

DIRECT LINEAR TRANSFORMATION CALIBRATION TECHNIQUE OF A LOW-COST PORTABLE 3D HUMAN MOTION ANALYSIS SYSTEM

Kengkaj Pongmit* and Nantakrit Yodpijit

Received: December 10, 2019; Revised: April 13, 2020; Accepted: April 22, 2020

Abstract

Camera calibration is a significant part of the accuracy of three-dimensional (3D) human motion analysis systems. Gait analysis is selected as the case study for consideration to apply a low-cost three-dimensional motion capture system to evaluate gait characteristics. Kinovea (free and open source) is used to retrieve the target position in two-dimensional (2D) coordinates from two cameras and the direct linear transformation (DLT) is then utilized to determine the 3D coordinates of an object using MATLAB. Statistical analysis for the study includes (1) the mean absolute error: MAE, (2) the root mean squared error: RMSE, and (3) %RMSE. Findings indicate that the acceptable accuracy for the low-cost gait analysis system at 95% confidence level is between 1.13-1.36 mm. It shows that most of the MAE, RMSE, and %RMSE calibration values of 13 markers in the XY, YZ, and XYZ planes are within acceptable range. However, it is found that some markers in the rear plane are out of bounds. Therefore, the use of two cameras for tracking human motions may affect the accuracy of the coordinate positions in the rear plane. Test-retest reliability is estimated using intraclass correlation coefficient (ICC3, 1) stability of measurement is statistically examined with the standard error of measurement (SEM) and minimal detectable change (MDC) at the 95% confidence level. The system showed good to excellent reliability (ICC $\geq$ 0.75) for both of kinematic gait parameters. Findings revealed that 3-D kinematic gait assessments systems using low-cost camera technology can be reliably used for human motion research and application.

Keywords: Camera calibration, low-cost human motion analysis system, 3-Dimensional camera capture system, gait analysis

Center for Innovation in Human Factors Engineering and Ergonomics, Department of Industrial Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand. E-mail: pongmitk@hotmail.com

** Corresponding author*

Introduction

The human movement has been used to examine many areas of work, such as medical diagnosis, medical rehabilitation, sport science, and product design (Perry *et al.*, 1992; Medved, 2000; Whittle, 2007; Winter, 2009; Huston, 2019). Especially, gait analysis is a useful clinical tool used for a variety of areas including neurological disease, fall risk, orthopedic disability, rehabilitation, and motion study in the manufacturing process (Salarian *et al.*, 2004; Narayanan, 2007; Bortolini *et al.*, 2018; Hausdorff *et al.*, 2001; Kubo *et al.*, 2011).

The 3D camera system in gait analysis is considered an appropriate method for analyzing kinematic gait. The main advantage of this system is reliability and high accuracy of the measurement (Wilken *et al.*, 2012). However, this technology has a disadvantage; it is expensive and requires high technical expertise. Thus, many researchers are unable to use this technology system, especially in developing countries (Carse *et al.*, 2013).

Human walking parameters, such as the position and direction of various body joints, can be used to monitor and analyze patient indications during treatment in the medical field (Stanic *et al.*, 1977). There are a study and design, the human walking parameters to be suitable assembly line in the manufacturing processes according to ergonomics (Al-Zuheri *et al.*, 2013). Human walking parameters can be measured using direct techniques or determinations from images. Especially, imaging measurement methods from the tracking marker have accuracy because it is directly measured from the image (Winter, 2009). The intrinsic (focal length, distortion variable, principal points, pixel scale factor) and extrinsic (location and orientation) of the camera are factors that affect the accuracy of the camera. Especially in gait analysis is using the marker system. The major factors of inaccuracy include the location of the skin and bone markers, the number and location of the camera, the distortion of the camera lens, the capture volume dimensions, and finally, the algorithm system used to reconstruction the

location of Marker in the 3D system. However, the effect of each of these parameters, intrinsic or extrinsic, depends on the difficulty to be determined and on the camera type. The image obtained from the camera is affected by the radial distortion of the camera. Greatest traditional camera calibration techniques need specific information about the geometric properties of the referenced object. We use Direct Linear Transformation (DLT), which solves the perspective matrix linearly. Camera calibration increases the accuracy of image measurement techniques (Ferryanto *et al.*, 2013). Therefore, the calibration of the camera is essential in the human motion analysis system. The purpose of this paper is the design of simplified and reliable calibration methods for a low-cost 3D human motion analysis system.

