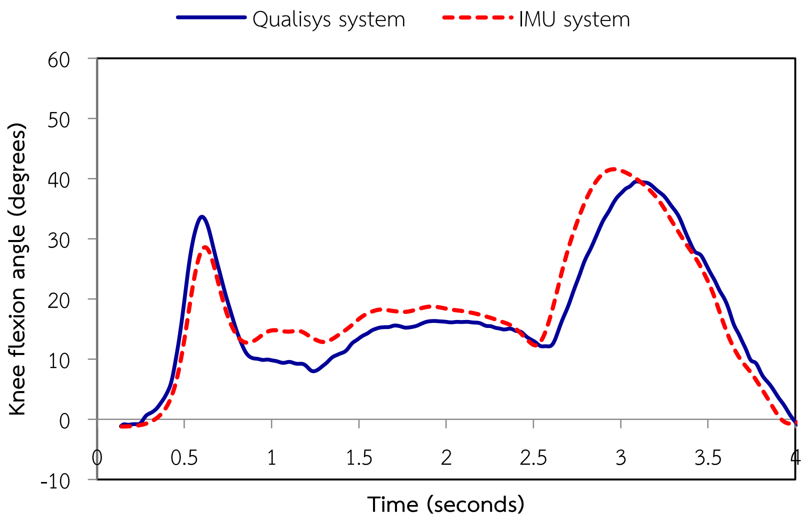


Figure I7 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.7).

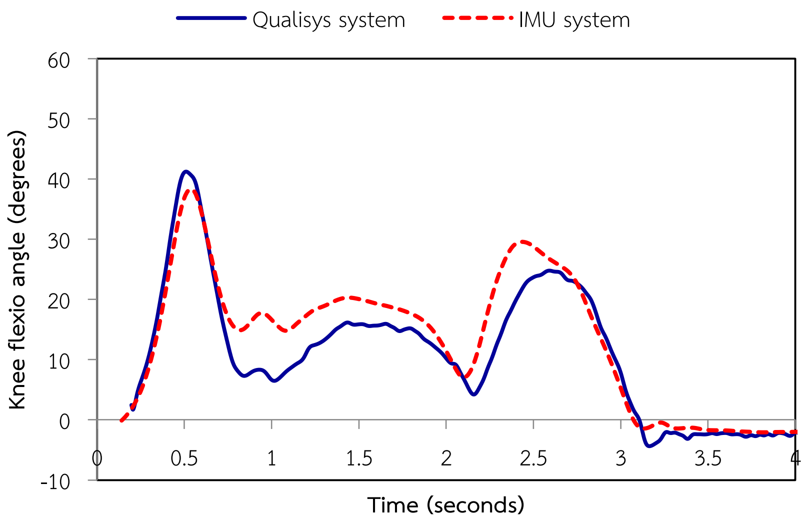


Figure I8 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.8).

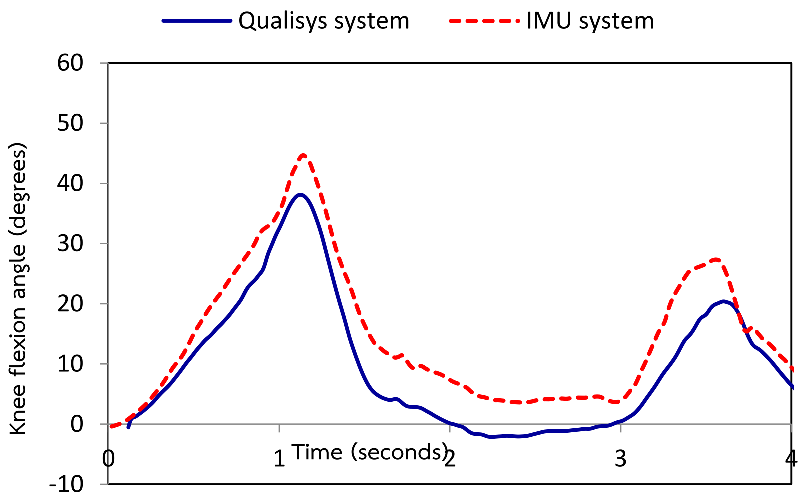


Figure I9 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.9).

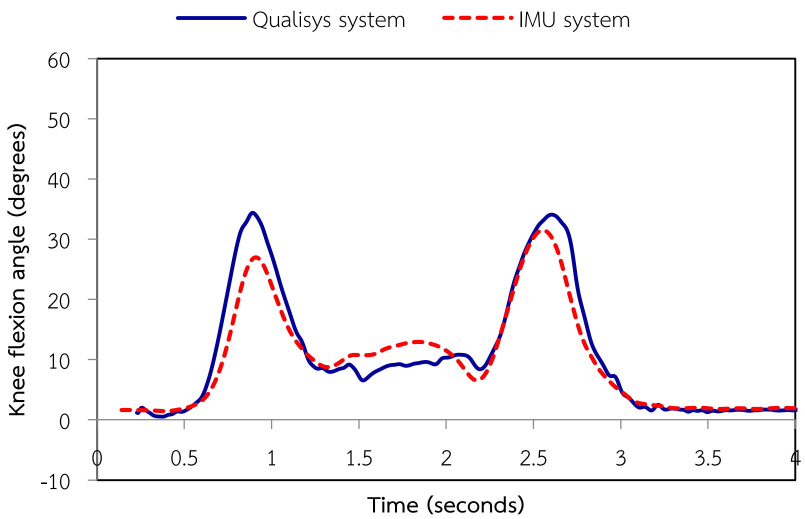


Figure I10 shows the line graphs of left knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.10).

APPENDIX J

THE FORWARD STEP TEST ON THE RIGHT LEG

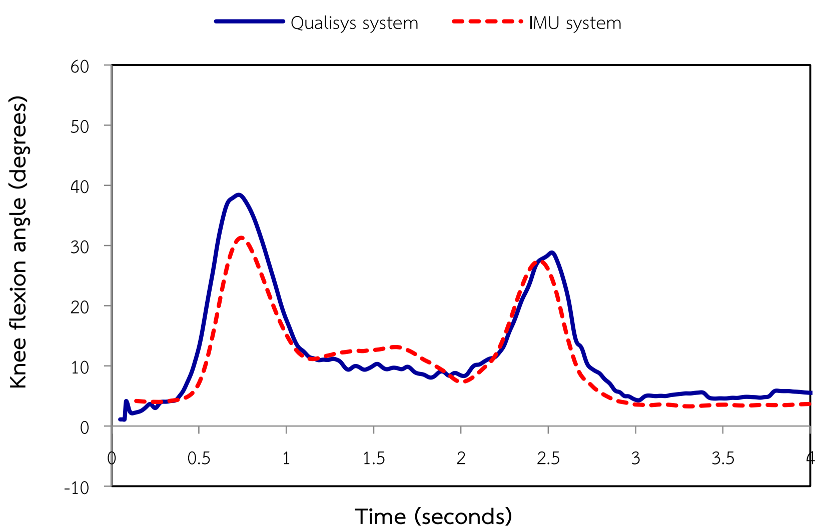


Figure J1 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.1).

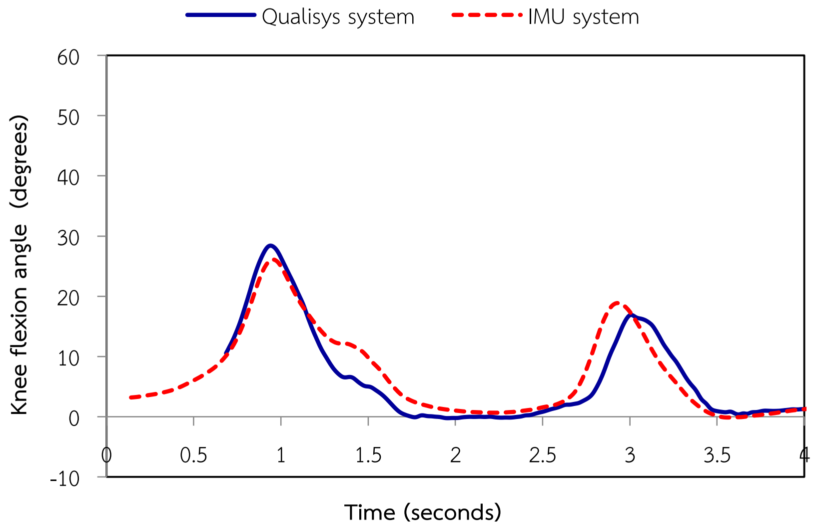


Figure J2 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.2).

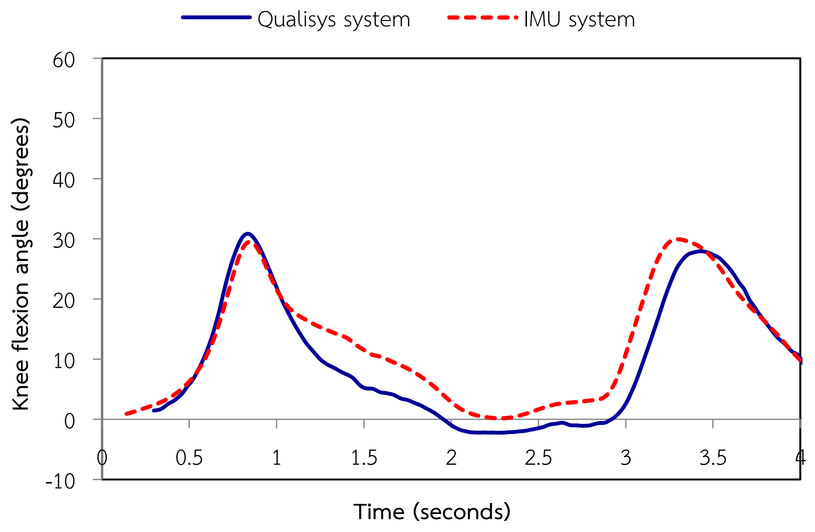


Figure J3 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.3).

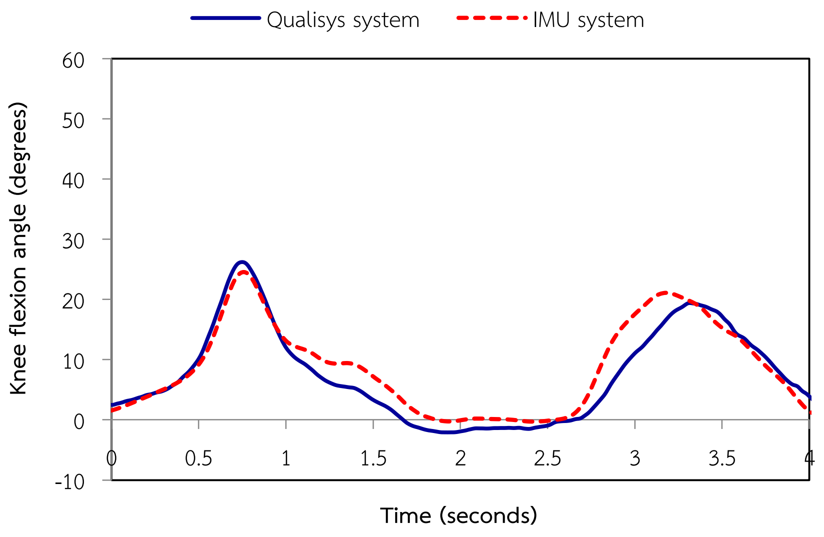


Figure J4 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.4).

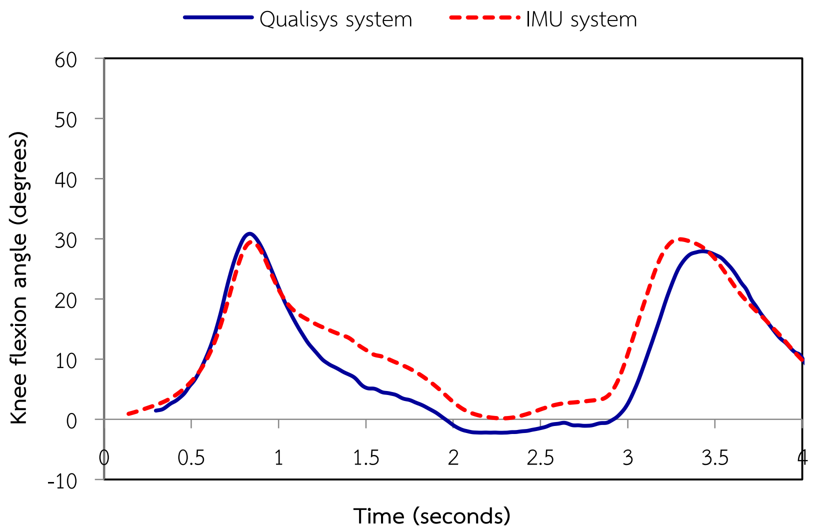


Figure J5 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.5).

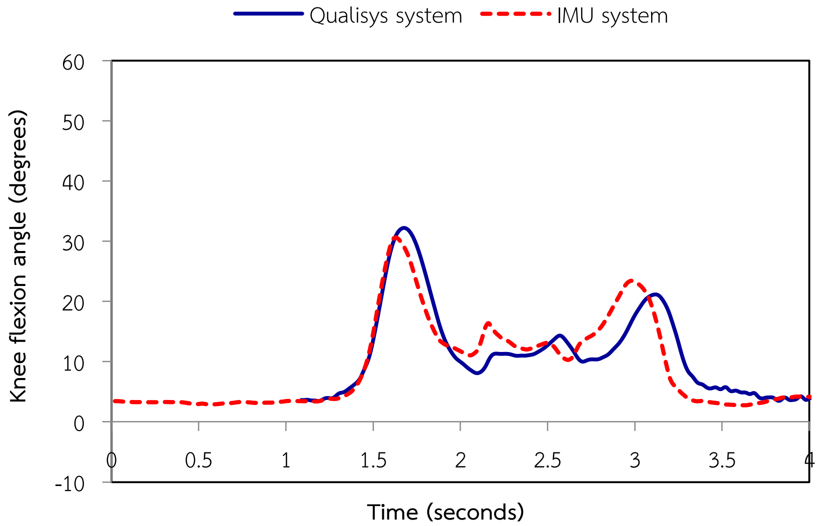


Figure J6 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.6).

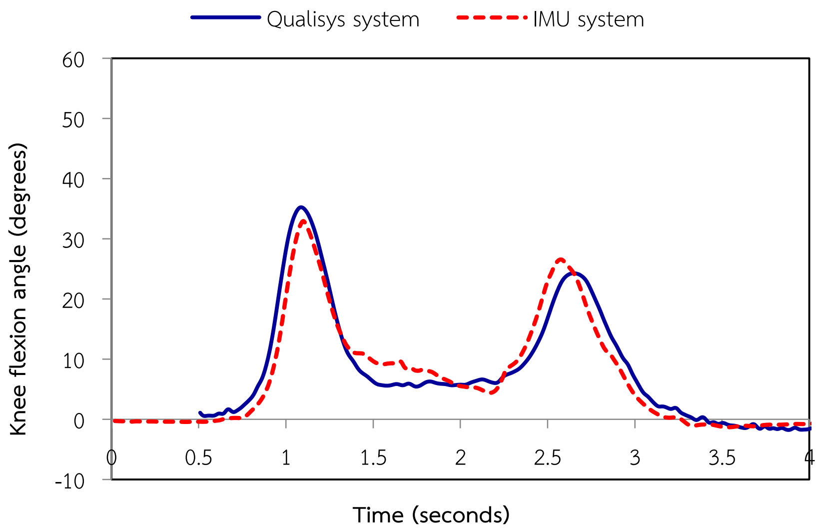


Figure J7 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.7).

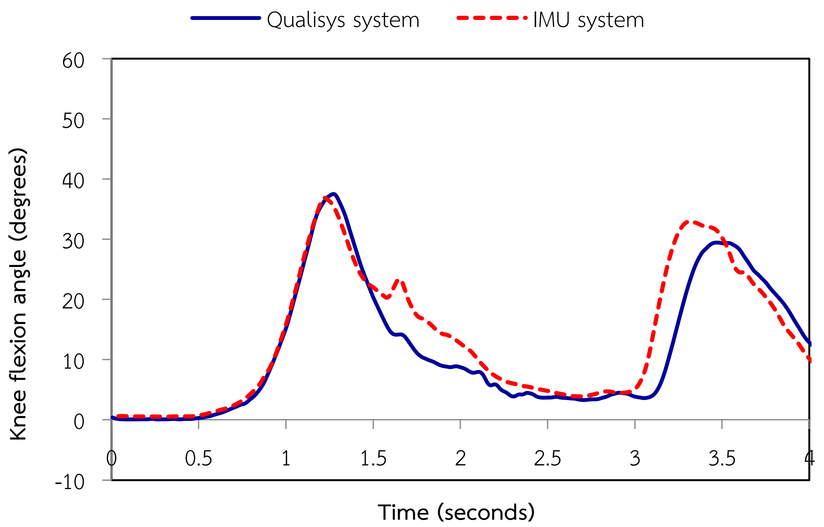


Figure J8 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.8).

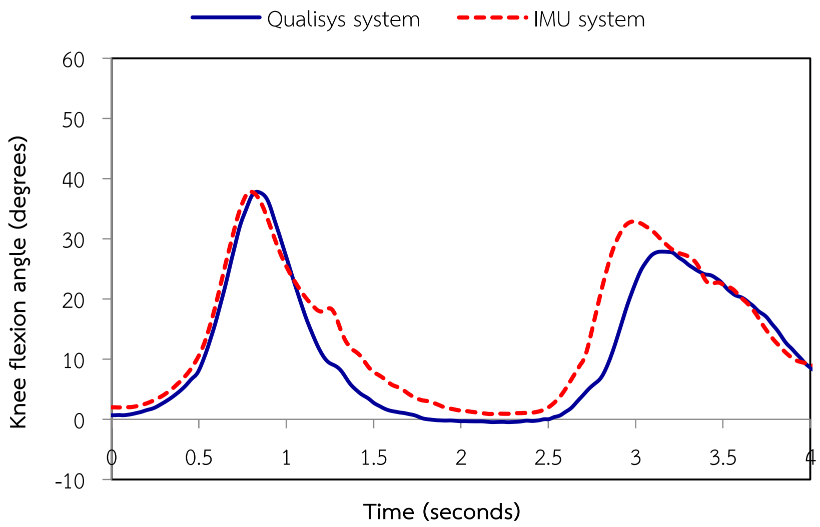


Figure J9 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.9).

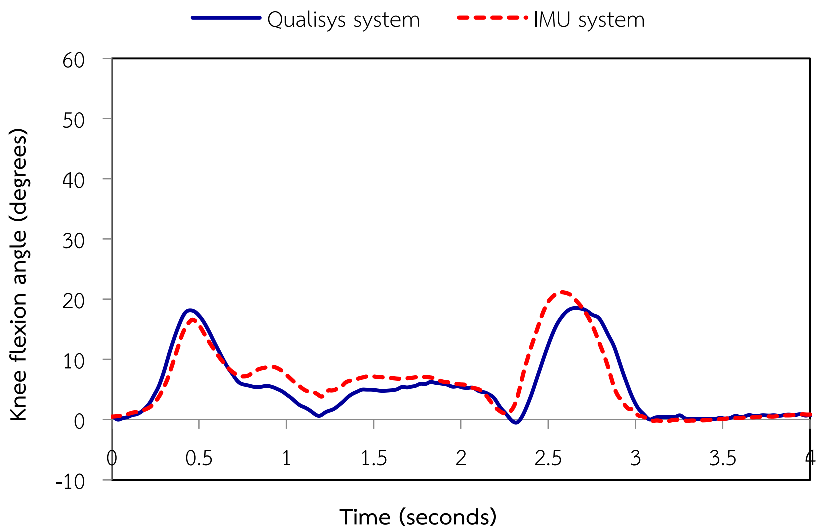


Figure J10 shows the line graphs of right knee flexion movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the forward step test. (The data are from the participant no.10).

