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Reliability and validity of pose estimation algorithm for measurement of knee range of motion after total knee arthroplasty

Y. Saiki,
T. Kabata,
T. Ojima,
Y. Kajino,
N. Kubo,
H. Tsuchiya

From Fukui General Hospital, Fukui, Japan

Aims

We aimed to assess the reliability and validity of OpenPose, a posture estimation algorithm, for measurement of knee range of motion after total knee arthroplasty (TKA), in comparison to radiography and goniometry.

Methods

In this prospective observational study, we analyzed 35 primary TKAs (24 patients) for knee osteoarthritis. We measured the knee angles in flexion and extension using OpenPose, radiography, and goniometry. We assessed the test-retest reliability of each method using intraclass correlation coefficient (1,1). We evaluated the ability to estimate other measurement values from the OpenPose value using linear regression analysis. We used intraclass correlation coefficients (2,1) and Bland–Altman analyses to evaluate the agreement and error between radiography and the other measurements.

Results

OpenPose had excellent test-retest reliability (intraclass correlation coefficient (1,1) = 1.000). The R^2 of all regression models indicated large correlations (0.747 to 0.927). In the flexion position, the intraclass correlation coefficients (2,1) of OpenPose indicated excellent agreement (0.953) with radiography. In the extension position, the intraclass correlation coefficients (2,1) indicated good agreement of OpenPose and radiography (0.815) and moderate agreement of goniometry with radiography (0.593). OpenPose had no systematic error in the flexion position, and a 2.3° fixed error in the extension position, compared to radiography.

Conclusion

OpenPose is a reliable and valid tool for measuring flexion and extension positions after TKA. It has better accuracy than goniometry, especially in the extension position. Accurate measurement values can be obtained with low error, high reproducibility, and no contact, independent of the examiner's skills.

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Keywords: Pose estimation, Reliability, Validity, Knee range of motion, Total knee arthroplasty

Article focus

- This article focuses on the reliability and validity of OpenPose, a posture estimation algorithm, for measurement of knee range of motion after total knee arthroplasty (TKA), in comparison to radiography and goniometry.

Key messages

- OpenPose measurement has perfect test-retest reliability (intraclass correlation coefficient (ICC) (1,1) = 1.000).
- OpenPose measurement has excellent agreement with radiography (ICC (2,1) =

Correspondence should be sent to Tamon Kabata; email: tamonkabata@yahoo.co.jp

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0.953 in the flexion position, 0.892 in the extension position).

- OpenPose measurements have smaller random and systematic errors than goniometry in the extension position.

Strengths and limitations

- This is the first study to compare the reliability and validity of OpenPose measurements with radiographs and goniometry in measuring knee joint range of motion after TKA.
- The reliability and validity of OpenPose needs to be validated in the knee before surgery to extend its applicability.
- Future clinical trials are needed to verify the reliability and validity in the mid- and deep-flexion positions.

Introduction

Knee range of motion (ROM) is one of the major clinical outcomes after total knee arthroplasty (TKA), and its measurement requires a method with high reliability and validity. Various methods of ROM measurement have been reported, including visual estimation,[1-3] goniometric measurement,[1-7] radiological imaging measurement,[1,2,4,5] optical motion capture,[8-12] and 2D/3D registration techniques.[13-16]

Edwards et al[1] had previously described the radiological value as the true ROM of the knee. Recently, the value obtained using the 2D/3D registration technique, which uses computer-assisted design models to reproduce the position of the femur and tibia from fluoroscopic images, was considered to be true ROM. However, these measurements may be challenging to perform owing to radiation exposure and the need for advanced analysis techniques. Therefore, in clinical practice, goniometry is performed. The reliability of goniometry has been widely reported.[3,4,6,7] The intraclass correlation coefficients (ICCs) for inter-rater reliability were good or excellent in the knee flexion position (0.88 to 0.93), but varied among reports in the knee extension position (0.21 to 0.93). Furthermore, the validity of goniometry as compared to that of radiography has been examined.[1,2,4,5] Edwards et al[1] reported that 22% of goniometric values differed by > 5° from radiography, indicating issues with validity. Consequently, extension ROM measurement may be unreliable. Therefore, developing a simple, inexpensive, non-invasive, and highly reliable ROM measurement tool will be effective in obtaining accurate data after TKA, which will be useful in determining surgical treatment and follow-up strategies.