Materials and Methods

Hardware

The hardware using 3-D human motion records as an application of gait analysis. Two cameras (Logitech-C930 e HD Pro) with sets screen resolution at 1080 pixel and the frame rate at 30 frames per second or frequency 30 Hz or 33 milliseconds per frame.

The camera set IMAQdx the program of camera [Video Mode = 32 (800×600 MJPJ 30 FPS), Gain = 255 (maximum), Exposure = -5 (medium); Brightness = 128 (medium); Contract = 128 (medium); Saturation = 0 (minimum) and sharpness = 0 (minimum). The filters the picture data for the brightest section of the picture. So, all- region of markers are set to white color and the outside area of all markers are set to black color (Krishnan *et al.*, 2015).

Software

In the part of the software, we used Kinovea (freeware) software to retrieve the target coordinates in two-dimensional (2D) with two cameras. Then, we concatenate 2D data with a DLT to obtain 3D with Matlab (Yodpigit *et al.*, 2018).

Experiment Setting

The study is performed in an ergonomic laboratory. The laboratory environment is allocated to the standard operating room, which eliminates various distractions in order to position the marker of various markers, as shown in Figure 1. The calibration frame correctly is calibrated in the experiment. The two cameras are placed at the side view (left) and front view (Right) of the object. The side and front cameras determined the coordinate of each marker in the XY plane and YZ plane to be used to transform the actual coordinate of each marker in the XY plane and YZ plane respectively, as shown in Figures 2 and 3.

Camera Model

The principle of camera calibration is to coordinate using DLT. It is a technique of determining the coordinate point 3D system of an object using two planes (XY, YZ) from two

cameras. There are define two coordinate systems and the reference frame shown in Figure 4. The uppercase letters represent the X, Y, and Z-axis coordinate system, while the lowercase letters are used to find points within the coordinate system. That object is in what we call “object space reference frame” and is referenced to as the XYZ coordinate system. It merely locates the object in the real three-dimensional space.

There are two-dimensional reference frames obtained from each camera image, which are called “image plane reference frames” and are indicated using left (L) and right(R) views. The left and right views show the coordinate position in the XY and YZ planes, respectively. Therefore the $[u_L, v_L]$ and $[u_R, v_R]$ coordinate systems are shown in the XY and YZ image plane reference frames, respectively. It can be concluded that one



Figure 1. Experiment setting in an ergonomic laboratory

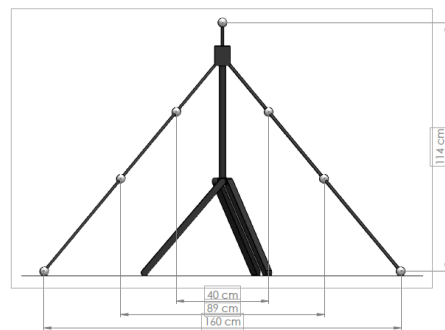


Figure 3. Imaging of marker points in YZ plane

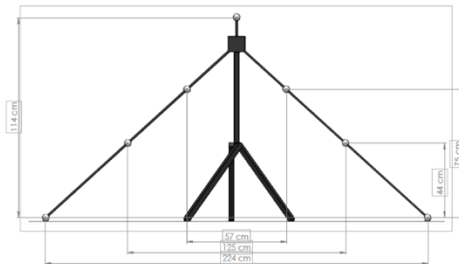


Figure 2. Imaging of marker points in XY plane

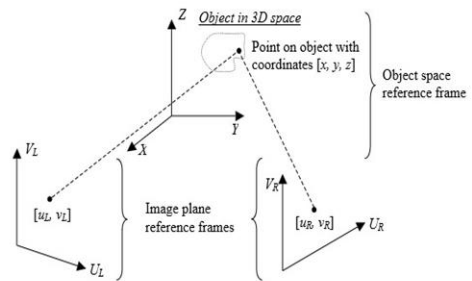


Figure 4. Object space and image plane reference frames coordinate systems

image plane reference frame for the left camera is the XY plane, and one for the right camera is the YZ plane.

The DLT's primary goal is to find the actual coordinate of the point $[x, y, z]$ based on $uL, vL, uR,$ and vR . Before being used to determine the coordinate of a real object, this system will be calibrated with the point of known position (Abdel-Aziz and Karara, 2015). This calibration uses 13 marker points of the calibration frames, which know the coordinate of the point $[x, y, z]$. The origin coordinate $[0, 0, 0]$ is referenced in the bottom middle coordinate of calibration frames shown in Figure 5.

