Validity and reliability of automatic range of motion measurement using the elbow joint photograph

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ความถูกต้อง และ ความน่าเชื่อถือ ของการวัดพิสัยการเคลื่อนไหวแบบอัตโนมัติโดยใช้ภาพถ่ายของข้อศอก

นายกฤษณ์ เจริญลาภ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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กฤษณ์ เจริญลาภ : ความถูกต้อง และ ความน่าเชื่อถือ ของการวัดพิสัยการเคลื่อนไหวแบบอัตโนมัติโดยใช้ภาพถ่ายของข้อศอก. (Validity and reliability of automatic range of motion measurement using the elbow joint photograph) อ.ที่ปรึกษาหลัก : รศ. นพ.ทวีชัย เตชะพงศ์วรชัย

ที่มา : การใช้ภาพถ่ายในการวัดพิสัยการเคลื่อนไหวข้อศอกจำเป็นต้องใช้ผู้ประเมิน และ ความแม่นยำของการวัดขึ้นอยู่กับประสบการณ์ของผู้ที่ทำการวัด

วัตถุประสงค์: งานวิจัยชิ้นนี้ต้องการนำเสนอการใช้เทคนิคการประมวลผลภาพถ่ายดิจิตอลเพื่อวัดพิสัยการเคลื่อนไหวข้อศอก

วัสดุและวิธีการ : ผู้ร่วมงานวิจัยรับสมัครจากนักเรียน และ พนักงานมหาวิทยาลัย ภาพถ่ายด้วยเครื่องฟลูโอโรสโคปบริเวณข้อศอกทั้งสองข้างถูกถ่ายในท่าเหยียด และ งอศอก นักกายภาพบำบัดสองคนทำการวัดพิสัยข้อศอกทั้งสองข้างด้วย โกนิโอมิเตอร์ อินไคลโนมิเตอร์ และ สมาร์ทโฟน ไจโรสโคป ช่างถายภาพถ่ายภาพข้อศอกในท่าเหยียด และ งอ ด้วยกล้องสมาร์ทโฟน ความละเอียด 8 ล้านพิกเซล มุมเหยียดและงอถูกคำนวณโดยใช้เทคนิคการประมวลผลภาพถ่ายดิจิตอล ความเชื่อถือได้ภายในผู้วัด และ ระหว่างผู้วัด ของทุกวิธีการวัดถูกคำนวณโดยใช้ intraclass correlation coefficient (ICC) Paired student t test และ Wilcoxon signed rank test เพื่อตรวจสอบอคติแบบเป็นระบบ ใช้ Bland-Altman plot เพื่อดูพิสัยความแตกต่างระหว่างวิธีการวัด

ผลการศึกษา: จำนวนข้อศอกทั้งหมด 56 ข้าง ความเชื่อถือได้ภายในผู้วัด และ ระหว่างผู้วัด ICC ของฟลูโอโรสโคป โกนิโอมิเตอร์ อินไคลโนมิเตอร์ และ ไจโรสโคป มีความเข้ากันได้ปานกลางถึงยอดเยี่ยม มุมเหยียดงอของฟลูโอโรสโคปสูงกว่าผลที่ได้จากเทคนิคการประมวลผลภาพถ่ายดิจิตอล ค่าเฉลี่ยมุมเหยียดงอของเทคนิคการประมวลผลภาพถ่ายดิจิตอลสูงกว่าโกนิโอมิเตอร์ อินไคลโนมิเตอร์ และ ไจโรสโคป ($P < 0.05$) แต่ พิสัยการเคลื่อนไหวข้อศอกไม่ต่างกัน (เปรียบเทียบ โกนิโอมิเตอร์ $P = 0.322$, เปรียบเทียบ อินไคลโนมิเตอร์ $P = 0.534$, เปรียบเทียบ ไจโรสโคป $P = 0.899$) ขอบเขตการเข้ากันได้ของมุมเหยียด งอ และ พิสัยการเคลื่อนไหวเท่ากับ 9.93-13.32, 9.81-12.66 และ 13.84-16.66 องศาตามลำดับ

สรุป: การวัดพิสัยการเคลื่อนไหวข้อศอกโดยการใช้เกณฑ์วิธีเทคนิคการประมวลผลภาพถ่ายดิจิตอลในงานวิจัยนี้ได้ผลเทียบเคียงกับมุมงอของภาพฟลูโอโรสโคป และ มุมงอและเหยียดของ โกนิโอมิเตอร์ อินไคลโนมิเตอร์ และ ไจโรสโคป แต่อาจแตกต่างกันได้มากถึง 16 องศา การศึกษาเพิ่มเติมและการจัดเกณฑ์วิธีเป็นสิ่งจำเป็นในการเพิ่มความแม่นยำให้กับเทคนิคการวิเคราะห์ภาพ

สาขาวิชา	การพัฒนาสุขภาพ	ลายมือชื่อนิสิต	
ปีการศึกษา	2561	ลายมือชื่อ อ.ที่ปรึกษาหลัก	

6074357030 : MAJOR HEALTH DEVELOPMENT

KEYWORD: Computer-Assisted Image Processing, Elbow joint, Measurement, Photography, Range of Motion

Chris Charoenlap : Validity and reliability of automatic range of motion measurement using the elbow joint photograph. Advisor: Assoc. Prof. TAWECHAI TEJAPONGVORACHAI, M.D.

Background: Photographic-based arc of motion measurement methods required human assessors and its accuracy is depend on observer experience.

Objectives: Current research proposed method of using digital image processing technique (DIPT) for measuring elbow range of motion.

Methods: Participants were enrolled from students and staffs in the university. Fluoroscopic images of both elbows were taken in flexion and extension positions. Two physiotherapists performed goniometer, inclinometer and smartphone gyroscope range of motion (ROM) measurement on bilateral elbows. Photographer took elbow images in fully extension and fully flexion three times for each position with 8-megapixel smartphone camera. The extension and flexion angles were calculated using DIPT protocol. Intra-rater reliability and inter-rater reliability of all methods were assessed using intraclass correlation coefficient (ICC). Paired student *t* test and Wilcoxon signed rank test were used to detect systematic bias. Bland-Altman plot was utilized to show possible range of difference between methods.

Results: There were total 56 elbows. Intra-rater and inter-rater ICCs of fluoroscope, goniometer, inclinometer, and gyroscope showed moderate to excellent agreement. Extension and flexion score of fluoroscopic images were higher than DIPT results. Mean extension and flexion angle of DIPT group was higher than goniometer, inclinometer and gyroscope group ($P < 0.05$), but total ROM were equaled, (vs goniometer $P = 0.322$, vs inclinometer $P = 0.534$, vs gyroscope $P = 0.899$). Limit of agreement of extension angles, flexion angles and total ROMs were 9.93-13.32, 9.81-12.66 and 13.84-16.66 degrees respectively.

Conclusions: Elbow ROM measurement from current DIPT protocol had comparable result with flexion agnle of fluoroscopic images and flexion-extension angle of goniometer, inclinometer and gyroscope, but it can be difference from other reference methods up to 16 degree. Further study and protocol adjustment are needed to improve accuracy of the image analytic technique.

Field of Study:	Health Development	Student's Signature ....
Academic Year:	2018	Advisor's Signature ....

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CHAPTER 1 - INTRODUCTION

Elbow joint is a hinge joint that allow single plane of movement, flexion and extension. Intra and extraarticular disease such as elbow contracture and fracture can cause functional impairment of this joint. Range of motion (ROM) is one of objective measurement of the elbow function and it is also part of the scoring system (1, 2).

Assessment of measurement methods for elbow ROM were reported in past literatures. Radiographic examination gives the most accurate result, but it is not the first choice for daily practice for evaluating elbow function because of the risk from radiation exposure (3). Standard clinical goniometer, universal and digital type, is very popular because of its availability. Inter and intra-rater reliability of the goniometer is also high from recent systematic review (3, 4). Inclinometer is a practical device, but it should be used by trained professional. In addition, digital inclinometer especially dual-type inclinometer is quite expensive. There are many methods for evaluate motion arc of the elbow joint including goniometer, inclinometer, photograph, gyroscope and radiograph with different benefits and drawbacks for each method (Table 1).

Table 1 Advantages and Disadvantage of elbow measurement methods.

Methods	Advantages	Disadvantages
Radiography	Most accurate	Radiation exposure, inconvenient
Inclinometer	Practical, recommended by AMA (5)	Digital inclinometer is expensive, required experience examiner
Goniometer	Practical, cheap, available	Examiner-dependent accuracy, good inter-rater reliability
Smartphone gyroscope	Allow self-assessment	Require mobile device and strap, accuracy depend on subject
Photography	Allow patient-reported functional status (6), non-contact measurement	Require assessor, accuracy depend on assessor and quality of photo

CHAPTER 2 - REVIEW OF THE RELATED LITERATURES

Photographic-based method has been proposed and validated in many literatures (1, 6-10). The concept of this method is taking a photo or video of elbow in extension and flexion position, and then drawing lines of arm and forearm axis on images by the assessor using visible reference point and calculate angle between these two lines. ROM value is obtained from flexion angle minus extension angle. It gives many benefits such as inexpensive, durable, easy data storage and transfer that allow multiple observers, measurement can be done at any time in any locations (8, 9). Image capturing devices can be a digital camera or smartphone which has been already validated for measuring elbow range of motion (7, 10). However, accuracy of this measurement methods is depend on observer experience (1).

Digital photography shows equivalent to goniometry when measuring elbow motion arc.(7, 8). The precision of measuring elbow flexion within 10° is ranging from 85% to 89%, and 98.3% in elbow extension (6). Some literatures claimed that digital photography has better inter-rater reliability than manual goniometry (9). Inter-rater reliability of photography-based is high (ICC0.97 for extension and 0.93 for flexion) and less relied on observer expertise than clinical goniometry (1).

Digital image processing technique (DIPT) is the method of using computer software to analyze digital images for several purposes such as image feature extraction, classification or pattern recognition. ROM measurement by using DIPT is an innovative concept of current study. The scenario that this method can be applied is patient, who is in remoted area, taking and sending his or her elbow image in flexed-extended position via smart device such as smartphone or tablet to hospital database. Then image analytic software is automatically measuring extension and flexion angle and sending a report to corresponding doctor. We wish that DIPT method can be used interchangeably with goniometer and inclinometer. This method can also reduce observational bias, examination time, labor burden and cost of transportation.

A wider range of algorithms can be applied to the input data to filter noise and extract attributes from images. There are 5 image analytic theories that related to current DIPT protocol including color space, masking, edge detection, line detection, and outlier detection. There are several color spaces based on physical model applications. Examples include RGB (light), CMYK (ink), HSV (art), and YCrCb (video) (11). Given that each channel in color space models may give different view of an image, there are several studies on using the color model for isolating objects or different surfaces from images. In this work, it is critical to differentiate skins from background. A study by Kolkur, et.al suggested that we can use a combination of color spaces to detect skin in an image (12). Masking is a standard bitwise operation technique for selecting a part of data. For image processing, masking is used for placing or replacing parts of image on each other. In our work, we use masking to replace the unrelated background with blank space. Edge detection employs a variety of mathematical methods for identifying points in a digital image. When points are sharply changes, they are segmented into edges. There exist several edge detection algorithms. Canny algorithm is selected for edge detection (13). With edges in an image, line detection is a process that takes on edges points to find all underlying lines. Hough Transform is a popular technique for finding lines. It is based on parametric description of the lines in an image (14). In real word data (image pixels in this case), may contains noises. Outlier detection (aka. Anomaly detection) is the identification of rare items or rare events. However, we can also use outlier detection to filter noises from data. There are several outlier detection algorithms. The simple form of outlier detection is based on density-based techniques. In our work, we use Local Outliers Factor [LOF] as a tool for filtering noise lines.

Currently, there is no automatic range of motion calculation from photograph in medical literatures. All photographic methods need human observer, who need training in order to give accurate measurement result. Innovative method using DIPT which was proposed in this study aim to solve this problem. This research aim to (1) propose DIPT for measuring elbow range of motion, (2) assess validity and reliability of this method compared with standard digital goniometer and inclinometer which are instruments for arc of motion measurement in daily clinical practice.

CHAPTER 3 - RESEARCH METHODOLOGY

Research questions

1. Is ROM measurement of elbow joint using DIPT valid and reliable?
2. Which measurement methods are comparable to DIPT range of motion measurement?
3. Is DIPT measurement a time-saving procedure?

Objectives

Current study aims to prove accuracy and feasibility of DIPT ROM measurement of elbow flexion-extension photo taken by smartphone.

Primary objectives

- Perform validation and reliability testing on DIPT ROM measurement by comparing with 'gold standard' fluoroscopic measurement.

Secondary objectives

- Comparing measurement error between DIPT ROM measurement with the other measurement methods, goniometer, inclinometer, and smartphone gyroscope.
- Comparing procedural time for ROM measurement between methods.

Research protocol was approved by institutional review board, Faculty of Medicine, Chulalongkorn University. Participants were enrolled from students and staffs in the university by poster announcement. Age of all subjects should be over 18 years, could lift shoulder perpendicular to the floor and hold still in elbow extension and flexion position. Exclusion criteria were those who has deformity of arm and forearm or pain and discomfort at the elbow. Sample size was determined by two-dependent mean sample size calculation (Figure 1). Ten degrees of elbow motion arc measurement error was considered as minimal clinically important difference (MCID) and used as summative difference. Standard deviation was obtained from difference between photographic and goniometric measurement (1). Total number of 14 elbows were required. Participants were informed about study protocol and risk, then signed the informed consent form.

$$\boxed{n = \frac{(Z_{1-\frac{\alpha}{2}} + Z_{1-\beta})^2\sigma^2}{\Delta^2}}$$

$$\sigma = 13, \Delta = 10, \alpha = 0.05, \beta = 0.2$$

$$\underline{\boldsymbol{n = 14}}$$

Figure 1 Two-dependent mean sample size calculation.

Ten dregrees of MCID was used for sample sizecalculation.

Digital goniometer and digital inclinometer were used as reference measuring devices for comparing with ROM measurement from DIPT. All measurements and photographs capturing were conducted on the same day in the orthopedic operating room of King Chulalongkorn Memorial Hospital. Gender, age, height and weight were recorded by researcher at registration point. Two trained physiotherapists with 2-year experience were briefed about measurement techniques and practiced with each other. Both examiners performed goniometer, inclinometer ROM measurement on bilateral subject's elbows simultaneously. They were assisted by two research assistants, who wrote down measurement value in the record forms.

Study workflow

There were 3 separated room including operating room, examining room and photographic room (Figure 2). One fluoroscopy technician and one researcher did fluoroscopic examination in Operating theatre. In the examination room, two physiotherapists performed goniometer, inclinometer and gyroscopic range of motion measurement. They worked with two data recorders, who wrote down measurement value and procedural time in case record form. Elbow photographs were taken by one researcher.

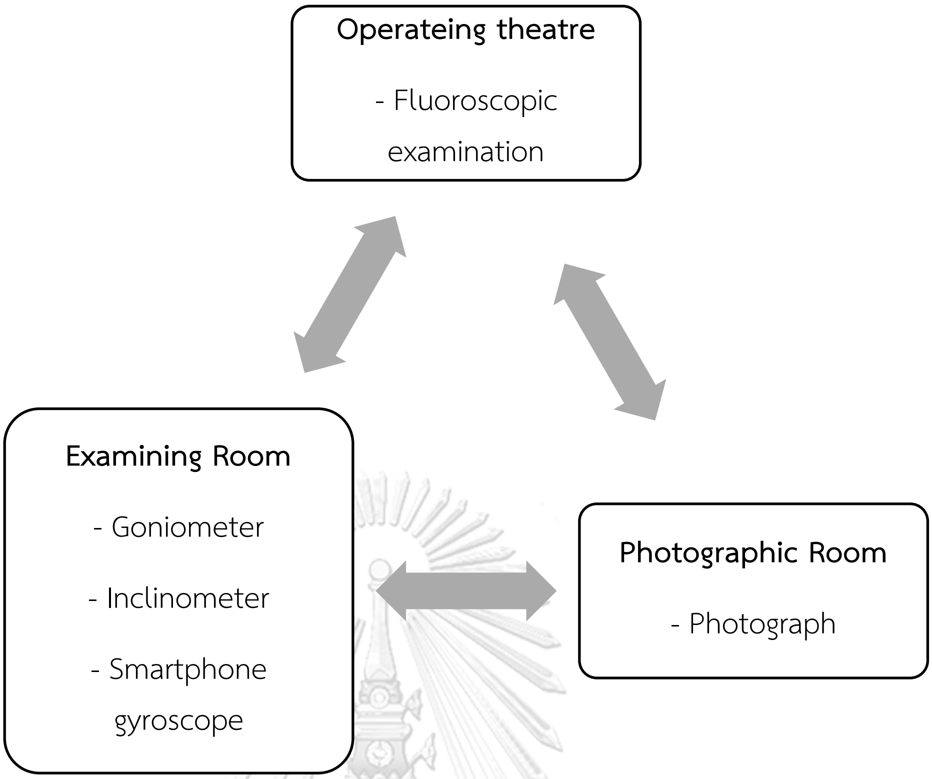

Figure 2 Measurement stations

Researcher recorded gender, age, weight and height. Participants were briefed about study workflow and signed the consent form. Participant moved from each station depend on availability of the rooms. There were checklists for every participant that were signed by examinees in each station after finishing measurement procedure. After passing through all examination, participant returned to registration point to receive traveling fee (Figure 3).

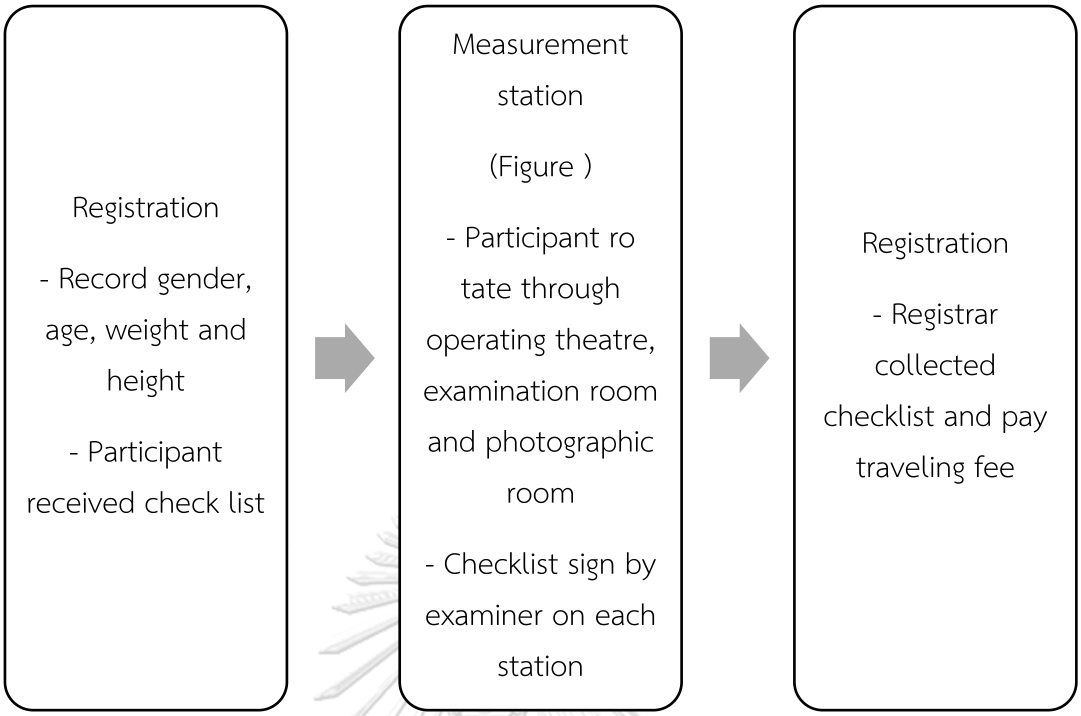

Figure 3 Study workflow

Fluoroscopic imaging

Fluoroscopic imaging procedure was done in operating theatre. Participant worn radioprotective suit and thyroid shield. Subject laid supine on surgical bed with radiolucent arm support. Shoulder laterally abducted to 90 degrees. Subject was instructed to supine his or her forearm. Fluoroscopic lateral view of both elbows in extension and flexion position were taken (2). Center projection of fluoroscope aimed at medial epicondyle of humerus. Middle third of both humerus and ulna was visible for accurate angle measurement (3, 15). If valid image could be achieved in first shot, arm position and fluoroscopic aiming was adjusted and re-shot image but would not exceed 2 times additional per side.