APPENDIX K

THE LEG ABDUCTION TEST ON THE LEFT LEG

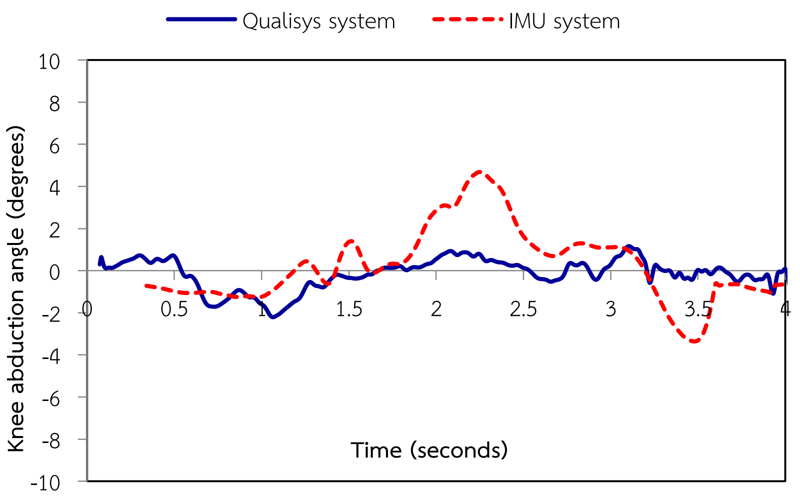


Figure K1 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.1).

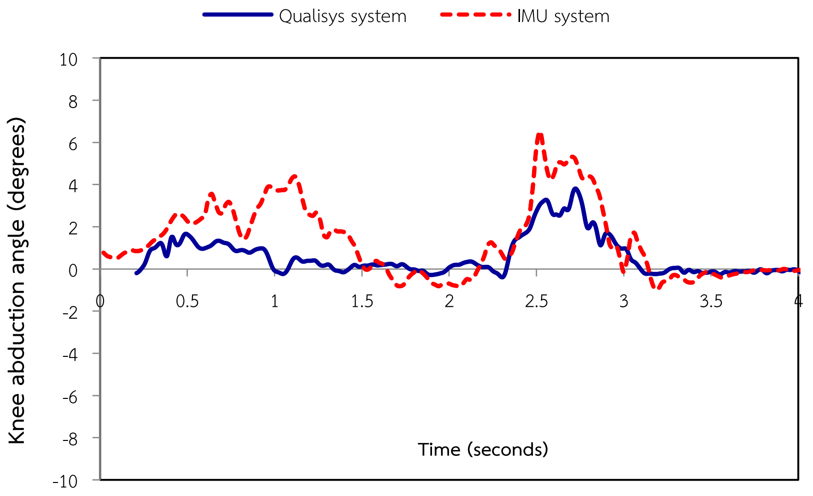


Figure K2 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.2).

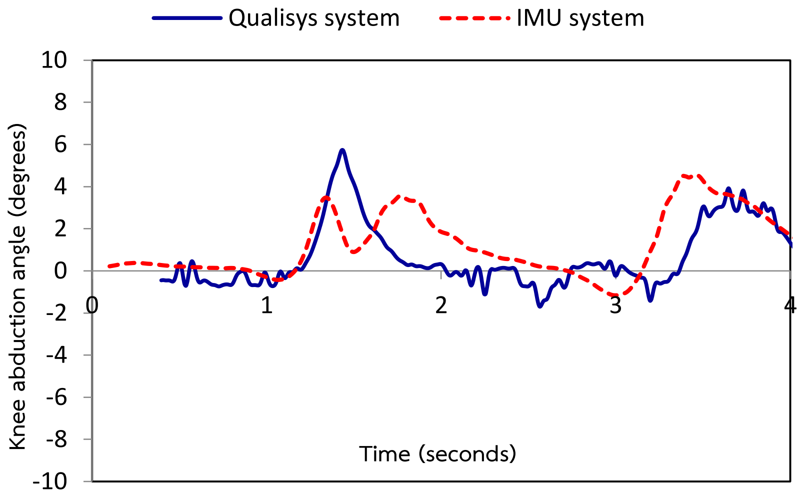


Figure K3 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.3).

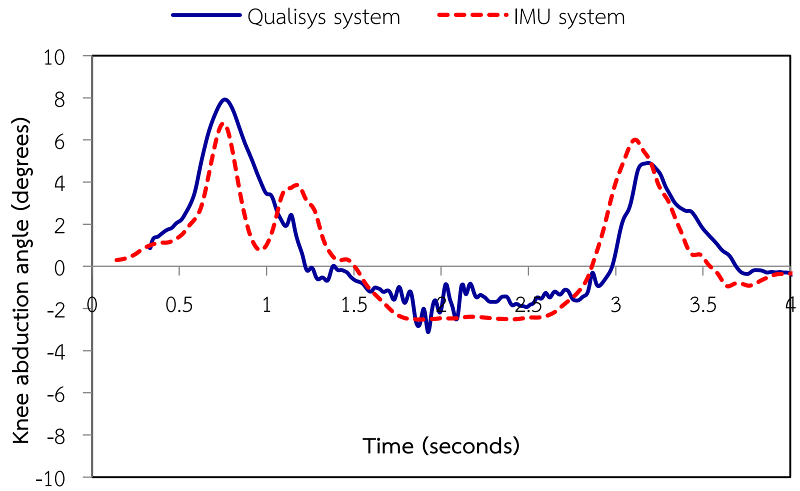


Figure K4 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.4).

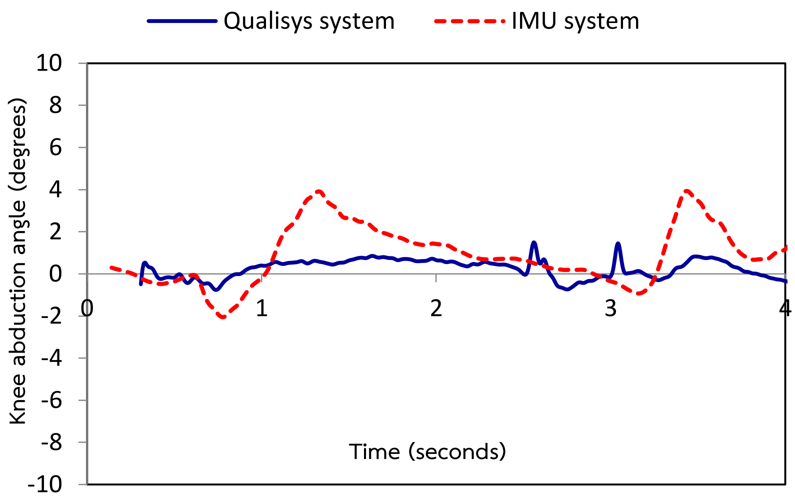


Figure K5 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.5).

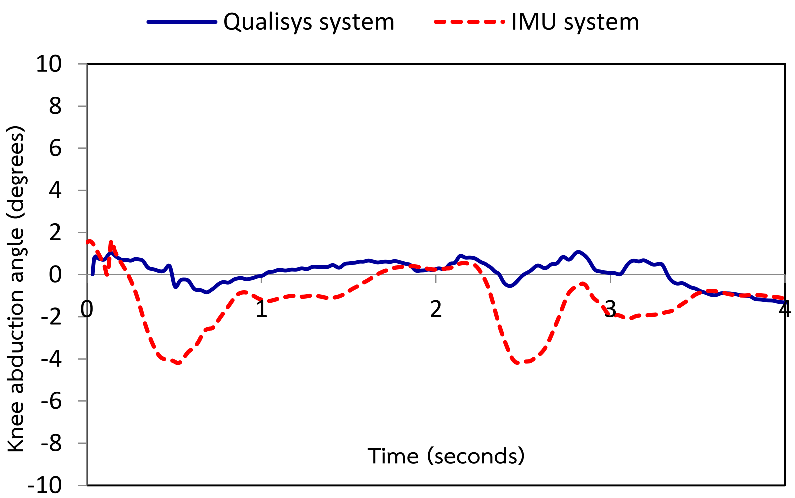


Figure K6 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.6).

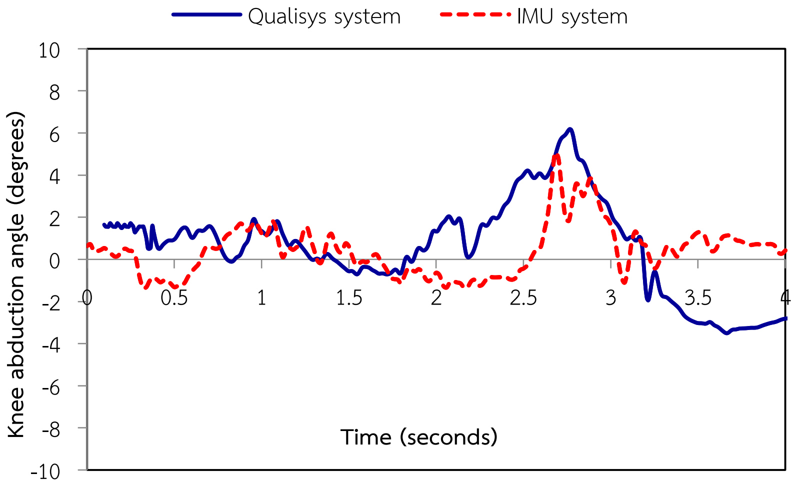


Figure K7 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.7).

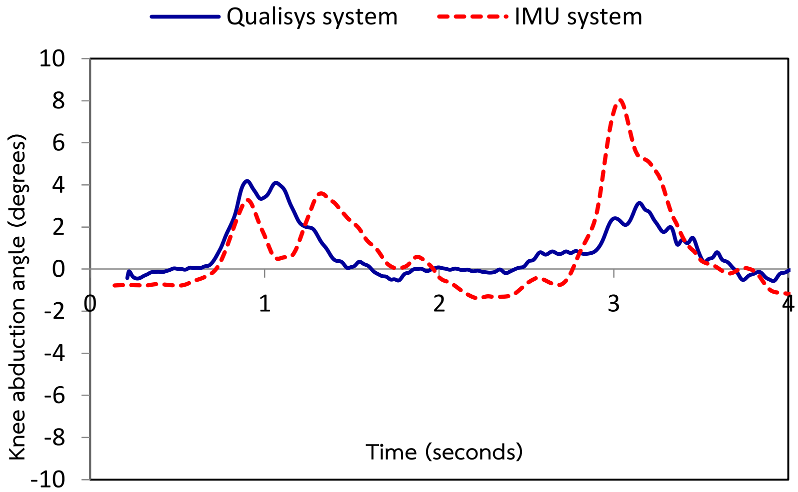


Figure K8 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.8).

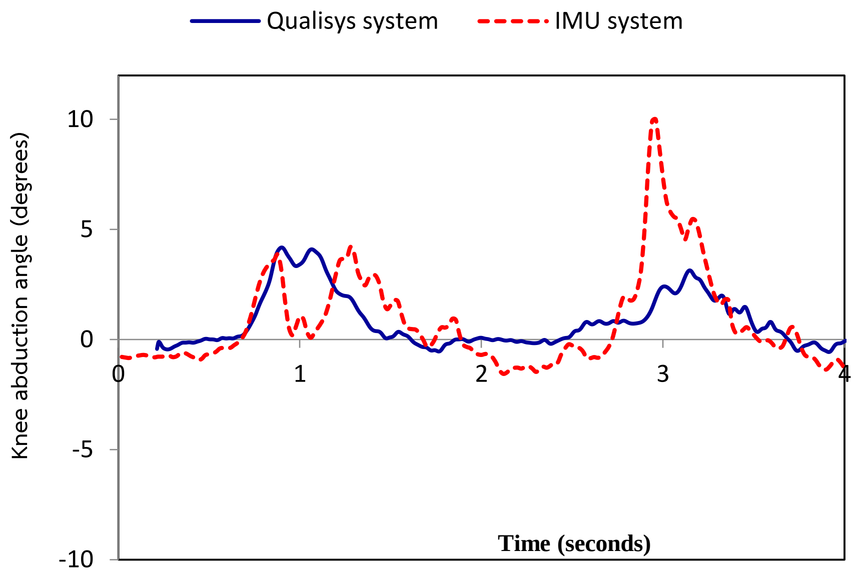


Figure K9 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.9).

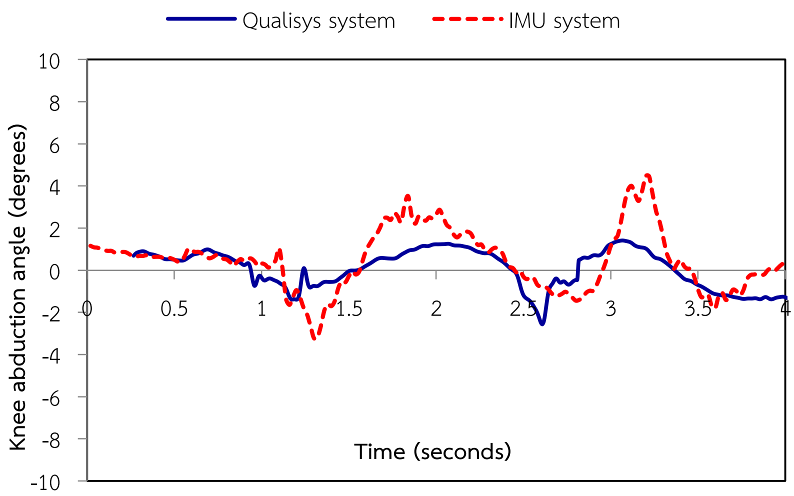


Figure K10 shows the line graphs of left knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.10).

APPENDIX L

THE LEG ABDUCTION TEST ON THE RIGHT LEG

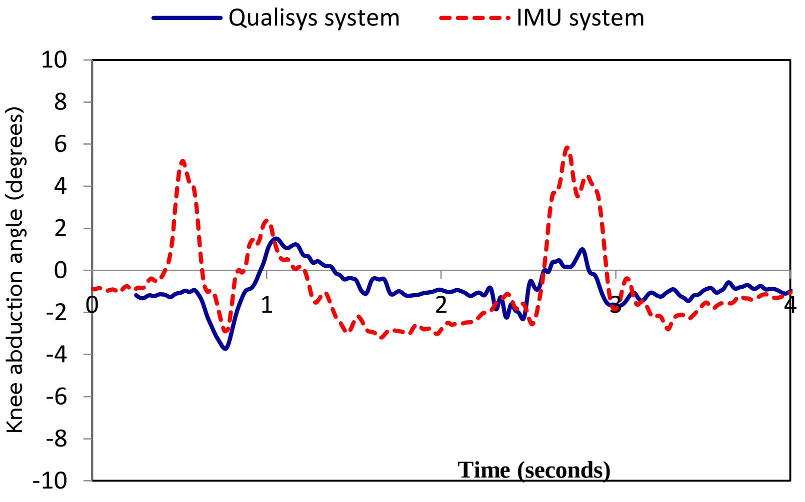


Figure L1 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.1).

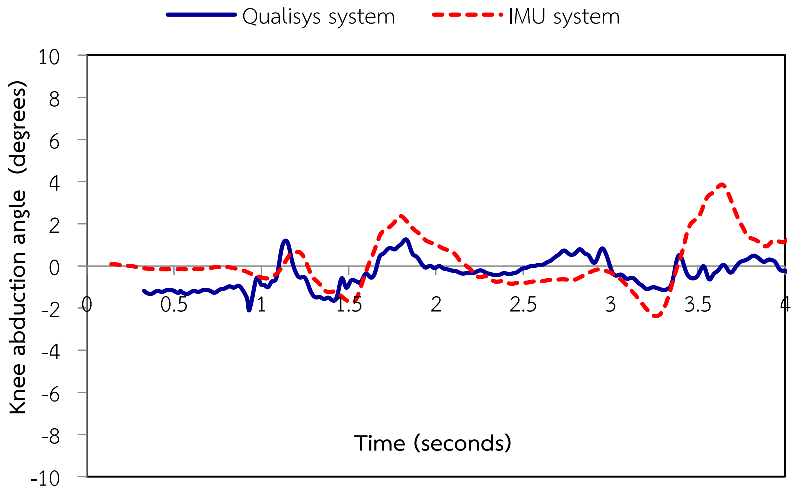


Figure L2 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.2).

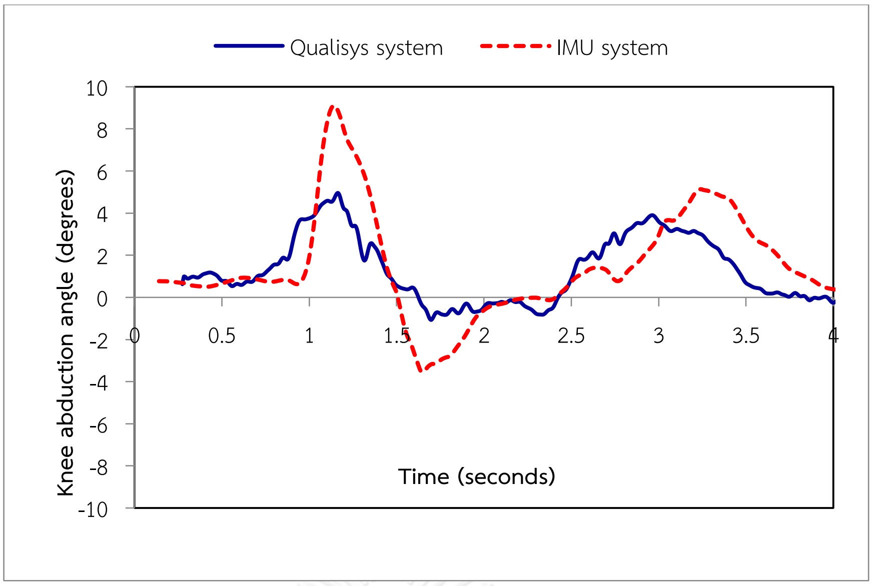


Figure L3 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.3).

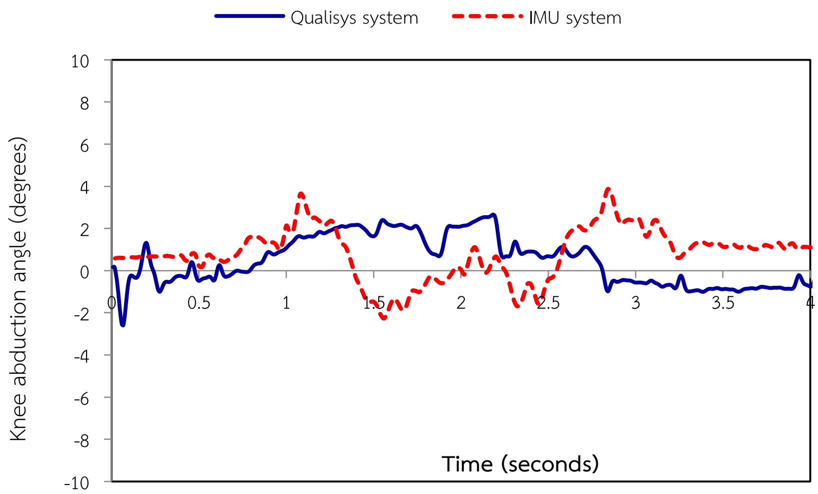


Figure L4 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.4).

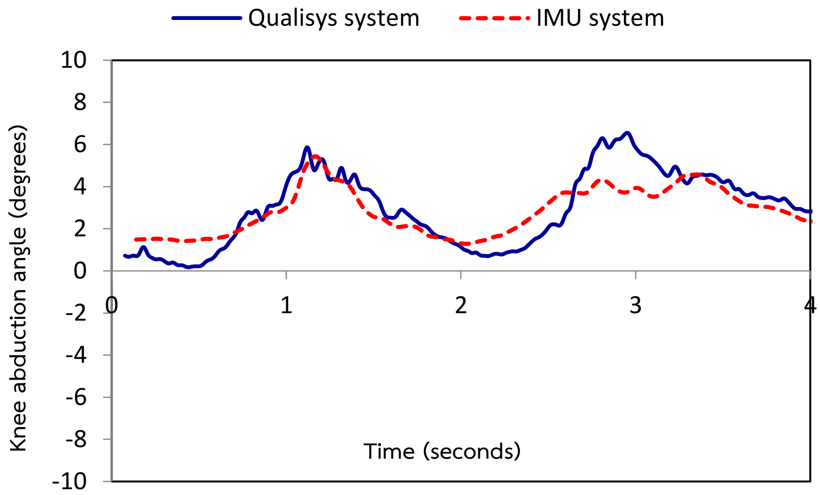


Figure L5 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.5).