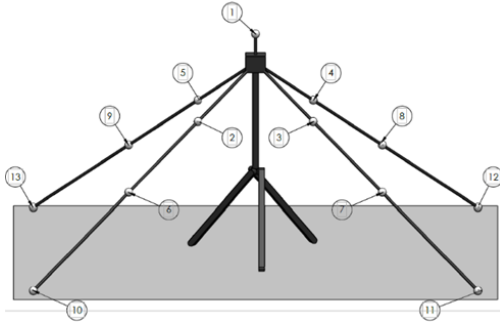


Figure 5. Location of markers calibration frames

We can determine the image points $[uL, vL]$ and $[uR, vR]$ from the actual coordinate of each marker to be calculated DLT by using Matlab.

Participants

In study, thirty healthy males aged 20-44 years (1.65 ± 0.15 m, 70.24 ± 10.23 kg.) participated in the experiment. The test is repeated twice, which are separated by about two days. All subjects joined the experiments in an ergonomics laboratory at King Mongkut's University of Technology North Bangkok (KMUTNB).

Statistical Analysis

The accuracy of this calibration method was compared between the actual coordinate positions with the transformed position from

both cameras in the XY, YZ plane. A total of 13 marker locations were repeated each marker was five times.

The statistical analysis used to test for accuracy included the mean, the standard deviation (SD), the minimum and maximum error, the mean absolute error (MAE), the root mean squared error (RMSE), and the value of RMSE was revealed as percentage (%RMSE) (Silvatti *et al.*, 2012) as shown from the source of the equations below.

$$MAE = \frac{1}{N} \sum_i^N |d_i - D| \quad (1)$$

$$RMSE = \frac{1}{N} \sqrt{\sum_i^N (d_i - D)^2} \quad (2)$$

$$\%RMSE = 100 \frac{\frac{1}{N} \sqrt{\sum_i^N (d_i - D)^2}}{D} \quad (3)$$

The error displacement values of the MAE, RMSE, and % RMSE values for each XY, YZ, and XYZ planes were determined by the formula below.

$$d_{xy} = \sqrt{d_x^2 + d_y^2} \quad (4)$$

$$d_{yz} = \sqrt{d_y^2 + d_z^2} \quad (5)$$

$$d_{xyz} = \sqrt{d_x^2 + d_y^2 + d_z^2} \quad (6)$$

At present, the reliability uses the test statistic, which is Interclass Correlation Coefficient (ICC). The reliability of a measure obtained in SPSS for window version 24 employing ICC, Pearson correlation coefficients, SEM and MDC values. The ICC values are computed using test-retest reliability (two-way mixed effects model type single measurement (ICC3, 1 model). The SEM and MDC values can be given below (Beckerman *et al.*, 2001).

$$SEM = SD \times \sqrt{1 - ICC} \quad (7)$$

$$MDC = SEM \times 1.96 \times \sqrt{2} \quad (8)$$

where SEM is the standard error of measurement and SD is the standard deviation of the first and the second experiment at the 95 percent confidence interval on the difference in mean each rate.

Interpretation of the ICC, which is the value between 0 to 1 can be shown as follows; reliability is low (0.00-0.50), reliability is moderate (0.50-0.74), reliability is good (0.75-0.90) and reliability is excellent with ICC value greater than 0.90 (Koo and Li, 2016).

Results and Discussion

In examining the accuracy of a measurement system, the first significant element is model adequacy checking. It is including the normally distributed, independently distributed, and variance stability. These values are analyzed using the MINITAB program (version17).

A greatly helpful procedure is to create a normal probability plot of the error to check the assumption of normality using test t-test. The analysis of independently distributed is conducted using a plot of error versus fitted values. There is no reason to suspect any violation of independence or constant variance assumptions. The analysis of variance stability is conducted using a plot of error versus run order. This plot should not show any distinct pattern.

The normal probability plot, as shown in Figures 6, 7, and 8. The typical result of examining this show is that the error distribution is generally reasonable. The data points approximately follow the straight line. These p values are more than 0.05, and we can conclude that the data becomes a normal distribution.