Recently, OpenPose, an algorithm for estimating 2D human poses in images using deep learning, has been developed.[17,18] OpenPose can estimate body feature points from photographs and videos using a standard digital camera and does not require contact with the subject or the laboratory environment. This open-source software permits non-commercial use for free. Because of its ease of implementation, it is beginning to be applied to joint angle estimation in the field of motion analysis research.[9-11] Reports on healthy participants have shown that ICCs have moderate-to-excellent agreement for peak knee flexion angle during squatting and gait assessments.[9,10] Contrarily, the ICCs for peak knee extension angle showed poor to moderate agreement and they decreased with increasing gait speed. OpenPose is expected to be more reliable for static measurements than gait measurements. Furthermore, the reliability and validity of OpenPose have not been investigated in patients with joint diseases. Its reliability during static measurements may lead to the establishment of a new, simple, and inexpensive ROM measurement tool, in clinical practice. Furthermore, as OpenPose does not require patient contact, it can contribute to the development of telemedicine and telerehabilitation.

Therefore, this prospective study aimed to assess the reliability and validity of knee ROM measurement using OpenPose after TKA, by comparing it with radiography and goniometry. We hypothesized that OpenPose would be a highly reliable and valid ROM measurement tool.

Methods

Study design and patients. In this prospective study, we enrolled all consecutive patients with TKA for knee osteoarthritis (OA), between April and July 2021. The exclusion criterion was severe pain during knee motion (pain on visual analogue scale ≥ 5) as this may interfere with reproducible measurements. However, none of the cases met this exclusion criterion. In total, we assessed 35 consecutive TKAs (24 patients). All procedures were performed using a cruciate-retaining Persona knee system (Zimmer Biomet, USA) by a single surgeon (TO) at a single institution. This study was approved by our institutional review board, performed in accordance with the principles of the Declaration of Helsinki,[19] and protected the rights of the participants. All patients provided written informed consent.

We used GPower 3.1.9.2 to determine the appropriate sample size. For linear regression analyses, 25 participants were needed to obtain an effect size (f^2) > 0.35 with a 0.80 power and a 0.05 error level on a two-tailed test. Previous studies examining the reliability and validity of ROM measurements included 21 to 41 participants.[1-7] Therefore, our study analyzed 35 knees. We instructed the participants to wear the most appropriate size of trousers from three different sizes (small, medium, and large) of tight-fitting, plain trousers to prevent misinterpretation of OpenPose.

Data collection and procedures. Three weeks after TKA, we collected three types of knee ROM measurement data in the following order: imaging for radiography, OpenPose, and goniometry. We performed these series of measurements with the knees extended and then flexed. The heel and foot were supported to maintain the same knee position during these measurements.

For radiography, lateral radiographs of the knee joint were recorded in the extension and flexion positions by radiological technologists (see Acknowledgements) who were blinded to this study. The patients were supine on the radiograph table. The knee joint was placed at the maximum extension or flexion angle, without causing pain. The leg was in neutral rotation, and it was neither abducted nor adducted. The X-ray beam was perpendicular to the plane of the leg and at the level of the knee joint. The imaging area was the distal half of the femur and the proximal half of the tibia.

For OpenPose, we recorded 2D lateral red-green-blue (RGB) images of the knee using a digital camera, immediately after obtaining a radiological image by one rater (YS). The RGB images were recorded perpendicular to the plane of the leg and at the level of the knee joint such that the entire body fitted on the screen (Supplementary Material).

For goniometry, the first rater performed measurements twice using a handheld two-arm goniometer (International Standard Goniometer R-360-W; Tiger Co., Japan) with a 1° marking, immediately after obtaining a RGB image by one rater (YS). Goniometry was performed following the standard procedure, as previously reported.[1-3,5-7] We evaluated the ICC for inter-rater reliability for goniometry prior to this study. Three raters (YS, see Acknowledgements) measured the maximal knee extension and flexion ROM of 20 healthy people; the results' reliability (0.791 for extension and 0.954 for flexion) was confirmed to be comparable to that of previous reports.[3,6]

Data analysis and procedures. After data collection by the three methods of measurements, each datum was analyzed. For radiography, two raters (YS and NK) evaluated the knee extension and flexion ROM using the same images, twice, at one-week intervals. ROM was defined as the angle between the lines along the posterior cortex of the femur and tibia, on the radiological images (Figure 1).[1,5,20] The mean of two measurements was calculated. The data from rater D, who was blinded to the other measurements, were used as the representative value.