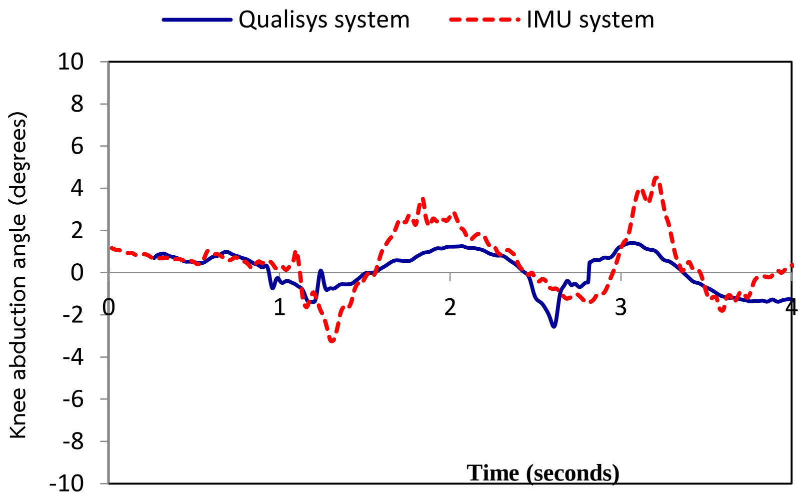


Figure L6 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.6).

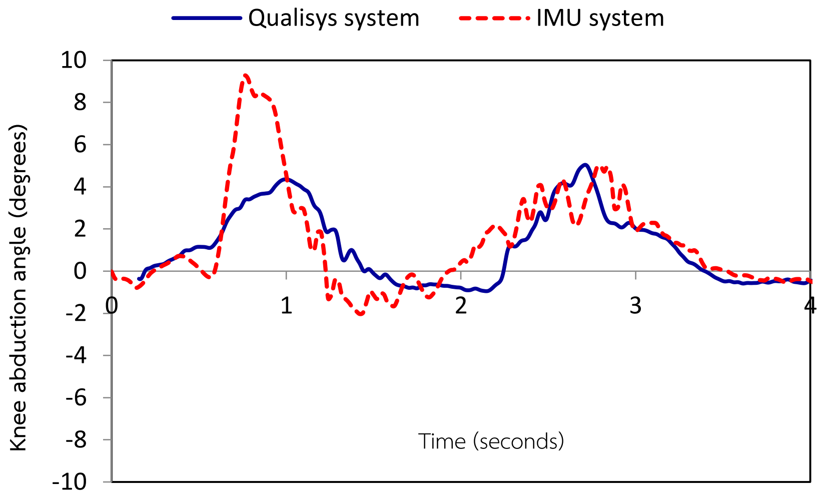


Figure L7 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.7).

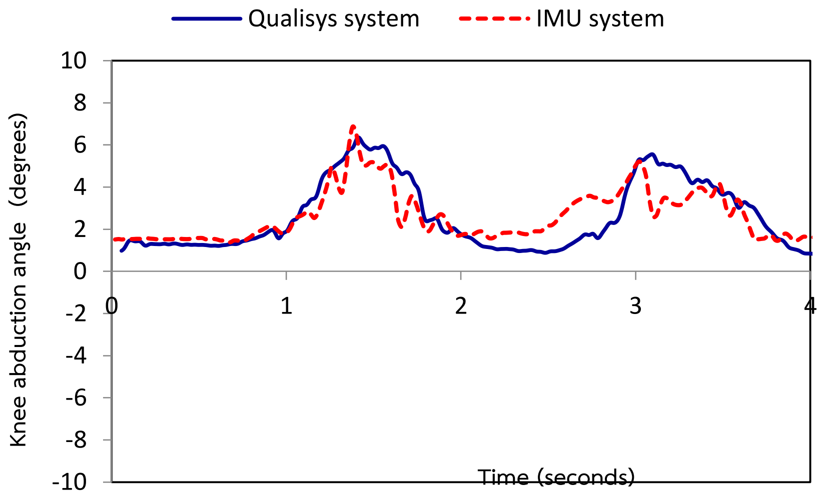


Figure L8 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.8).

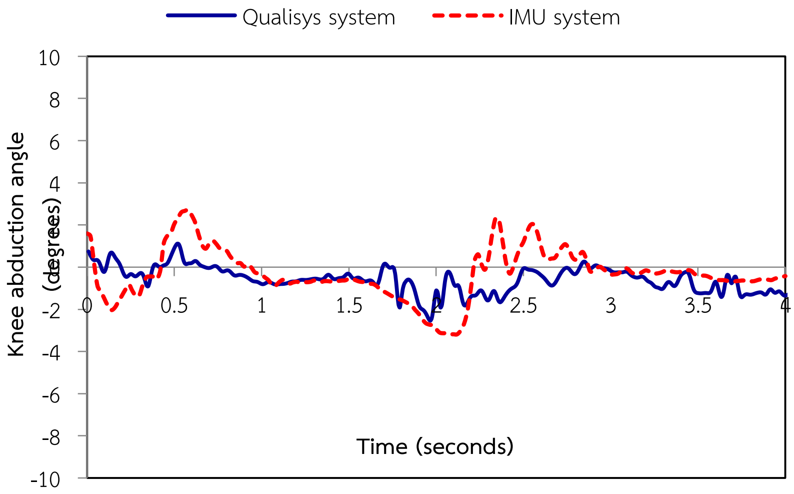


Figure L9 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.9).

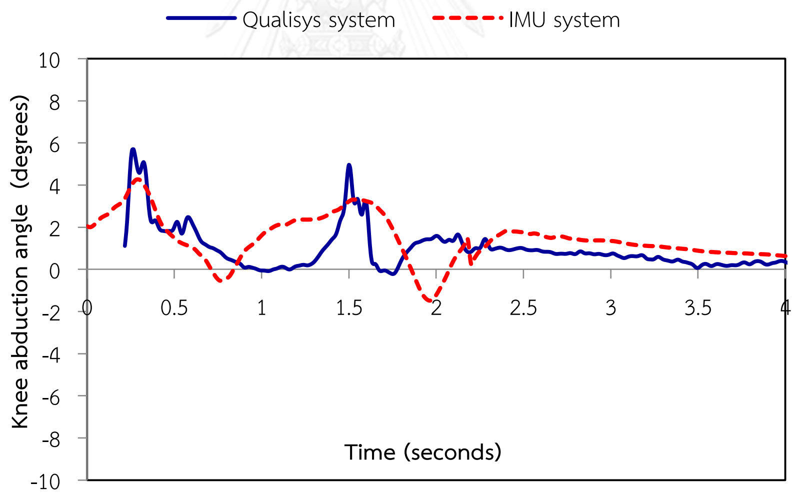


Figure L10 shows the line graphs of right knee abduction movement (in degrees) versus time (in seconds), which compared the measuring angles between the IMU system and the Qualisys system, during the leg abduction test. (The data are from the participant no.10).

APPENDIX M

THE WALKING TEST ON THE LEFT LEG

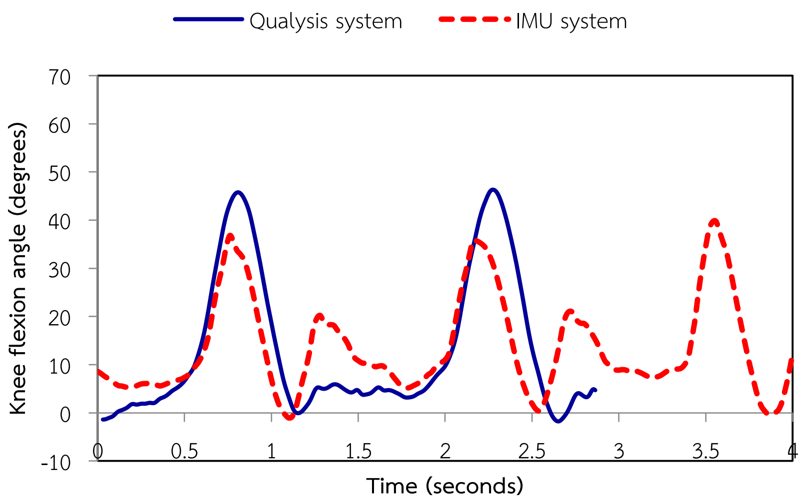


Figure M1 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.1).

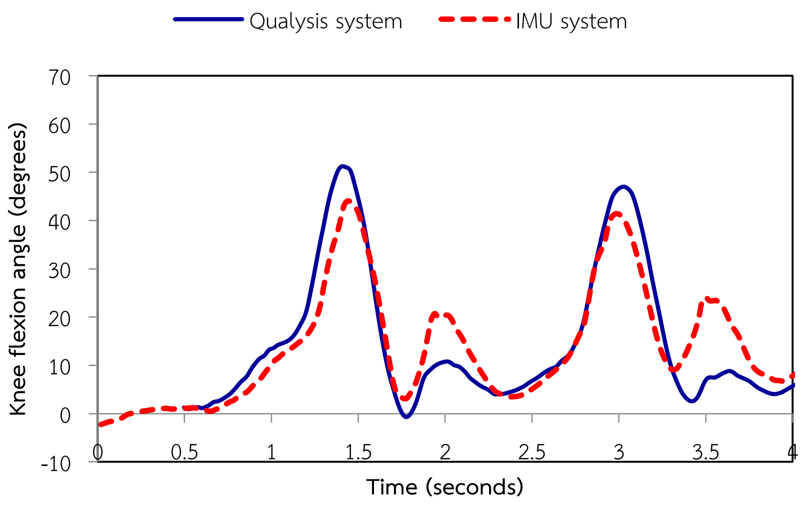


Figure M2 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.2).

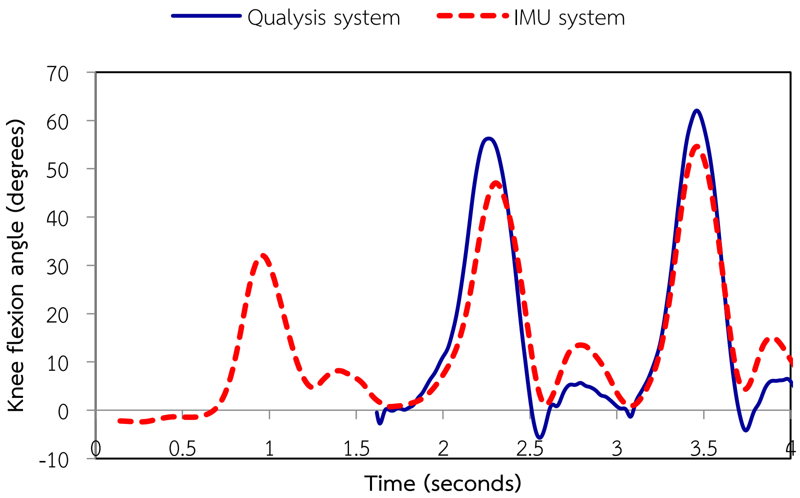


Figure M3 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.3).

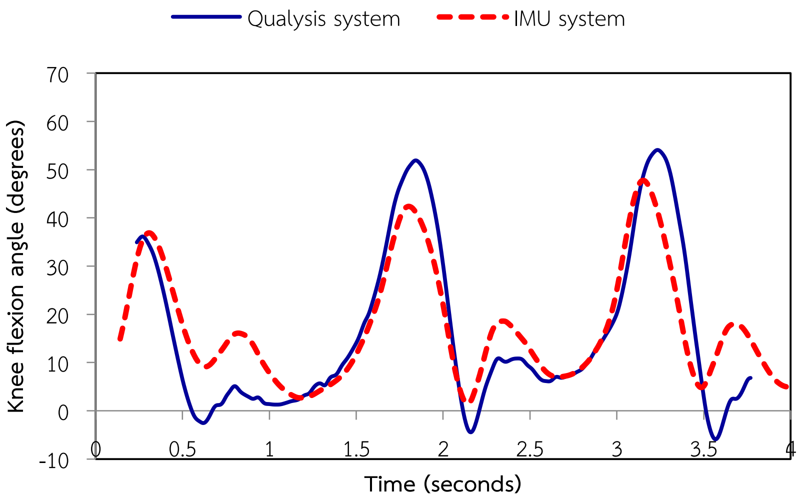


Figure M4 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.4).

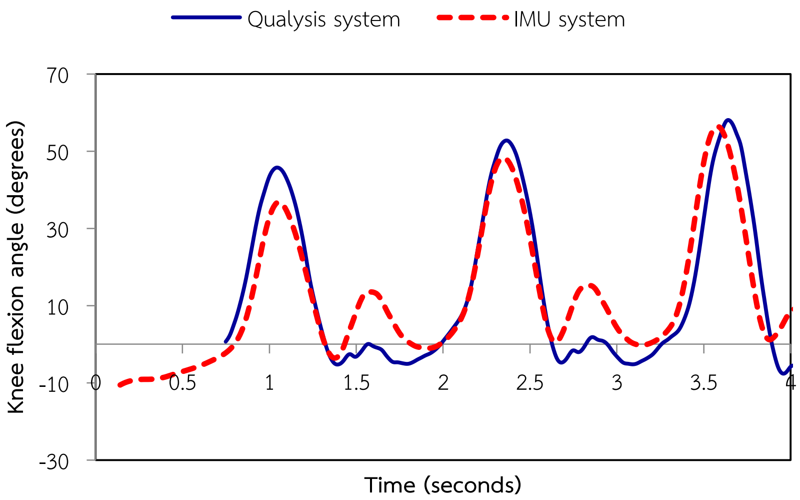


Figure M5 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.5).

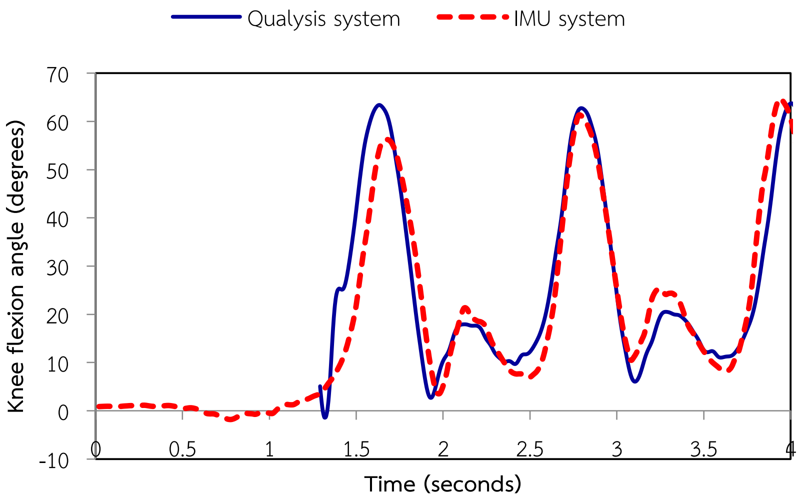


Figure M6 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.6).

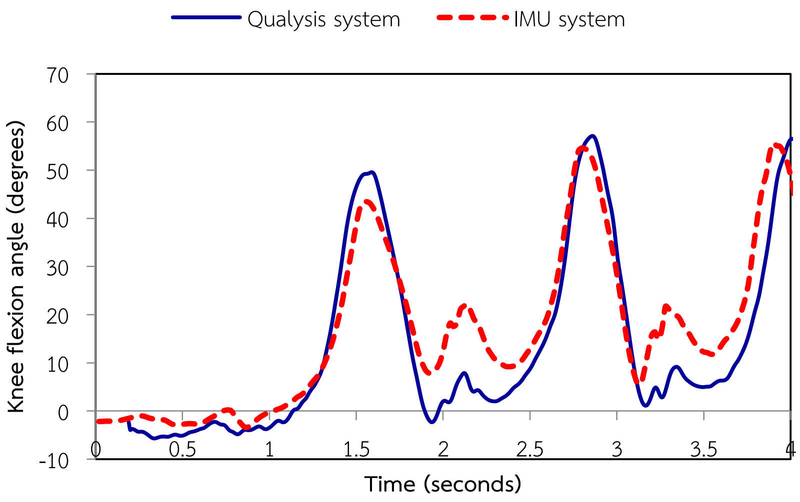


Figure M7 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.7).

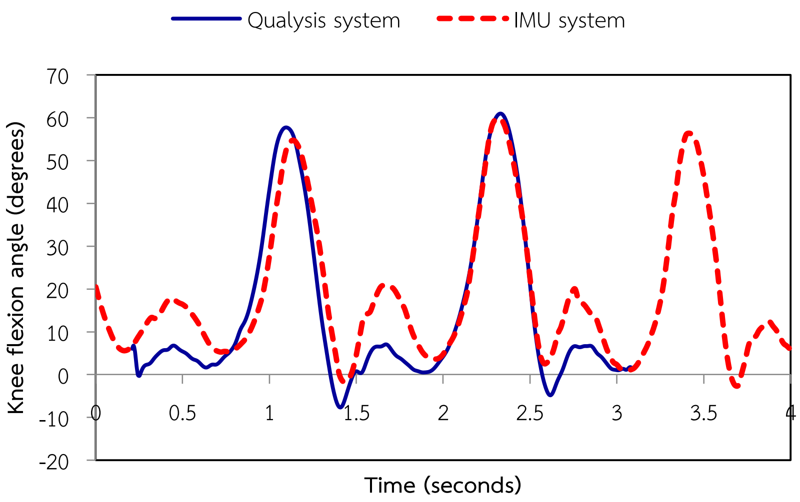


Figure M8 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.8).

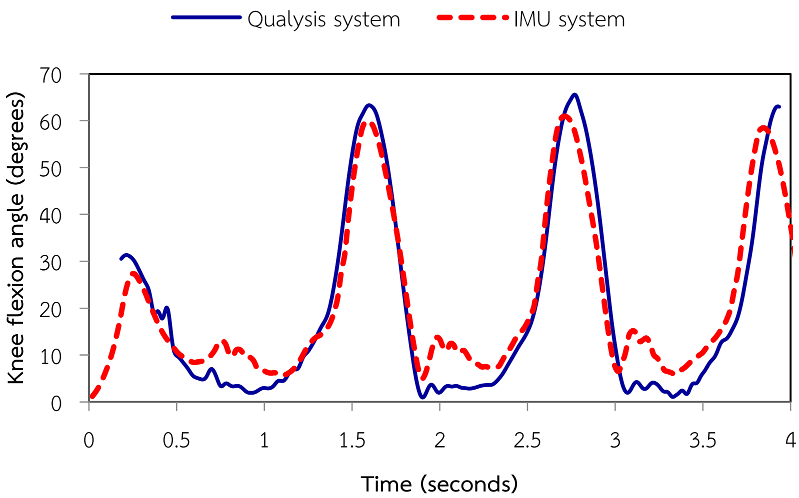


Figure M9 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.9).

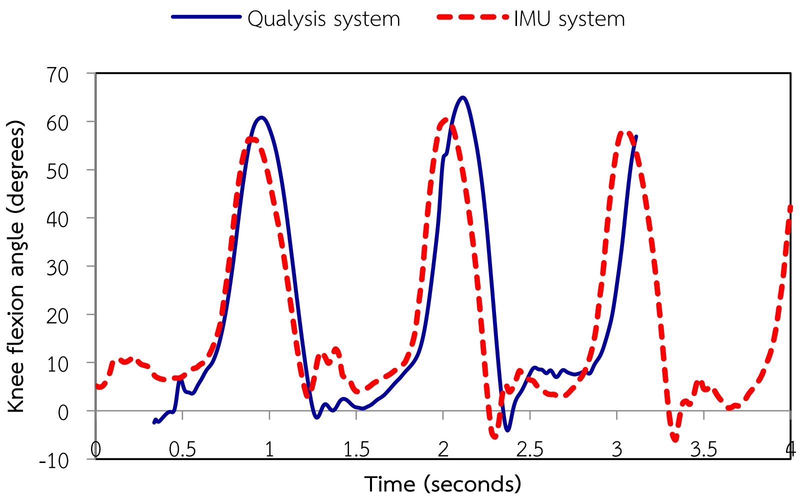


Figure M10 shows the line graphs of left knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.10).

APPENDIX N

THE WALKING TEST ON THE RIGHT LEG

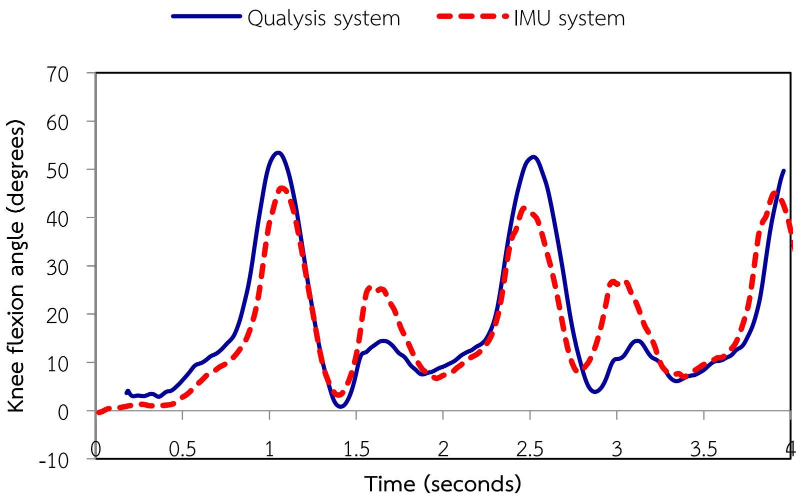


Figure N1 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.1).