Fluoroscopic image data was transferred via flash drive. One orthopedist and one 6th year medical student examines and measures range of motion using 'ImageJ' (NIH, USA) software. Long axis line of humerus and ulna will be draw for measuring angle between both bones (Figure 4) (3). Procedural time for fluoroscopy was record from patient standing beside operating table to finish imaging on each side.

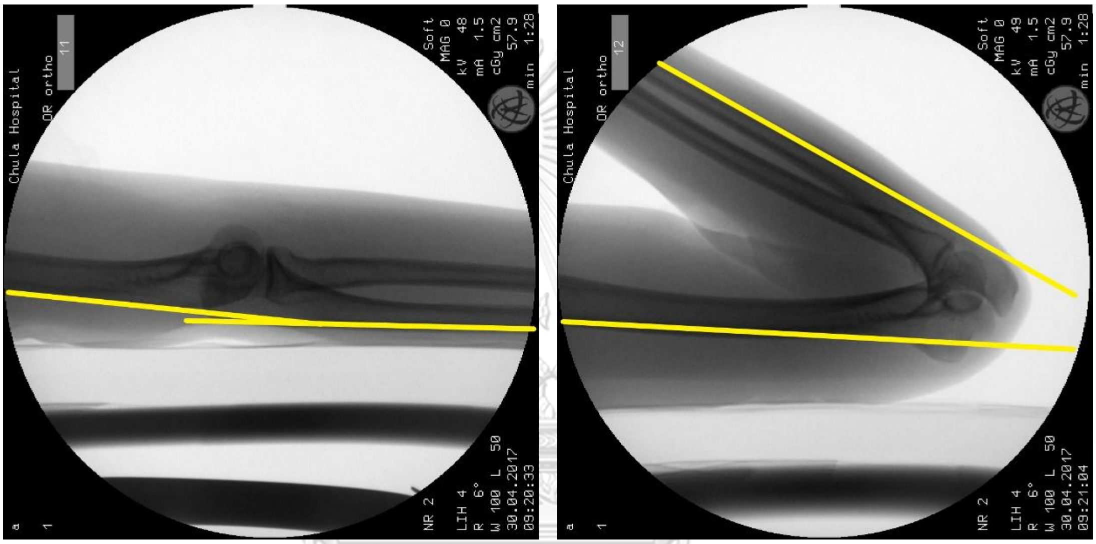

Figure 4 Fluoroscopic image measurement

Digital goniometer

Digital Protractor Goniometer ± 0.5° precision (Mediguage®, Columbia USA) was used. The goniometer is centered on the lateral epicondyle. The proximal part of goniometer point at the greater tuberosity of humerus and the distal part point at the middle portion of wrist (3) (Figure 5). Examiner measure flex and extend position of elbow 3 times for each side. Procedural time for goniometer was record from patient lying on examination bed to finish goniometer measurement on each side.

Figure 5 Goniometric measurement

Digital inclinometer

Baseline® digital inclinometer (Fabrication Enterprises Inc, New York USA) was calibrated. The measurement technique for inclinometer was modified from American Medical Association (AMA) recommendation (5). Examinee was in the supine position and elbows with before using. supinated forearm was hanged beyond the edge of table. For extension angle, align inclinometer on the long axis of forearm and set inclinometer to zero and then asked examinee to extend their elbow and record the measurement value. For flexion angle, the subject fully flexed the elbow while examiner aligned inclinometer with forearm and read flexion angle then repeat the same protocol for extension and flexion 2 more times (Figure 6). The three measurement values for the same limb and same position should be within 5 degrees or 10% of the mean.

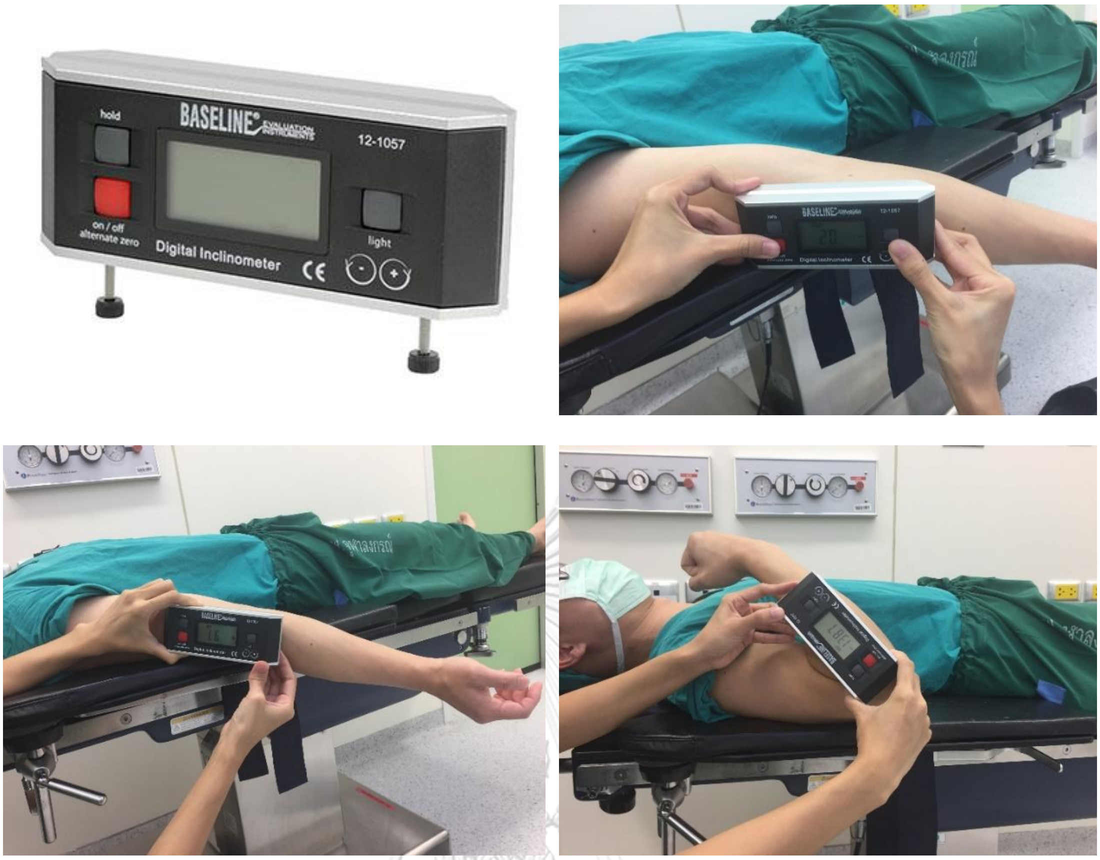

Figure 6 Digital inclinometer and inclinometer measurement technique

Smartphone gyroscopic measurement

Gyroscope function of smartphone (iPhone 6) was utilized for measuring motion angle with commercially available “yROM Goniometer” application (Connecticut USA) (Figure 7). The patient position and measurement procedure were the same as inclinometer technique described above. Examiner tap finger on the screen to begin measurement. Examinee extend the elbow and examiner tap screen to record. Then examinee fully flex the elbow, the examiner taps to record and calculate arc of motion (Figure 8). Same procedure was repeated 2 times. Procedural time for gyroscope will be record from patient lying on examination bed to finish gyroscopic measurement on each side.

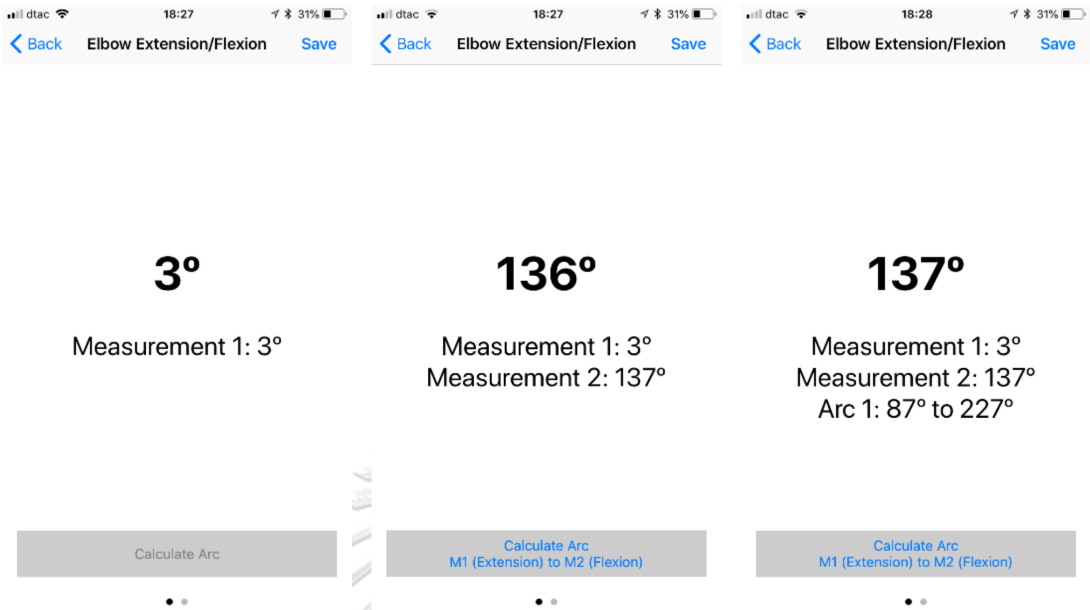

Figure 7 Screen captions of yROM goniometer application

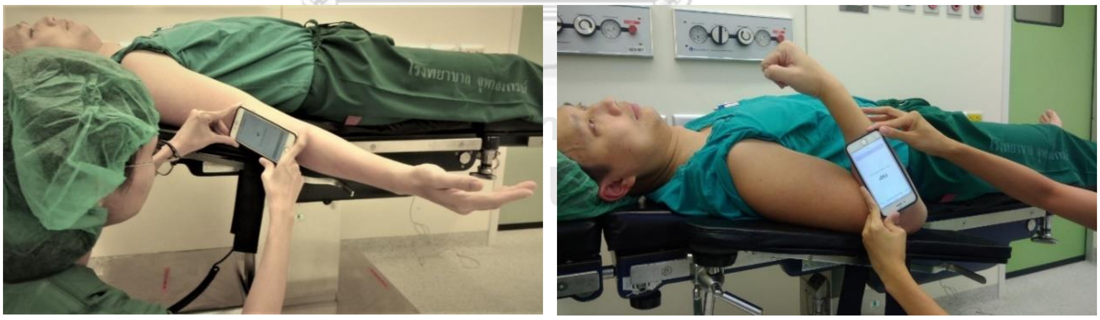

Figure 8 Smartphone gyroscope application measurement

Smartphone photography

Participant stood as close as possible in front of a blue screen to control horizontal plane of the arm and then performed lateral abduction of the shoulder to 90 degrees perpendicular to the floor. This photographic position is considered practical for patient to take his or her elbow photo at home and monotonous-color contrast background also help reduce image processing error. Upper extremity was exposed from shoulder to hand. Photographer took elbow images in fully extension and fully flexion three times for each position (Figure 9A and 9B). The smartphone camera was at the same level of elbow joint when taking a shot. Participant was told to drop their arm and then raised up between each photo shot. All images were taken using iPhone 6 (Apple, USA) with 8-megapixel rear camera (3264x2448 pixels 72 dpi).

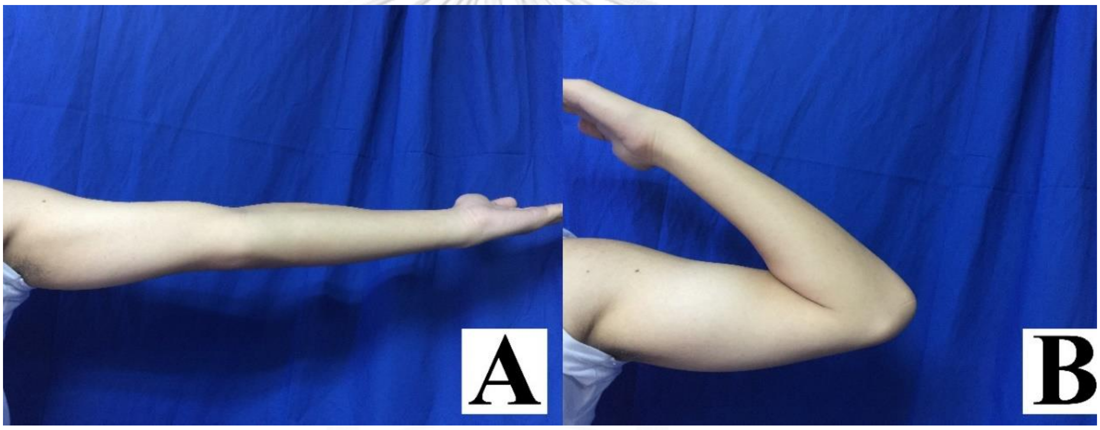

Figure 9 Photographic positions.
A, Subject laterally abducted shoulder perpendicular to the floor and fully extended elbow. B, Elbow was maximally flexed.

Digital image processing technique (Appendix IV)

The first step is 'Line detection', which is protocol for finding all possible lines in an image. All upper extremity images were cropped at below wrist level in the distal part and at deltoid muscle insertion in the proximal part. Horizontal and vertical blue area were deleted from 4 edges to eliminate the blue screen background as much as possible (Figure 10A). A median filter is applied to reduce noise from camera and light by converting the color space from Red, Green and Blue (RGB) to Hue-Saturation-Value (HSV) and create a mask with color range (100,0,0) and (180,255,255) in HSV color space (Figure 10B). Then a mask is applied to the find the contour of the skin and clean the noise with median blur filter (Figure 10C). Detection of lines is based on Canny and Hough transformation (Figure 3A and 4A) (13, 14). To improve the accuracy, outlier detection is being used to eliminate unrelated lines.

Figure 10 Line detection process.
A, Cropped image. B, Converting Red, green and blue (RGB) to Hue-saturation-value (HSV). C, Detection of lines using Canny and Hough transformation

After the line detection process, next step is 'Angle calculation'. Algorithm for flexion and extension angle are similar. They are varied depending on sides. For left flexion, right flexion, left extension and right extension, the variation are the base lines for detecting upper and lower arms. For both flexion and extension, four base lines (upper arm, lower arm, upper forearm and lower forearm) are located differently. Protocol for extension and flexion angle calculation are described below.

Extension angle

(1) Determine two scan lines: left scan line and right scan line. The first scan line is located from one-third distance of a dominate edge (right edge for left hand and vice versa). The second scan line is a quarter from another edge (Figure 11A).

(2) For both scan line, find the cutting points for classifying lines into two groups on each side. The cutting points are determined by the middle point of the skin (calculated from the mask).

(3) Partition lines into four groups: top left lines, top right lines, lower left lines, and lower right lines. Between the left edge and the middle point, use the intersection of each line and the scan line to determine the upper left lines and the lower left lines. The similar method is applied between right edge and the middle point to determine the upper right lines and the lower right lines.

(4) To calculate the angle, average slopes between the upper lines and the lower lines are calculated. The angle is calculated from the difference between the two slopes (Figure 11B).

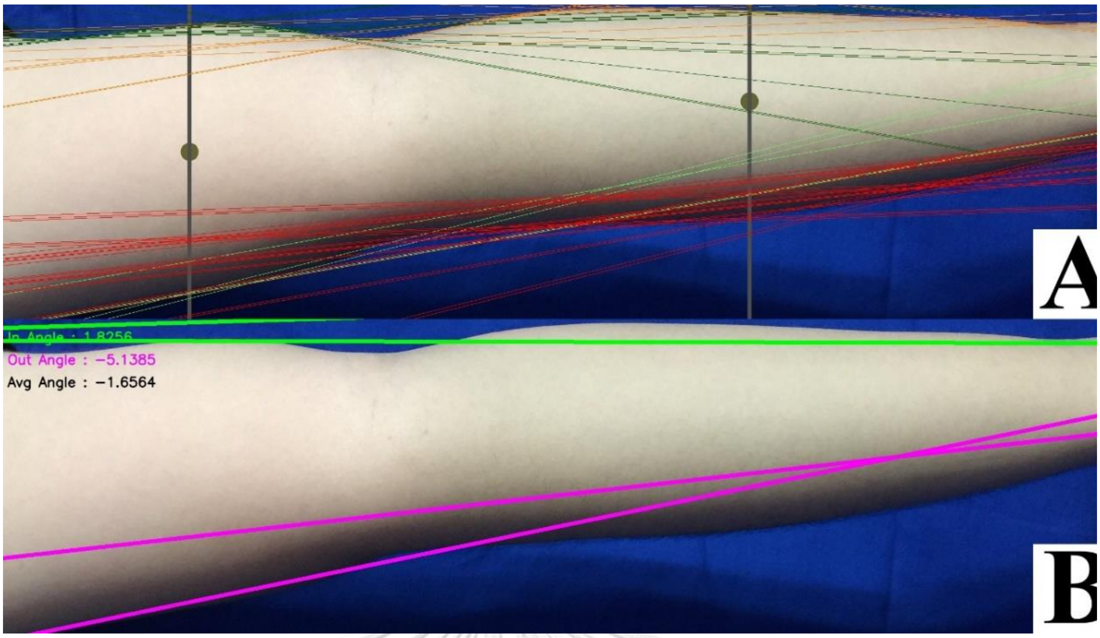

Figure 11 Angle calculation step for extended elbow image.
A, Locate middle points of arm and forearm from one-third of distance of both edges. B, Calculate angle from difference between two slopes

Flexion angle

(1) Determine a scan line by using a vertical line from 10% of the edge. Either left edge or right edge is used based on the side of the elbow.

(2) Scanning the scan line to find the cutting points for classifying four lines. The top point is determined by the middle point of the forearm. The lower point is determined by the middle point of the arm. The middle point between the empty space in the middle is used for partitioning between the forearm and the arm (dots in Figure 12A).

(3) For each line, determine whether the line is a part for upper or lower line by calculating the intersection at the scan line. The intersection point is then partition

into four groups based on the detection points in the second step. There are total four groups, upper top lines, lower top lines, upper low lines, and lower low lines. (colored lines in Figure 12A.)

(4) For each group of lines, find and average slope. There will be four slope values.

(5) Use a slope from upper top line as a top reference line. This line is likely to be aligned with the ulnar bone. Use an average between the two slopes from the lower top lines and lower low lines as a base line. The angle is calculated from the two slopes, top reference line and base line. The angle is calculated from the two slopes using arctan function (Figure 12B).

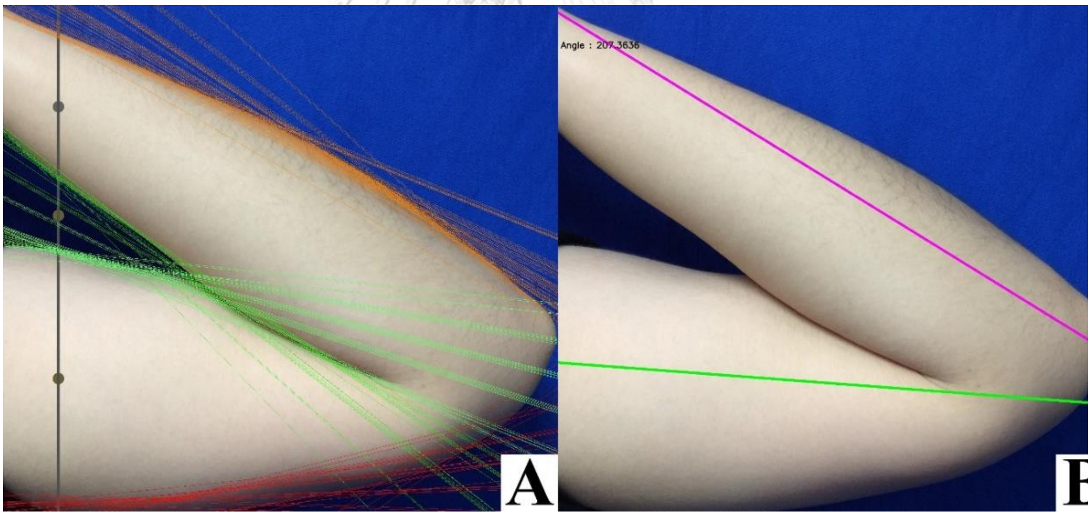

Figure 12 Angle calculation step for flexed elbow image.
A, Determine cutting point for classifying 4 reference lines. B, Calculate angle from two slopes

To validate our algorithm, we implement our design using python 3.6. The imaging processing library is OpenCV [OpenCV] version 3.3. Outlier detection was based on local outlier factor found in Scikit-learn library version 0.19 (16).