Figure 9, showing that the distribution of residual no proper format means the data is

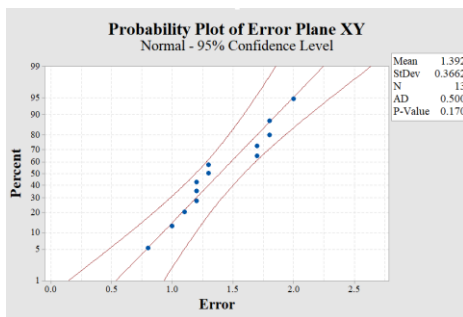


Figure 6. The normal probability plot XY plane

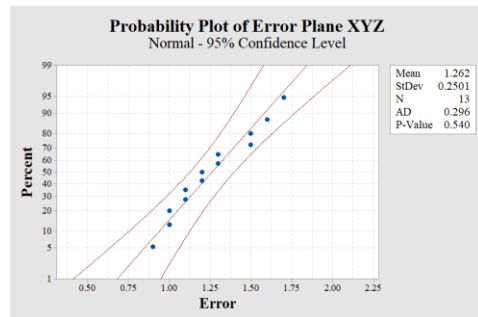


Figure 8. The normal probability plot XYZ plane

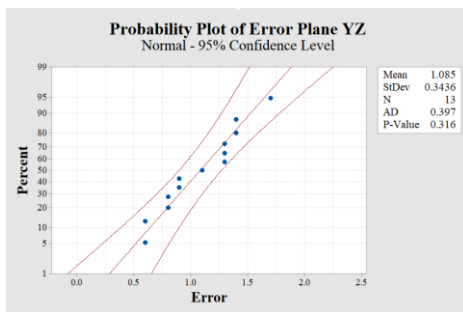


Figure 7. The normal probability plot YZ plane

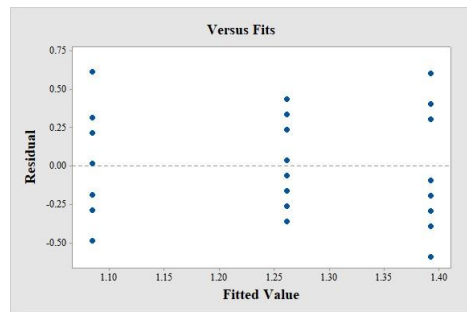


Figure 9. Plot of residuals versus fitted values

independent. For the data variance stability testing, it is found that the distribution of the data characteristics is not a trend or random distribution. Therefore, it can be concluded that it is stable, as shown in Figure 10. Consequently, these three tests are gathered, that the data are reliable for additional analysis and statistical examination.

The analysis of variance (ANOVA) and tests for equality of variance are analyzed by using MINITAB software. The P-value is 0.07, we conclude that the means in each plane are not different at the 95 percent confidence level as shown Table 1.

Although residual plots are commonly used to diagnose differences of variation, several statistical tests have likewise been proposed. These tests will be shown tests of the hypotheses.

$$H_0 : \sigma_1^2 = \sigma_2^2 = \sigma_3^2 \quad (9)$$

$$H_i : \sigma_1^2 \neq \sigma_2^2 \neq \sigma_3^2 \quad (10)$$

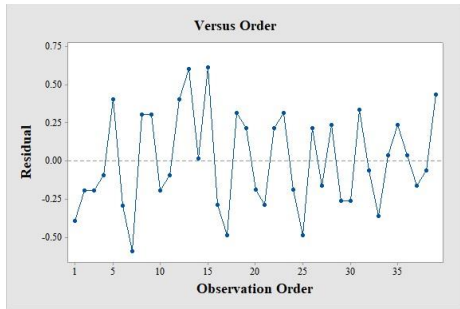


Figure 10. Plot of residuals versus run order

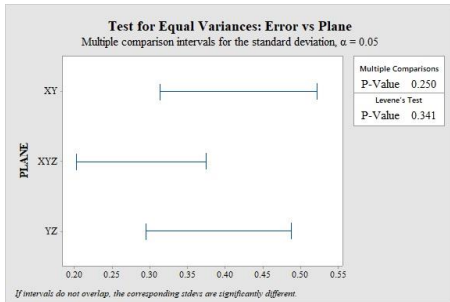


Figure 11. Tests equality of variance for calibration camera system

From Figure 11, we find that the P-value is 0.341 (Levene test), so we accept the null hypothesis (H_0), which reasons that the variances in each plane are not different at the 95 percent confidence level. This is the same conclusion reached by analyzing the plot of residuals versus fitted values. The results of the analysis of variance and tests for equality of variance can use as a single confidence interval in comparing the accuracy of all three planes.

Table 2 shows the mean, standard deviation, and confidence interval at 95 percent confidence level. By using confidence interval for evaluation of confidence in comparing the accuracy of the camera.