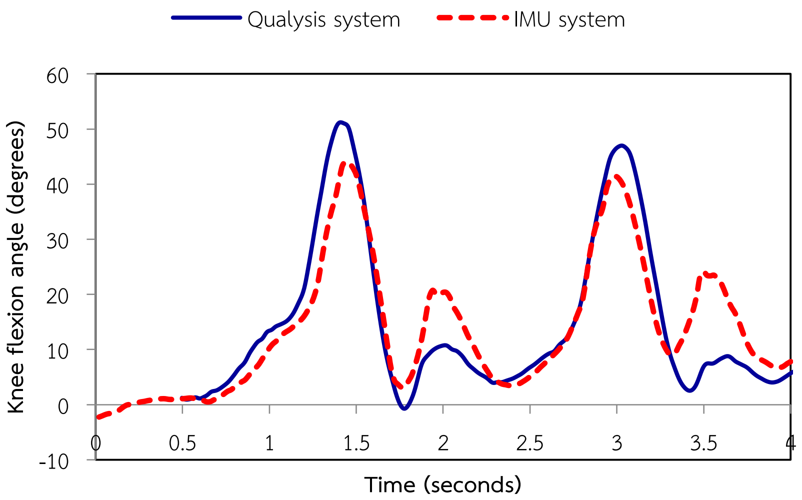


Figure N2 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.2).

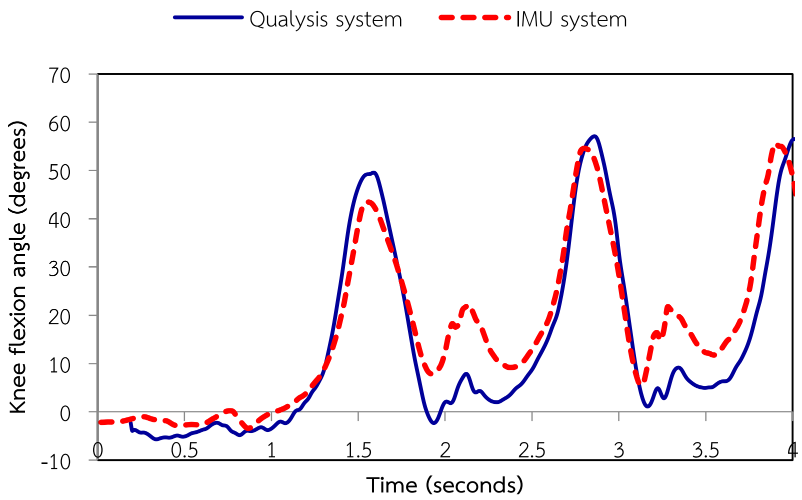


Figure N3 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.3).

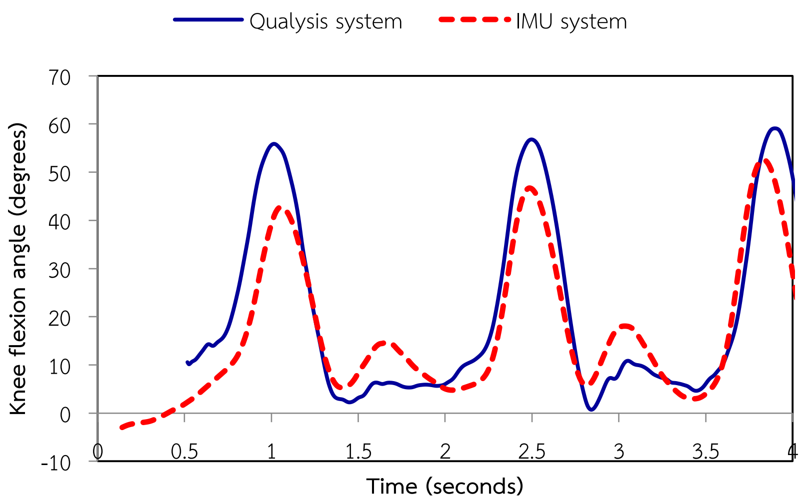


Figure N4 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.4).

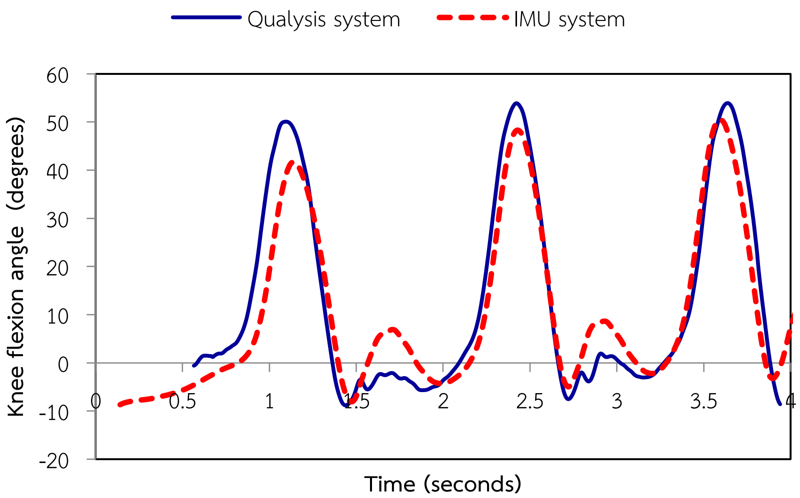


Figure N5 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.5).

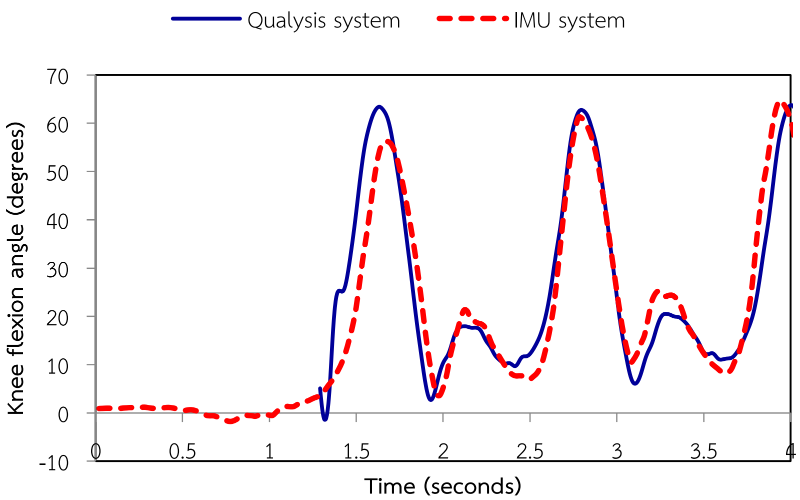


Figure N6 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.6).

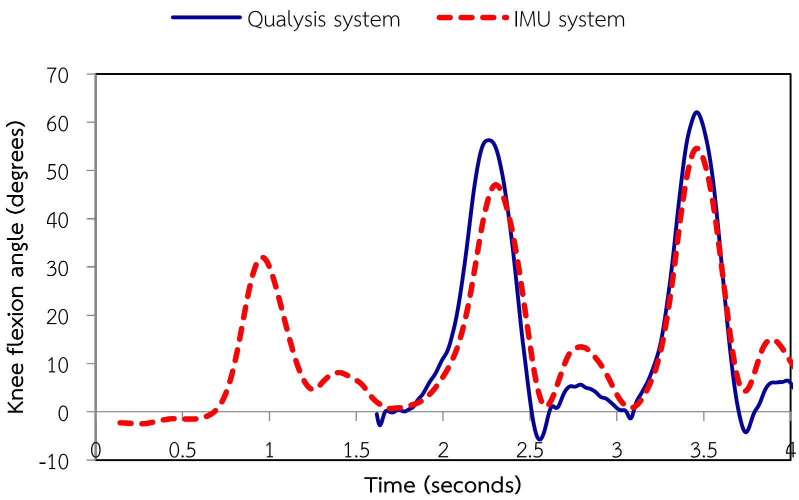


Figure N7 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.7).

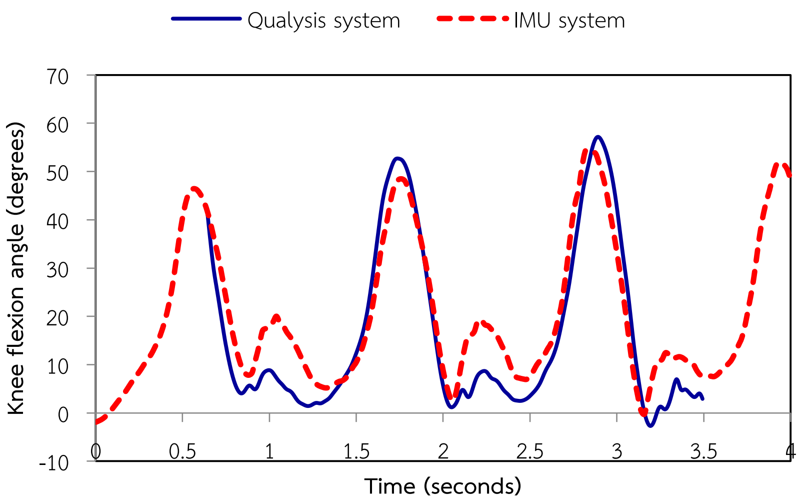


Figure N8 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.8).

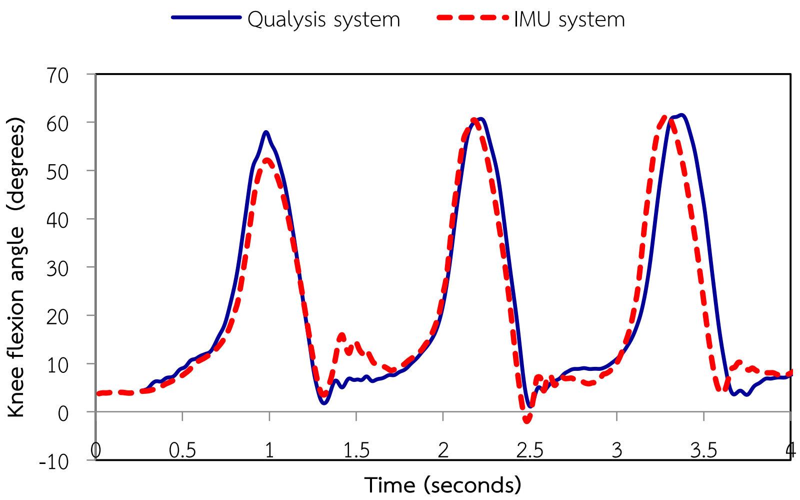


Figure N9 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.9).

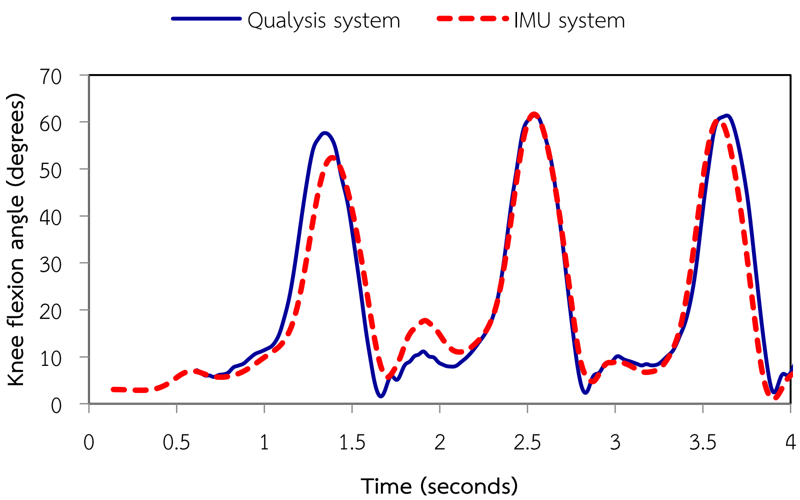
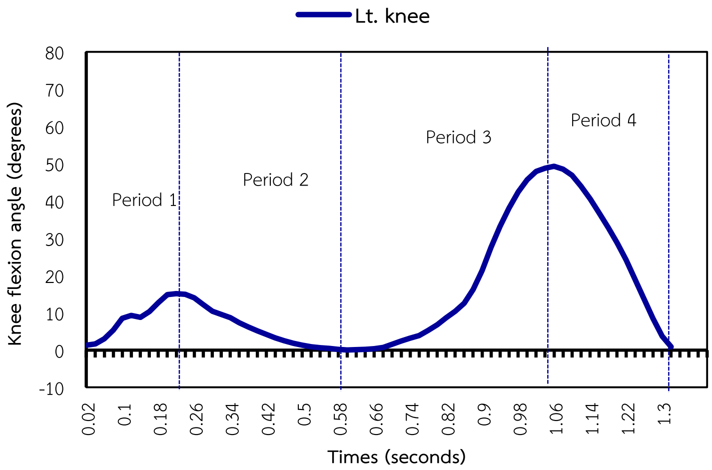
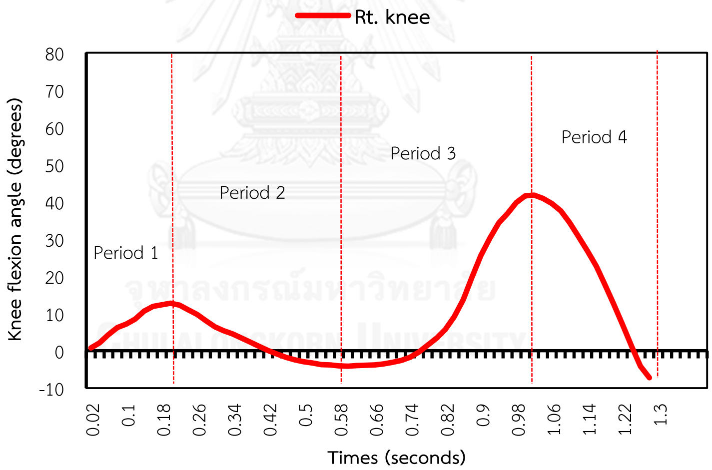


Figure N10 shows the line graphs of right knee flexion movement in the gait cycle (in degrees) versus time (in seconds), which compared between the IMU system and the Qualisys system, during the walking test. (The data are from the participant no.10).

APPENDIX O

KNEE ANGULAR MOTION IN A GAIT CYCLE IN THE ELDERLY WOMAN WITHOUT SYMPTOMATIC KNEE OSTEOARTHRITIS





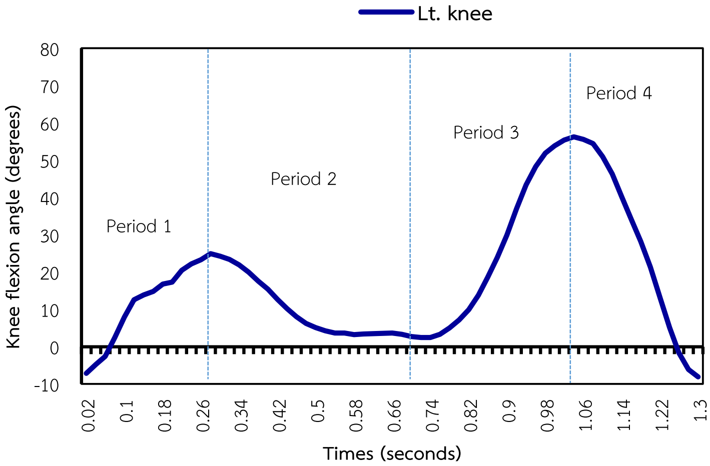
Figures O1 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.1.)

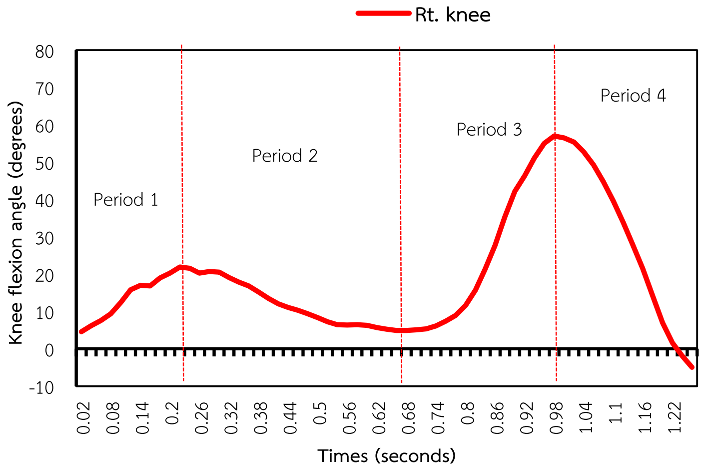
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





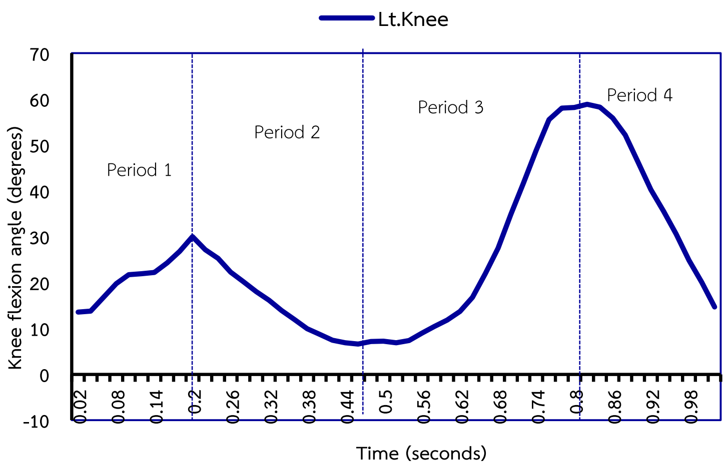
Figures O2 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.2.)

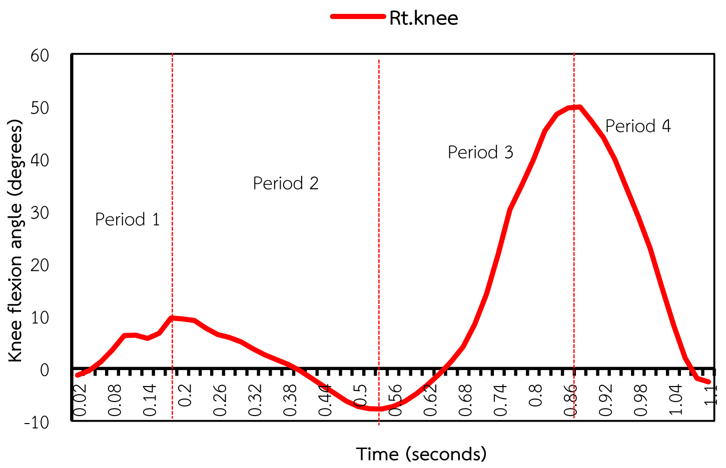
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





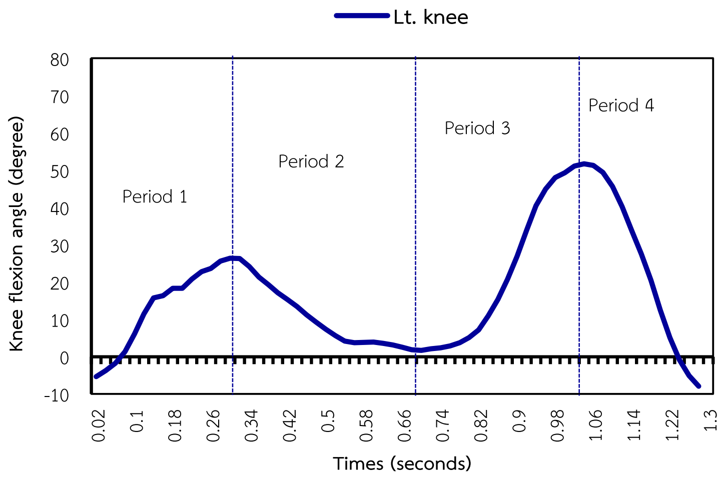
Figures O3 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.3.)