Statistical analyses

Intra-rater reliability and inter-rater reliability of all methods was computed using intraclass correlation coefficient (ICC). The model for intra-rater reliability of goniometer, inclinometer and photographic image analysis was 'two-way mixed' and 'absolute agreement'. Inter-rater reliability of goniometer and inclinometer between two physiotherapists analytic model was 'two-way random' and 'absolute agreement'. Excellent, good and moderate agreement are determined by ICC value above 0.9, 0.75 to 0.90 and 0.50 to 0.75 respectively (17). Reliability test was analyzed by using SPSS version 22 (IBM, USA).

Average of flexion and extension score from both examiners and DIPT were used in the analysis. Total ROM value was flexion angle minus extension angle. Minimal clinical significance difference for elbow range of motion is 10 degrees. Shapiro-Wilk test was used to verify if variables were normally distributed. Paired student *t* test and Wilcoxon-signed rank test were used to detect systematic bias between all measurement techniques. Bias and possible range of difference between methods were illustrated using Bland-Altman plot and limits of agreement (LOA) analysis. Bland-Altman analysis was conducted in R (R Core Team, Vienna Austria) with 'blandr' package (18, 19). DIPT measurement values that were less than 10 degree of difference compared to other two references methods were calculated in percentage.

CHAPTER 4 - RESULTS

Thirty healthy volunteers joined the study. After inspected all images, two participants were removed from final analysis because the elbows were not fully flexed (Figure 13). There were total 56 elbows from 15 male and 13 female subjects. Average age was 20.6 years (range, 19-31 years). Mean weight, height, and body mass index were 58.9 Kg (range, 39-110 Kg), 165.3 cm (range, 150-189 cm), 21.4 Kg/cm^2 (range, 16.7-34.0 Kg/cm^2).

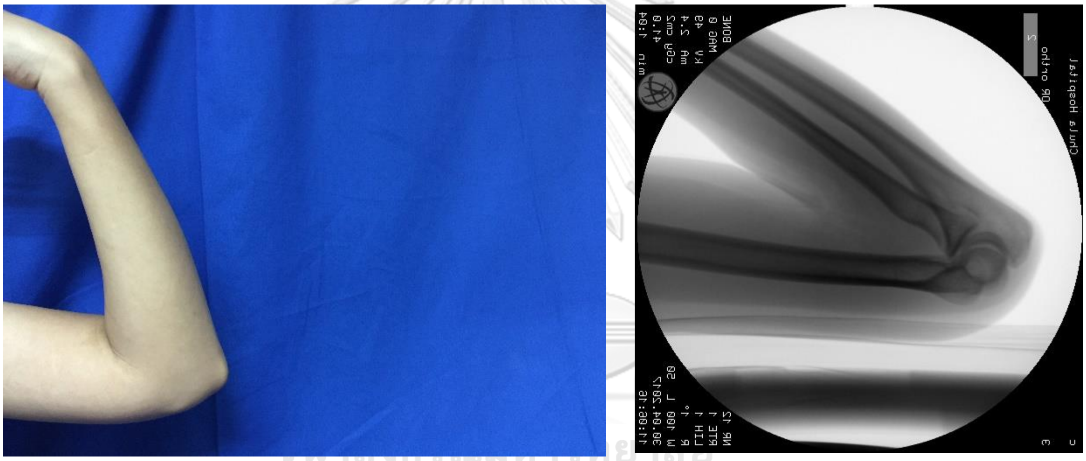

Figure 13 Photograph and fluoroscopic image of excluded participant

Intra-rater ICC of goniometric, inclinometer and gyroscope in flexion and extension position showed excellent agreement between 0.912 to 0.994. Intra-rater ICCs of DIPT was also excellent agreement, 0.943 in extension and 0.886 in flexion (Table 2).

Table 2 Intra-rater reliability of all methods

ICC	DIPT	Goniometer		Inclinometer		Smartphone Gyroscope	
		E1	E2	E1	E2	E1	E2
Extension	0.943	0.994	0.970	0.993	0.960	0.912	0.985
Flexion	0.886	0.972	0.953	0.964	0.960	0.964	0.976

E1, Examiner 1; E2, Examiner 2

There were moderate to good interrater reliability of extension (E) and flexion (F) angle ICC between two examiners, 0.862 (E), 0.738 (F) for goniometer and 0.882 (E), 0.784 (F) for inclinometer. Inter-rater ICCS of fluoroscopic image measurement between two observers showed good agreement. Smartphone gyroscope ICC of flexion showed moderate agreement (Table 3).

Table 3 Inter-rater reliability

ICC	Fluoroscope	Goniometer	Inclinometer	Smartphone Gyroscope
Extension	0.793	0.862	0.882	0.819
Flexion	0.783	0.738	0.784	0.553

Goniometer-extension, inclinometer – extension, gyroscope-extension, DIPT-ROM were not normally distributed (Table 4). Comparing DIPT to fluoroscope, mean extension and flexion score was lower significantly. Mean extension and flexion angle of DIPT group was significantly higher than goniometer, inclinometer and gyroscope group ($P < 0.05$), but Total ROM were comparable with three reference methods (DIPT vs goniometer $P = 0.350$, DIPT vs inclinometer $P = 0.527$, DIPT vs gyroscope $P = 0.899$) (Table 5).

Table 4 Shapiro-Wilk test results of measurement value set from different devices

Device	**Position**	**Shapiro-Wilk**		
		Statistic	**df**	**Sig.**
Fluoroscope	Extension	.966	56	.113
Fluoroscope	Flexion	.981	56	.529
Fluoroscope	ROM	.984	56	.670
Goniometer	Extension	.937	56	.006*
Goniometer	Flexion	.967	56	.123
Goniometer	ROM	.975	56	.299
Inclinometer	Extension	.928	56	.002*
Inclinometer	Flexion	.976	56	.321
Inclinometer	ROM	.989	56	.902
Gyroscope	Extension	.942	56	.010*
Gyroscope	Flexion	.979	56	.422
Gyroscope	ROM	.992	56	.966
DIPT	Extension	.976	56	.341
DIPT	Flexion	.976	56	.327
DIPT	ROM	.958	56	.047*

* statistically significant

Table 5 Comparison measurement of digital image processing method with other reference methods

Position	Image analysis mean ± SD (range)	Fluoroscope mean ± SD (range)	Goniometer mean ± SD (range)	Inclinometer mean ± SD (range)	Smartphone Gyroscope mean ± SD (range)
Extension	-2.01 ± 6.30 (-16.86, 8.92)	6.0 ± 3.1 (-1.4, 16.3)	-6.67 ± 3.48 (-11.83, -0.28)	-6.74 ± 3.58 (-11.87, -0.15)	-6.80 ± 3.60 (-12.67, -0.17)
P value		< 0.05	< 0.05	< 0.05	< 0.05
Flexion	146.80 ± 5.20 (137.05, 157.16)	148.7 ± 4.3 (135.0, 157.7)	141.28 ± 4.71 (129.98, 148.80)	142.79 ± 6.58 (129.97, 155-.97)	142.24 ± 6.55 (127.50, 156.83)
P value		0.012	< 0.05	< 0.05	< 0.05
Total ROM	148.81 ± 7.72 (135.89, 164.70)	142.7 ± 4.7 (132.2, 152.4)	147.95 ± 6.89 (132.12, 160.53)	149.55 ± 8.36 (131.63, 167.27)	149.04 ± 8.74 (127.67, 168.17)
P value		< 0.05	0.350	0.527	0.899

Normality of score differences between image analysis and other two methods, goniometer and inclinometer, were proved using Shapiro-Wilk test. All groups demonstrated normal distribution pattern (P = 0.06 to 0.39). There was significant bias of fluoroscope 8 degree higher than DIPT. Less degree of difference from DIPT in fluoroscopic-flexion image was detected (Table 6). Absolute error of fluoroscope image measurements was higher than MCID in all positions including total ROM (Figure 14). Bland-Altman analysis showed extension and flexion angle bias of DIPT-goniometer 4.51 (95%CI 3.14,5.88), 5.46 (95%CI 4.12,6.80) and DIPT-inclinometer 4.61 (95%CI 3.25,5.96), 3.98 (95%CI 2.45,5.50) (Appendix V). Total ROM mean difference of DIPT-goniometer and DIPT-inclinometer were 0.94 (-0.95,2.84) and -0.63 (-2.64,1.38). (Figure 15 and 16) Absolute maximal error of flexion and extension angle were 9.81-11.17 degrees and total ROM angles were 13.84-15.99 degrees. Measurement bias of gyroscope when compare with DIPT were 10-16.66 degrees (Figure 17). There were 80.4-91.1% of DIPT values that were less than 10 degrees of MCID compared with goniometer, 83.9-87.5% compared with inclinometer and 75-87.5% compared with gyroscope (Table 6).

Only procedural time of goniometer is normal distributed (Table 7). Fluoroscope seem to be the quickest procedure, but it was only time for one fluoroscopic shot and did not include time for angle measurement. The fastest among examiner measurement procedure is smartphone gyroscope followed by goniometer and inclinometer (Table 8). Comparison between paired of all reference methods showed statistically difference from Wilcoxon signed rank test ($P < 0.05$).

Table 6 Bland-Altman analytic results and percentage of DIPT measurement error within 10 degrees compare with fluoroscope, goniometer, inclinometer and gyroscope

Angle measurement	Mean of difference (95%CI)	Upper LOA (95%CI)	Lower LOA (95%CI)	Absolute maximal error†	Within 10 degrees of error (%)
Fluoroscope					
Extension	-8.02 (-9.84, -6.20)	5.30 (2.17,8.43)	-21.34 (-24.47, -18.21)	± 13.32	53.6
Flexion	-1.89 (-3.34, -0.438)	8.74 (6.24, 11.24)	-12.52 (-15.02, -10.02)	± 10.63	87.5
Total ROM	6.13 (4.18, 8.08)	20.42 (17.06, 23.78)	-8.16 (-11.52, -4.80)	± 14.29	64.3
Goniometer					
Extension	4.51 (3.14, 5.88)	14.56 (12.2, 16.92)	-5.54 (-7.9, -3.18)	± 10.05	91.1
Flexion	5.46 (4.12, 6.80)	15.26 (12.96, 17.57)	-4.35 (-6.66, -2.05)	± 9.81	82.1
Total ROM	0.94 (-0.95, 2.84)	14.79 (11.54, 18.04)	-12.90 (-16.16, -9.65)	± 13.84	80.4
Inclinometer					
Extension	4.61 (3.25, 5.96)	14.53 (12.2, 16.86)	-5.32 (-7.65, -2.99)	± 9.93	87.5
Flexion	3.98 (2.45, 5.50)	15.15 (12.52, 17.77)	-7.19 (-9.81, -4.57)	± 11.17	85.7

Total ROM	-0.63 (-2.64, 1.38)	14.10 (10.64, 17.56)	-15.36 (-18.82, -11.9)	± 15.99	83.9
Gyroscope					
Extension	4.64 (3.27, 6.01)	14.65 (12.30, 17.00)	-5.36 (-7.71, -3.01)	± 10	87.5
Flexion	4.33 (2.60, 6.05)	16.98 (14.00, 19.95)	-8.33 (-11.30, -5.35)	± 12.66	83.9
Total ROM	-0.32 (-2.59, 1.96)	16.34 (12.42, 20.25)	-16.97 (-20.88, -13.0)	± 16.66	75.0

† Absolute maximal error = Mean – Lower LOA

CI, confidence interval; LOA, limit of agreement; ROM, range of motion

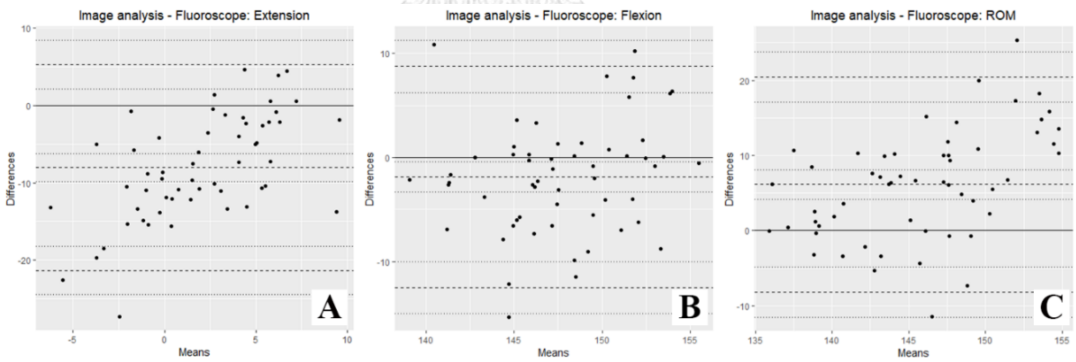

Figure 14 Bland-Altman plot of digital image analysis (DIPT) and fluoroscope. A, Extension. B, Flexion. C, Elbow range of motion (ROM).

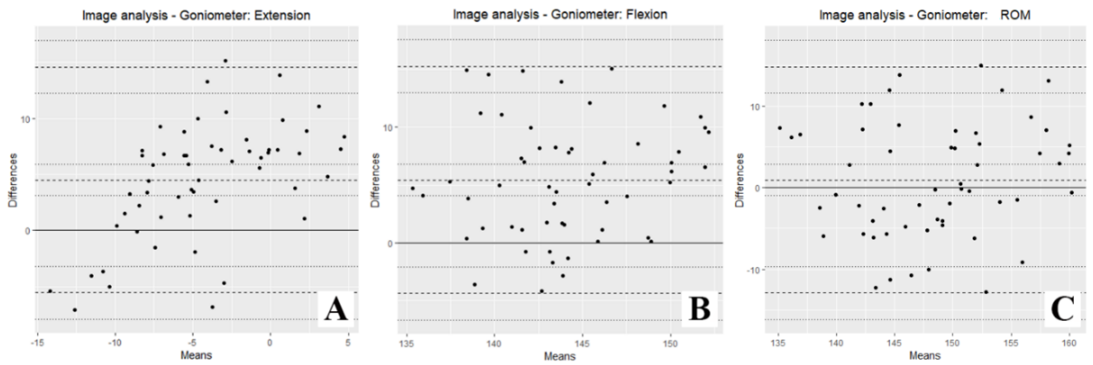

Figure 15 Bland-Altman plot of digital image analysis (DIPT) and goniometer. A, Extension. B, Flexion. C, Elbow range of motion (ROM).

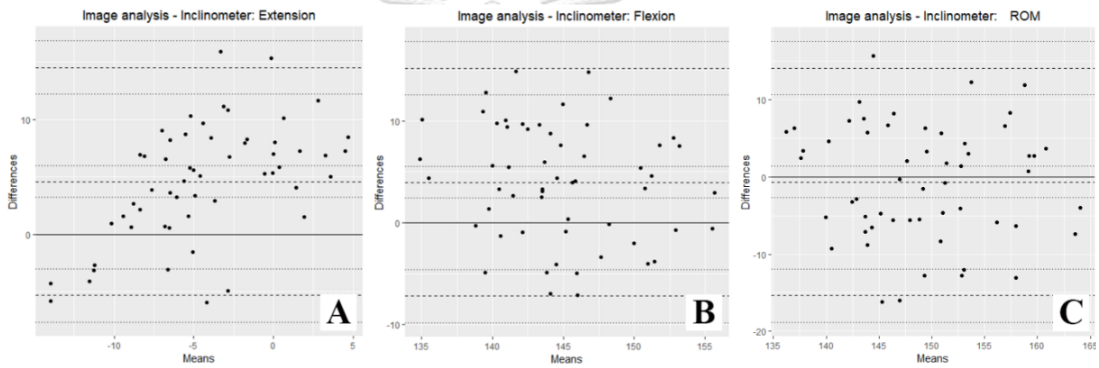

Figure 16 Bland-Altman plot of digital image analysis (DIPT) and inclinometer. A, Extension. B, Flexion. C, Elbow range of motion (ROM).

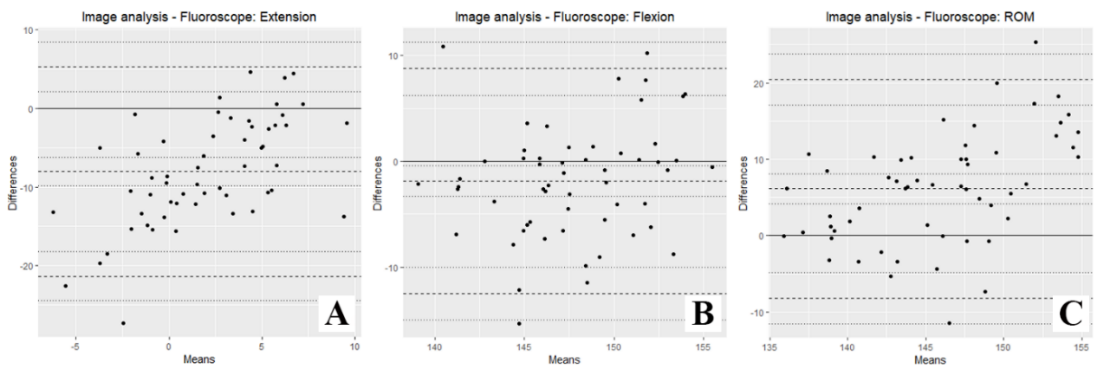

Figure 17 Bland-Altman plot of digital image analysis (DIPT) and gyroscope. A, Extension. B, Flexion. C, Elbow range of motion (ROM).

Table 7 Normality test of procedural time for each measurement method

Methods	**Shapiro-Wilk**		
	Statistic	**df**	**Sig.**
Fluoroscope	.831	56	.000
Goniometer	.988	56	.835
Inclinometer	.962	56	.077
Gyroscope	.919	56	.001

Table 8 Procedural time of reference methods for measuring range of motion of one elbow

Procedural time	**Fluoroscope mean ± SD (range)**	**Goniometer mean ± SD (range)**	**Inclinometer mean ± SD (range)**	**Smartphone Gyroscope mean ± SD (range)**
Time (second)	23.41 ±10.93 (12.0, 66.0)	50.80 ± 9.69 (31.50, 73.50)	62.96 ± 7.05 (50.00, 82.00)	41.81 ± 7.86 (29.50, 68.00)

CHAPTER 5 - DISCUSSION

There are several advantages of using photographic-based ROM measurement especially in telemedicine era. Innovative method to collect data from patient remotely has been popularized in recent years. Physicians can assess their patient function and made suggestion via internet portal without having patients come to the clinic. Photographic and video-based ROM measurement method required human observers, who need proper training to achieve high accuracy (7). Most photographic-goniometric methods use bony or alternative landmarks for drawing two references line that may be difficult to locate in some cases (1, 4, 5, 7). This study aims solve these observer-related problems using DIPT.

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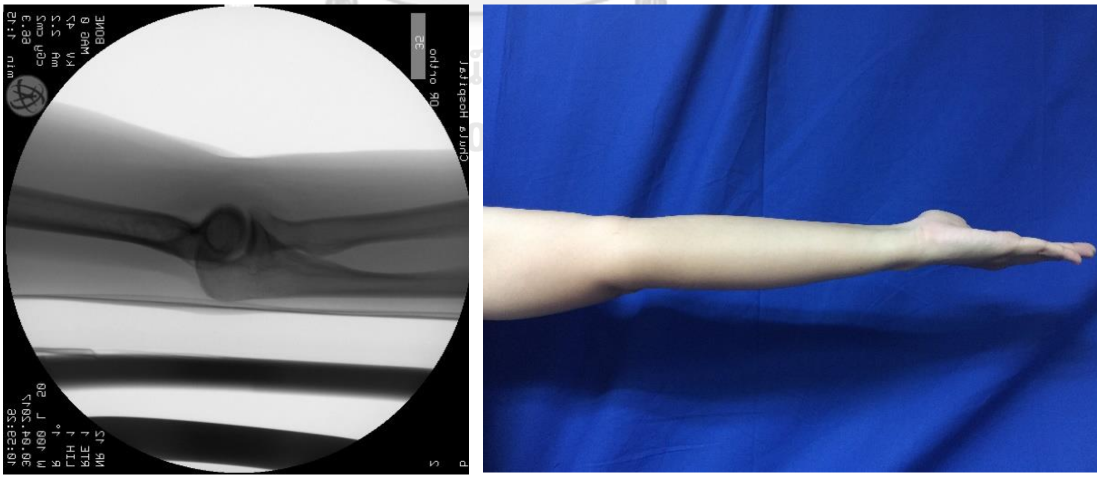

Figure 18 Demonstrate error of fluoroscopic image in extension position and photographic image

Average of fluoroscopic measurement in extension position was higher than DIPT around 8 degree. We suspected that participants put their arms on the arm rest and did not active extend the elbows when taking a fluoroscopic shot, this may cause measurement value to be higher than other methods (Figure 18). Hence, the difference of extension angle when compare with fluoroscopic image was unreliable, but flexion angle was not affected by this measurement bias. Flexion angle result is around 2 degrees of bias, range of error 11 degrees and 88% of measurement value was within 10 degrees, that is comparable with other reference methods.