In testing, the accuracy of calibration utilized statistical analysis values consisting of MAE, RMSE, and %RMSE. Table 3 shows the mean absolute errors (MAE) in XY, YZ, and XYZ planes. In the XY plane, the MAE values

Table 1. ANOVA for calibration camera system

Source of Variation	DOF	SS	MS	F	P
Plane	2	0.62	0.31	2.95	0.07
Error	36	3.78	0.10		
Total	38	4.40			

Table 2. The confidence interval at 95% confidence level

Mean	SD	Confidence level Interval (95%)
1.25	0.34	(1.13-1.36)

Table 3. The mean square error (MAE) in XY, YZ, XYZ

Location MARKER	MAE XY Plane (mm)	mae YZ Plane (mm)	mae XYZ Plane (mm)
1	1.00	1.00	1.10
2	1.20	1.70	1.50
3	1.20	0.80	1.00
4	1.30	0.60	1.00
5	1.80	1.40	1.60
6	1.10	1.30	1.20
7	0.80	0.90	0.90
8	1.70	0.80	1.30
9	1.70	1.30	1.50
10	1.20	1.40	1.30
11	1.30	0.90	1.10
12	1.80	0.60	1.20
13	2.00	1.30	1.70

found at marker eight points are between 0.90 to 1.30 mm. In the YZ plane, the MAE values found at marker ten points are between 0.60 to 1.30 mm. The error-values are less than the other points in each this the plane. In the XYZ plane was synchronized between the XY and YZ plane, the MAE values found at marker four points are higher than others points, which are between 1.50 to 1.70 mm.

Table 4 shows the root mean square error (RMSE) in XY, YZ, and XYZ planes. In the XY plane, the RMSE values found at marker six points are between 0.90 to 1.50 mm. In the YZ plane, the RMSE values found at marker eight points are between 0.80 to 1.30 mm. In the XYZ plane was synchronized between the XY and YZ plane, the RMSE values found at marker three points are higher than other points, which are between 1.50 to 1.60 mm. From the results of examining the MAE and RMSE values in XYZ plane, it found three points are higher than other points similarly.

Table 5 shows the percent of the root mean square error (%RMSE) in XY, YZ, and XYZ plane. In the XY plane, the %RMSE values found at marker 1, 2, 3, 6, 7, 10, and 11 are between (4.59-6.65%). In the YZ plane, the %RMSE values found at marker 1, 3, 4, 7, 8, 11, and 12 are between (3.46-5.46%). In the XYZ plane was synchronized between the XY and YZ plane, the %RMSE values found at marker 5, 9, and 13 were higher than other points, which were between (6.67-7.04%). The results of %RMSE in the XY, YZ, and XYZ, which are similar with MAE and RMSE.

The test-retest reliability for kinematic systems included the hip, knee joint angles in the XY, YZ, and XZ plane and angular velocities in the XY plane are shown in Table 6.

Based on the analysis, it is found that the ICC values of the hip, knee joint angles in the XY plane is higher than in the YZ and XZ plane. The ICC values in the XY plane is between 0.86 to 0.96, the YZ plane is between 0.79 to 0.86, and the XZ plane is between 0.76 to 0.81. So it is concluded that the reliability for kinematic systems in the XY plane is higher than the YZ and XZ plane. However, the reliability of the three planes varies from

good to excellent because the ICC all values are more than or equal 0.75. The SEM and MDC values of hip, knee joint angles in the XY YZ and XZ planes are in the interval 0.54-1.41 (1.51-3.91), 0.43-1.65 (1.28-4.57) respectively. In summary, the ICC value is an inverse correlation with SEM and MDC value which interpreted if ICC value is an increase, SEM and MDC value are decreased or vice versa if ICC value is decreased, SEM and MDC value are increased. The SEM and MDC value of angular velocity is more than the SEM and MDC value of joint angle have effected from the standard deviation of angular velocity. However, the result of statistical analysis, the SEM and MDC have been similar to those of previous research (Mentiplay and Clark, 2018). Kinematic graphs for knee joint angles in the XY, YZ, and XZ plane as shown in Figures12, 13, and 14.