For OpenPose, one rater (A) estimated the feature points of each joint from the RGB image for one image in the flexion position and another in the extension position using OpenPose (version 1.7.0 GPU release) after a series of data acquisitions (Figure 2). The training data for OpenPose are photographic collections that capture moments of personal significance,[18] and these photographs tend to be recorded in an upright position. Therefore, to estimate the feature points more accurately, the images were converted such that the patient's head was positioned at the top of the screen, just before the joint estimation. The joint estimation resulted in output of the estimated coordinates of the hip, knee, and ankle joints. Based on the output, the first rater calculated the extension and flexion ROM. Joint estimation and ROM calculations were performed twice for the same image, and the mean value was compared with those of the other measurements. Supplementary Material shows the procedures for image pre-processing, OpenPose download, and joint angle measurement.

For goniometry, the average values measured by one rater (A) were compared with those of the other measurements. For all measurements, positive and negative values were considered to represent hyperextension and flexion contracture in extension ROM, respectively.

Statistical analysis. We evaluated the radiological measurement reliability of rater D by calculating the agreement between the radiological measurement data of rater A and D using ICC (2,1), which indicates inter-rater reliability. We evaluated the test-retest reliability of the three measurements using ICC (1,1), which indicates intra-rater reliability. The ICC values of < 0.5, 0.5 to 0.75, 0.75 to 0.9, and > 0.9 indicated poor, moderate, good, and excellent agreement, respectively.[21,22] We compared the OpenPose values with those of radiography to assess its validity. Further, we used the goniometric value to determine the extent of errors in the OpenPose measurement. We used linear regression analysis to evaluate the ability to estimate other measurement values from the OpenPose value. The R^2 values of 0.01 to 0.09, 0.09 to 0.25, and > 0.25 indicated small, medium, and large correlations, respectively.[10] Subsequently, we used ICCs (2,1) and Bland–Altman analysis to evaluate the agreement and errors between the measurements, respectively.[23,24] Furthermore, the effect of sex on OpenPose estimation errors, which is calculated by subtracting the OpenPose value from the radiological value, was analyzed using the Mann-Whitney U test. The relationship between OpenPose estimation errors and mean BMI was analyzed using Spearman's rank correlation. All statistical analyses were performed using the R software version 4.1.0 (R Foundation for Statistical Computing, Austria), with a significance level of $p < 0.05$.

Results

A total of 35 knees were analyzed (24 women, 11 men; mean age 73.0 years (standard deviation (SD) 6.1); mean BMI 25.6 kg/m^2 (SD 2.5)). The mean flexion ROMs were 89.3° (SD 13.6°), 90.0° (SD 13.6°), and 91.7° (SD 13.1°) for OpenPose, radiography, and goniometry, respectively, and the mean extension ROMs were -4.8° (SD 4.7°), -2.5° (4.6°), and -6.6° (4.1°), respectively. ICCs (2,1) between rater A and D indicated excellent agreement (0.977 for extension and 0.989 for flexion).

For the test-retest reliability, ICCs (1,1) in the flexion position were 1.000, 0.994, and 0.994 for OpenPose, radiography, and goniometry, respectively. ICCs (1,1) in the extension position were 1.000, 0.978, and 0.963 for OpenPose, radiography, and goniometry, respectively.

The regression models and ICCs (2,1) between radiography and the other two measurements are shown in Table I. The R^2 of all regression models indicated large correlations (0.709 to 0.927). In the flexion position, ICCs (2,1) of OpenPose indicated excellent agreement (0.953) with radiography and good agreement (0.892) with goniometry. The ICC (2,1) between goniometry and radiography indicated excellent agreement (0.956).