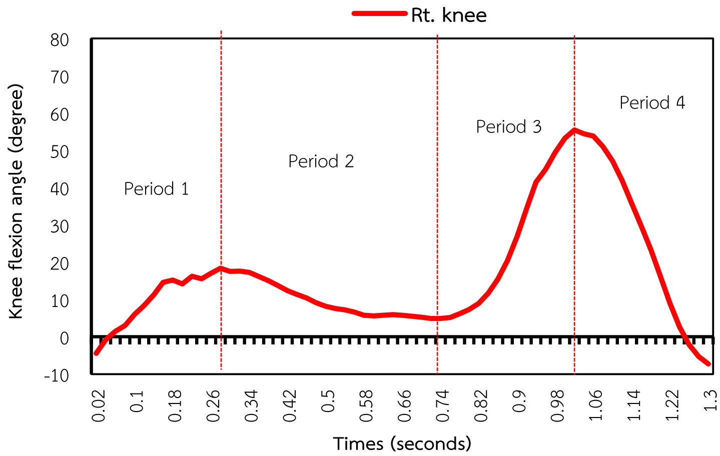
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





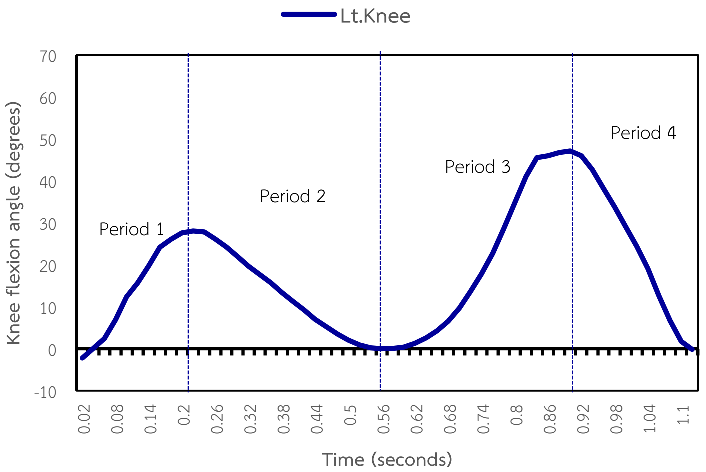
Figures O4 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.4.)

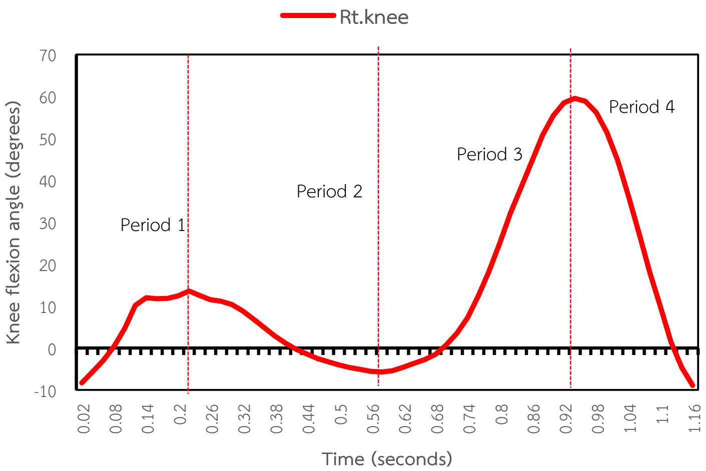
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





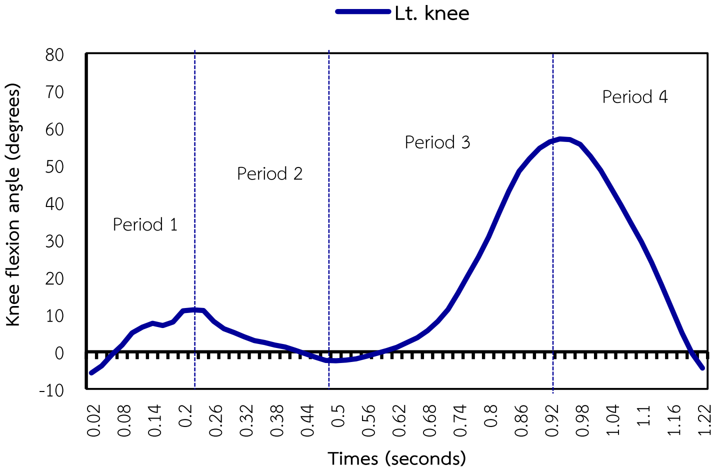
Figures O5 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.5.)

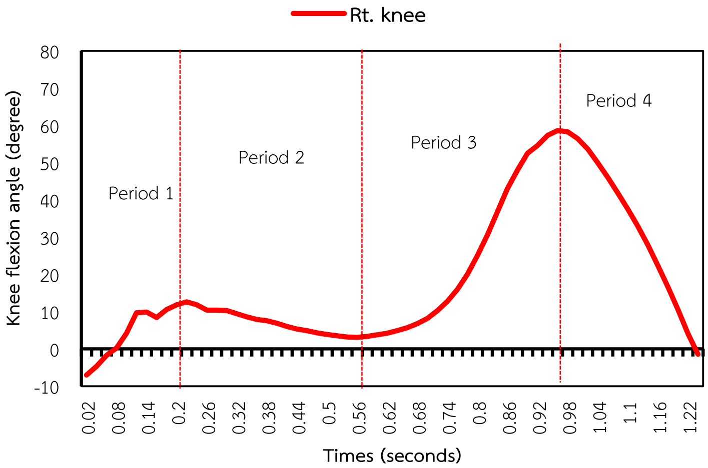
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

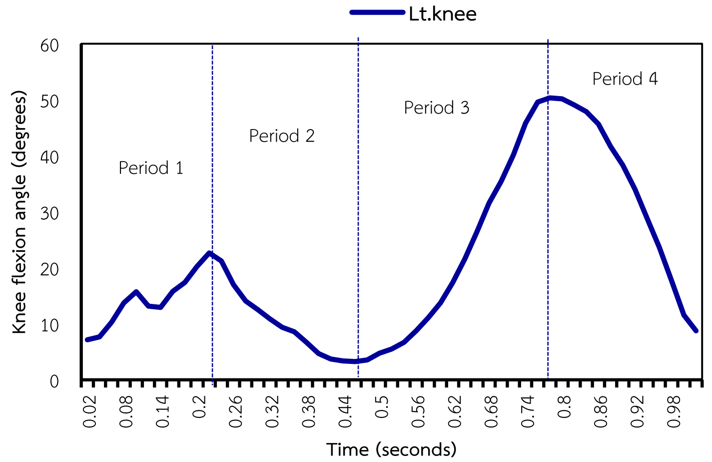
The 4th period is the knee movement from the MFS to the FHS phase.

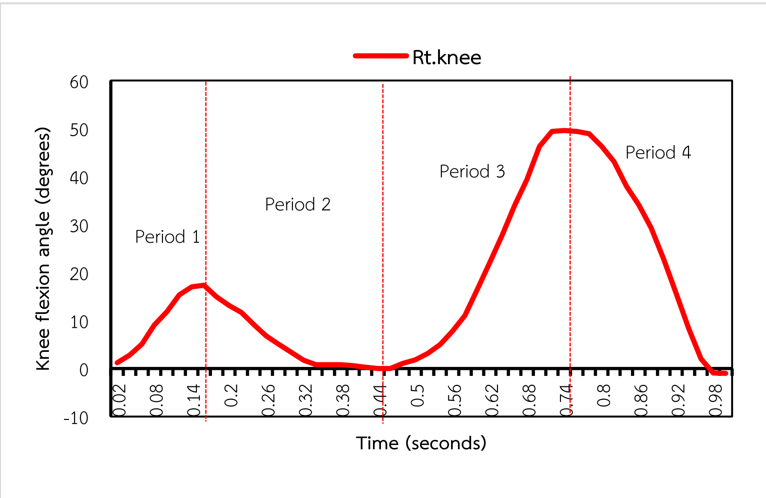




Figures O6 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.6.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.
The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.
The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.
The 4th period is the knee movement from the MFS to the FHS phase.





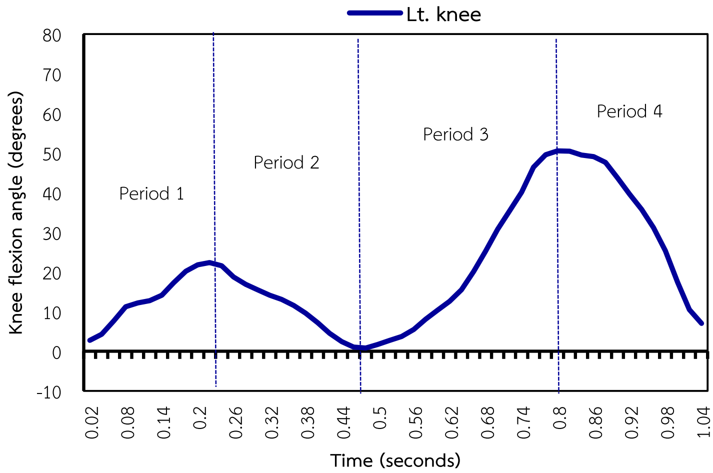
Figures O7 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.7.)

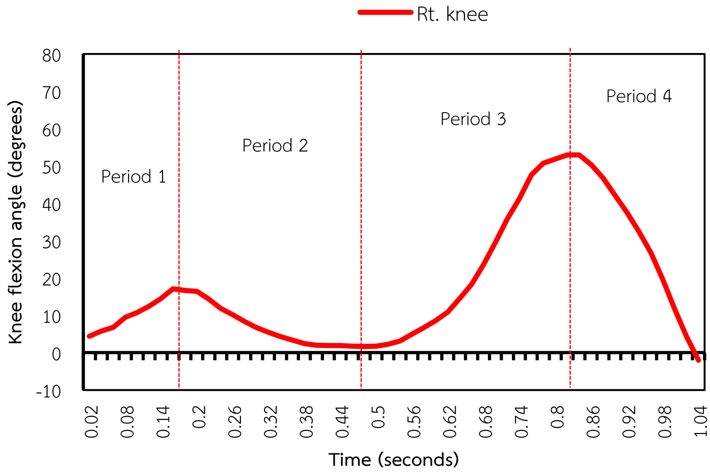
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

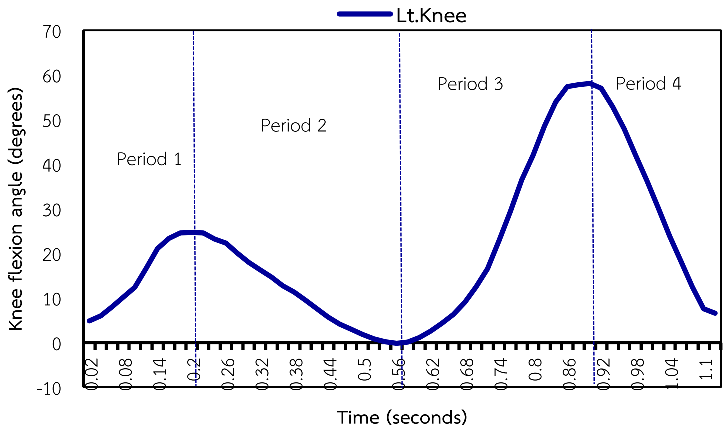
The 4th period is the knee movement from the MFS to the FHS phase.

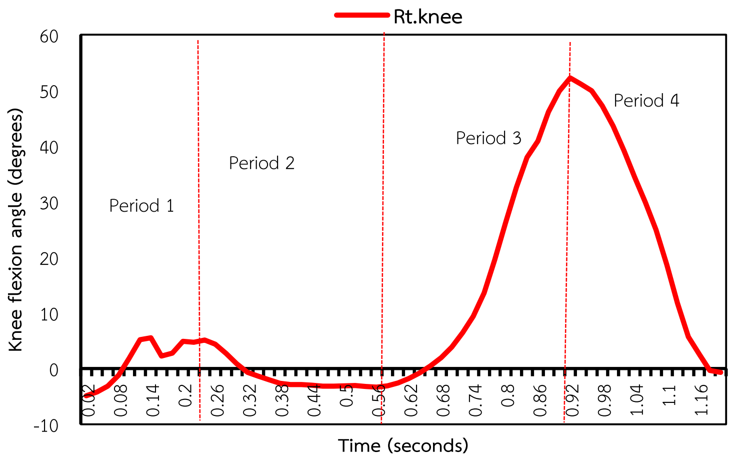




Figures O8 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.8.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.
The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.
The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.
The 4th period is the knee movement from the MFS to the FHS phase.





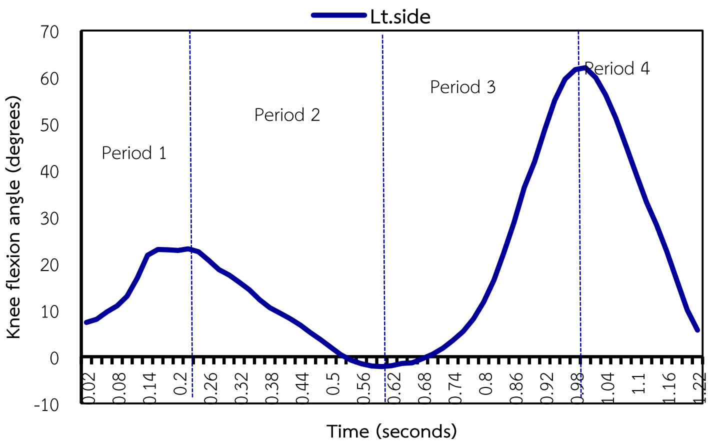
Figures O9 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.9.)

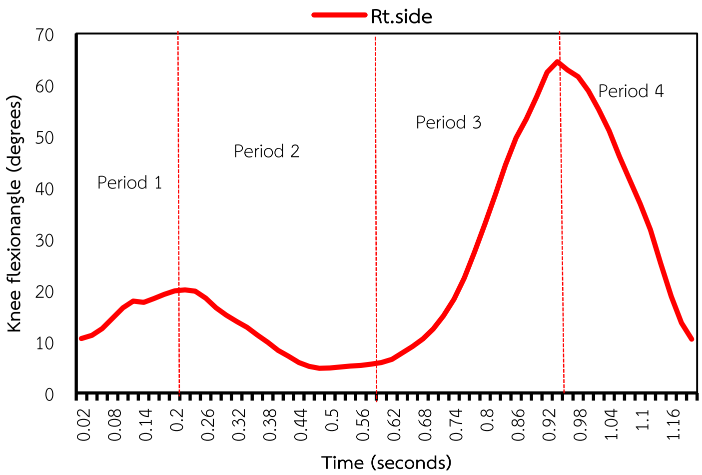
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





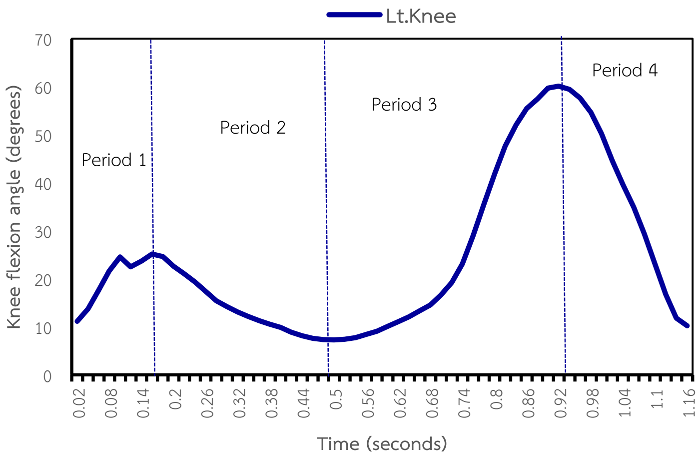
Figures O10 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.10.)

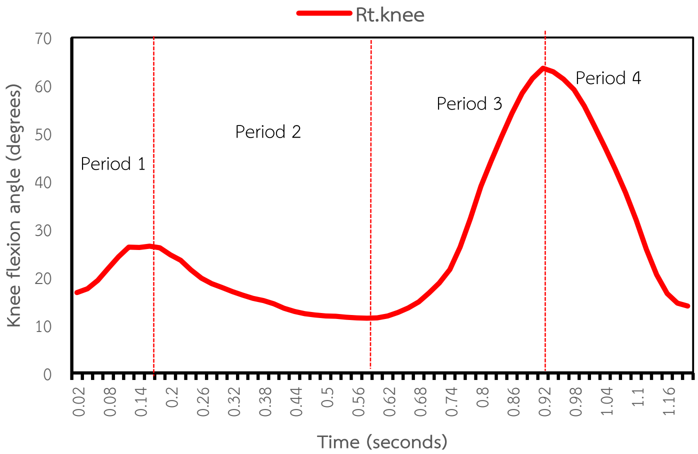
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





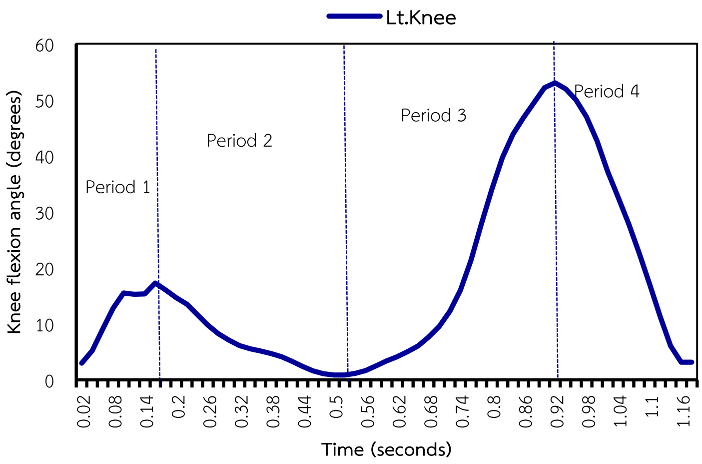
Figures O11 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.11.)

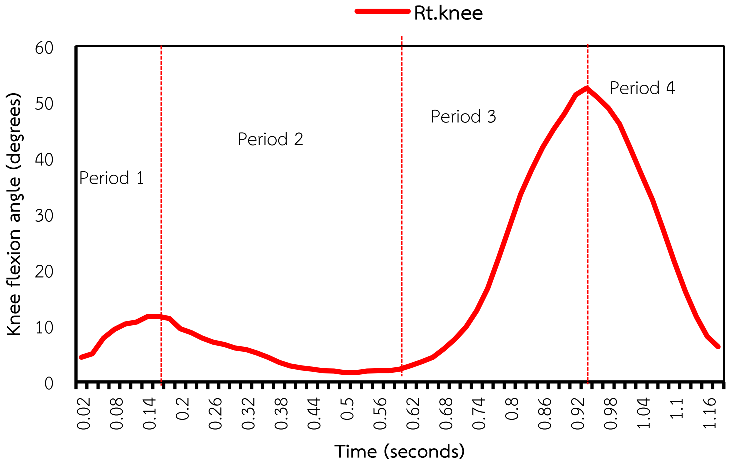
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

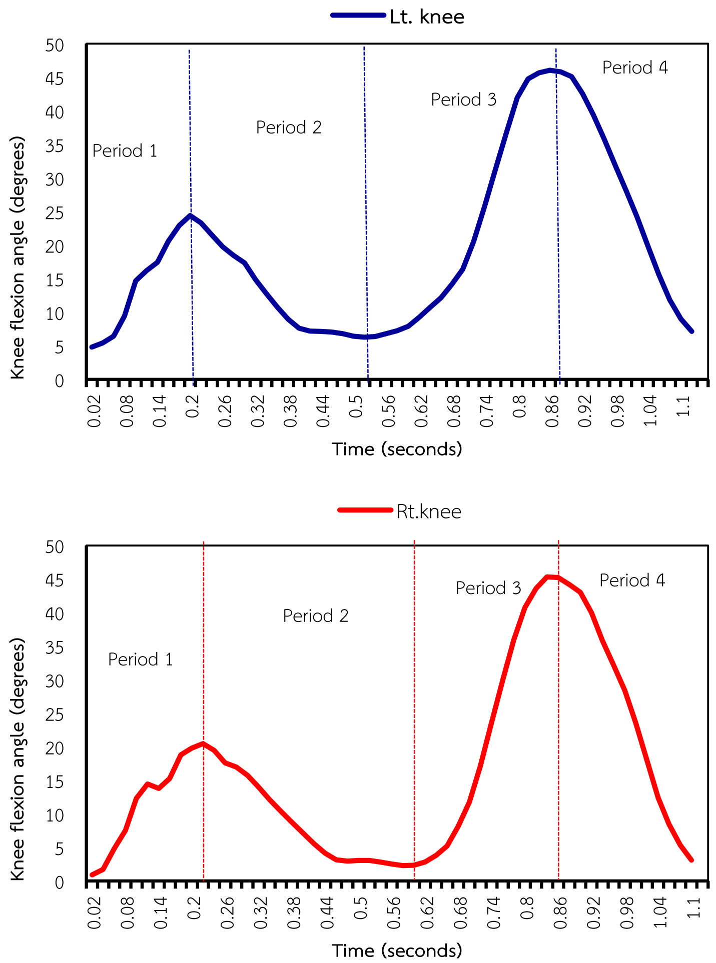
The 4th period is the knee movement from the MFS to the FHS phase.