DIPT measurement of flexion and extension have bias around 4-5 degrees higher than the others method. There are some explanations for this deviation. First is difference in vertex location, goniometer and inclinometer measurement begin with localizing lateral epicondyle as vertex of angle first and then projecting it arm to distal and proximal bony landmark. DIPT is different from reference methods, it uses extremity contour to create proximal arm and distal forearm line, and the vertex is intersection between these lines. Second, the dorsal surface of the forearm is thin and close to ulnar shaft alignment that affect distal reference line when calculating angle using DIPT. Also, vertex of goniometer and inclinometer angle lie anteriorly compare to ulnar bone shaft line. This is demonstrated with geometric illustration using fluoroscopic images of the elbow that use similar DIPT protocol for drawing angle alignment (Figure 18A and 18B). Another possible cause can be found from images review, some participants minimal flexed instead of fully extended their elbows in extension image, probably because they use biceps muscle function to control shoulder joint in abduction plane.

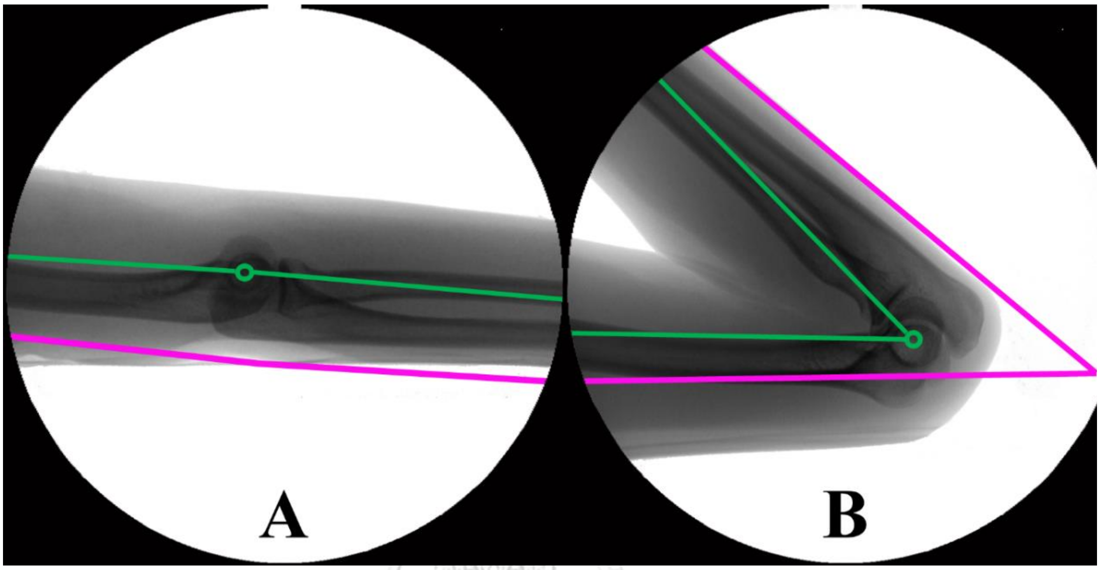

Figure 19 Conceptual illustration of systematic measurement bias between landmark-based method, goniometer and inclinometer, and contour-based DIPT. Green circles are lateral epicondyle location and green lines are imaginary line of goniometer and inclinometer measurement. Pink lines are the result of using DIPT on fluoroscopic image. A, Extension image. B, Flexion image.

Total ROM had comparable result with reference methods but had absolute error higher than 10 degrees margin of MCID for elbow joint. Total ROM is the calculated value from flexion angle minus extension angle, so the error is combination between these two values. Twenty from total 116 DIPT measurement,11 compared with goniometer and 9 compared with inclinometer, had difference over 10 degrees. These can be divided into 3 groups, group 1 lower extension angle and higher flexion angle, group 2 higher extension angle and lower flexion angle, and group 3 extension and flexion angle were higher. There were 8,7, and 5 measurements in group 1, group 2 and group 3 respectively. Fifteen out of twenty measurements, higher value had more effect than lower value, and other five measurements had nearly equal effect between higher and lower value. This can be speculated that significant difference of total ROM between DIPT measurement and reference methods occurred because DIPT measurement tend to have higher value either flexion or extension angle than goniometer and inclinometer.

Time for each measurement procedure is important when considered workload and labor cost. Average time for all measurements were statistically significant, but it was only 10 – 20 seconds difference. Most examiner-based methods (goniometer, inclinometer and gyroscope) use around 1 minute to finish measuring ROM of each elbow. Time for taking 3 photos may not difference from other procedures, but it can be done by patients themselves before coming to clinic that might save a lot of time and workload of examiner.

Table 9 Photographic-based ROM measurement of elbow literatures

Study	Elbows	Subject	Reference method	Image capturing device	Initial position of shoulder	Measuring side	Mean difference (Bias)			LOA absolute error			Percentage within 10 degree of reference method		
							Extension	Flexion	EROM	Extension	Flexion	EROM	Extension	Flexion	EROM
Blonna et al.	50	Patients	UG	Digital camera	90-degree Forward flexion	Lateral side	0	1		7-31	8-21				
Meislin et al.	64	Healthy volunteers	UG	Smartphone	Anatomic position	Lateral side			0.2-0.3			8.3-9.5			95
Keijsers et al.	80	Healthy volunteers	UG	Digital camera	90-degree Forward flexion	Lateral side	1	0							
Russo et al.	20	Cadaver	Motion capture analysis	Digital camera	90-degree lateral abduction	Medial side	4	11.7					16 (Within 5°)	93	
Chanlalit & Kongmalai	60	Healthy volunteers	UG	Smartphone	90-degree Forward flexion	Lateral side	2.6	2.1		7.8	13.4		98.3	85	
Current study (UG)	56	Healthy volunteers	UG	Smartphone	90-degree lateral abduction	Medial side	4.5	5.5	0.9	10.1	9.81	13.8	91.1	82.1	80.4
Current study (DI)	56	Healthy volunteers	DI	Smartphone	90-degree lateral abduction	Medial side	4.6	4.0	0.6	9.9	11.2	16	87.5	85.7	83.9

UG- Universal goniometer, DI – Digital inclinometer, F – Flexion, E – Extension, R – Range of motion, LOA – Limit of agreement

There are several studies using photograph for elbow arc of motion measurement with variety of methods (Table 9). Image capturing devices in literatures were either digital camera (4, 7, 8), or smartphone. (1, 5). Most reports except Russo et al. use lateral side of arm and forearm for measurement. Healthy volunteers were recruited in most study, but Blonna et al tested with patient and Russo et al use cadaveric elbows. The accuracy of photographic-based elbow ROM measurement among papers were varied and also depend on observer experience (1). The mean differences of current study were comparable with previous literatures; however, the error margins were higher.

Current study has some limitations. First, DIPT protocol assess only active range of motion. Examiner is needed to perform passive range of motion measurement. Second, some participants may be effortless or did not understand instruction clearly and did not fully extend or flex their elbow. There were 4 images needed to be excluded. Though all images were taken by assigned photographer. Third, the extension rod as recommended by AMA was not available for digital inclinometer use in current study.

There are some implementation problems of DIPT that should be concerned. Firstly, the initial position for photographic images was 90-degrees lateral abduction of shoulder, which was difference from other standard methods which elbow joint was lie beside torso in anatomical position. The reasons for modification are outline detection function which requires body lie on the monotonous background. For this reason, current method cannot be used in some patients, if they have problems such as shoulder joint stiffness or muscle weakness, thus they cannot lift their elbow against the background. Secondly, the compliance of patient to obtain valid images is very important. It is important to follow proper image capturing protocol to prevent photographic error such as incorrect projection. Thirdly, if patient loss the normal contour of arm or forearm from injury, morbid obesity or other diseases, this method may not give an accurate result. Lastly, image should be cropped by observer in current protocol. Developing algorithm for detect anatomy and position of arm and forearm may help alleviate this burden.

CONCLUSIONS

This research explored innovative method for measuring range of motion from photograph of elbow. Elbow ROM measurement from current DIPT protocol had comparable result with flexion angle of fluoroscopic image and both flexion and extension angle of goniometer and inclinometer, but it can be difference from other two methods up to 16 degree. Further investigations and protocol adjustment are needed to increase accuracy of the image analytic technique.

APPENDIX

Appendix I Participant data record form

แบบบันทึกข้อมูลผู้เข้าร่วมการวิจัย

รหัสผู้เข้าร่วมวิจัย	
วันที่ทำการเก็บข้อมูล (วัน/เดือน/ปี)	

1. เพศ

   ☐(1) ชาย ☐(2) หญิง

2. อายุ (ปี)

3. น้ำหนัก (กิโลกรัม)

4. ส่วนสูง (เซนติเมตร)

5. โรคประจำตัว

กรุณาให้ผู้ตรวจลงชื่อเมื่อผ่านการตรวจ

	รายการตรวจ	**ลงชื่อผู้ทำการตรวจ**
1.	อุปกรณ์ฟลูโอโรสโคปี	
2.	อุปกรณ์โกนิโอมิเตอร์	
3.	อุปกรณ์ไจโรสโคป	
4.	อุปกรณ์อินไคลโนมิเตอร์	
5.	ถ่ายภาพข้อศอก	

Appendix II Goniometer, Gyroscope, Inclinometer data record form

แบบเก็บข้อมูล อุปกรณ์โกนิโอมิเตอร์ อุปกรณ์ไจโรสโคป อุปกรณ์อินไคลโนมิเตอร์

รหัสผู้เข้าร่วมวิจัย		
วันที่ทำการเก็บข้อมูล (วัน/เดือน/ปี)		
ข้าง	☐(1) ขวา	☐(2) ซ้าย

ครั้งที่	Goniometer		Gyroscope		Inclinometer	
	Ext	Flex	Ext	Flex	Ext	Flex
1.						
2.						
3.						
เวลา						

Appendix III Procedural time data record form

แบบเก็บข้อมูลเวลาในการถ่ายภาพข้อศอก

วันที่ทำการเก็บข้อมูล (วัน/เดือน/ปี)	

	รหัสผู้เข้าร่วมวิจัย	เวลารวมในการถ่ายภาพ
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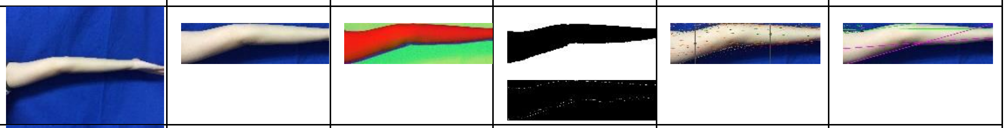
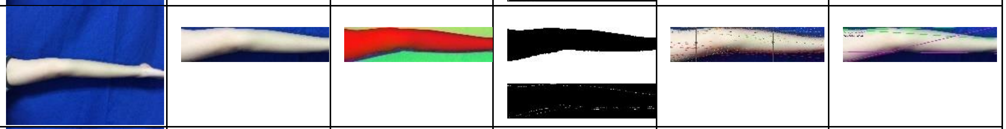
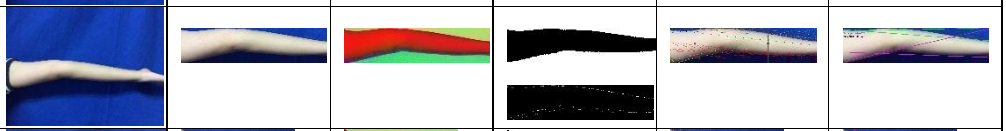
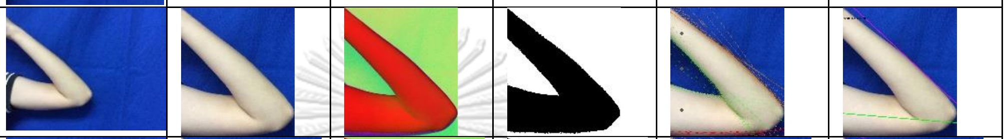
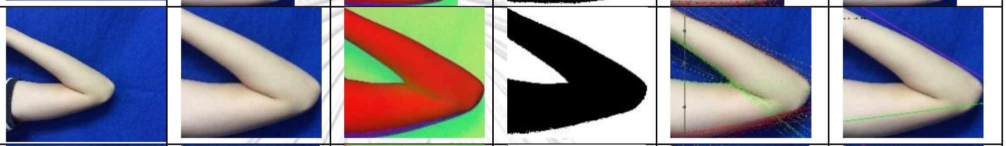
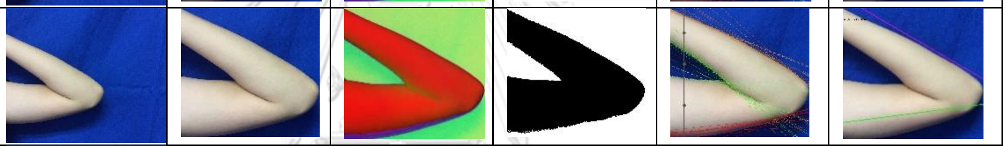
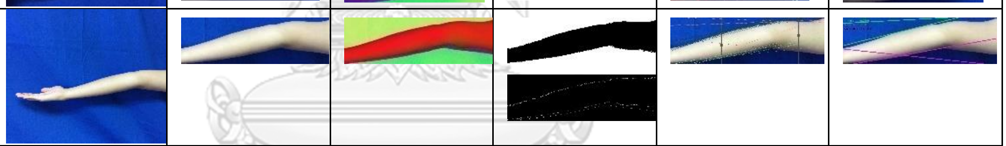
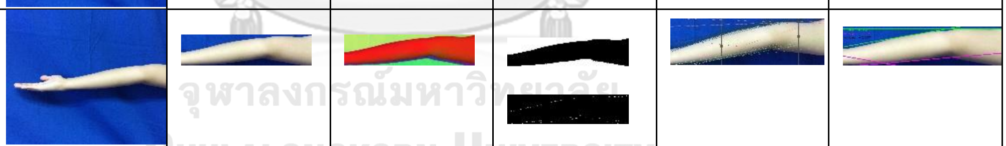
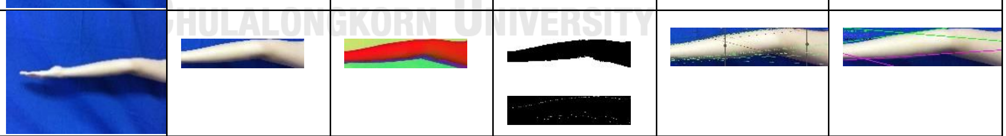
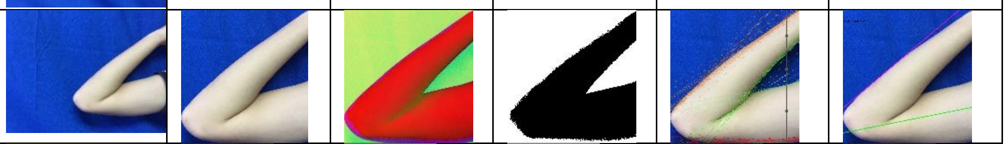
Appendix IV Digital Image Processing Technique – Example case

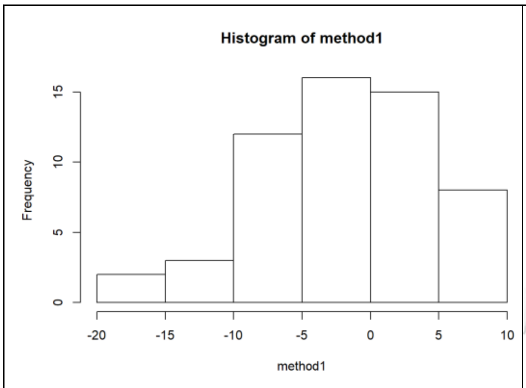
Code	Original	Cropped	RGB to HSV	Mask	Hough lines	Result
LE1						
LE2						
LE3						
LF1						
LF2						
LF3						
RE1						
RE2						
RE3						
RF1						
RF2						
RF3						

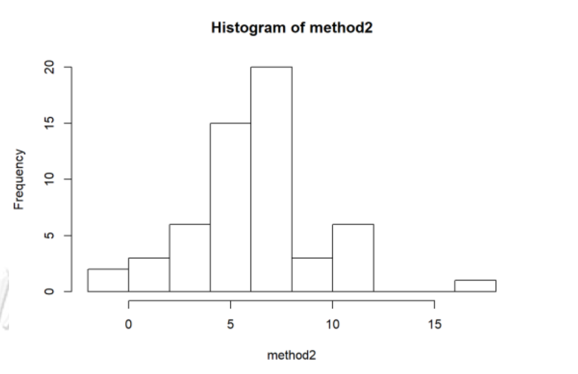
E, Extension; F, Flexion; L, Left; R, Right; 1-3, Number of image

Appendix V Bland-Altman plot of DIPT compared with other reference methods

Comparison:	**DIPT – Fluoroscope**	**Position:**	**Extension**
Method 1:	DIPT	Method 2:	Fluoroscope

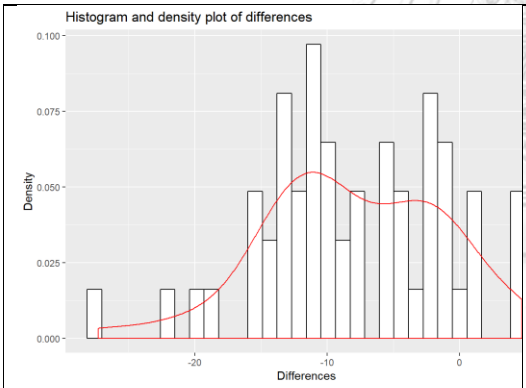
Histogram

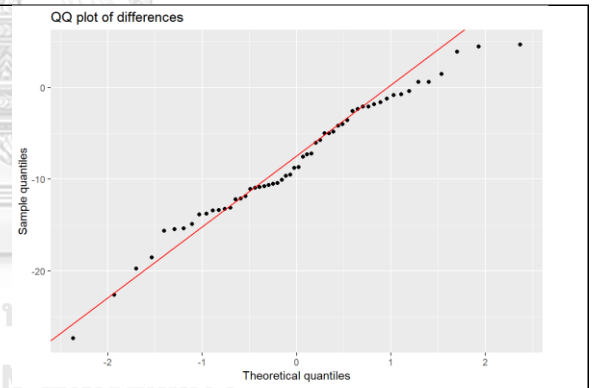




Mn, Md, Mn, Mx	-16.865, -2.282, -2.007, 8.922	Mn, Md, Mn, Mx	-1.431, 6.113, 6.014, 16.310