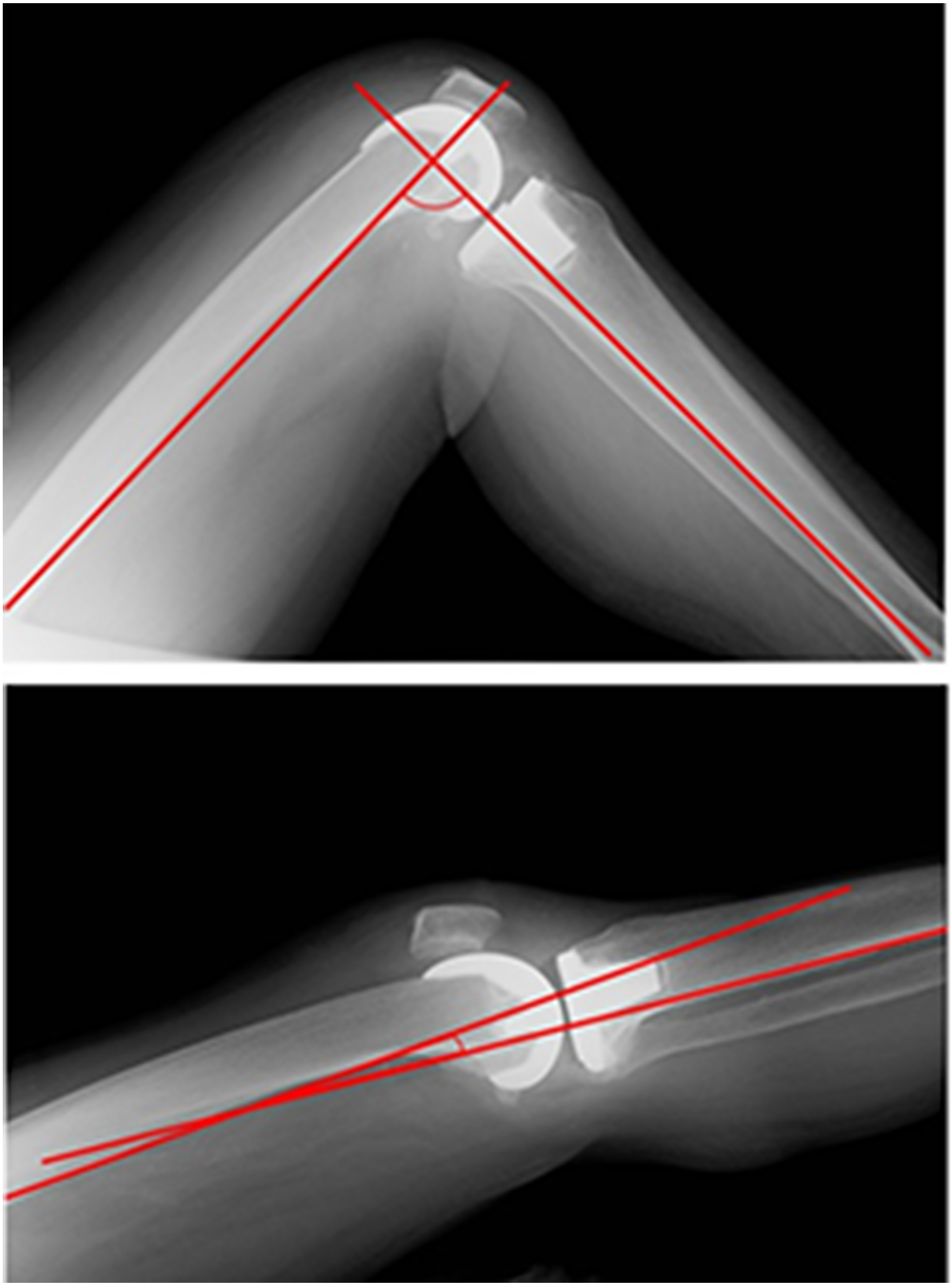

Fig. 1

Lateral radiograph of a 68-year-old female patient in 2021. Above: flexion position. Below: extension position.