Table 4. The root mean square error (RMSE) in XY, YZ, XYZ

Location MARKER	rmse XY Plane (mm)	rmse YZ Plane (mm)	rmse XYZ Plane (mm)
1	1.00	1.20	1.10
2	1.10	1.50	1.30
3	1.30	0.90	1.10
4	1.60	0.80	1.20
5	1.70	1.50	1.60
6	1.20	1.30	1.20
7	0.90	1.00	1.00
8	1.50	0.90	1.20
9	1.60	1.40	1.50
10	1.20	1.50	1.30
11	1.50	1.00	1.20
12	1.60	0.80	1.20
13	1.70	1.40	1.50

Table 5. The percent of root mean square error (%RMSE) in XY, YZ, XYZ

Location MARKER	%rmse XY Plane (%)	%rmse YZ Plane (%)	%RMSE XYZ Plane (%)
1	4.59	5.29	4.94
2	4.83	6.63	5.73
3	5.84	4.00	4.92
4	7.32	3.46	5.39
5	7.44	6.63	7.04
6	5.29	5.98	5.64
7	4.24	4.65	4.44
8	6.59	4.00	5.30
9	7.19	6.15	6.67
10	5.29	6.63	5.96
11	6.65	4.65	5.65
12	7.32	5.46	6.39
13	7.73	6.15	6.94

Conclusions

The objective of this research study was to analyze and calibration of a low-cost 3D camera systems in gait analysis. The calibration frame was calibrated in this experiment. This research

focuses a determine coordinates in the XY, YZ, and XYZ plane, which is 13 points. The statistics used in the analysis, including MAE, RMSE, and %RMSE. It reveals that the great MAE, RMSE, and %RMSE values found at marker 1, 2, 3, 6, 7, 10, and 11 in the XY plane,

Table 6. The test-retest reliability of kinematics for the low-cost 3-D camera system

	Day 1	Day 2	ICC	SEM	MDC
Hip in the XY plane (Degree)					
Peak Flexion Stance	34.09±3.83	34.29±3.89	0.95	0.86	(2.38)
Peak Extension Stance	29.34±1.51	29.29±1.50	0.87	0.54	(1.51)
Peak Flexion Swing	9.71±2.02	9.69±2.04	0.89	0.67	(1.87)
Hip in the YZ plane (Degree)					
Peak Abduction Stance	7.94±2.13	8.33±2.20	0.89	0.72	(2.01)
Peak Adduction Stance	6.84±2.57	6.57±2.67	0.86	0.98	(2.72)
Peak Abduction Swing	7.87±2.10	8.29±2.17	0.85	0.83	(2.30)
Hip in the XZ plane (Degree)					
Peak Rotation Internal Stance	8.07±2.64	8.31±2.50	0.81	1.12	(3.11)
Peak Rotation External Stance	9.48±3.04	9.63±2.98	0.78	1.41	(3.91)
Peak Rotation Internal Swing	8.28±2.93	8.49±2.47	0.86	1.02	(2.83)
Knee in the XY plane (Degree)					
Peak Flexion Stance	36.29±1.77	36.15±1.78	0.93	0.47	(1.30)
Peak Extension Stance	-6.39±1.96	-6.35±1.88	0.86	0.72	(1.99)
Peak Flexion Swing	60.81±2.17	60.62±2.13	0.96	0.43	(1.19)
Peak Extension Swing	-3.93±2.19	-3.64±2.54	0.89	0.79	(2.18)
Knee in the YZ plane (Degree)					
Peak Varus Stance	6.98±3.38	6.60±3.35	0.80	1.51	(4.17)
Peak Valgus Stance	2.14±1.01	2.31±1.00	0.79	0.46	(1.28)
Peak Varus Swing	8.64±2.66	8.27±2.69	0.86	1.01	(2.80)
Peak Valgus Swing	2.45±1.10	2.55±0.95	0.75	1.65	(4.57)
Knee in the XZ plane (Degree)					
Peak Rotation Internal Stance	6.62±2.16	6.12±1.93	0.76	1.00	(2.78)
Peak Rotation External Stance	8.03±2.02	7.96±2.20	0.81	0.92	(2.55)
Peak Rotation Internal Swing	7.20±1.78	7.14±1.90	0.82	0.78	(2.16)
Peak Rotation External Swing	8.49±2.81	8.33±2.66	0.85	0.90	(2.49)
Hip Angular Velocity (Degree/s)					
Peak Flexion Stance	121.82±12.38	120.94±12.66	0.87	4.51	(12.51)
Peak Extension Stance	146.33±14.39	147.75±15.24	0.92	4.19	(11.61)
Peak Flexion Swing	204.37±17.33	206.29±18.17	0.93	4.70	(13.01)
Knee Angular Velocity (Degree/s)					
Peak Flexion Stance	306.74±26.45	308.80±26.55	0.86	9.92	(27.49)
Peak Extension Stance	107.93±19.05	108.86±19.34	0.91	5.76	(15.96)
Peak Flexion Swing	328.88±23.67	330.33±25.32	0.82	10.39	(28.80)
Peak Extension Swing	376.67±40.06	374.27±39.58	0.90	12.59	(34.90)

