sciendo ASIAN BIOMEDICINE
DOI 10.1515/abm-2020-0006 — Asian Biomed (Res Rev News) 2020; 14(1):37–44

Technical report **Open access**

Digital image processing technique to measure the range of motion of the elbow

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Abstract

Background: Most photography-based arc of motion measurements require human assessment and their accuracy depends on the observer.

Objectives: To develop a digital image processing technique (DIPT) for measuring elbow range of motion (ROM), and to assess its validity and reliability compared with standard methods.

Methods: Physiotherapists performed digital goniometer and inclinometer ROM measurements bilaterally on healthy volunteer elbows. A photographer took digital images of elbows fully extended and fully flexed 3 times using an 8-megapixel smartphone camera. Extension and flexion angles were calculated using the DIPT. Intra- and inter-rater reliability of all methods was assessed using an intraclass correlation coefficient (ICC). A paired Student's t test and Wilcoxon-signed rank test were used to assess systematic bias. A Bland–Altman plot was used to show possible range of difference between the methods.

Results: We measured 56 elbows from 28 participants. Intra- and inter-rater ICCs of goniometer and inclinometer showed moderate-to-excellent agreement. Mean extension and flexion angles for the DIPT were greater than those for the goniometer and inclinometer measurements ($P < 0.05$), but the total ROMs were not significantly different (vs goniometer $P = 0.32$, vs inclinometer $P = 0.53$). Limits of agreement were 9.93°–10.05° for extension angle, 9.81°–11.7° for flexion angle, and 13.84°–15.99° for total ROMs.

Conclusions: Elbow ROM measurement using the current DIPT produces results comparable with goniometer and inclinometer measurements, but the difference from the standard methods was up to 15.99° for total ROM.

Keywords: artificial intelligence; computer-assisted; diagnostic techniques and procedures; elbow joint; image analysis; range of motion

The elbow joint is a hinge joint that allows single plane of movement: flexion and extension. Intra- and extra-articular disease such as elbow contracture and fracture can cause functional impairment of this joint. Range of motion (ROM) is an objective measurement of the elbow function and it is part of a scoring system [1].

Assessment of measurement methods for elbow ROM has been reported in the literature. Radiographic examination

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gives the most accurate result, but it is not the first choice in daily practice for evaluating elbow function due to the risk from radiation exposure [2]. A 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 as indicated by recent systematic review [2, 3]. An inclinometer is a practical device, but it should be used by a trained professional. Moreover, a digital inclinometer especially a dual-type inclinometer is quite expensive.

Photography-based methods have been proposed and validated in many studies [1, 4–8]. The concept of this method is to take a photo or video of elbow in extension and flexion position, and then to draw lines of arm and forearm axis on images by the assessor using a visible reference point and calculating the angle between these two lines. ROM value is obtained from flexion angle minus extension angle. This provides many benefits such as being inexpensive, durable, easy data storage and transfer to allow multiple observers, and possibility of measurement at any time in any location [4, 6]. Image capturing devices can be a digital camera or smartphone, as has been already validated for measuring elbow ROM [1, 8]. However, accuracy of these measurement methods depends on observer's experience [7].

Digital image processing technique (DIPT) is a 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 the innovative concept of the present study. This method can be applied to a patient who is in a remote area taking and sending his or her elbow image in flexed–extended position via a smart device such as a smartphone or a tablet to a hospital database. Then image analysis software is used to automatically measure extension and flexion angles and send a report to a corresponding physician. We anticipated that the DIPT method can be used interchangeably using goniometer and inclinometer. The DIPT method can also reduce observational bias, examination time, labor burden, and cost of transportation.

The present study aimed to develop a DIPT for measuring elbow ROM, and to assess validity and reliability of this technique compared with standard digital goniometer and inclinometer which are instruments for measuring arc of motion in daily clinical practice.