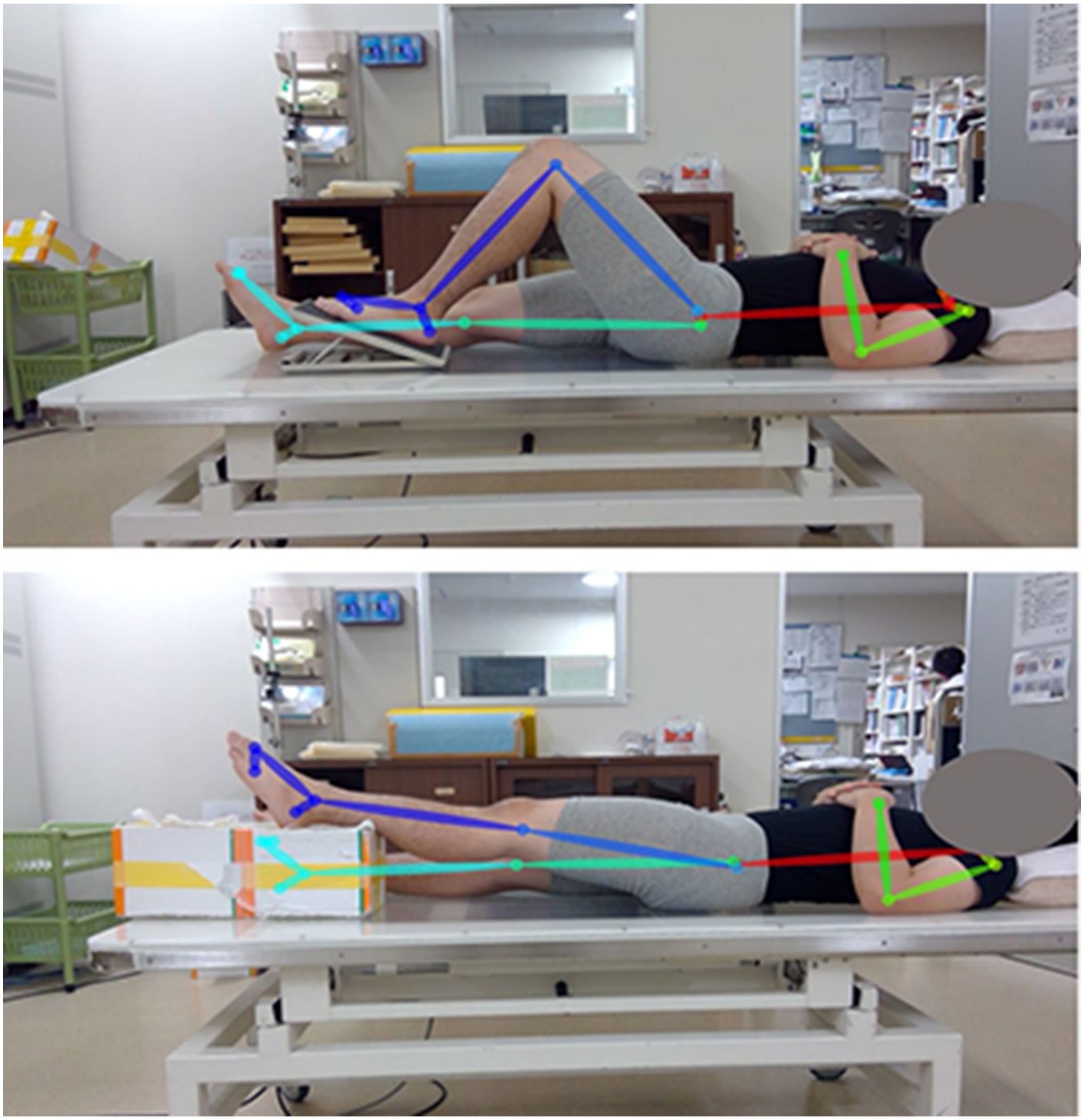

Fig. 2

Image after pose estimation by OpenPose. Above: flexion position. Below: extension position.

In the extension position, ICCs (2,1) of OpenPose indicated good agreement with radiography (0.815) and goniometry (0.768). The ICCs (2,1) between goniometry and radiography indicated moderate agreement (0.593). The Bland–Altman analysis for errors is shown in Table II, and Bland–Altman plots are shown in Figure 3. No significant difference was found in the OpenPose estimation errors between sex (flexion position: $p = 0.619$; extension position: $p = 0.534$, Mann-Whitney U test). Furthermore, no significant correlation was found between OpenPose estimation error and BMI (flexion position: $r = 0.252$, $p = 0.142$; extension position: $r = 0.056$, $p = 0.742$, Spearman's rank correlation).