Figures O12 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.12.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.
The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.
The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.
The 4th period is the knee movement from the MFS to the FHS phase.



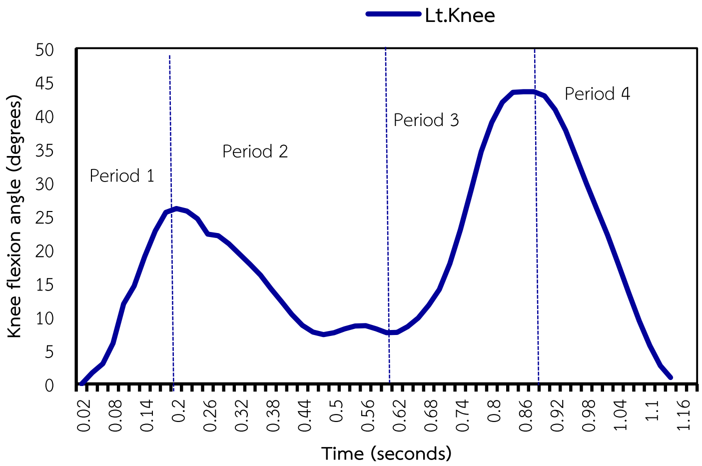
Figures O13 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.13.)

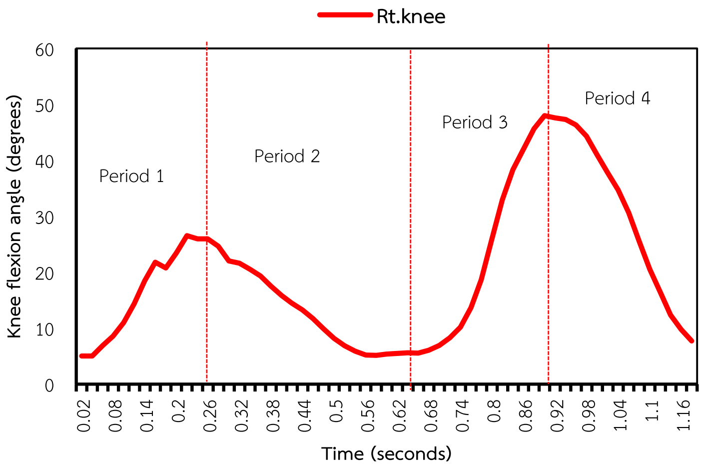
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





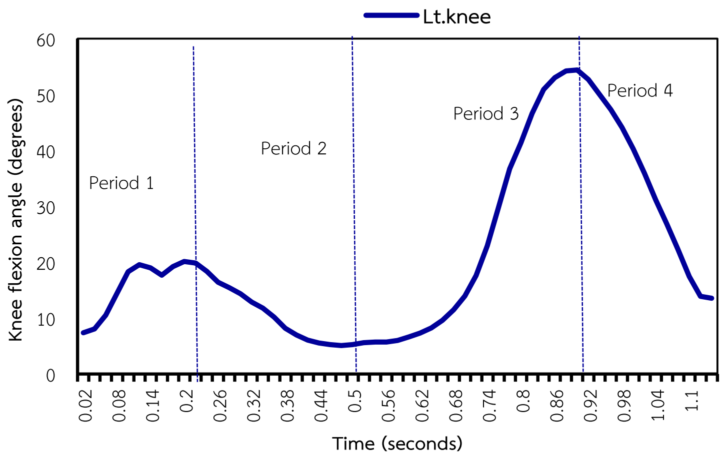
Figures O14 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.14.)

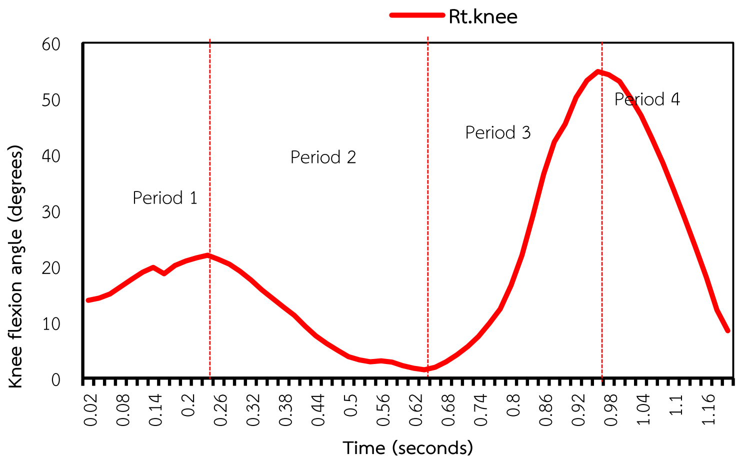
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

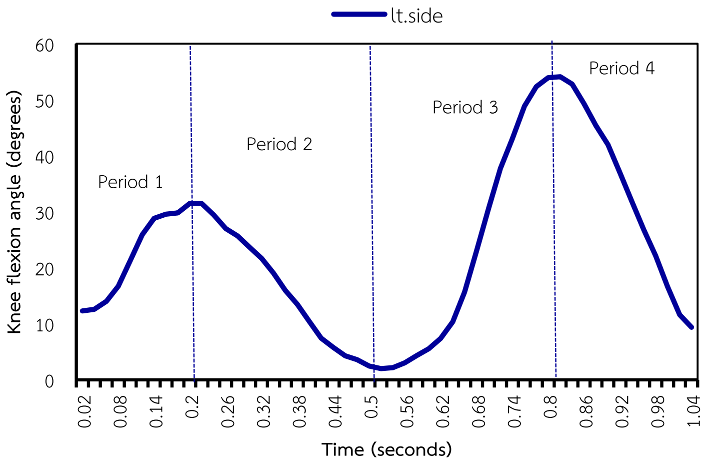
The 4th period is the knee movement from the MFS to the FHS phase.

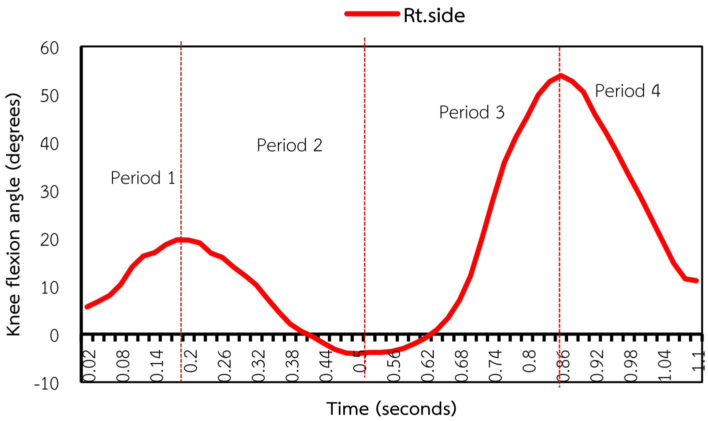




Figures O15 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.15.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.
The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.
The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.
The 4th period is the knee movement from the MFS to the FHS phase.





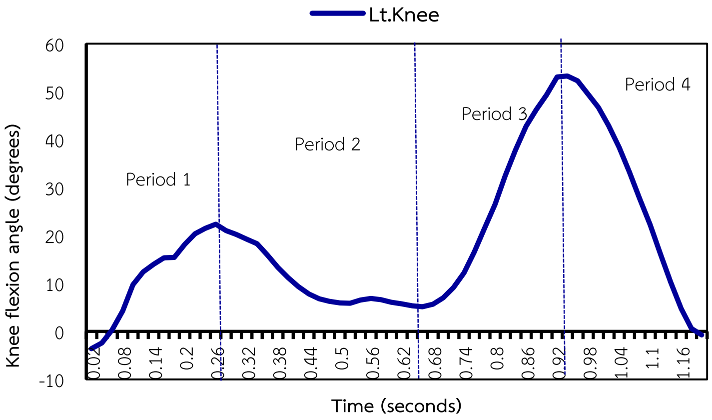
Figures O16 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.16.)

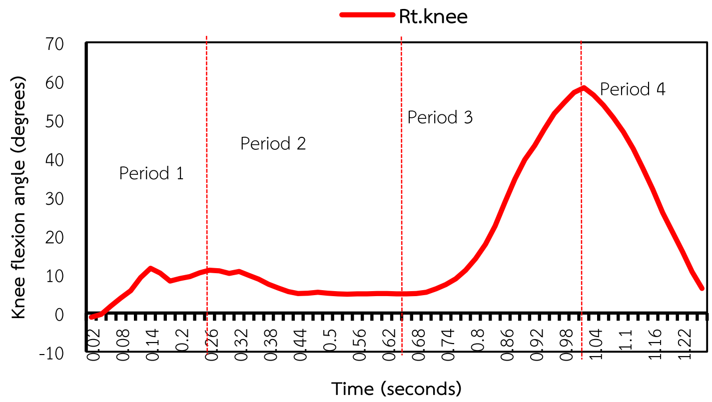
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





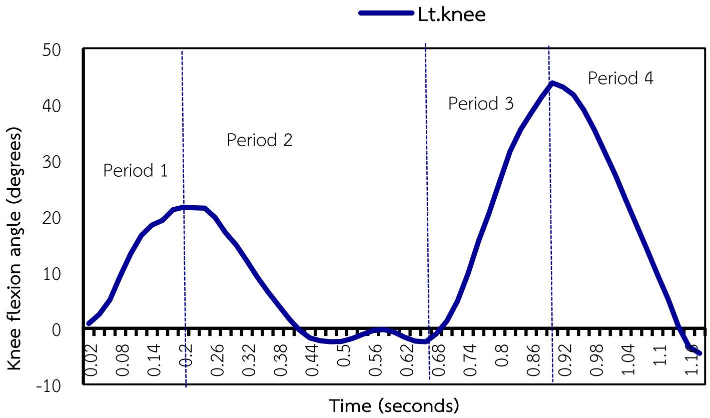
Figures O17 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.17.)

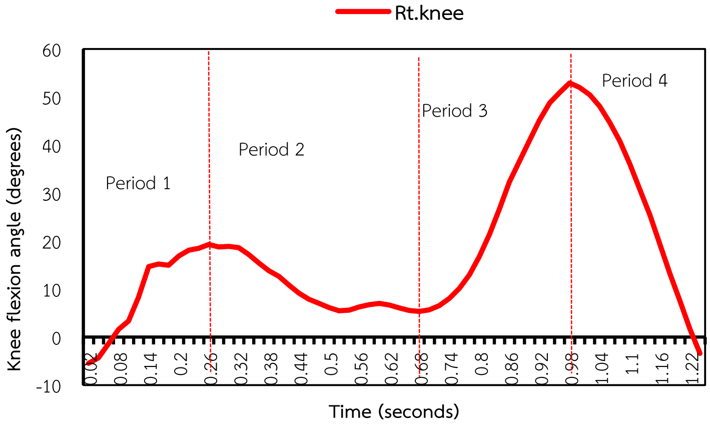
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





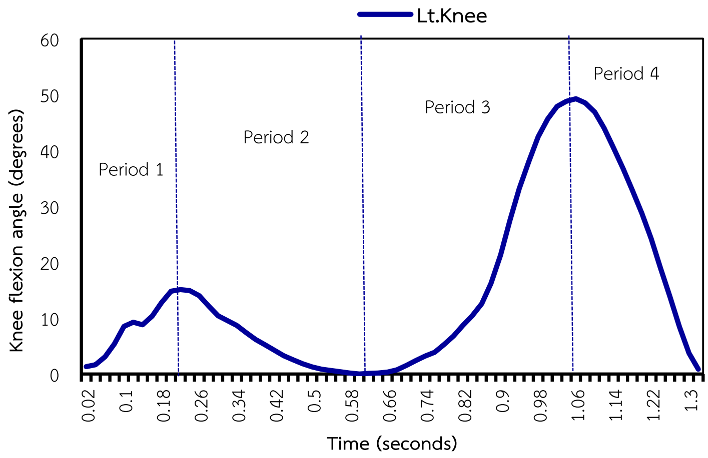
Figures O18 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.18.)

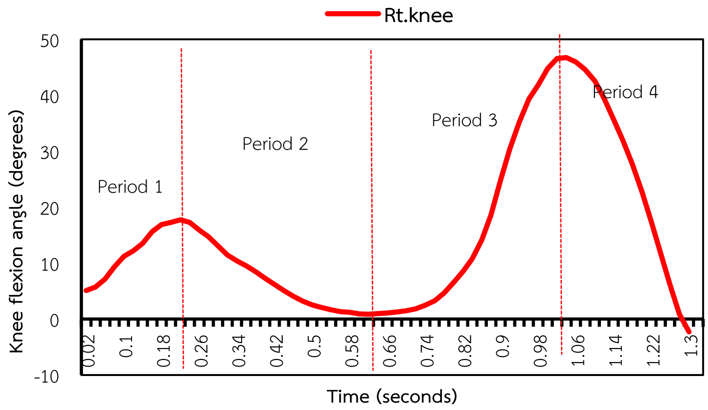
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





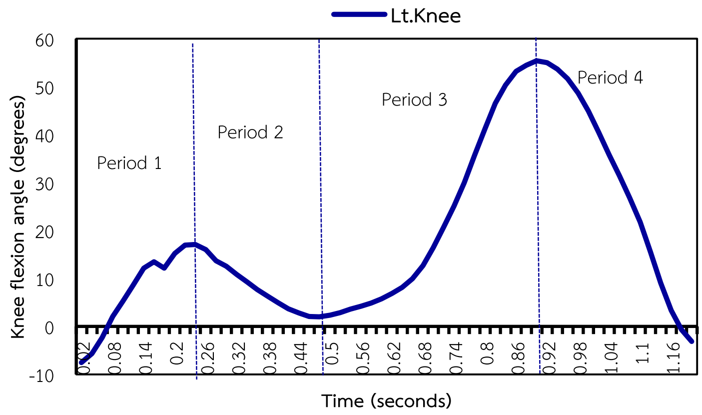
Figures O19 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.19.)

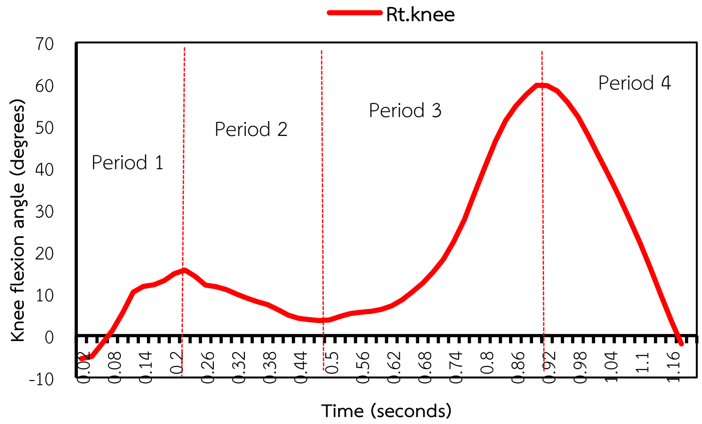
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





Figures O20 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman without knee osteoarthritis during the walking. (The data are from participant no.20.)

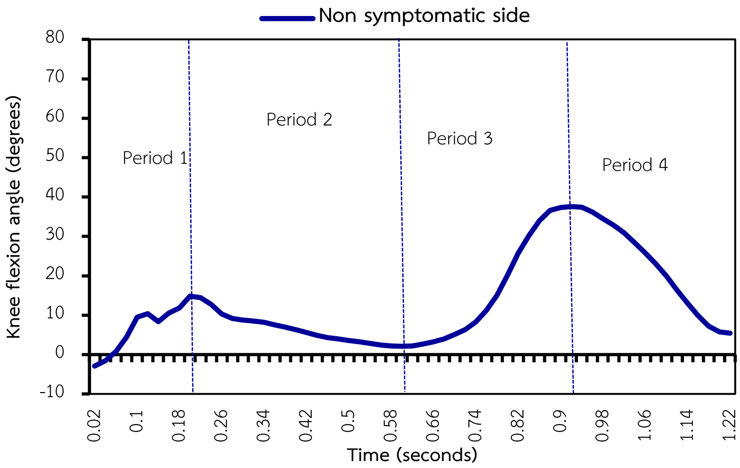
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

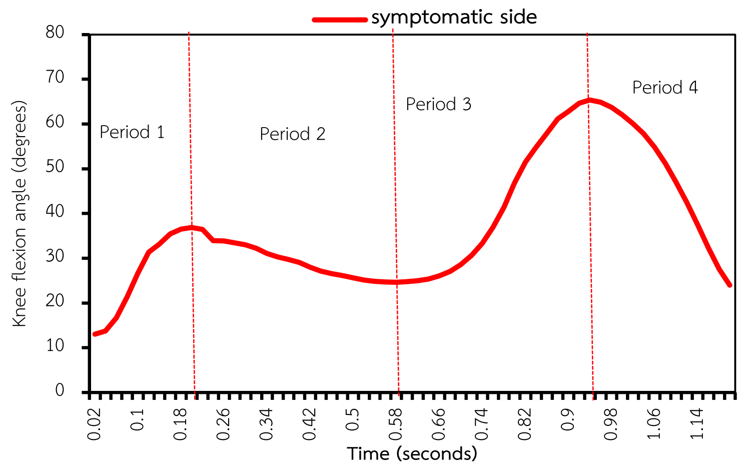
The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.

APPENDIX P
KNEE ANGULAR MOTION IN A GAIT CYCLE IN THE ELDERLY WOMAN WITH SYMPTOMATIC KNEE OSTEOARTHRITIS





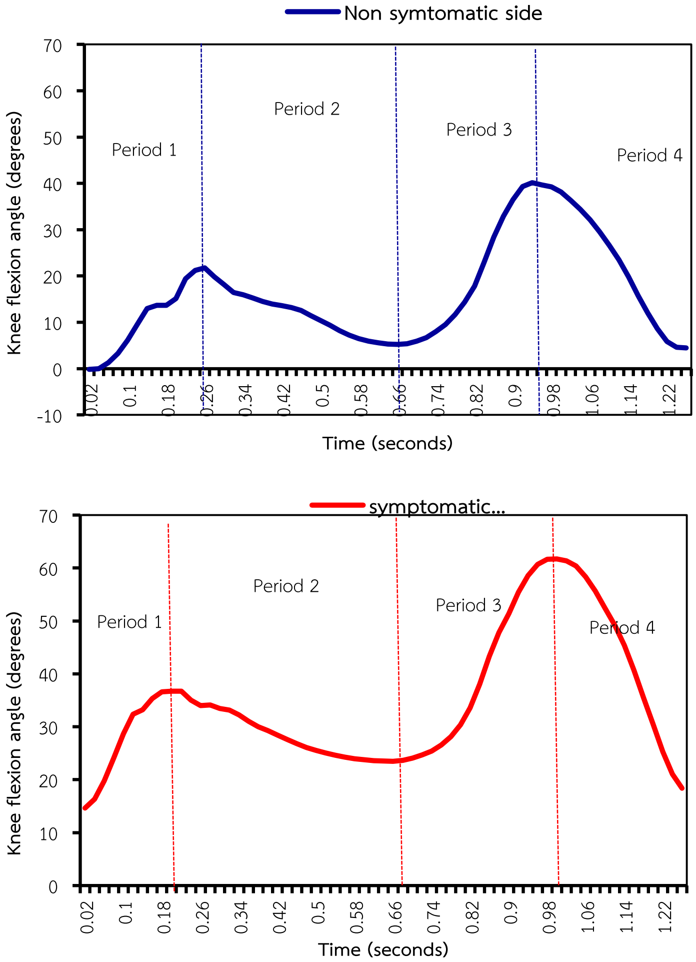
Figures P1 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.1.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.