Materials and methods

This study was approved by the Institutional Review Board of the Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand (Certificate of Approval No. 198/2019). Participants were recruited from students and staff in the university by poster announcement. Inclusion criteria included all volunteer participants aged over 18 years who were able to lift their shoulder perpendicular to the floor and hold it still in an elbow extension and flexion position. Exclusion criteria included those who had deformity of arm and forearm or pain and discomfort at the elbow. Participants were informed about study protocol and risks involved in this study. The written informed consent was provided. Sample size was determined by calculating two-dependent mean sample sizes. Ten degree of elbow motion arc measurement error was considered as minimal clinically important difference (MCID) and used as summative difference. Standard deviation was obtained from the difference between photographic and goniometric measurements [7]. A total of 14 elbows were required.

A digital goniometer and digital inclinometer were used as reference measuring devices to compare ROM measurements with those from DIPT. All measurements and capturing photographs were conducted on the same day (April 20, 2019) in the orthopedic operating room of King Chulalongkorn Memorial Hospital. Two trained physiotherapists with 2 years' experience were briefed about the measurement techniques and they practiced the measurements on each other. Both examiners performed goniometer, inclinometer, and ROM measurements on the bilateral elbows of participants. Two research assistants recorded the measurement values on record forms.

Digital goniometer

A digital protractor goniometer with ±0.5° precision (Mediguage) was used. The goniometer was centered on the lateral epicondyle. The proximal part of goniometer pointed at the greater tuberosity of humerus and the distal part pointed at the middle portion of wrist [2]. The examiner measured the flexion and extension position of elbow three times for each side.

Digital inclinometer

A baseline digital inclinometer (Fabrication Enterprises) was calibrated. The measurement technique for the inclinometer was modified from the American Medical Association (AMA) recommendation [9]. The participant laid supine on a bed and both elbows hung beyond the edge of the bed. To measure the extension angle, the inclinometer was aligned on the long axis of forearm and set to zero. The participant was then asked to extend his or her elbow and the measurement value was recorded. To measure the flexion angle, the participant fully flexed his or her elbow while the examiner aligned the inclinometer with the forearm, read the flexion angle, and then repeated the same protocol two more times for extension and flexion. Three measurement values for the same limb and same position should be within 5° or 10% of the mean.

Smartphone photography

The participant stood as close as possible in front of a blue screen to control the horizontal plane of the arm and then performed lateral abduction of the shoulder to 90° perpendicular to the floor. This position is considered as practical for a patient to take a photograph of his or her elbow at home and the monotonous color contrast background should help reduce image processing error. The upper extremity was exposed from shoulder to hand. A photographer took elbow images in with the arm fully extended and fully flexed three times for each position (**Figure 1**). The smartphone camera was at the same level of the elbow joint while taking a shot. Participant was told to drop his or her arm to a relaxed position between each photo shot and then raised it again so that the next image could be acquired. All images were taken using a iPhone 6 (Apple) with 8-megapixel rear camera (3,264 × 2,448 pixels, 72 dpi).

Digital image processing technique

The first step is "line detection," which is the 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. The horizontal and vertical blue areas were deleted from edges to eliminate the blue screen background as much as possible (**Figure 2A**). A median filter was applied to reduce noise from the camera and reduce light by converting the colored space from red, green, and blue (RGB) to hue saturation value (HSV) to create a mask with color range (100,0,0) and (180,255,255) in the HSV color space (**Figure 2B**). A mask was then applied to find the contour of the skin and clean the noise with a median blur filter (**Figure 2C**). Detection of lines was based on a Canny and Hough transformation (**Figures 3A** and **4A**) [10, 11]. To improve accuracy, outlier detection was used to eliminate unrelated lines.

After the line detection process, the next step is "angle calculation." The algorithm for flexion and extension angles is similar. They 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. The protocols for calculation of extension and flexion angles are described as follows.