Discussion

The main findings of our study were that OpenPose has perfect test-retest reliability and excellent agreement with radiography. Moreover, OpenPose measurement of extension ROM showed a higher ICC (2,1) and smaller 95% limits of agreement (LOA) than goniometry. The novelty of this study is that OpenPose measurement was shown to have better reliability and validity than goniometry.

In OpenPose, joint positions are estimated mechanically. Therefore, OpenPose may have perfect reproducibility for the same image. Herein, the ICCs (1,1) of

Table I. Regression models and intraclass correlation coefficients (2,1) between radiography and the other measurements.

Objective variable × Explanatory variables	Coefficients B	95% CI for B	R^2	ICCs (2,1)	95% CI for ICCs
Flexion					
Radiography × OpenPose	0.951	0.844 to 1.059	0.908	0.953	0.909 to 0.976
Radiography × goniometry	0.994	0.895 to 1.092	0.927	0.956	0.899 to 0.979
Extension					
Radiography × OpenPose	0.936	0.784 to 1.088	0.827	0.815	0.152 to 0.939
Radiography × goniometry	0.771	0.612 to 0.930	0.747	0.593	-0.088 to 0.865

CI, confidence interval; ICC, intraclass correlation coefficients; R^2, coefficient of determination.

Table II. Bland–Altman analysis between radiography and the other measurements.

			Fixed error	Proportional error		
Measurement	MD, °	LOA (lower to upper)	95% CI for MD	Coefficient B	95% CI for B	p-value
Flexion						
Radiography – OpenPose	0.681	16.381 (-7.510 to 8.871)	-0.755 to 2.116	-0.001	-0.112 to 0.109	0.979
Radiography – goniometry	-1.711	14.359 (-8.891 to 5.468)	-2.970 to -0.453*	0.033	-0.068 to 0.134	0.116
Extension						
Radiography – OpenPose	2.251	7.765 (-1.632 to 6.133)	1.570 to 2.931*	-0.031	-0.185 to 0.124	0.690
Radiography – goniometry	4.113	9.033 (-0.404 to 8.629)	3.321 to 4.904*	0.122	-0.069 to 0.312	0.203

*Indicates that there was a fixed error.
CI, confidence intervals; LOA, 95% limits of agreement; MD, mean difference.

OpenPose were perfect, and OpenPose indicated a higher test-retest reliability than other measurements.

In the flexion ROM, the results of the regression analysis and ICCs (2,1) suggested that radiography has large correlations and excellent agreements with OpenPose, indicating its high validity. OpenPose had no systematic errors with radiography, indicating that it is a valid ROM measurement tool that can be used without an offset for a systematic error. We observed a fixed error between radiography and goniometry, indicating that goniometry may be overestimated by an average of 1.7°, as compared to radiography. Previous studies have also reported an error of 0.6° to 6.0° between radiography and goniometry.[1,2,25] Therefore, OpenPose is comparable to goniometry in terms of validity. For clinical use, it is important to examine the acceptable range of random errors using LOA. When we calculated the LOA between radiography and goniometry using data obtained from previous reports, it was 10.2° according to Edwards et al[1] and 35.2° according to Lavernia et al.[5] The 16.4° LOA of OpenPose in our study was comparable to these values of goniometry against radiography. Thus, OpenPose can be compared to goniometry in terms of reliability.