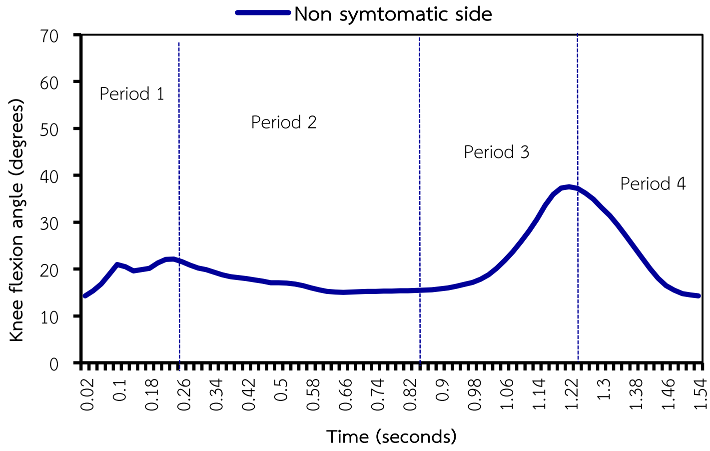
Figures P2 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.2.)

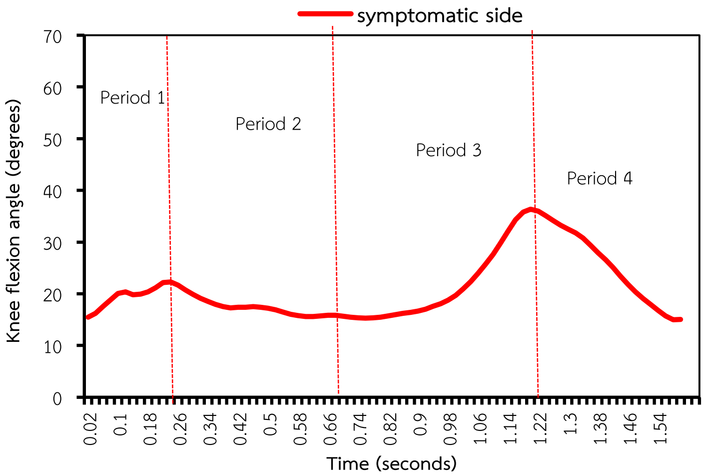
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





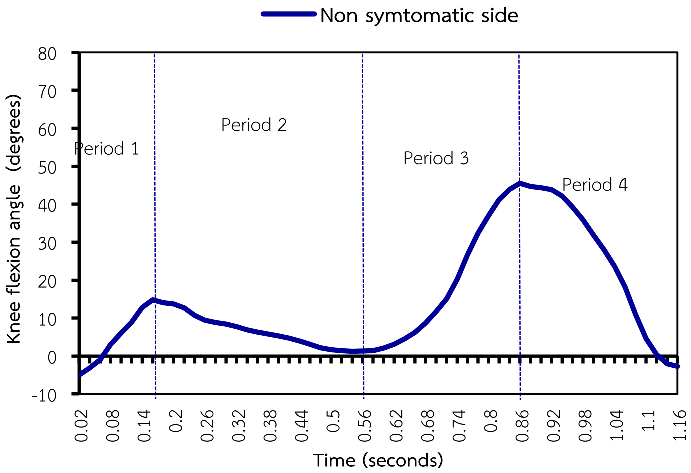
Figures P3 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with left knee osteoarthritis during the walking. (The data are from participant no.3.)

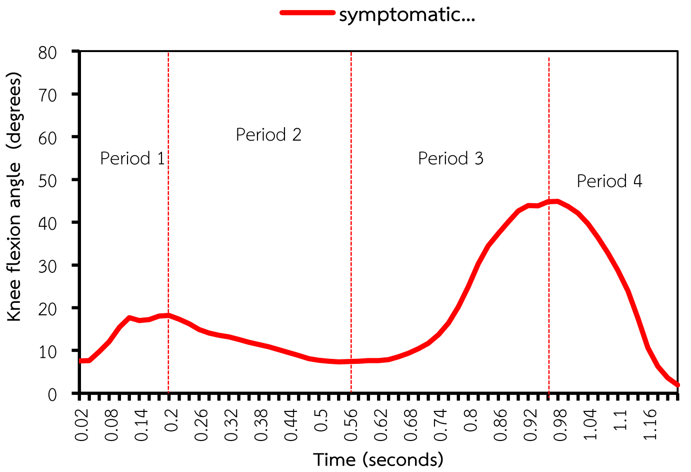
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





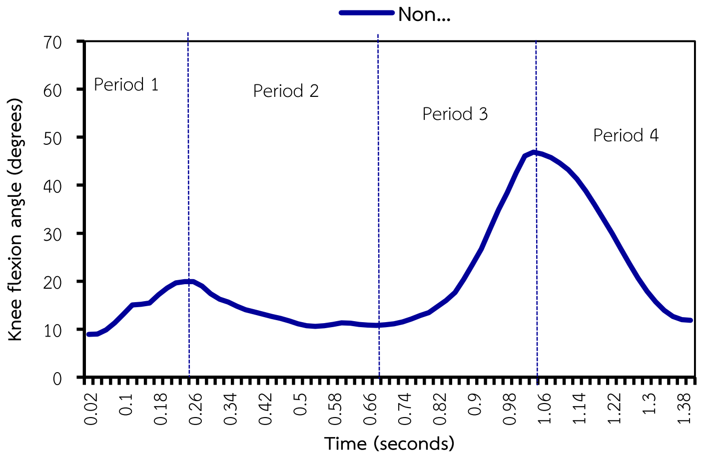
Figures P4 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.4.)

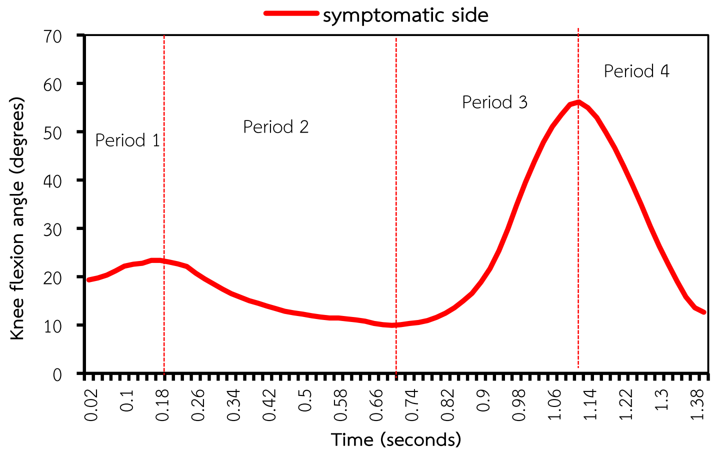
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





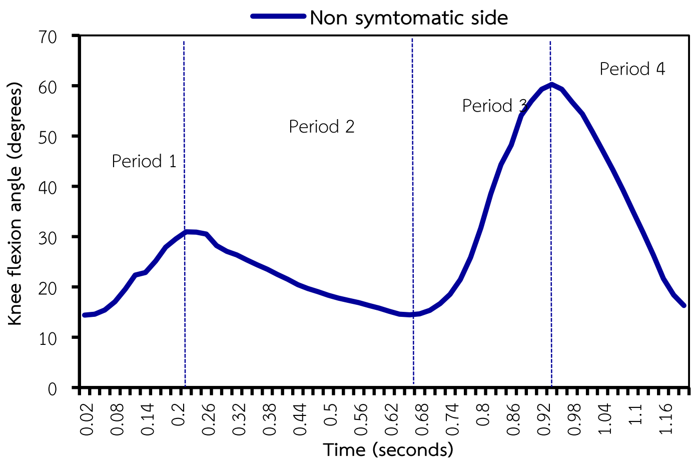
Figures P5 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.5.)

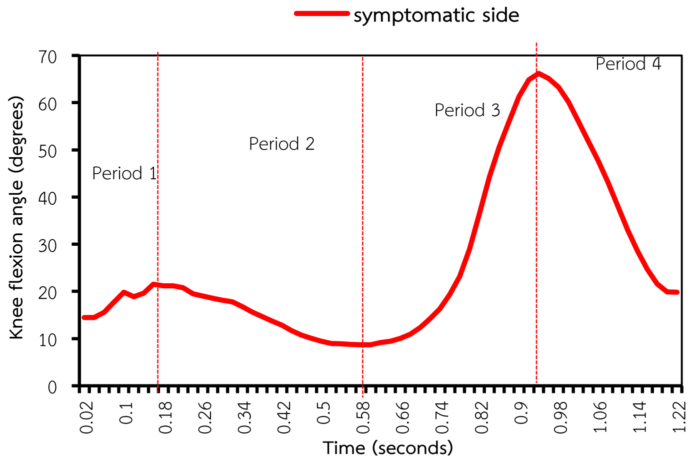
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





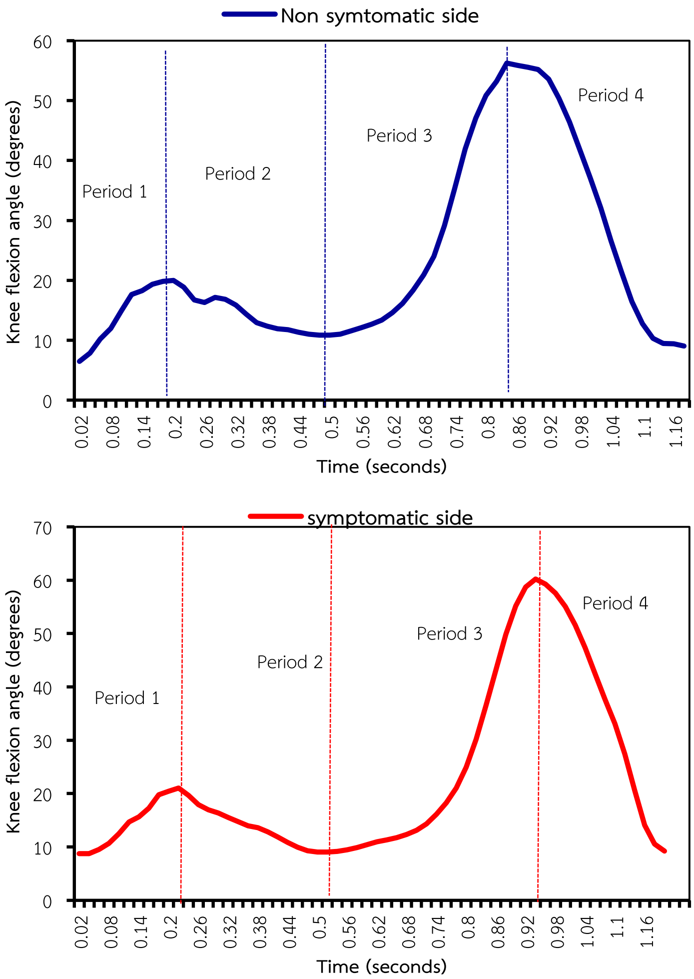
Figures P6 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.6.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.



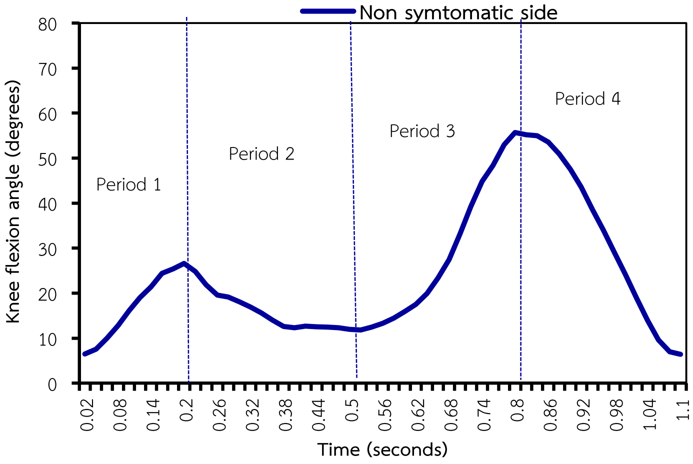
Figures P7 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with left knee osteoarthritis during the walking. (The data are from participant no.7.)

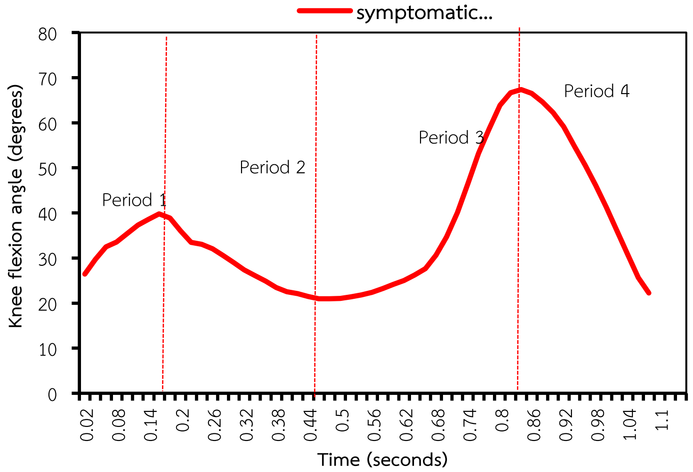
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

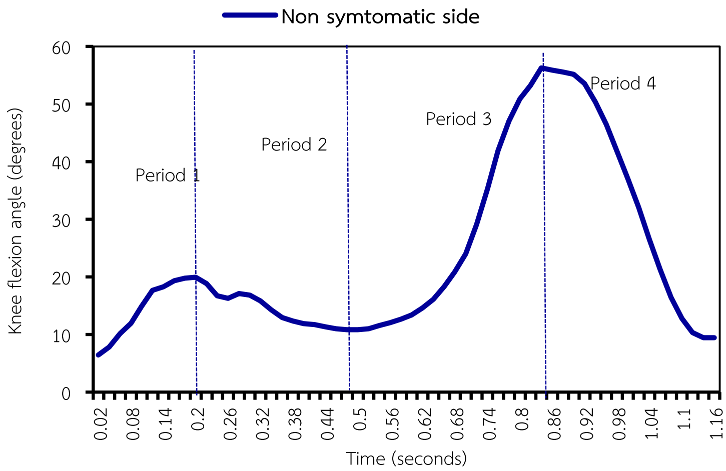
The 4th period is the knee movement from the MFS to the FHS phase.

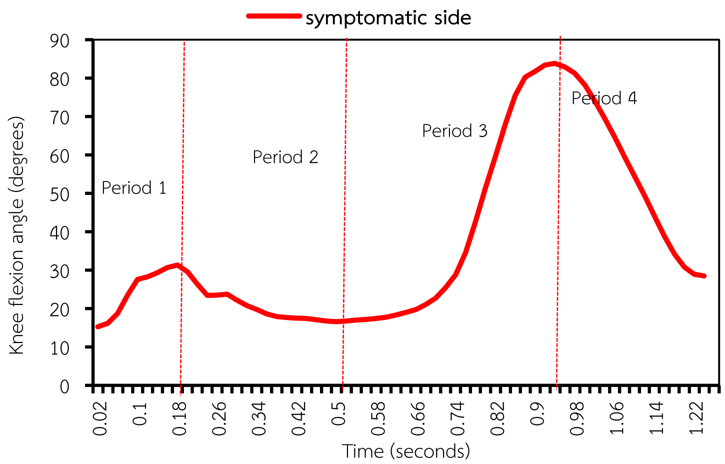




Figures P8 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with left knee osteoarthritis during the walking. (The data are from participant no.8.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.
The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.
The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.
The 4th period is the knee movement from the MFS to the FHS phase.





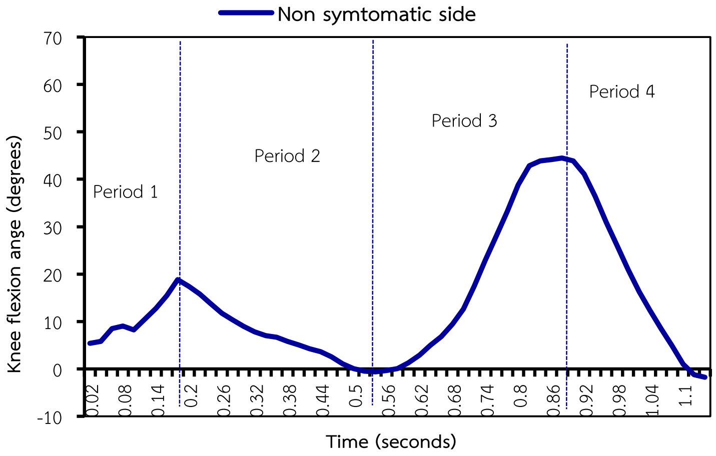
Figures P9 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with left knee osteoarthritis during the walking. (The data are from participant no.9.)

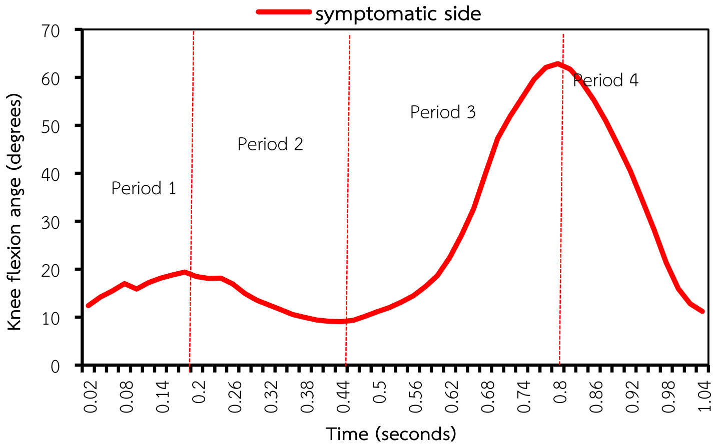
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





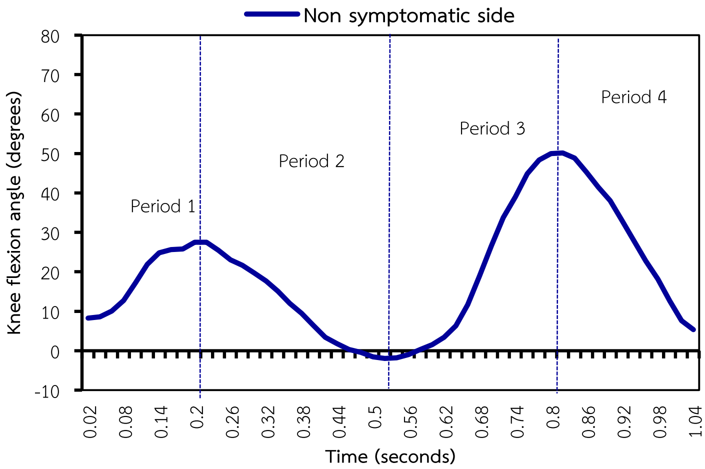
Figures P10 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.10.)

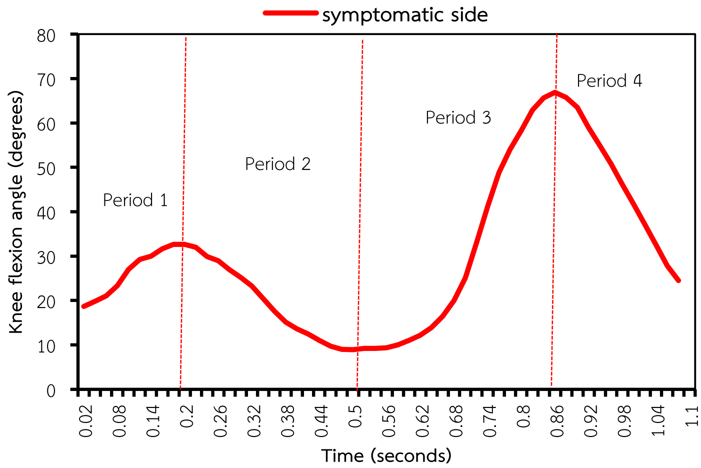
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





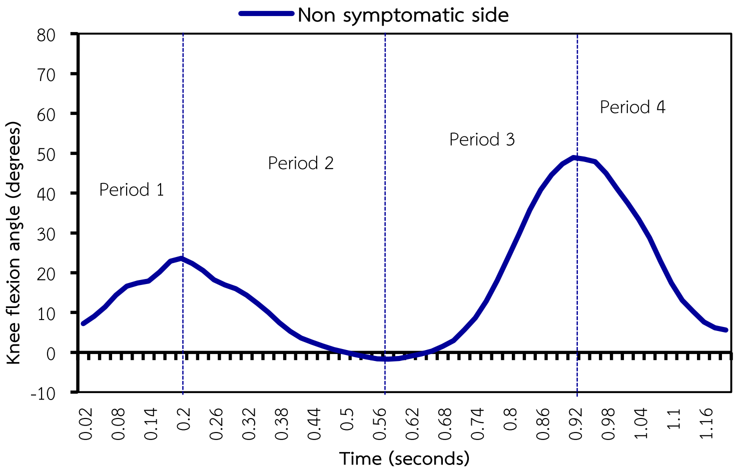
Figures P11 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.11.)