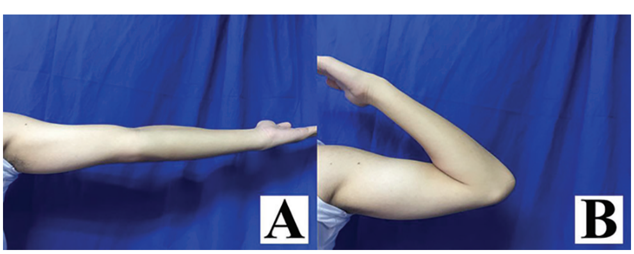

Figure 1. Photographic positions. Subject laterally abducted shoulder perpendicular to the floor and fully extended elbow **(A)**. Elbow was maximally flexed **(B)**.

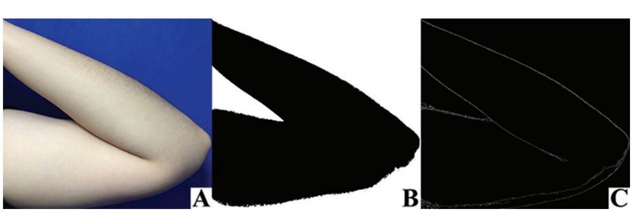

Figure 2. Line detection process. **(A)** Cropped image. **(B)** Converting red, green, and blue (RGB) to hue saturation value (HSV). **(C)** Detection of lines using Canny and Hough transformation.

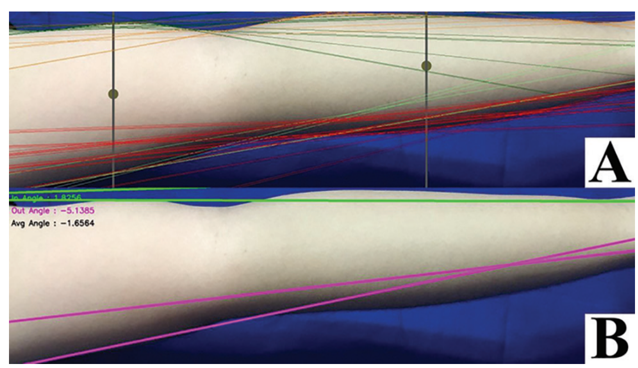

Figure 3. Angle calculation step for extended elbow image. **(A):** Locate middle points of arm and forearm from one-third of distance of both edges. **(B):** Calculate angle from difference between two slopes.

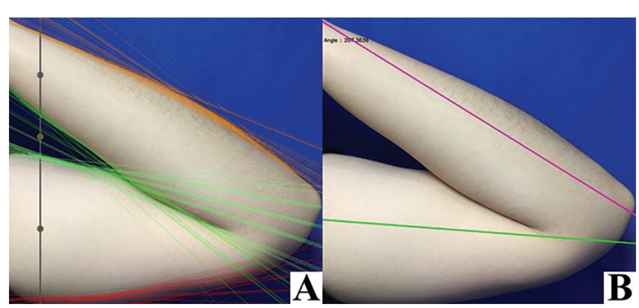

Figure 4. Angle calculation step for flexed elbow image. **(A)** Determine cutting point for classifying four reference lines. **(B)** Calculate angle from two slopes.

Extension angle

(1) Two scan lines, such as a left scan line and a right scan line, were determined. The first scan line was located in one-third distance of the dominate edge (right edge for the left hand and vice versa). The second scan line was a quarter from another edge (**Figure 3A**).
(2) For both scan lines, we found the cutting points for classifying lines into two groups on each side. The cutting points were determined by the middle point of the skin (calculated from the mask).
(3) Lines were partitioned into four groups: top left lines, top right lines, lower left lines, and lower right lines. Between the left edge and the middle point, the intersection of each line and the scan line was used to determine the upper left lines and the lower left lines. A similar method was applied between the right edge and the middle point to determine the upper right lines and the lower right lines.
(4) To calculate the angle, the average slopes between the upper lines and the lower lines were calculated. The angle was calculated from the difference between the two slopes (**Figure 3B**).