In the extension ROM, the results of the regression analysis and ICCs (2,1) revealed that OpenPose has large correlations and good agreements, indicating its validity. The ICC of 0.815 for OpenPose measurement in the present study is higher than the ICC of 0.234 to 0.507 for gait measurement in a previous study.[10] It is easier to control the positional relationship of the camera and the knee joint, which may be the reason for the higher ICC of static measurement than that of the gait measurement. Therefore, a static measurement may provide a more accurate 2D image than gait measurement. However, OpenPose and goniometry had a fixed error relative to radiography and underestimated the extension ROM by an average of 2.3° and 4.1°, respectively. Previous studies have reported that goniometry may have underestimated the extension ROM by approximately 3.8° to 6.8° compared to radiography.[25,26] The OpenPose fixed error in our study was slightly smaller than the goniometric measurement errors in our study and previous studies. Hence, OpenPose can have higher validity than goniometry. This fixed error could be due to a radiological measurement error or an OpenPose estimation error. The mechanical axis of the femur in the sagittal plane was 0.5° (SD 2.3°) in extension as compared to the anatomical axis, and studies have reported that older women tend to have an increased femoral anterior bowing[27,28] In our study, half of the femur was X-rayed, which reduced the radiological measurement errors due to the extra-articular deformities. Moreover, OpenPose joint estimation uses models trained on numerous images to predict a confidence map of each joint at each pixel in the 2D image.[18] OpenPose takes the maximum of the confidence maps to distinguish the accuracy of peaks in proximity, and the pixel with the maximum value is considered the joint centre. Therefore, joint estimation errors may occur more frequently for the hip joint, where there is more surrounding soft-tissue, than for the knee and ankle joints. In the future, we will be able to improve the estimation accuracy by identifying which joints have more errors and the causes of those errors. In our study, the LOA of OpenPose was 7.8°, which was comparable to 9.0° of goniometry against radiography. OpenPose measurements could be more reliable because there