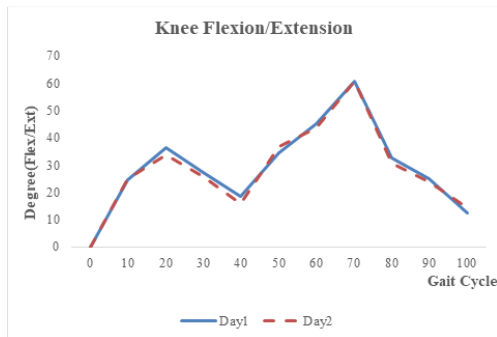


Figure 12. Kinematic graphs on knee joint angles in the sagittal (XY) plane

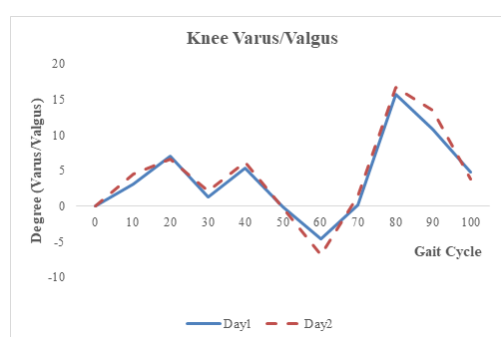


Figure 13. Kinematic graphs on knee joint angles in the frontal (YZ) plane

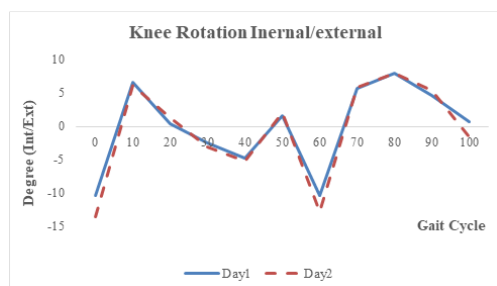


Figure 14. Kinematic graphs on knee joint angles in the transverse (XZ) plane

1, 3, 4, 7, 8, 11, and 12 in the YZ plane, and 1, 2, 3, 4, 6, 7, 8, 10, 11, and 12 in the XYZ plane which were similarly previous research (Pribani *et al.*, 2009; Silvatti *et al.*, 2012; Feng and Max, 2014). In the positions of marker 5, 9, and 13 have been the values of MAE, RMSE, and %RMSE were higher than other points. From the analysis, it was found those positions were at the rear of the plane on each side of XY, YZ planes. Capturing images using two cameras was not enough for the accuracy back each plane.

The study is a test-retest reliability of low-cost camera systems designed for 3-D gait analysis. The data of kinematics obtained in the experiments, using ICC and MDC values for estimation of reliability based on the percentage of gait cycle. The ICC values are found between 0.75-0.96 which showed good to excellent reliability for this test. The MDC values are ranged 1.19-4.57, 11.61-34.90 and SEM values are ranged 0.43-1.65, 4.19-12.59 of joints angles, angular velocities respectively as shown in Table.

The limitation of this research that using the KINOVEA program to capture the X, Y, and Z coordinates can only use two cameras. This limitation influences the accuracy of the position coordinates back each plane. Therefore, in the development of the system in the future, the researchers will write an algorithm for image positioning using program LABVIEW or MATLAB to be capable of using more than two cameras. It will help to improve the capacity to define the X, Y, and Z coordinates in the back of each plane even better.

Acknowledgments

This research was partially supported by King Mongkut's University of Technology North Bangkok - Contract no. KMUTNB-NRU-59-07. Experiments were conducted in the Center for Innovation in Human Factors Engineering and Ergonomics, Department of Industrial Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Thailand.