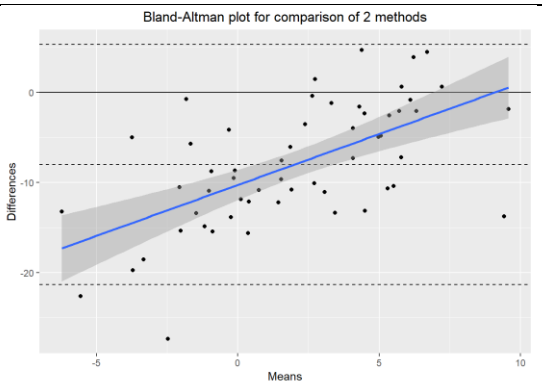
Check for normality of difference



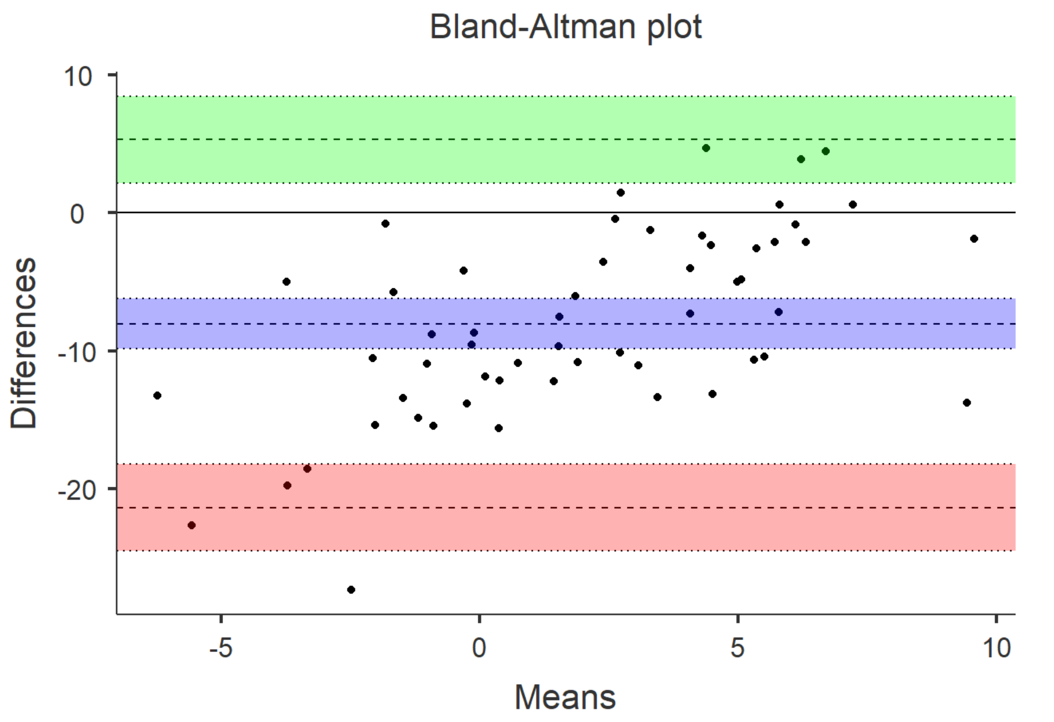


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.427

Plot comparison with best fit line to investigate for proportional bias

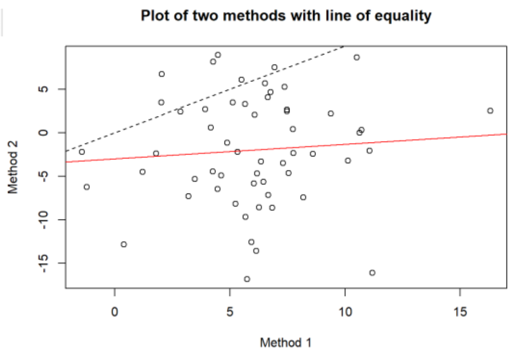


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	-8.02	-9.84	-6.20
Lower limit of agreement	-21.34	-24.47	-18.21
Upper limit of agreement	5.30	2.17	8.43

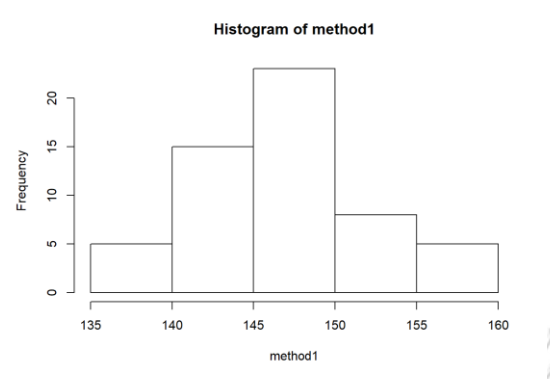
Additional comparison data

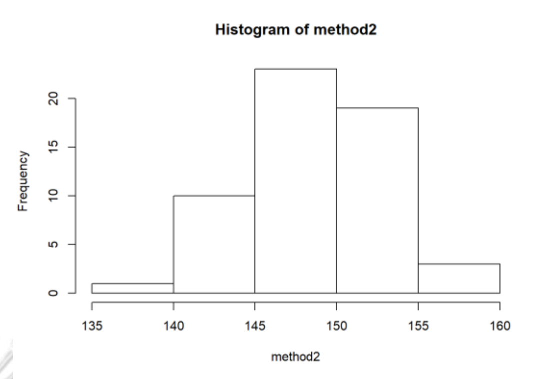


Paired *t* test p-value:	3.942664e-12 (<0.05)
Correlation coefficient:	0.08409099
Regression equation:	method 2 = 0.1686583 x method 1 + -3.021309

Comparison:	**DIPT-Fluoroscope**	**Position:**	**Flexion**
Method 1:	DIPT	Method 2:	Fluoroscope

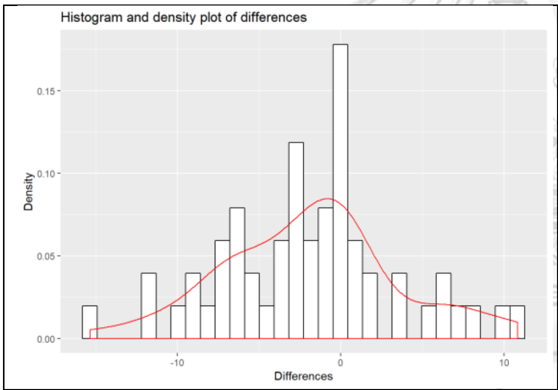
Histogram

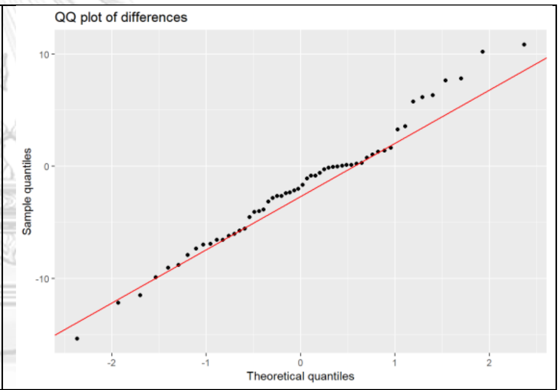




Mn, Md, Mn, Mx	137.1, 146.3, 146.8, 157.2	Mn, Md, Mn, Mx	135.0, 148.3, 148.7, 157.7

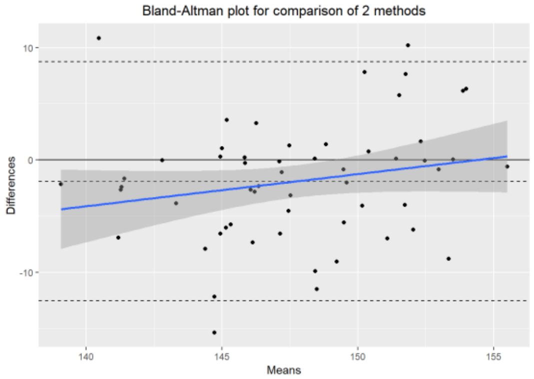
Check for normality of difference



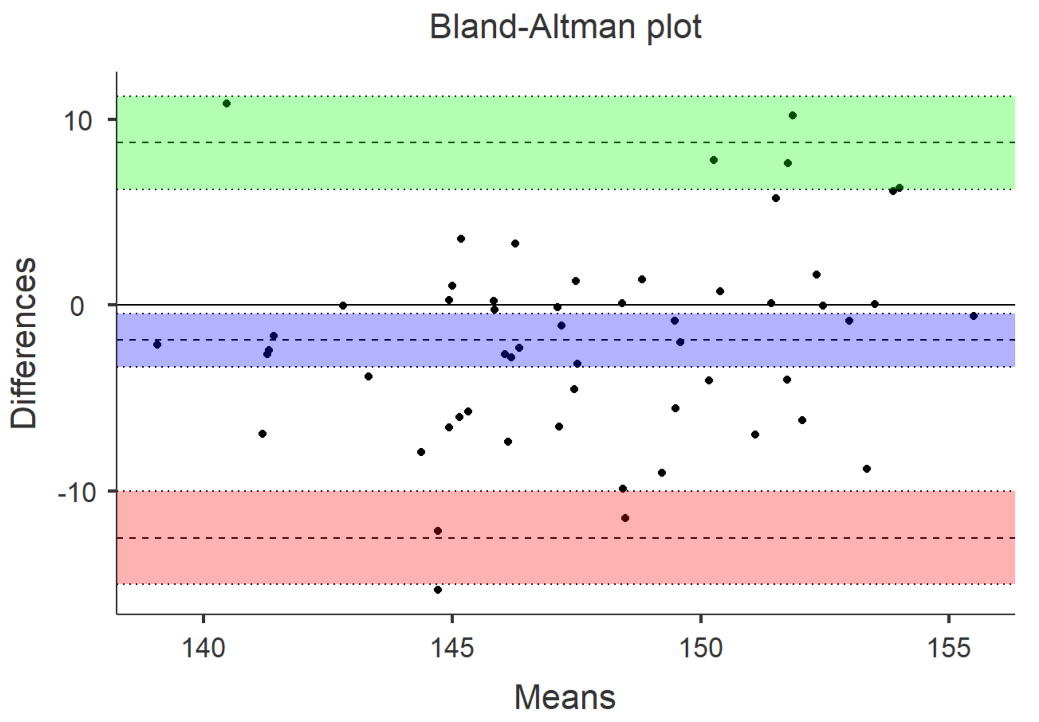


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.6446

Plot comparison with best fit line to investigate for proportional bias

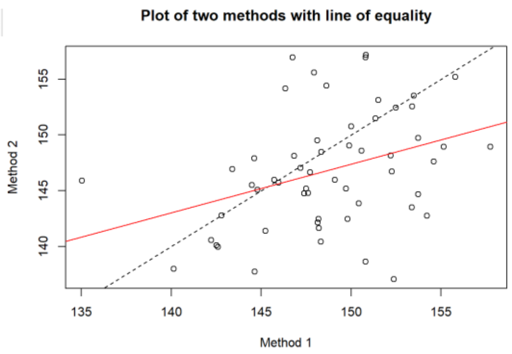


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	-1.89	-3.34	-0.438
Lower limit of agreement	-12.52	-15.02	-10.023
Upper limit of agreement	8.74	6.24	11.236

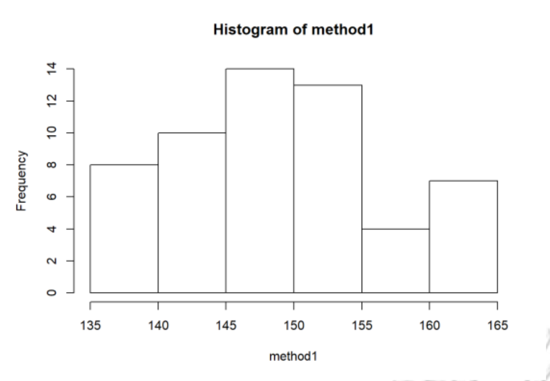
Additional comparison data

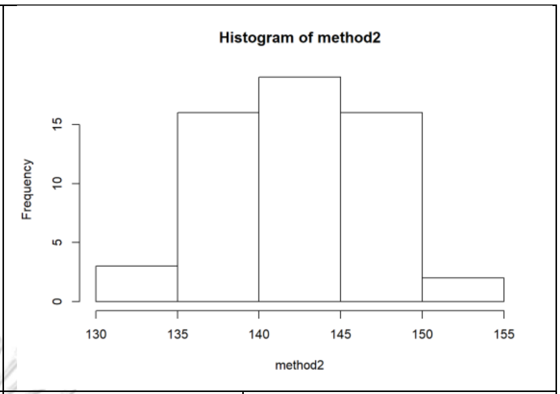


Paired *t* test p-value:	0.01168335
Correlation coefficient:	0.358468
Regression equation:	method 2 = 0.435907 x method 1 + 81.98555

Comparison:	**DIPT-Fluoroscope**	**Position:**	**ROM**
Method 1:	DIPT	Method 2:	Fluoroscope

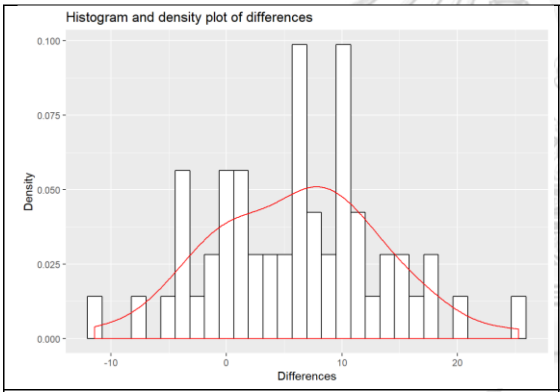
Histogram

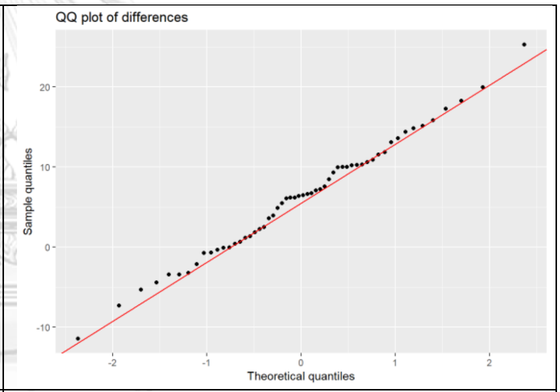




Mn, Md, Mn, Mx	135.9, 148.2, 148.8, 164.7	Mn, Md, Mn, Mx	132.2, 142.5, 142.7, 152.4

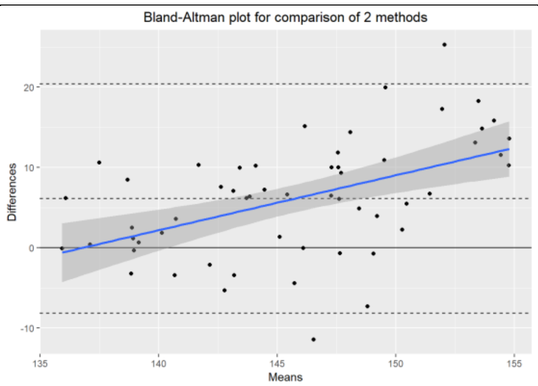
Check for normality of difference



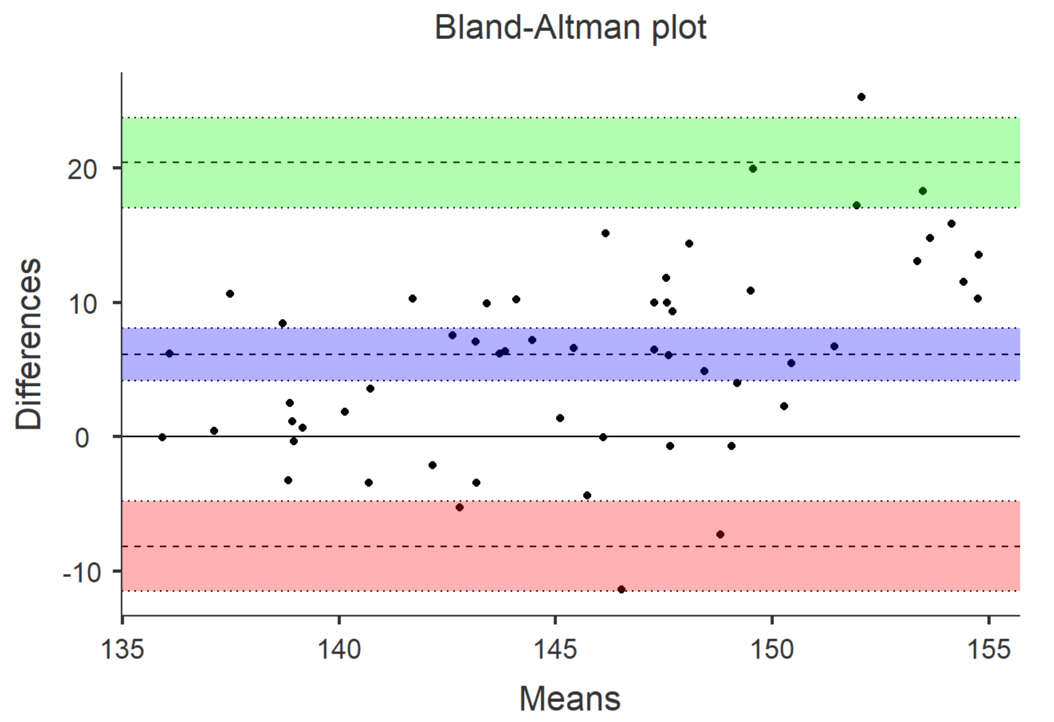


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.9962

Plot comparison with best fit line to investigate for proportional bias

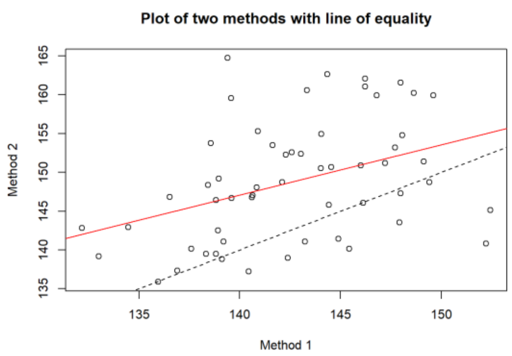


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	6.13	4.18	8.08
Lower limit of agreement	-8.16	-11.52	-4.80
Upper limit of agreement	20.42	17.06	23.78

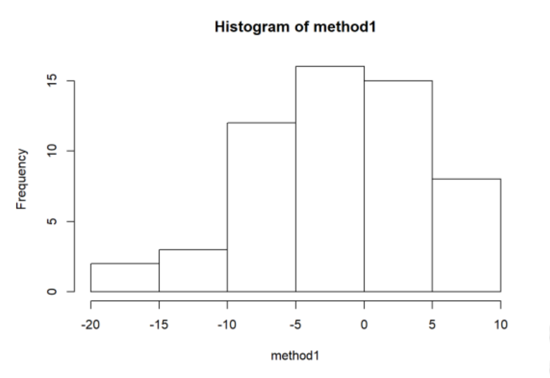
Additional comparison data

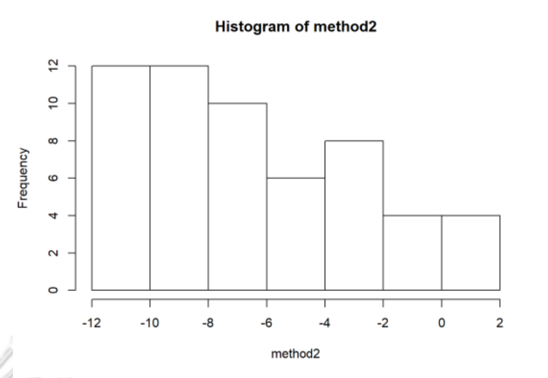


Paired *t* test p-value:	5.409128e-08 (< 0.05)
Correlation coefficient:	0.3930114
Regression equation:	method 2 = 0.6476949 x method 1 + 56.39664

Comparison:	**DIPT – Goniometer**	**Position:**	**Extension**
Method 1:	DIPT	Method 2:	Goniometer

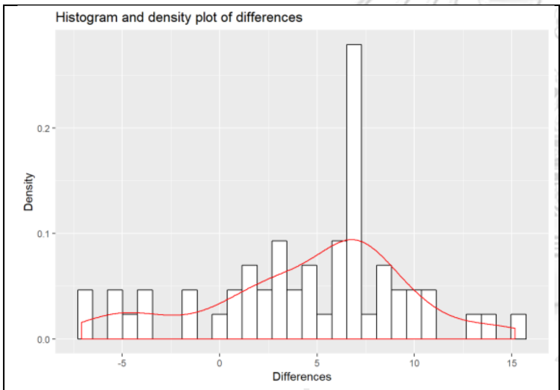
Histogram

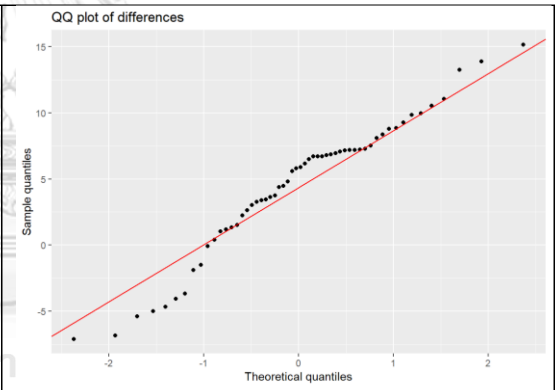




Mn, Md, Mn, Mx	-16.865, -2.282, -2.007, 8.922	Mn, Md, Mn, Mx	-11.833, -7.192, -6.519, 1.650