Flexion angle

(1) A scan line was determined by using a vertical line from 10% of the edge. Either the left edge or right edge was used based on the side of the elbow.
(2) The scan line was scanned to find the cutting points for classifying four lines. The top point was determined by the middle point of the forearm. The lower point was determined by the middle point of the arm. The middle point between the empty spaces in the middle was used to partition between the forearm and the arm (dots in **Figure 4A**).
(3) For each line, we determined whether the line was a part for the upper or lower line by calculating the intersection at the scan line. The intersection point was then partitioned into 4 groups based on the detection points in the second step: upper top lines, lower top lines, upper low lines, and lower low lines (colored lines in **Figure 4A**).
(4) For each group of lines, we found and averaged the slope. There were slopes.
(5) We used a slope from the upper top line as the top reference line. This line is likely to be aligned with the ulnar bone. We used an average between the 2 slopes from the lower top lines and lower low lines as a base line. The angle was calculated from the 2 slopes, such as top reference line and base line, using an arctan function (**Figure 4B**).

To validate our algorithm, we implemented our design using Python version 3.6. The imaging processing library is OpenCV [OpenCV] version 3.3. The outlier detection was based on local and outlier factor found in the Scikit-learn library version 0.19 [12].

Statistical analyses

Intra- and inter-rater reliability of all methods was computed using an intraclass correlation coefficient (ICC). The model for intrarater 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’ analytical models was “two-way random” and “absolute agreement.” Excellent agreement was determined by an ICC value >0.9, good agreement 0.75–0.90, and moderate agreement 0.50–0.90 [13]. Reliability test was conducted using IBM SPSS for Windows version 22.

The average of flexion and extension scores from both examiners and DIPT were used in the analysis. Total ROM value was the flexion angle minus the extension angle. Minimal clinical significance difference for elbow ROM was considered as 10°. Kolmogorov–Smirnov and Shapiro–Wilk tests were used to verify if variables were normally distributed. A paired Student’s *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) using the “blandr” package [14, 15]. DIPT measurement values that were <10° of difference were compared with the other 2 reference methods calculated in percentage.

Results

Thirty healthy volunteer participants joined this study. After inspecting all images, two participants were removed from final analysis because their elbows were not fully flexed. Ultimately, we used data from a total 56 elbows from 15 male and 13 female participants. The 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).

Intrarater ICC of goniometric and inclinometer in flexion and extension position showed excellent agreement between 0.953 and 0.994. Intrarater ICC of DIPT was 0.943 in extension and 0.886 in flexion. There was moderate-to-good inter-rater reliability of extension (E) and flexion (F) angle ICC between the two examiners, 0.862 (E) and 0.738 (F) for goniometer and 0.882 (E) and 0.784 (F) for inclinometer.

All variable groups, except extension position of inclinometer group ($P = 0.026$), were normally distributed. Mean extension and flexion angles as measured by DIPT were significantly greater than those measured by goniometry and inclinometry ($P < 0.05$), but total ROM was comparable with both reference methods (DIPT vs goniometer $P = 0.322$, DIPT vs inclinometer $P = 0.534$) (**Table 1**).

Normality of score differences in image analysis and the goniometer and inclinometer methods were assessed using a Shapiro–Wilk test. All methods demonstrated a normal distribution pattern ($P = 0.06$–0.39).

Bland–Altman analysis showed extension and flexion angle bias of the 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). Total ROM mean difference of DIPT–goniometer and DIPT–inclinometer was 0.94 (–0.95 to 2.84) and –0.63 (–2.64 to 1.38). Absolute maximal error of flexion and extension angles was 9.81°–11.17° and total ROM angle was 13.84°–15.99°. There were 80.4%–91.1% of DIPT values that were <10° of MCID compared with goniometer and 83.9–87.5% compared with inclinometer (**Table 2** and **Figures 5** and **6**).