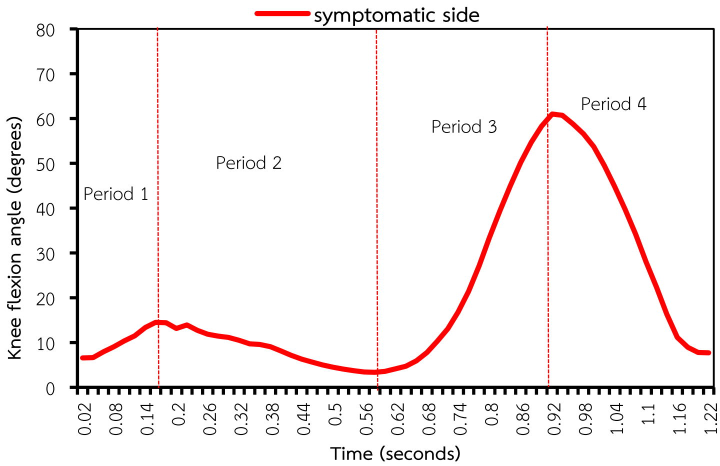
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





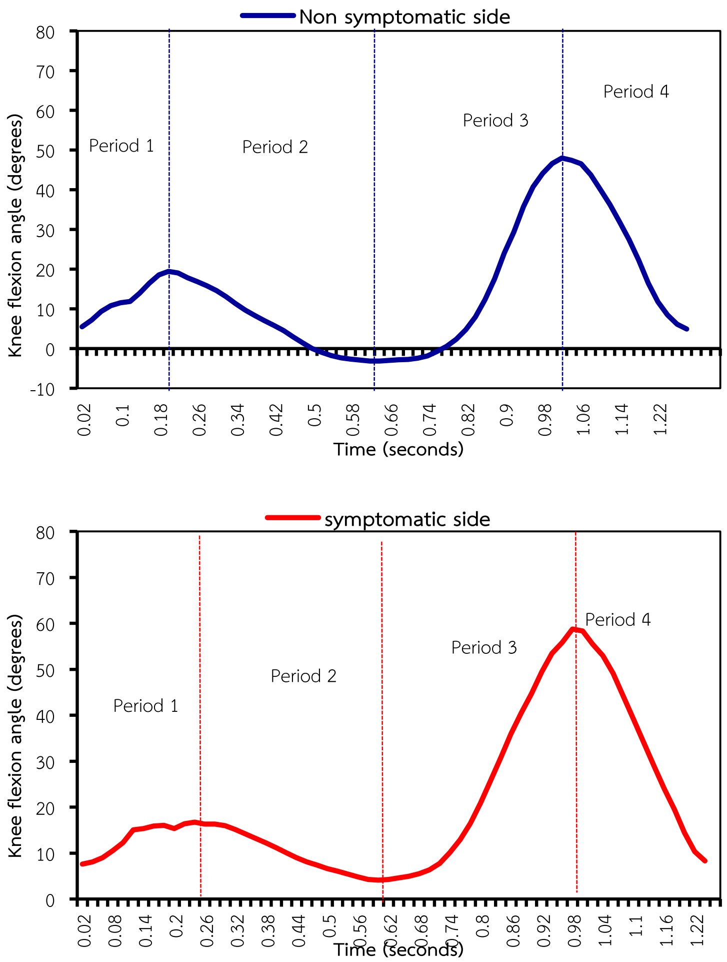
Figures P12 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.12.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3rd period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.



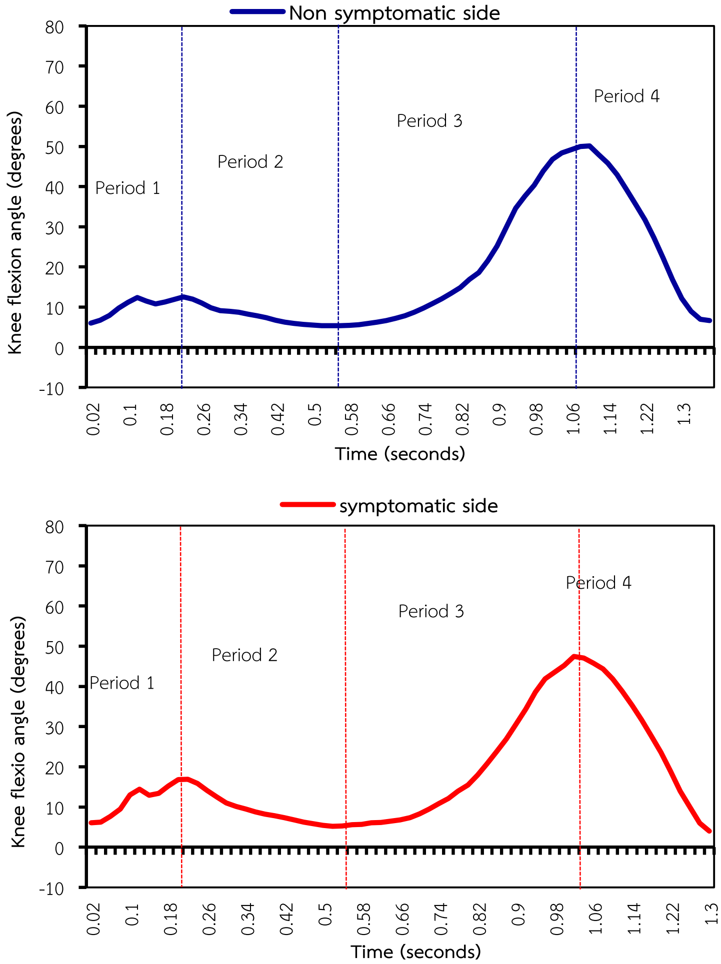
Figures P13 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.13.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.



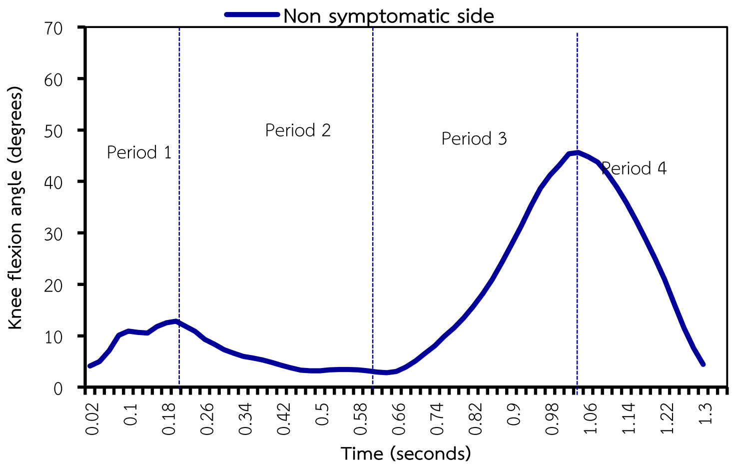
Figures P14 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.14.)

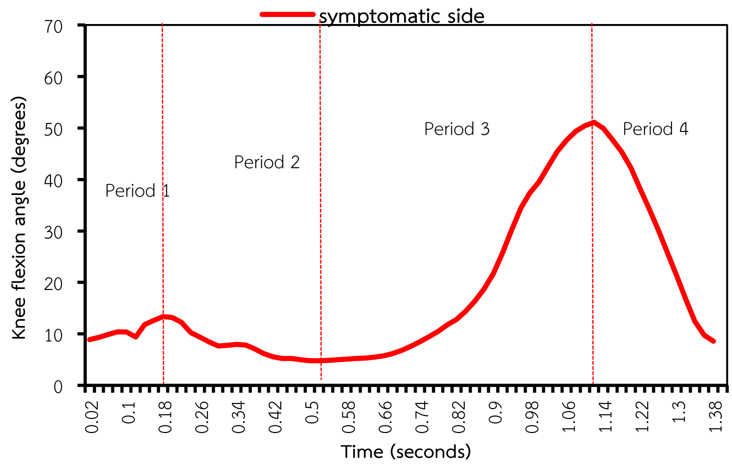
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





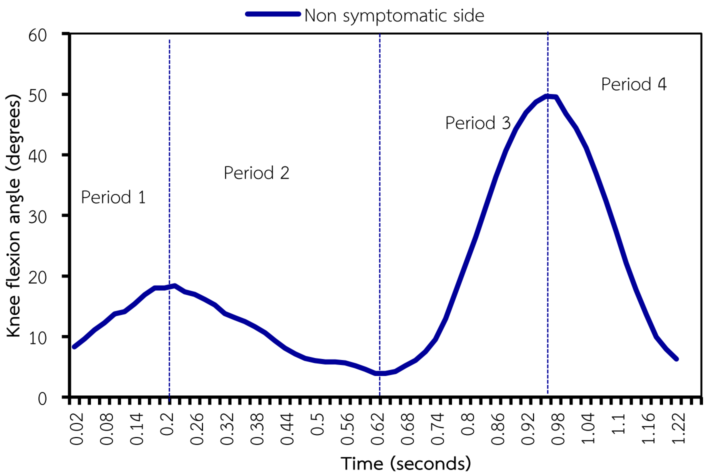
Figures P15 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with right knee osteoarthritis during the walking. (The data are from participant no.15.)

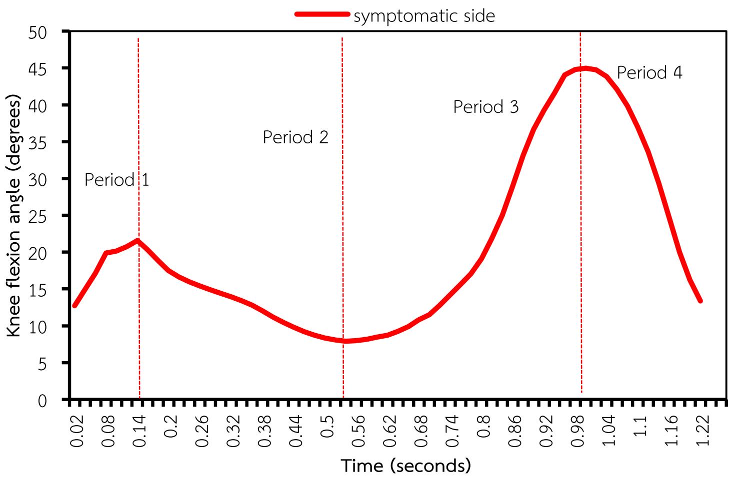
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





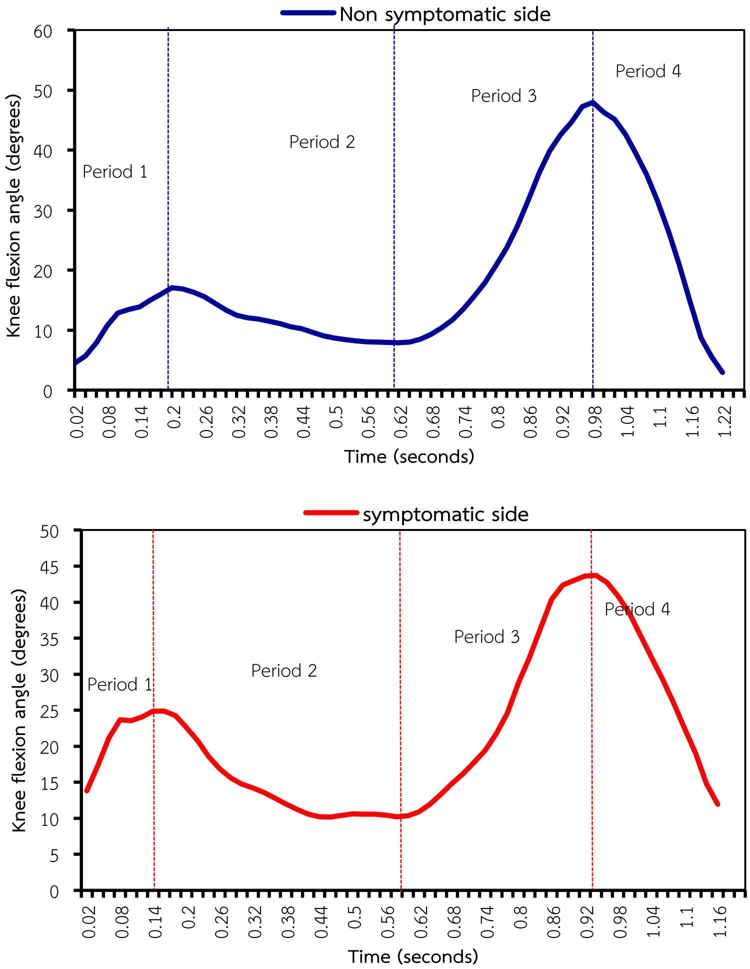
Figures P16 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with left knee osteoarthritis during the walking. (The data are from participant no.16.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

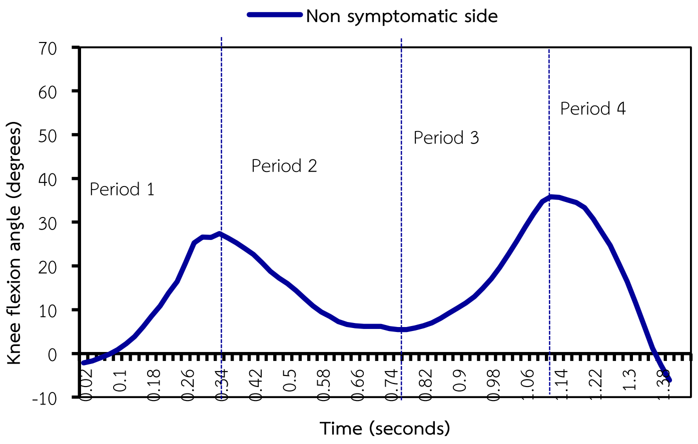
The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

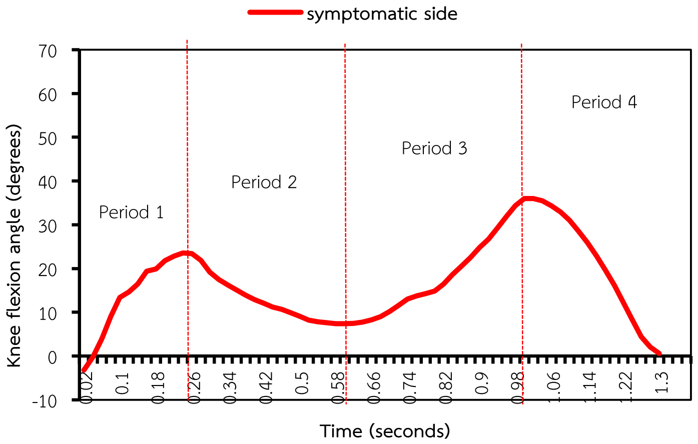
The 4th period is the knee movement from the MFS to the FHS phase.



Figures P17 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with left knee osteoarthritis during the walking. (The data are from participant no.17.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.
The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.
The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.
The 4th period is the knee movement from the MFS to the FHS phase.





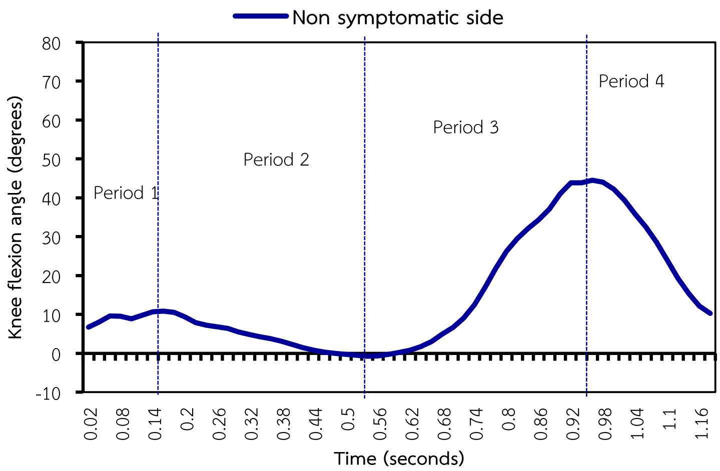
Figures P18 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with both (Lt.>Rt.) knee osteoarthritis during the walking. (The data are from participant no.18.)

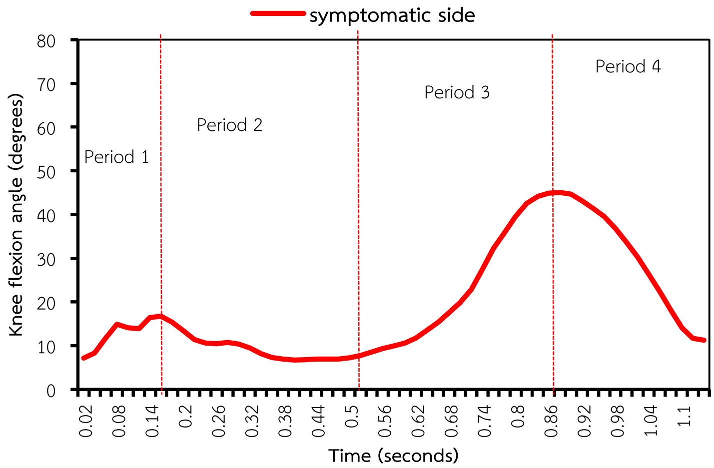
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





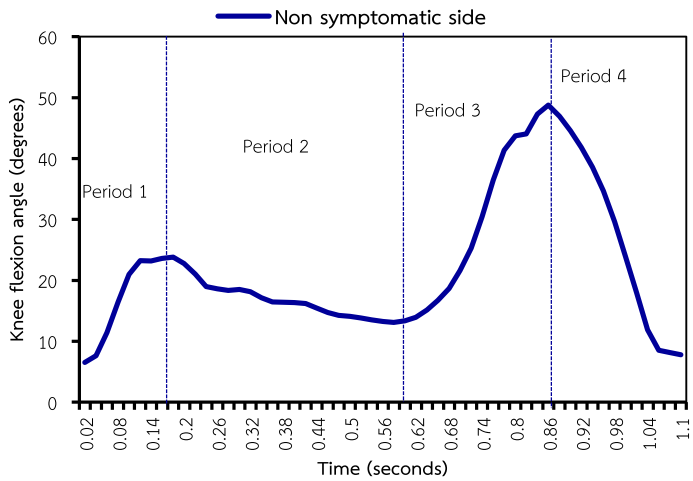
Figures P19 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with both (Rt.>Lt.) knee osteoarthritis during the walking. (The data are from participant no.19.)

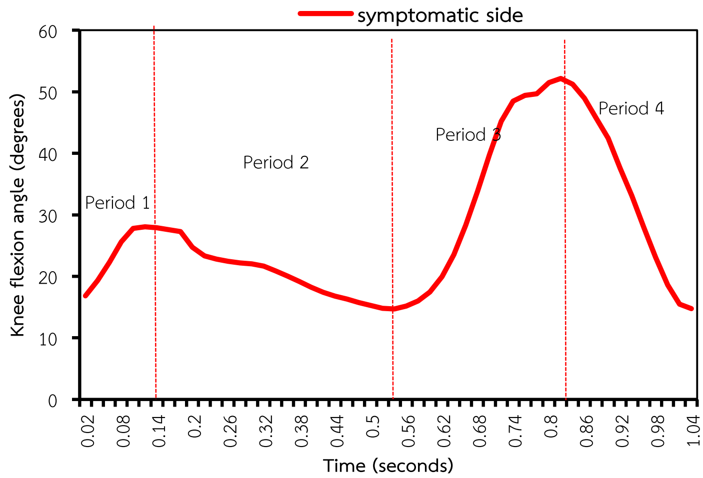
The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.





Figures P20 show the line graphs of knee flexion movement in the gait cycle that were measured on the both legs in the elderly woman with both (Lt.>Rt.) knee osteoarthritis during the walking. (The data are from participant no.20.)

The 1st period is the knee movement from the Flexion at Heel Strike (FHS) phase to the Maximum Flexion at Loading Responses (MFLR) phase.

The 2nd period is the knee movement from the MFLR phase to the Maximum Extension in Stance (MES) phase.

The 3th period is the knee movement from the MES phase to the Maximum Flexion in Swing (MFS) phase.

The 4th period is the knee movement from the MFS to the FHS phase.

VITA

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Some parts of this work were presented in the conference. I got the scholarship for the oral presentation from the National Electronics and Computer Technology Center (NECTEC) and the Graduate School of Chulalongkorn University. The article is as follow:-

Jaysrichai T, Suputtitada A, Khovidhungij W, Chanwimalueang T.: Application of Inertial Measurement Units for Angular Motion Detection. The 7th International Convention on Rehabilitation Engineering and Assistive Technology. 29-31 August 2013. Kintex, Gyeonggi, Korea.