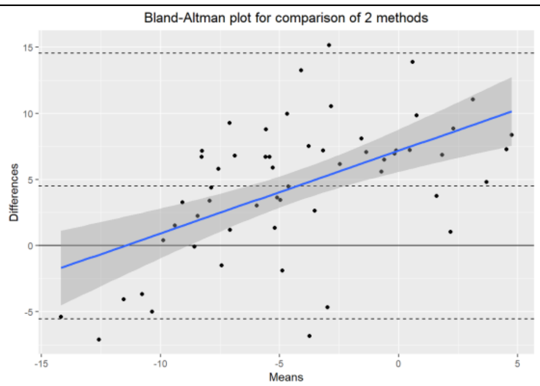
Check for normality of difference



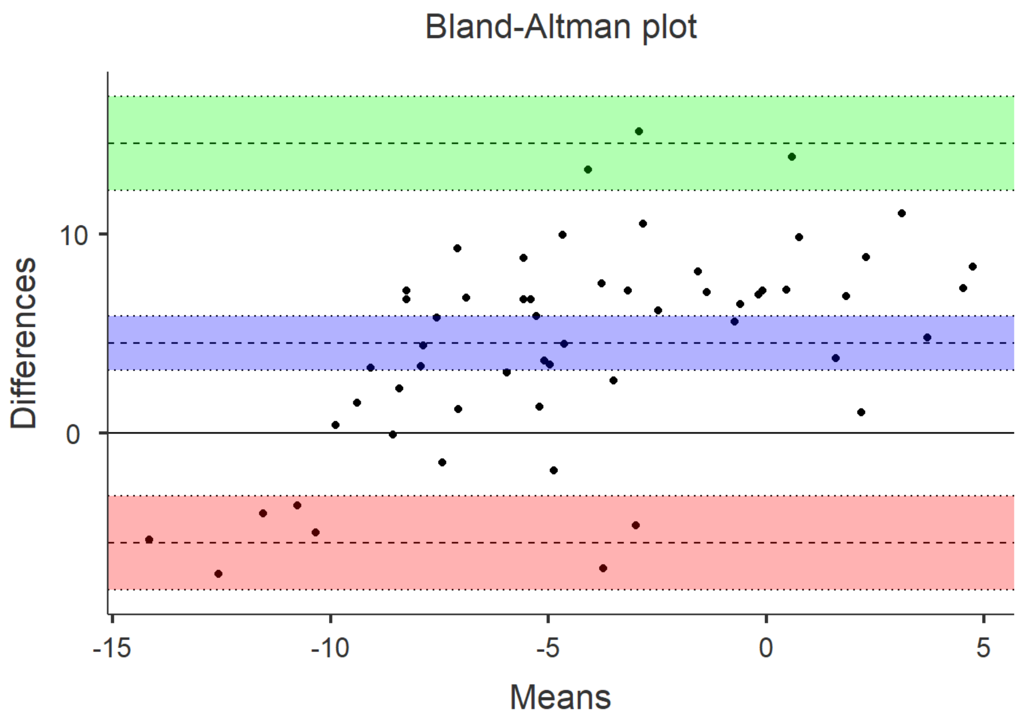


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.05561

Plot comparison with best fit line to investigate for proportional bias

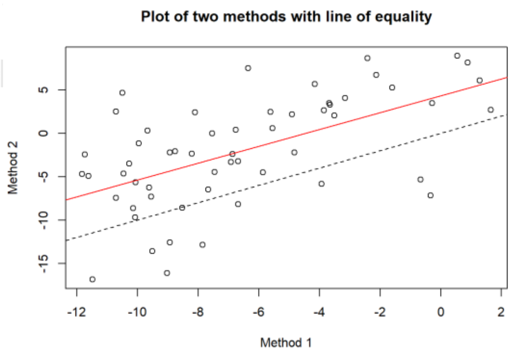


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	4.51	3.14	5.88
Lower limit of agreement	-5.54	-7.90	-3.18
Upper limit of agreement	14.56	12.20	16.92

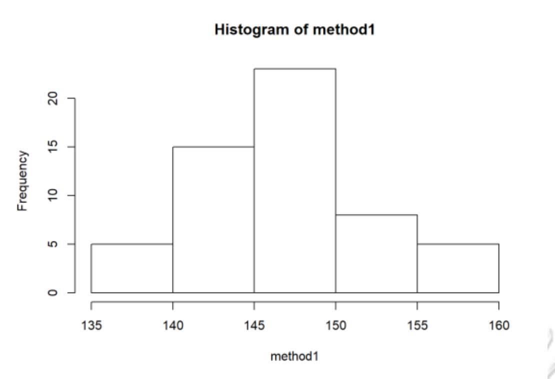
Additional comparison data

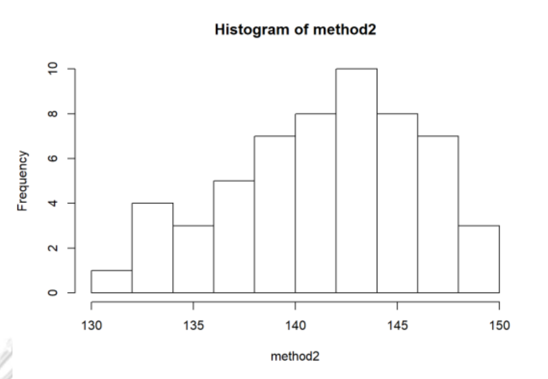


Paired *t* test p-value:	1.801037e-08 (<0.05)
Correlation coefficient:	0.5810162
Regression equation:	method 2 = 0.9713433 x method 1 + 4.324803

Comparison:	**DIPT-Goniometer**	**Position:**	**Flexion**
Method 1:	DIPT	Method 2:	Goniometer

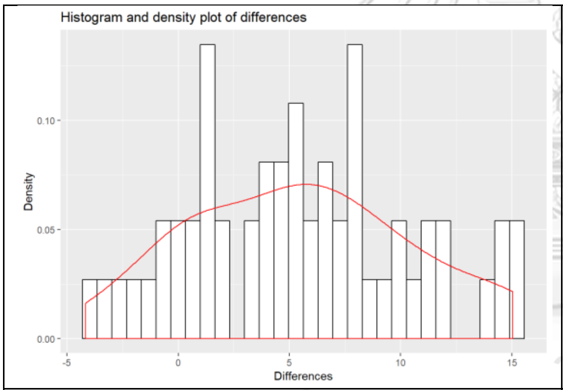
Histogram

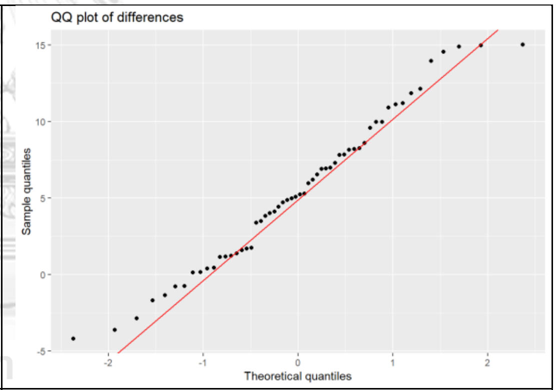




Mn, Md, Mn, Mx	137.1, 146.3, 146.8, 157.2	Mn, Md, Mn, Mx	130.9, 141.9, 141.3, 148.8

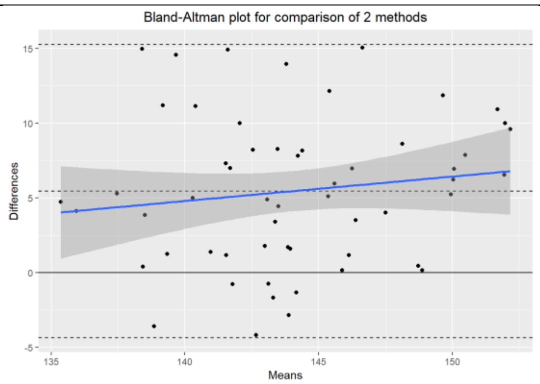
Check for normality of difference



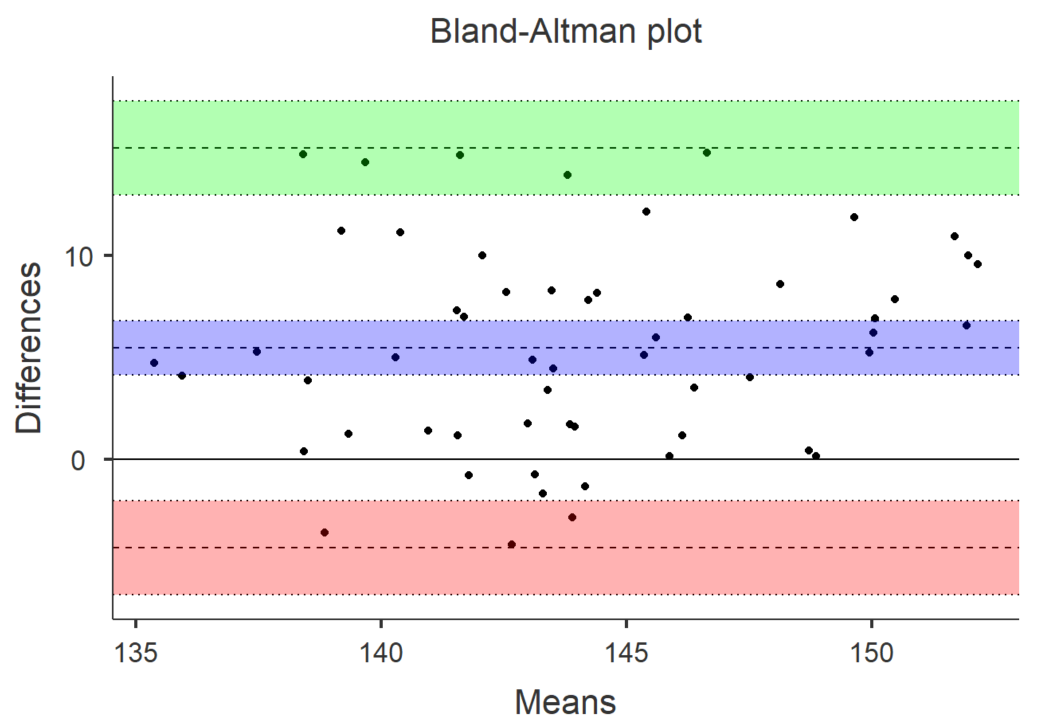


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.361

Plot comparison with best fit line to investigate for proportional bias

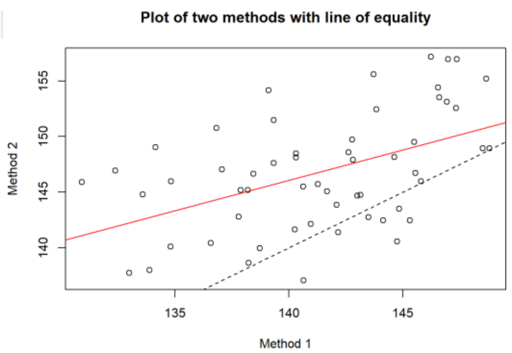


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	5.46	4.12	6.80
Lower limit of agreement	-4.35	-6.66	-2.05
Upper limit of agreement	15.26	12.96	17.57

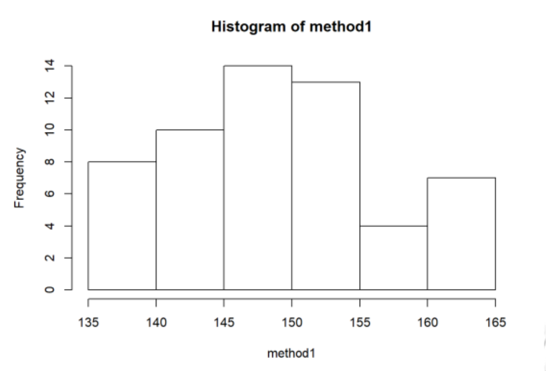
Additional comparison data

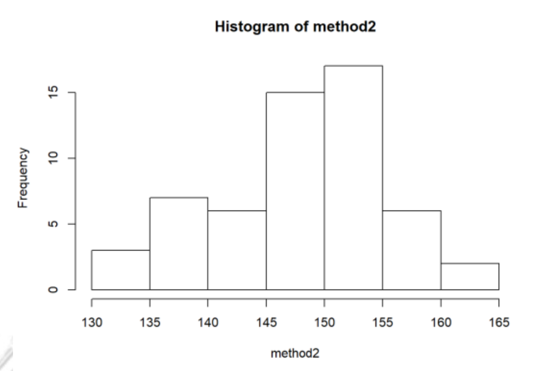


Paired *t* test p-value:	4.819966e-11 (< 0.05)
Correlation coefficient:	0.4848882
Regression equation:	method 2 = 0.547757 x method 1 + 69.37804

Comparison:	**DIPT-Goniometer**	**Position:**	**ROM**
Method 1:	DIPT	Method 2:	Goniometer

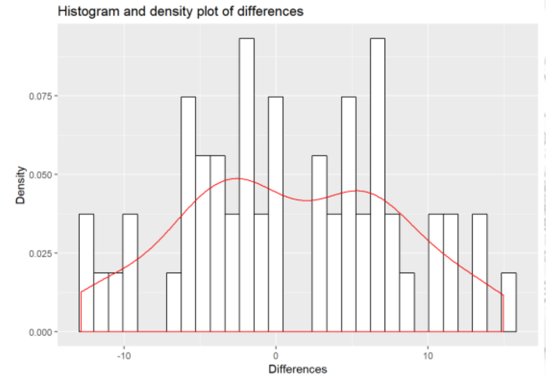
Histogram

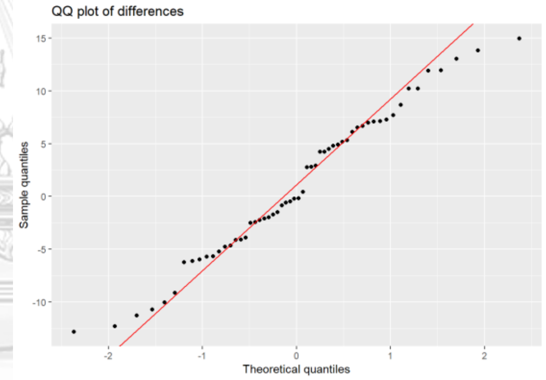




Mn, Md, Mn, Mx	135.9, 148.2, 148.8, 164.7	Mn, Md, Mn, Mx	131.5, 148.6, 147.9, 160.5

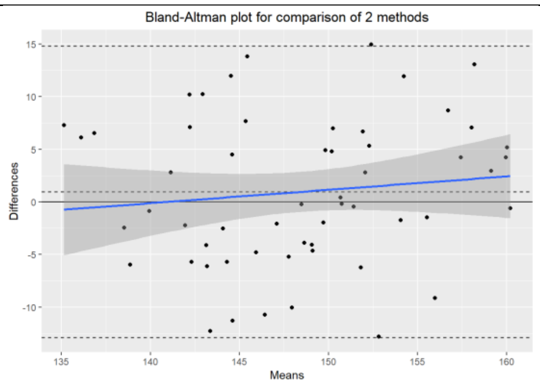
Check for normality of difference



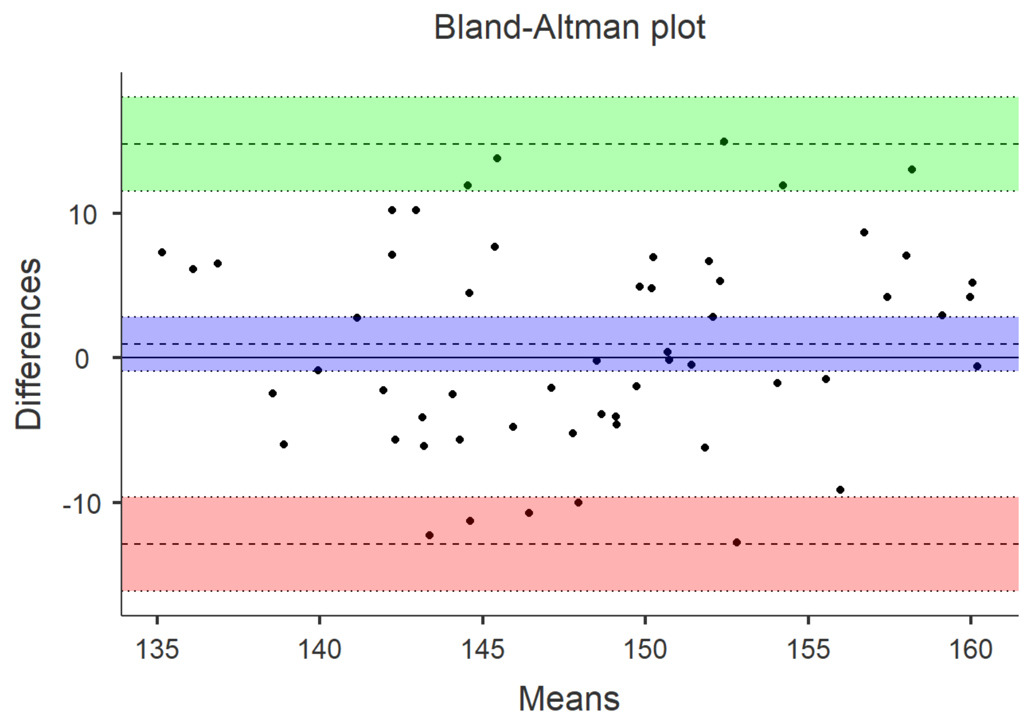


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.3632

Plot comparison with best fit line to investigate for proportional bias

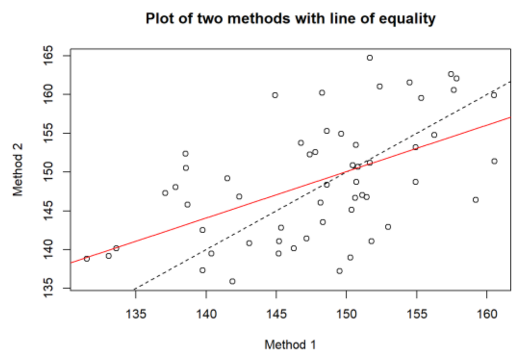


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	0.944	-0.948	2.84
Lower limit of agreement	-12.904	-16.157	-9.65
Upper limit of agreement	14.792	11.539	18.04

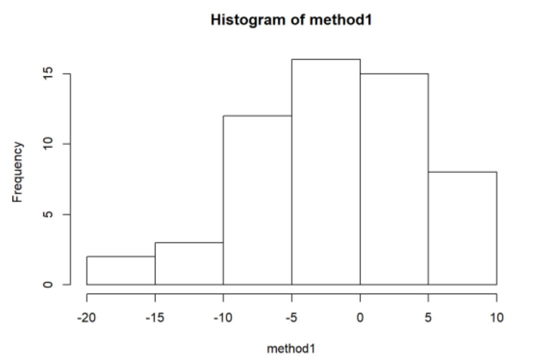
Additional comparison data

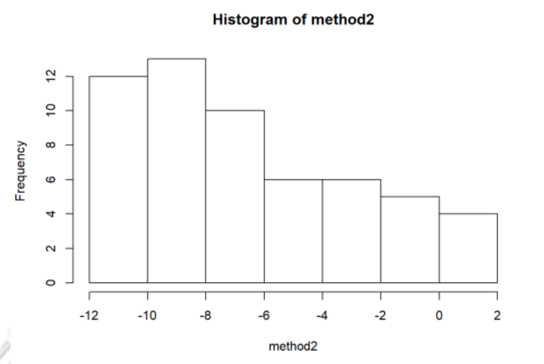


Paired *t* test p-value:	0.3219531
Correlation coefficient:	0.5431282
Regression equation:	method 2 = 0.599295 x method 1 + 60.19376

Comparison:	**DIPT – Inclinometer**	**Position:**	**Extension**
Method 1:	DIPT	Method 2:	Inclinometer

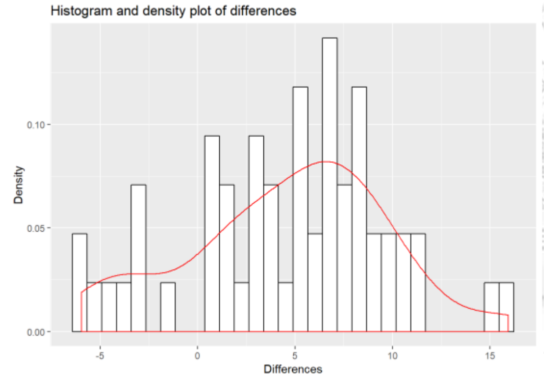
Histogram

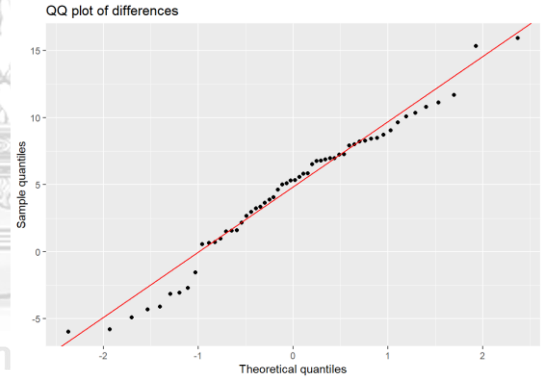




Mn, Md, Mn, Mx	-16.865, -2.282, -2.007, 8.922	Mn, Md, Mn, Mx	-11.867, -7.733, -6.613, 1.183