Discussion

There are several advantages of using photography-based ROM measurement, especially in the era of telemedicine. Innovative methods to collect data remotely from a patient have been popularized in recent years. Physicians can assess their patients' function and make suggestion via Internet portal without having patients come to the clinic. Photography- 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 reference lines that may be difficult to locate in some cases (1, 4, 5, 7). The present study aimed to solve these observer-related problems using DIPT.

The present study has some limitations. First, DIPT protocol assesses only the active ROM. An examiner is needed

Table 1. Comparison measurement of digital image processing method with digital goniometer and digital inclinometer

Angle measurement	Digital image processing	Digital goniometer	Digital inclinometer
	Mean ± SD (range)	Mean ± SD (range)	Mean ± SD (range)
Extension	–2.01 ± 6.30 (–16.86 – 8.92)	–6.67 ± 3.48 (–11.83 – –0.28)	–6.74 ± 3.58 (–11.87 – –0.15)
Flexion	146.80 ± 5.20 (137.05 – 157.16)	141.28 ± 4.71 (129.98 – 148.80)	142.79 ± 6.58 (129.97 – 155.97)
Total ROM	148.81 ± 7.72 (135.89 – 164.70)	147.95 ± 6.89 (132.12 – 160.53)	149.55 ± 8.36 (131.63 – 167.27)

ROM, range of motion.

Table 2. Bland–Altman analytic results and percentage of DIPT measurement error within 10° compared with goniometer and inclinometer

Angle measurement	Mean of difference (95% CI)	Upper LOA (95% CI)	Lower LOA (95% CI)	Absolute maximal error[†]	Within 10° of error (%)
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

[†]Absolute maximal error = Mean – lower LOA.
CI, confidence interval; LOA, limit of agreement; ROM, range of motion.

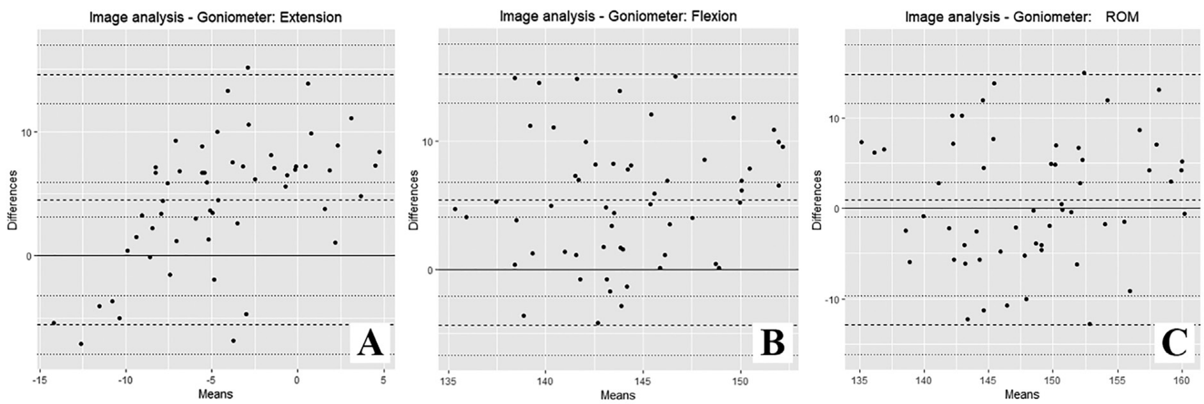

Figure 5. Bland–Altman plot of digital image analysis and goniometer. **(A)** Extension. **(B)** Flexion. **(C)** Elbow range of motion (ROM).