References

- Abdel-Aziz, Y.I., and Karara, H.M. (2015). Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. *Photogrammetric Engineering and Remote Sensing*, 81(2):103-107.
- Al-Zuheri, A., Luong, L., and Xing, K. (2013). Impact of walking worker assembly line configuration on ergonomics performance. *Australian J. Multi-Discip. Eng.*, 9(2):96-101.
- Beckerman, H., Roebroek, M.E., Lankhorst, G.J., Becher, J.G., Bezemer, P.D., and Verbeek, A.L. (2001). Smallest real difference, a link between reproducibility and responsiveness. *Quality of Life Research: Int. J. Quality Life Asp. Treat. Care Rehabil.*, 10(7):571-578.
- Bortolini, M., Faccio, M., Gamberi, M., and Pilati, F. (2018). Motion Analysis System (MAS) for production and ergonomics assessment in the manufacturing processes. *Comp. Indus. Eng.*, 10(1):1-13.
- Carse, B., Meadows, B., Bowers, R., and Rowe, P. (2013). Affordable clinical gait analysis: An assessment of the marker tracking accuracy of a new low-cost optical 3D motion analysis system. *Physiotherapy (United Kingdom)*, 99(4):347-351.
- Feng, Y., and Max, L. (2014). Accuracy and precision of a custom camera-based system for 2-d and 3-d motion tracking during speech and nonspeech motor tasks. *JSLHR.*, 57(2):426-438.
- Ferryanto, F., Mihradi, S., Dirgantara, T., and Mahyuddin, A.I. (2013). Camera calibration technique improvement for 3d optical gait analyzer system. *Appl. Mechan. Mat.*, 393:976-981.
- Hausdorff, J.M., Rios, D.A., and Edelberg, H.K. (2001). Gait variability and fall risk in community-living older adults: A 1-year prospective study. *Arch. Phys. Med. Rehabil.*, 82(8):1,050-1,056.
- Huston, R. (2019). *Principles of Biomechanics*. 1st ed. CRC Press, 442p.
- Koo, T.K. and Li, M.Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J. Chiropr. Med.*, 15(2):155-163.

- Krishnan, C., Washabaugh, E.P., and Seetharaman, Y. (2015). A low cost real-time motion tracking approach using webcam technology. *J. Biomech.*, 48:544-548.
- Kubo, K., Miyoshi, T., Kanai, A., and Terashima, K. (2011). Gait rehabilitation device in central nervous system disease: a review. *J. Robot.*, 2011:1-14.
- Medved, V. (2000). *Measurement of Human Locomotion*. 1st ed. CRC Press, 272p.
- Mentiplay, B.F. and Clark, R.A. (2018). Modified conventional gait model versus cluster tracking: Test-retest reliability, agreement and impact of inverse kinematics with joint constraints on kinematic and kinetic data. *Gait and Posture*, 64:75-83.
- Narayanan, U.G. (2007). The role of gait analysis in the orthopaedic management of ambulatory cerebral palsy. *Current Opinion in Pediatrics*, 19(1):38-43.
- Perry, J., Slac T., and Davids, J.R. (1992). Gait analysis: normal and pathological function. *J. Pediat. Orthop.*, 12(6):815.
- Pribani, T., Peharec, S., and Medved, V. (2009). A comparison between 2D plate calibration and wand calibration for 3D kinematic systems. *Kinesiology*, 41:147-155.
- Salarian, A., Russmann, H., Vingerhoets, F.J.G., Dehollain, C., Blanc, Y., Burkhard, P.R., and Aminian, K. (2004). Gait assessment in Parkinson's disease: Toward an ambulatory system for long-term monitoring. *IEEE Trans. Biomed. Eng.*, 51(8): 1,434-1,443.
- Silvatti, A.P., Salve Dias, F.A., Cerveri, P., and Barros, R.M.L. (2012). Comparison of different camera calibration approaches for underwater applications. *J. Biomechan.*, 45(6):1,112-1,116.
- Stanic, U., Bajd, T., Valencic, V., Kljajić, M., and Acimović, R. (1977). Standardization of kinematic gait measurements and automatic pathological gait pattern diagnostics. *Scandinavian J. Rehabilit. Med.*, 9(3):95-105.
- Whittle, M. (2007). *Gait analysis: an introduction*. 4th ed. Butterworth-Heinemann, 244p.
- Wilken, J.M., Rodriguez, K.M., Brawner, M., and Darter, B.J. (2012). Reliability and minimal detectable change values for gait kinematics and kinetics in healthy adults. *Gait Posture*, 35(2):301-307.
- Winter, D.A. (2009). *Biomechanics and motor control of human movement*. 4th ed. Wiley, 384p.
- Yodpigit, N., Jongprasithporn, M., Pongmit, K., and Sittiwanchai, T. (2018). A low-cost portable 3D human motion analysis system: An application of gait analysis. In: *IEEE International Conference on Industrial Engineering and Engineering Management*; December 10-13, 2017; Singapore, p. 1,164-1,168.