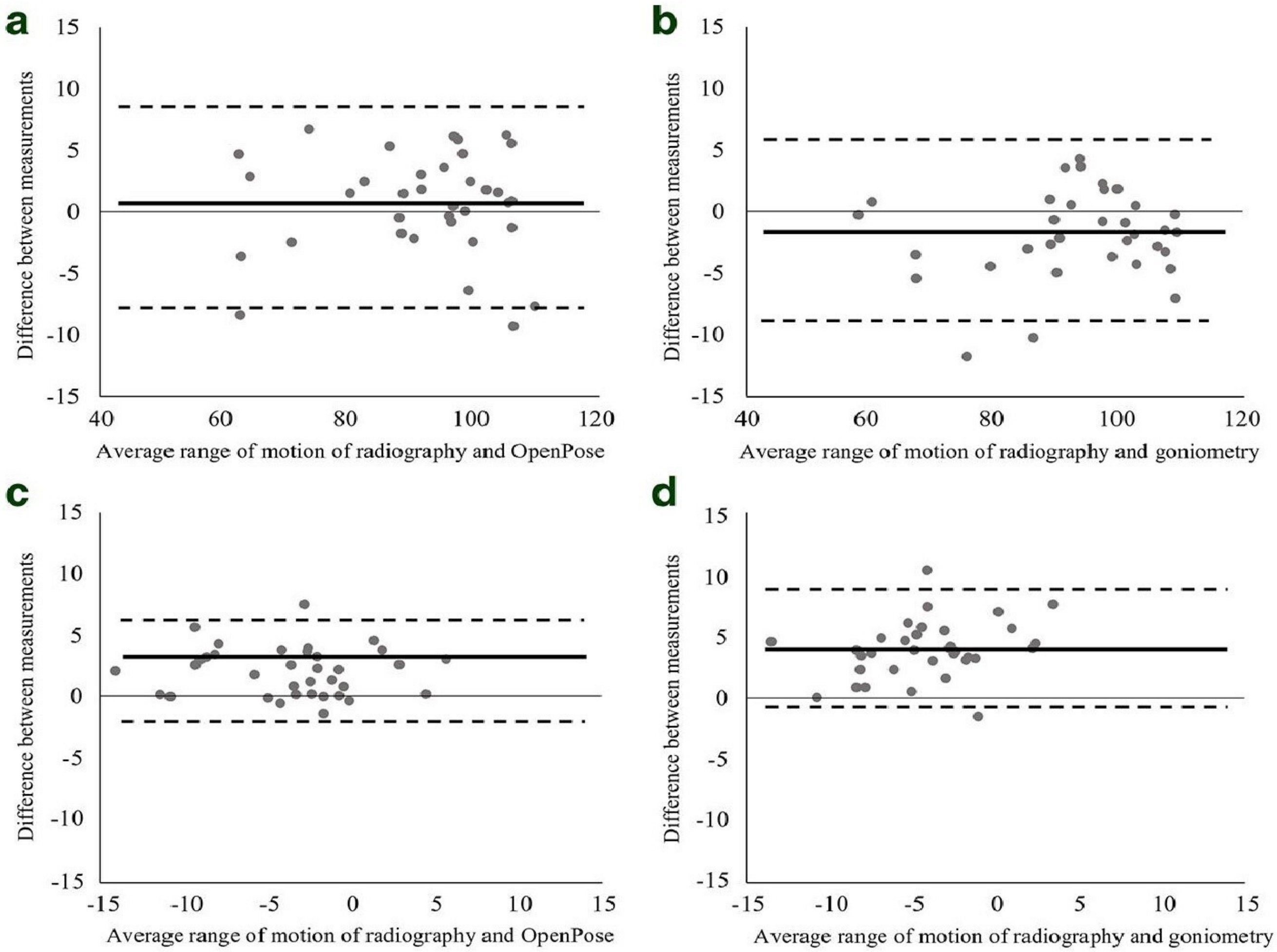

Fig. 3

Bland–Altman plots for a) radiography and OpenPose in flexion range of motion (ROM); b) goniometry and radiography in flexion ROM; c) radiography and OpenPose in extension ROM; and d) goniometry and radiography in extension ROM. The figure shows the mean difference between measurements (solid line at the centre) and the limits of agreement (dashed outer lines correspond to ± 1.96 × standard deviation of the mean difference between measurements).

is no misrecognition of landmarks as in case of manual goniometry.

This study has several limitations. First, it only included TKA knees because OA knees have a valgus or varus deformity that makes it difficult to accurately capture 2D lateral images of the knee. To expand the applicability of OpenPose in the future, validation in OA knees is necessary. Second, it is impossible to perform radiography, goniometry, and 2D imaging simultaneously. Therefore, the same knee joint angle was maintained by using the support during the three measurements. Furthermore, we ensured that the lower limb did not move during these measurements. Third, the three measurements were not in random order. Radiological ROM data were obtained by a second rater, who was blinded to the other measurements. Since OpenPose measurement is performed mechanically, no information bias can be introduced. Therefore, we believe that bias is unlikely to be introduced by the order of measurement. Fourth, we did not verify the estimation accuracy in the mid- or deep-flexion position. Ota et al[10] reported moderate agreement between OpenPose and a 3D motion capture in a knee mid-flexion angle during gait. During static ROM measurements, OpenPose may have an even higher validity than that reported. In future research, the accuracy should be verified in the mid- and deep-flexion positions.

In conclusion, OpenPose is a reliable and valid tool for measuring knee ROM after TKA. The accuracy of OpenPose is comparable to goniometry for measuring knee flexion ROM and more reliable and valid than goniometry for measuring extension ROM. OpenPose has the potential to be an alternative to goniometry or a tool that compensates for its unreliability.

Supplementary material

OpenPose installation and analysis procedure.

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Author information:
- Y. Saiki, PT, MSc, Physical Therapist, Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kanazawa University, Kanazawa, Japan; Department of Rehabilitation Physical Therapy, Faculty of Health Science, Fukui Health Science University, Fukui, Japan.
- T. Kabata, MD, PhD, Orthopaedic Surgeon
- Y. Kajino, MD, PhD, Orthopaedic Surgeon
- H. Tsuchiya, MD, PhD, Orthopaedic Surgeon
  Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kanazawa University, Kanazawa, Japan.
- T. Ojima, MD, PhD, Orthopaedic Surgeon, Department of Orthopaedic Surgery, Fukui General Hospital, Fukui, Japan.
- N. Kubo, PT, MSc, Physical Therapist, Department of Rehabilitation Physical Therapy, Fukui General Hospital, Fukui, Japan.

Author contributions:
- Y. Saiki: Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing.
- T. Kabata: Conceptualization, Project administration, Supervision, Writing – review & editing.
- T. Ojima: Project administration, Supervision.
- Y. Kajino: Methodology, Supervision, Writing – review & editing.
- N. Kubo: Data curation, Validation.
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- The data that support the findings for this study are available to other researchers from the corresponding author upon reasonable request.

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- This study was approved by the appropriate ethics review board (Nittutaduka ethics review committee, Number; 2021-1).

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