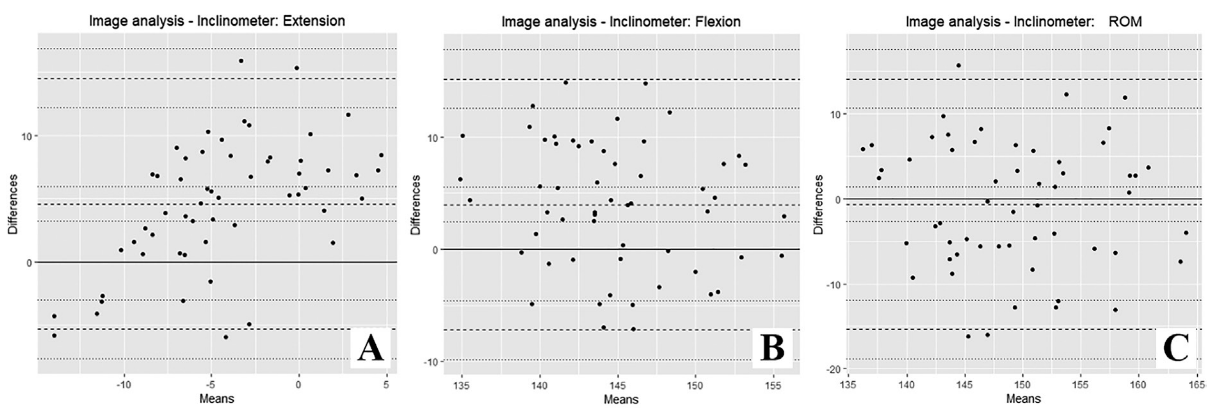

Figure 6. Bland–Altman plot of digital image analysis and inclinometer. **(A)** Extension. **(B):** Flexion. **(C):** Elbow range of motion (ROM).

to perform passive ROM measurement. Second, some participants may not produce their best effort, do not understand instructions clearly, and do not extend or flex their elbow fully. We needed to exclude four images from the analysis. Third, the extension rod as recommended by AMA was not available for digital inclinometer used in the current study.

DIPT measurement of flexion and extension had higher bias around 4°–5° than in the other methods. There are various explanations for this deviation. First is the difference in vertex location, and goniometer and inclinometer measurements begin with localizing lateral epicondyle as vertex of angle and then projecting its 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 intersected between these lines. Second, the dorsal surface of the forearm is thin and close to ulnar shaft alignment which affects distal reference line when calculating angle using DIPT. Also, vertex of goniometer and inclinometer angles lies anteriorly compared with ulnar bone shaft line. This is demonstrated from geometric illustration obtained using fluoroscopic images of the elbow which use similar DIPT protocol for drawing angle alignment (**Figures 7A** and **7B**). Another possible cause can be found from images review, and some participants minimally flexed instead of fully extended their elbows in extension image, probably because they used biceps muscle function to control shoulder joint in the abduction plane.

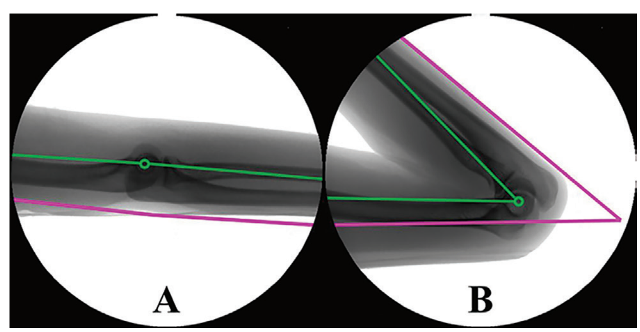

Figure 7. Conceptual illustration of systematic measurement bias between landmark-based method, goniometer and inclinometer, and contour-based DIPT. Green circles are lateral epicondyle location and green lines are imaginary lines of goniometer and inclinometer measurements. Pink lines are the result of using DIPT on fluoroscopic image. **(A)** Extension image. **(B)** Flexion image.