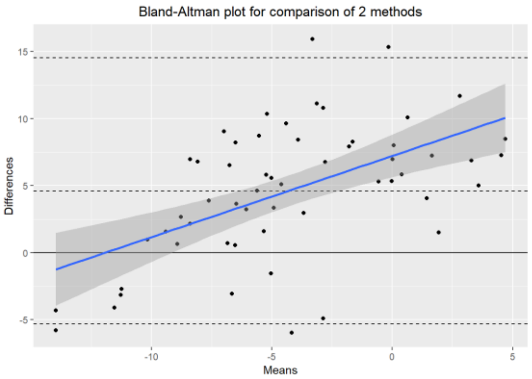
Check for normality of difference



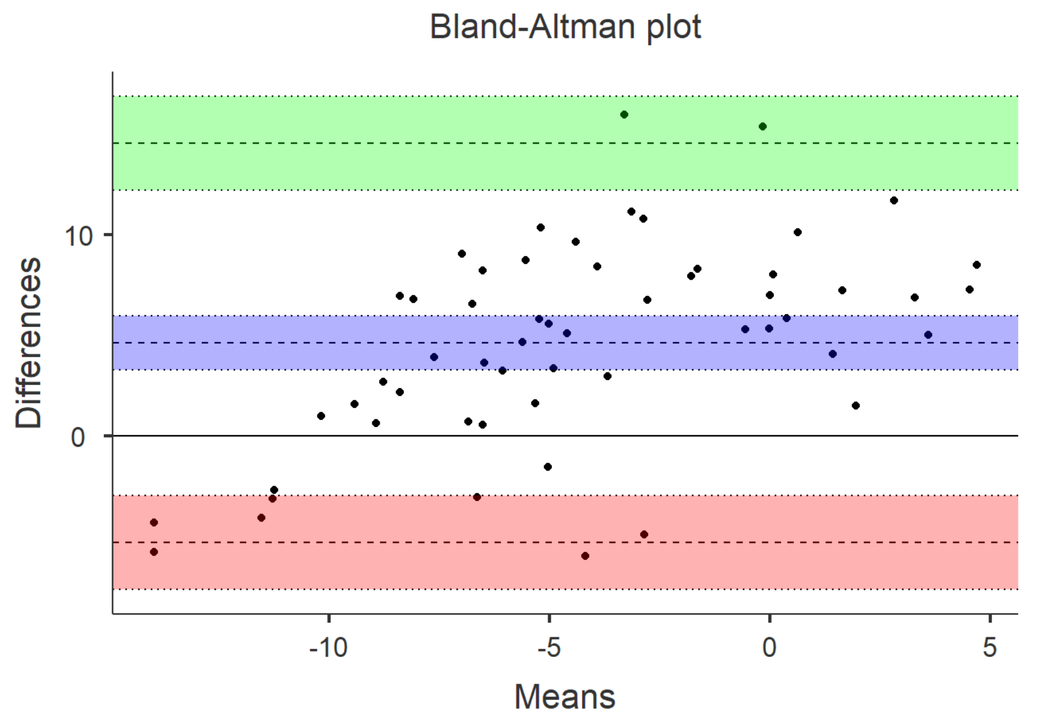


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.2402

Plot comparison with best fit line to investigate for proportional bias

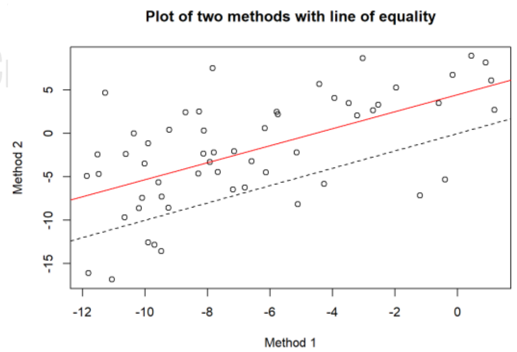


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	4.61	3.25	5.96
Lower limit of agreement	-5.32	-7.65	-2.99
Upper limit of agreement	14.53	12.20	16.86

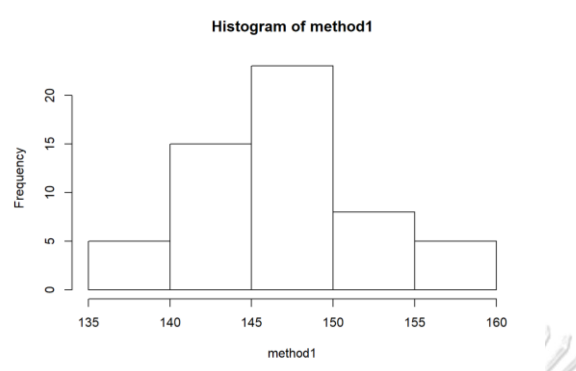
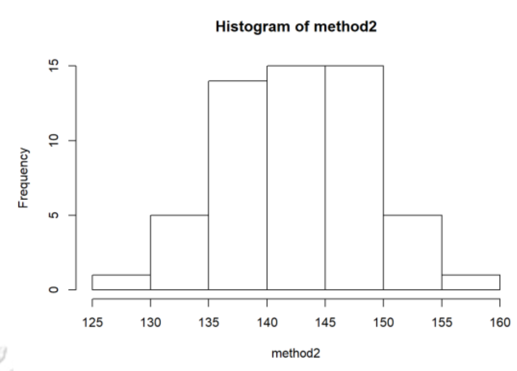
Additional comparison data



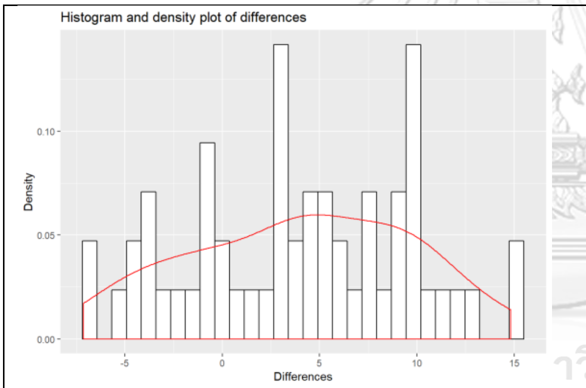
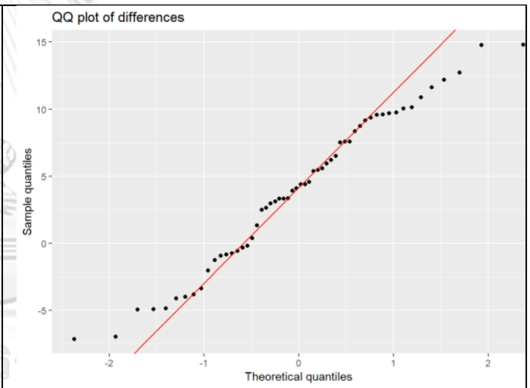
Paired *t* test p-value:	7.761427e-09 (<0.05)
Correlation coefficient:	0.5949633
Regression equation:	method 2 = 0.9814415 x method 1 + 4.483369

Comparison:	**DIPT-Inclinometer**	**Position:**	**Flexion**
Method 1:	DIPT	Method 2:	Inclinometer

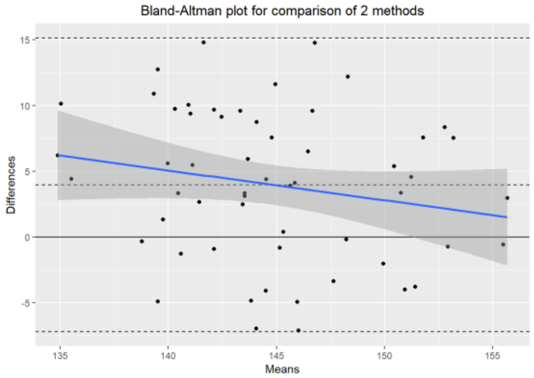
Histogram

			
Mn, Md, Mn, Mx	137.1, 146.3, 146.8, 157.2	Mn, Md, Mn, Mx	130.0, 142.1, 142.8, 155.8

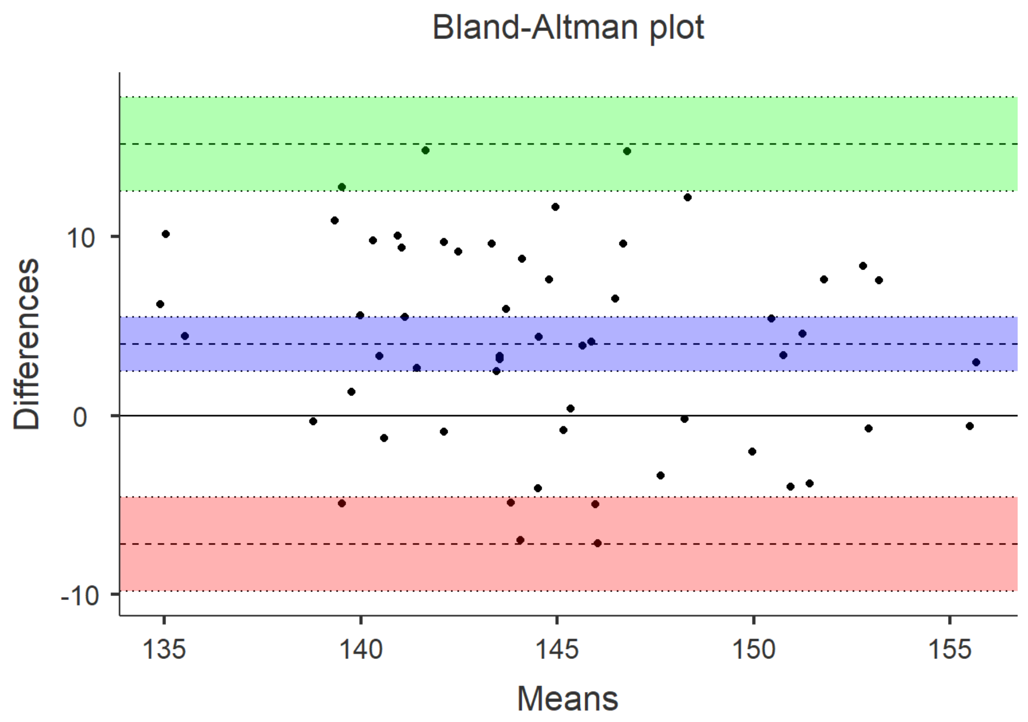
Check for normality of difference

	
Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.2569

Plot comparison with best fit line to investigate for proportional bias

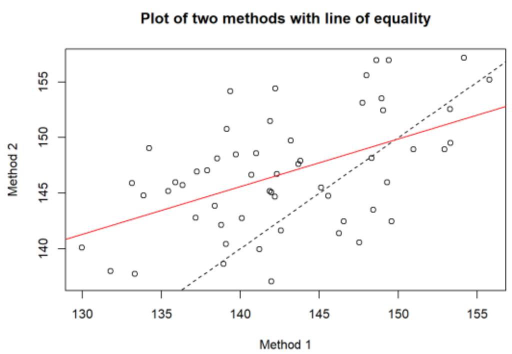


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	3.98	2.45	5.50
Lower limit of agreement	-7.19	-9.81	-4.57
Upper limit of agreement	15.15	12.52	17.77

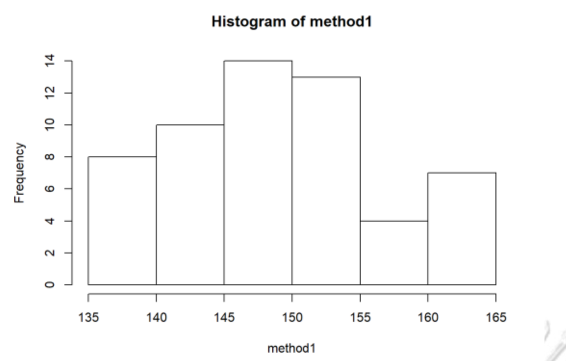
Additional comparison data

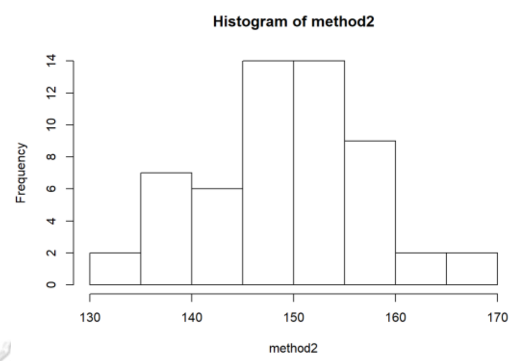


Paired *t* test p-value:	2.773264e-06 (<0.05)
Correlation coefficient:	0.5095362
Regression equation:	method 2 = 0.4291305 x method 1 + 85.51157

Comparison:	**DIPT-Inclinometer**	**Position:**	**ROM**
Method 1:	DIPT	Method 2:	Inclinometer

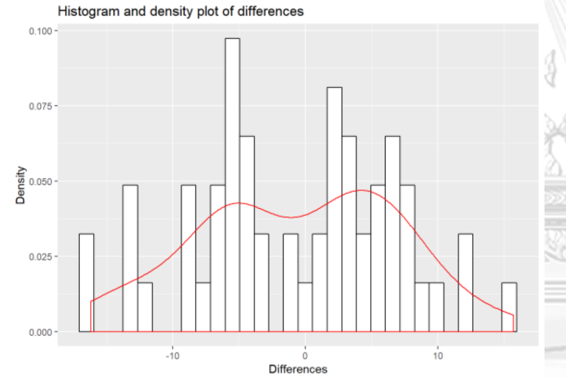
Histogram

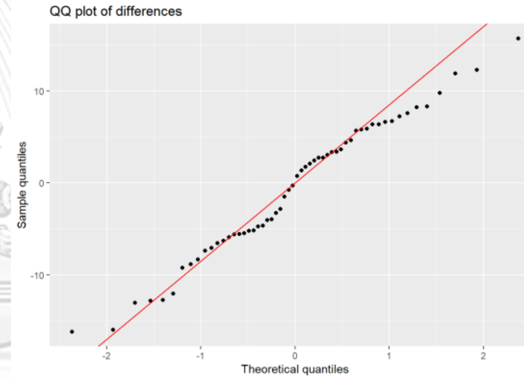




Mn, Md, Mn, Mx	135.9, 148.2, 148.8, 164.7	Mn, Md, Mn, Mx	133.3, 149.5, 149.4, 167.3

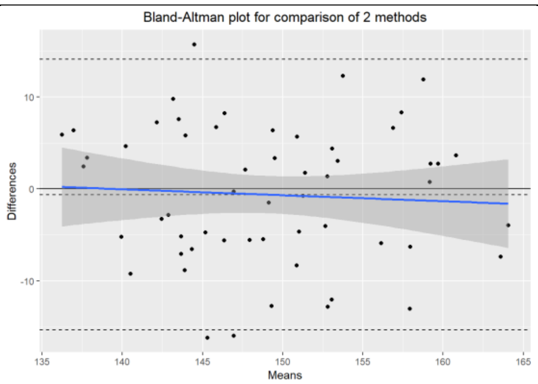
Check for normality of difference



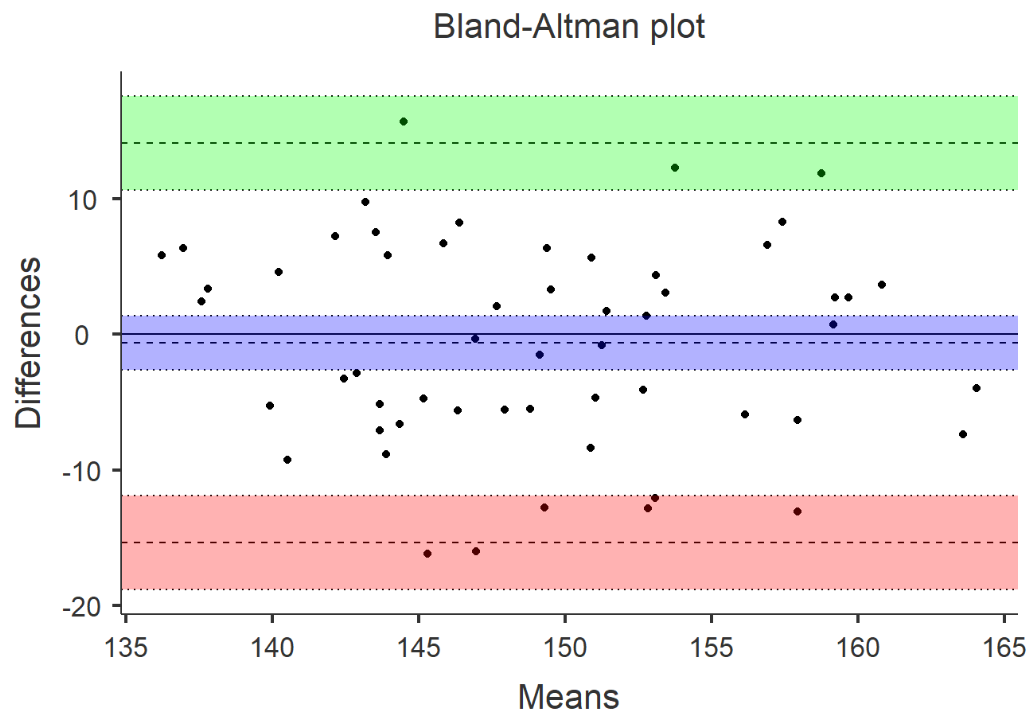


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.3869

Plot comparison with best fit line to investigate for proportional bias

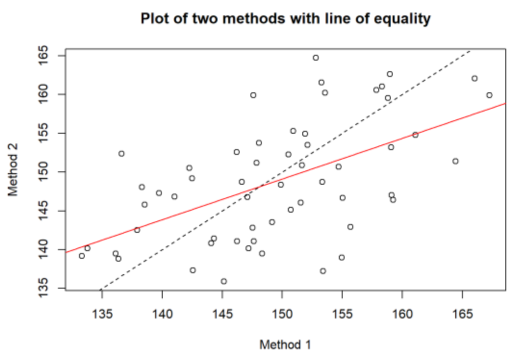


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	-0.628	-2.64	1.38
Lower limit of agreement	-15.357	-18.82	-11.90
Upper limit of agreement	14.101	10.64	17.56

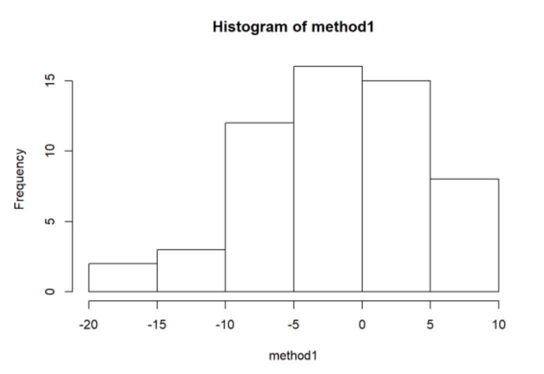
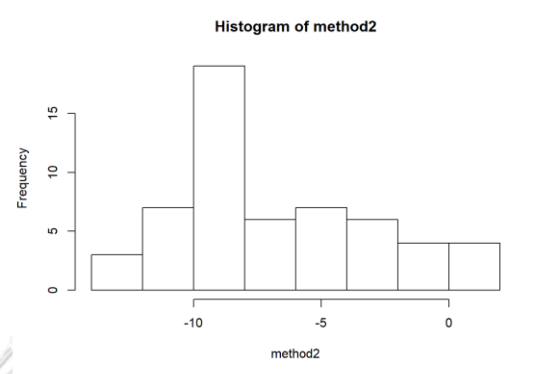
Additional comparison data



Paired *t* test p-value:	0.5343572
Correlation coefficient:	0.551182
Regression equation:	method 2 = 0.5240558 x method 1 + 70.49539

Comparison:	**DIPT – Gyroscope**	**Position:**	**Extension**
Method 1:	DIPT	Method 2:	Gyroscope