Table 3. The results of photography-based ROM of the elbow measurement from previous literatures compared with current study

Study	Elbows	Reference method	Mean difference (°)			95% LOA (°)			Within 10° (%)		
			Extension	Flexion	ROM	Extension	Flexion	ROM	Extension	Flexion	ROM
Blonna et al. [7]	50	DG	0	1		7–31	8–21				
Meislin et al. [1]	64	DG			0.2–0.3			8.3–9.5			95
Keijsers et al. [8]	80	DG	1	0							
Russo et al. [4]	20	MCA	4	11.7					16†	93	
Chanlalit and Kongmalai [5]	60	DG	2.6	2.1		7.8	13.4		98.3	85	
Current study (DG)	56	DG	4.5	5.5	0.9	10.1	9.81	13.8	91.1	82.1	80.4
Current study (DI)	56	DI	4.6	4.0	0.6	9.9	11.2	16	87.5	85.7	83.9

†Within 5°.

DI, digital inclinometer; DG, digital goniometer; LOA, limit of agreement; MCA, motion capture analysis; ROM, range of motion.

Total ROM had comparable result with reference methods, but had an absolute error >10° 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 measurements, 11 compared with goniometer and 9 compared with inclinometer, had difference >10°. These can be divided into 3 groups: group 1 denotes lower extension angle and higher flexion angle; group 2 denotes higher extension angle and lower flexion angle; and group 3 denotes higher extension and flexion angles. There were 8, 7, and 5 measurements in group 1, group 2, and group 3, respectively. Of note, 15 of 20 measurements had higher value and more effect than lower value, and other 5 measurements had nearly equal effect between higher and lower values. This can be speculated that significant difference of total ROM between DIPT measurement and reference methods occurred because DIPT measurement tended to have higher value of either flexion or extension angle than goniometer and inclinometer measurements.

There are several studies using photograph for elbow arc of motion measurement with variety of methods (**Table 3**). Image capturing devices in literatures were either digital camera [4, 7, 8], or smartphone [1, 5]. Most reports except those reported by Russo et al. use lateral side of arm and forearm for measurement. Healthy volunteers were recruited in most studies, but Blonna et al. tested with patients and Russo et al. used cadaveric elbows. The accuracy of photography-based elbow ROM measurement among studies varied and also depended on observer's experience [7]. The mean differences of current study were comparable with previous literature; however, the error margins were higher.

There are some implementation problems of DIPT that should be concerned. First, the initial position for photographic images was 90° lateral abduction of shoulder, which was different from other standard methods, in which elbow joint lied beside torso in anatomical position. The reasons for modification are outline detection function that requires body lie on the monotonous background. For this reason, the 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. Second, 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. Third, in case of loss in the normal contour of arm or forearm from injury, morbid obesity, or other diseases in patients, this method may not give an accurate result. Finally, image should be cropped by the observer in the current protocol. Developing algorithm to detect anatomy and position of arm and forearm may help alleviate this burden.

Conclusions

This research developed an innovative method for measuring ROM from photograph of elbow. Elbow ROM measurement from current DIPT protocol had comparable result with goniometer and inclinometer, but it can be different from other two methods up to 15.99°. Further investigations and protocol adjustment are needed to increase the accuracy of the image analytic technique.

Author contributions. Both authors made substantial contributions to the conception, design of the study, and acquisition of the data, analyzed, and interpreted the data. CC drafted the manuscript and KP critically revised it. Both authors approved the final version submitted for publication and take responsibility for the statements made in the published article.

Acknowledgments. We would like to acknowledge our research team, especially our two physiotherapists Ms. Benchaporn Kotnarin and Ms. Nichapa Khumpaneid, and Dr. Peeranut Purngpiputtrakul for their contribution to this research. This research was supported by Ratchadapisek Fund, Chulalongkorn University.

Conflict of interest statement. Both authors have each completed and submitted an International Committee of Medical Journal Editors Uniform Disclosure Form for Potential Conflicts of Interest. Neither of the authors has any potential conflict of interest to disclose.

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