Histogram

<table>
<tr><td colspan="2">
</td><td colspan="2">
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<tr><td>Mn, Md, Mn, Mx</td><td>-16.865, -2.282, -2.007, 8.922</td><td>Mn, Md, Mn, Mx</td><td>-12.667, -8.000, -6.648, 1.500</td></tr>
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Check for normality of difference

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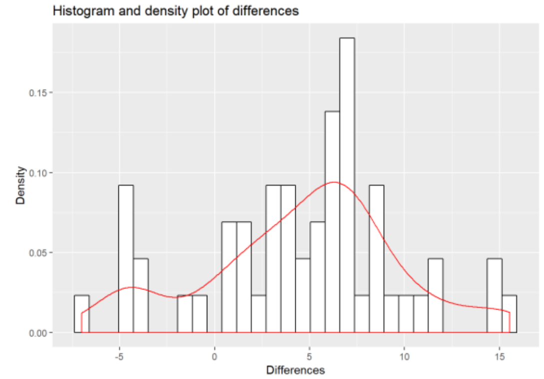
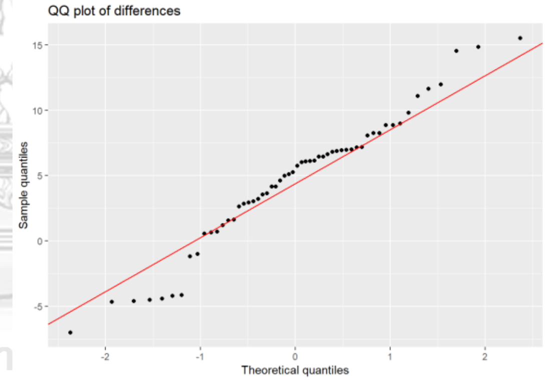
<tr><td>
</td><td>
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<tr><td>Histogram</td><td>QQ-Plot</td></tr>
<tr><td>Shapiro-Wilk normality test (p-value)</td><td>0.1388</td></tr>
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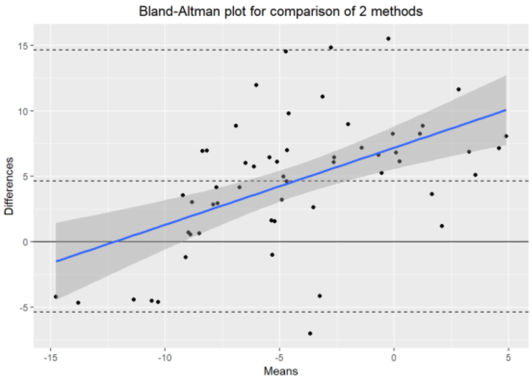
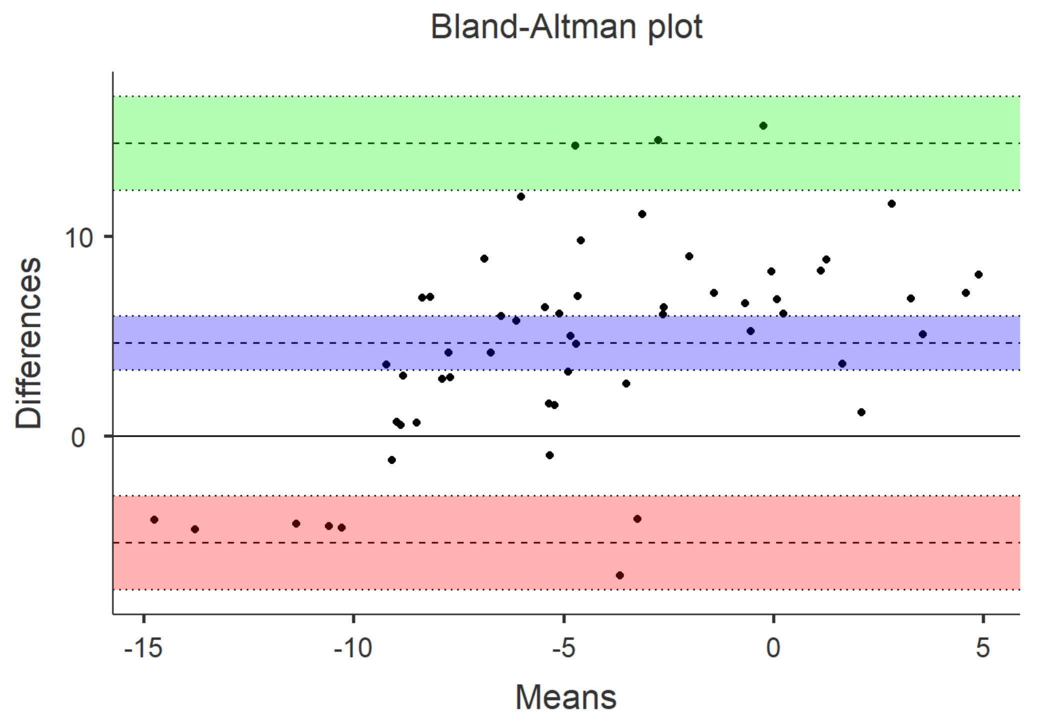
Plot comparison with best fit line to investigate for proportional bias

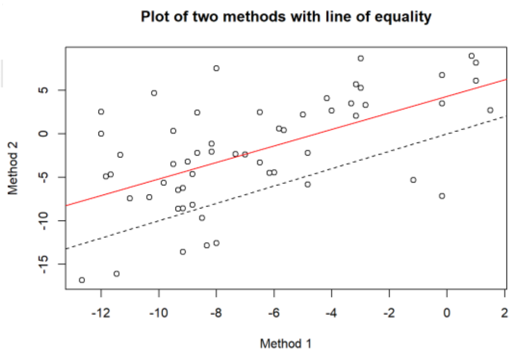


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	4.64	3.27	6.01
Lower limit of agreement	-5.36	-7.71	-3.01
Upper limit of agreement	14.65	12.30	17.00

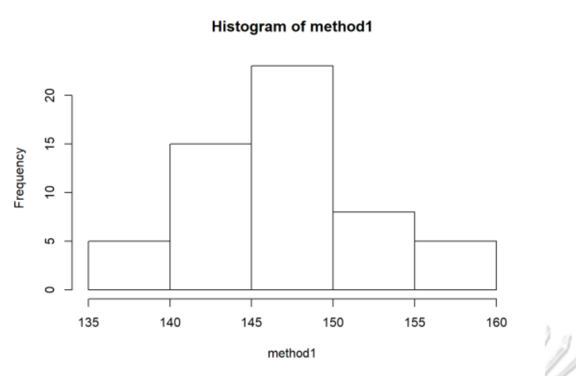
Additional comparison data

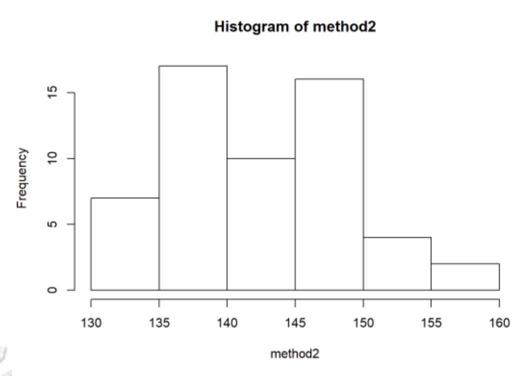


Paired *t* test p-value:	7.900673e-09 (< 0.05)
Correlation coefficient:	0.5865745
Regression equation:	method 2 = 0.9505447 x method 1 + 4.312145

Comparison:	**DIPT-Gyroscope**	**Position:**	**Flexion**
Method 1:	DIPT	Method 2:	Gyroscope

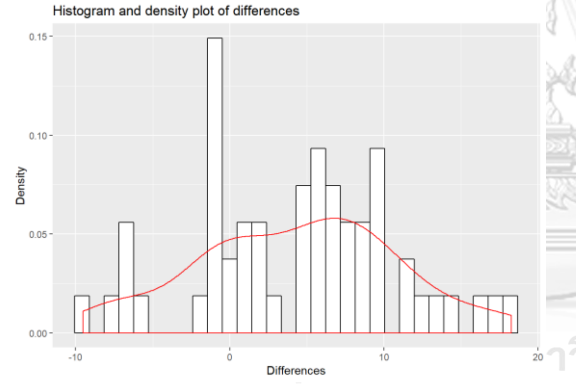
Histogram

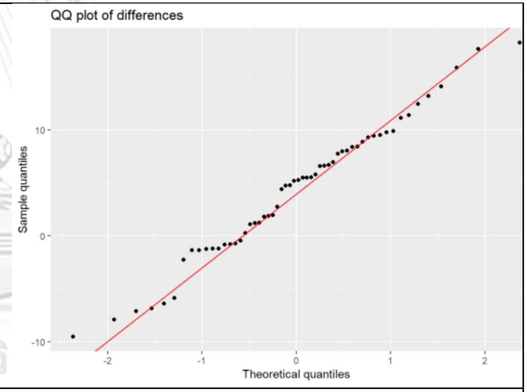




Mn, Md, Mn, Mx	137.1, 146.3, 146.8, 157.2	Mn, Md, Mn, Mx	131.8, 141.2, 142.5, 156.8

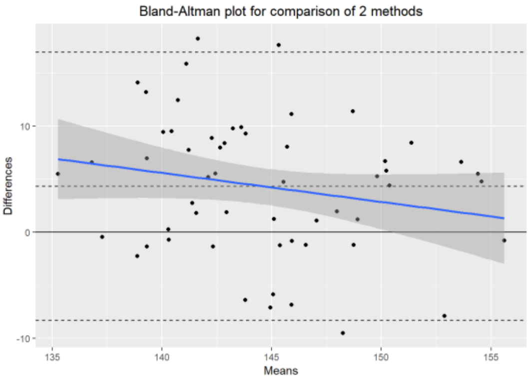
Check for normality of difference



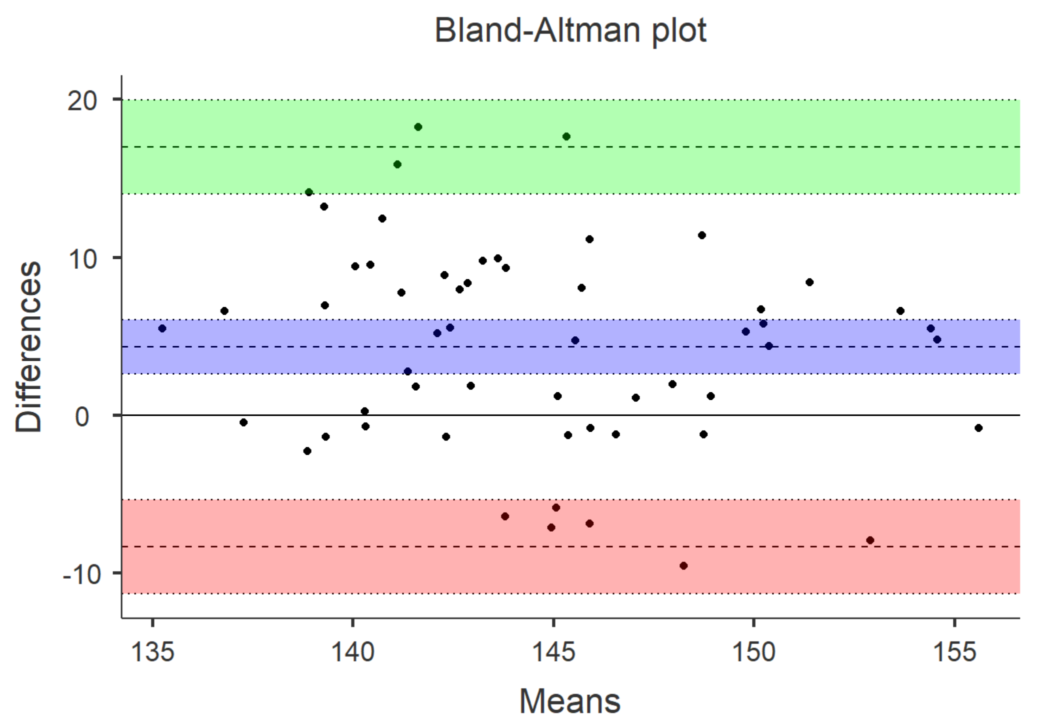


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.6201

Plot comparison with best fit line to investigate for proportional bias

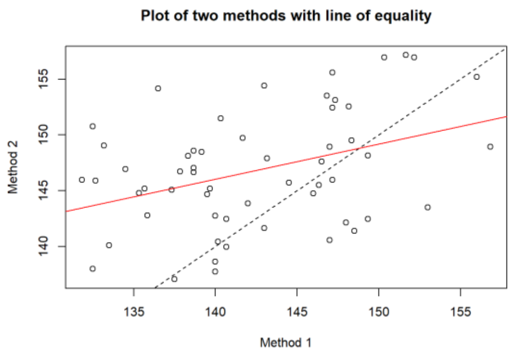


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	4.33	2.60	6.05
Lower limit of agreement	-8.33	-11.30	-5.35
Upper limit of agreement	16.98	14.00	19.95

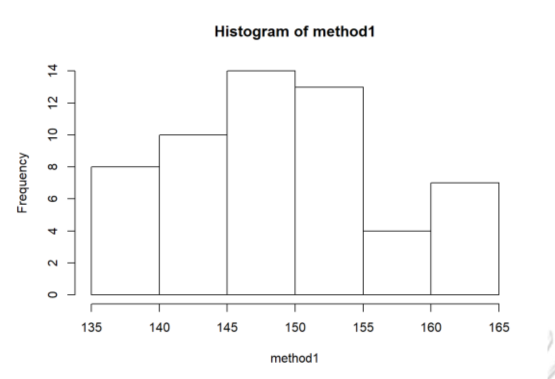
Additional comparison data

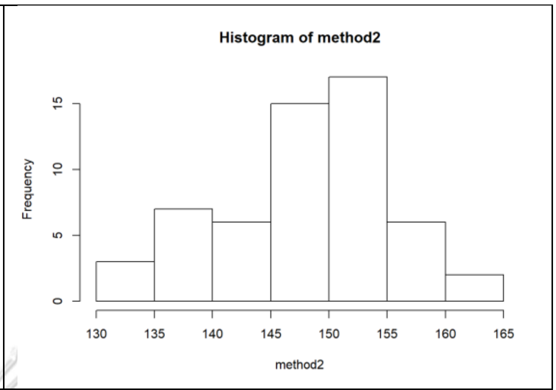


Paired *t* test p-value:	5.879955e-06 (< 0.05)
Correlation coefficient:	0.3820897
Regression equation:	method 2 = 0.3158022 x method 1 + 101.8071

Comparison:	**DIPT-Gyroscope**	**Position:**	**ROM**
Method 1:	DIPT	Method 2:	Gyroscope

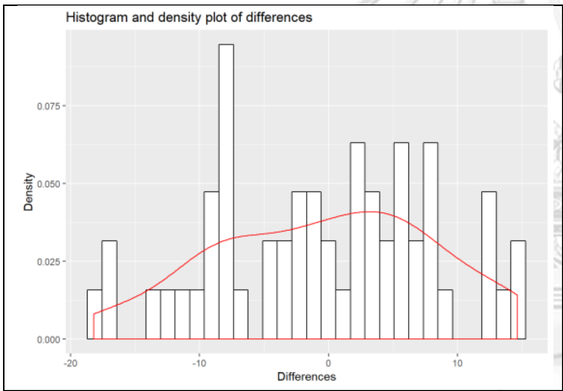
Histogram

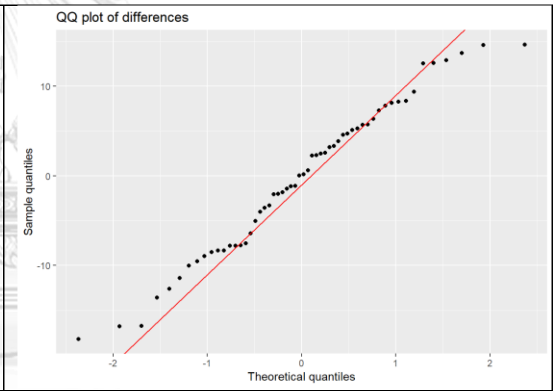




Mn, Md, Mn, Mx	135.9, 148.2, 148.8, 164.7	Mn, Md, Mn, Mx	132.3, 149.8, 149.1, 168.2

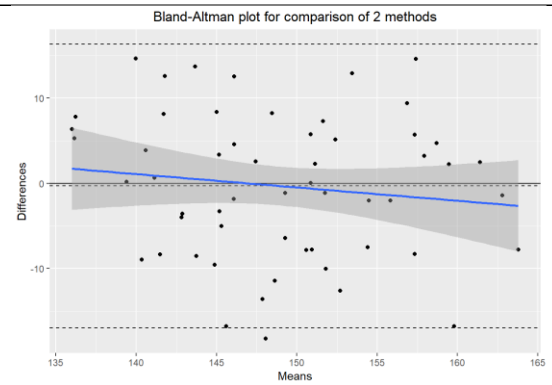
Check for normality of difference



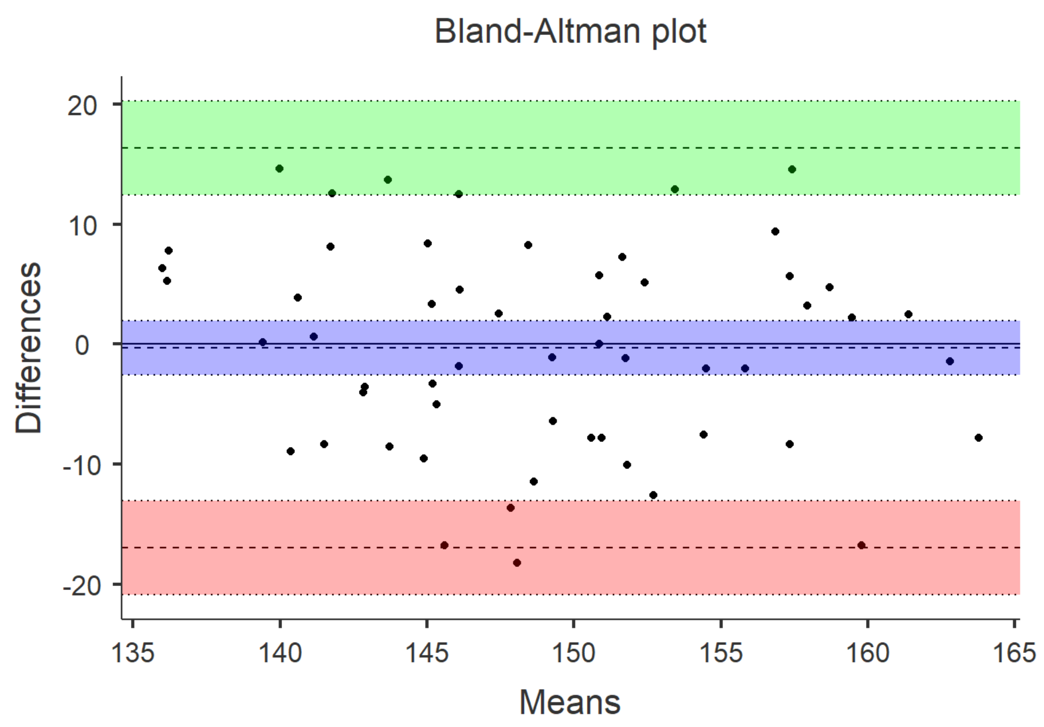


Histogram	QQ-Plot
Shapiro-Wilk normality test (p-value)	0.3257

Plot comparison with best fit line to investigate for proportional bias

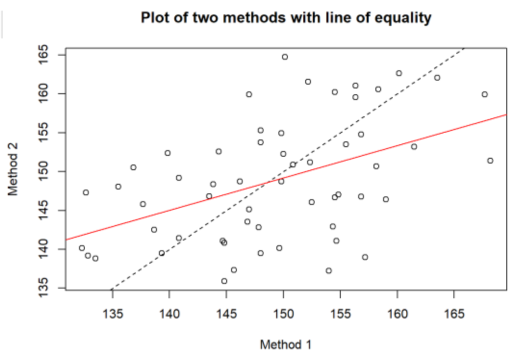


Bland-Altman analysis (with assumption of normal distribution of differences)



	Mean	Lower 95%CI	Upper 95%CI
Bias (n = 56)	-0.316	-2.59	1.96
Lower limit of agreement	-16.967	-20.88	-13.0
Upper limit of agreement	16.336	12.42	20.25

Additional comparison data



Paired *t* test p-value:	0.7819646
Correlation coefficient:	0.4673172
Regression equation:	method 2 = 0.4165562 x method 1 + 86.68979

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