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Hellstén, T., Arokoski, J., Karlsson, J., Ristolainen, L., & Kettunen, J. (2025) Reliability and validity of computer vision-based markerless human pose estimation for measuring hip and knee range of motion. *Healthc. Technol. Lett.* 12(1) e70002.

DOI: <https://doi.org/10.1049/htl2.70002>

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LETTER

Reliability and validity of computer vision-based markerless human pose estimation for measuring hip and knee range of motion

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Funding information

Fonden för teknisk undervisning & forskning, Grant/Award Number: 1580; Ministry of Social Affairs and Health in Finland, Grant/Award Number: A2500/502

Abstract

Telerehabilitation requires accurate joint range of motion (ROM) measurement methods. The aim of this study was to evaluate the reliability and validity of a computer vision (CV)-based markerless human pose estimation (HPE) application measuring active hip and knee ROMs. For this study, the joint ROM of 30 healthy young adults (10 females, 20 males) aged 20–33 years (mean: 22.9 years) was measured, and test–retests were assessed for reliability. For validity evaluation, the CV-based markerless HPE application used in this study was compared with an identical reference picture frame. The intraclass correlation coefficient (ICC) for the CV-based markerless HPE application was 0.93 for active hip inner rotation, 0.83 for outer rotation, 0.82 for flexion, 0.82 for extension, and 0.74 for knee flexion. Correlations (r) of the two measurement methods were 0.99 for hip-active inner rotation, 0.98 for outer rotation, 0.87 for flexion, 0.85 for extension, and 0.90 for knee flexion. This study highlights the potential of a CV-based markerless HPE application as a reliable and valid tool for measuring hip and knee joint ROM. It could offer an accessible solution for telerehabilitation, enabling ROM monitoring.

1 | INTRODUCTION

For professionals in the healthcare sector, measuring joint range of motion (ROM) is vital in daily practice for the assessment and treatment of joint disorders [1]. Such measurement provides objective information about factors influencing the functioning of the joints and helps in assessing a patient's ability to perform daily activities, such as walking, running, or lifting [2], establish goals, and follow up on the progress of their treatment [3]. Therefore, information about joint ROM must be accurate [4]. Restriction or excessive joint ROM can be indicative of various disorders, such as osteoarthritis [5], joint deformities [6], or ligament injuries [7].

Different methods can be used to measure joint ROM. Universal goniometry is the most commonly used method by healthcare professionals [8] and it has been reported to be very close to the golden standard (radiographic image) in measuring ROM in the knee joint [9, 10]. A goniometer is accessible, low-cost, portable, and user-friendly; however, it requires the use of both hands by professionals, making it challenging to stabilize other body segments while measuring ROM [11]. Other methods commonly used by healthcare professionals to assess ROM are different inclinometers [11, 12], digital goniometers [4] and visual estimation [13]. Inclinometers are reliable for measuring certain joint angles, demonstrating good inter-rater reliability; however, accurate and consistent positioning at the zero point

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is crucial to avoid measurement errors [14]. Visual estimation is quick, easy to use, and shows strong agreement with universal goniometer measurements when performed by an experienced healthcare professional [13]. The choice of method for measuring ROM depends on the joint being assessed and the availability of equipment [4], highlighting the need for novel approaches to overcome existing limitations.

The use of telerehabilitation (TR) by healthcare organizations has increased in the last few years [15–17]. TR promotes equality by offering easier access to healthcare to people who live, for example, in rural areas, by reducing travel and waiting times [18, 19]. TR can be a more cost-effective method than clinical methods, and it provides opportunities for regular joint and posture assessments [20], offering important information and feedback about patients' progress in treatment [21, 22]. According to some evidence, assessment that requires hands-on interaction, such as specific measures such as ROMs is demanding to perform accurately with TR methods [23]. However, it has been discussed that developing TR assessment methods is important and seems to be feasible [20, 24].

A potential and novel method of implementing assessment in TR is computer vision (CV)-based markerless human pose estimation (HPE) [20, 25], as the only technical equipment a patient needs in this method is a computing device (computer, tablet, smartphone) with an integrated camera. For tracking and analysing human motion, CV has been a significant and highly regarded research topic for several years [26]. To achieve accurate joint ROM measurements with CV-based markerless HPE, joints must be accurately localized. Dense human pose estimation (DensePose) has become a promising technique for CV-based markerless HPE joint ROM measurement due to its ease of use and accuracy. DensePose focuses on human anatomy, and the technique is designed to map two-dimensional (2D) human images onto the three-dimensional (3D) surface of the human body [27]. However, DensePose technique remains challenging on different background, hidden views, scale variations, and postural diversity [28]. Usually, CV-based HPE motion analyses use marker-based approaches that require the installation of reflective material on certain key points of the body, such as hip, knee, or shoulder joints. This limitation makes routine use of motion analysis systems impractical, as they require significant technical preparations prior to analysing motion. A 3D CV system such as Vicon has been used as the golden standard in the field of CV [29]; however, precisely calibrated equipment with several cameras requires high costs. Human motion analysis could also benefit from novel approaches, such as metaheuristic optimization methods [30], which can enhance the modelling and interpretation of complex motion patterns. Additionally, more traditional movement intensity data from accelerometers [31] can provide valuable insights, complementing advanced computational methods by offering direct measurements of motion dynamics. Nevertheless, they often require additional wearable equipment, which can make their use less practical compared to CV-based markerless HPE, where users can leverage devices they already own.

In continuation of the previous article of the researchers of this study about the potential use of CV-based markerless HPE

in rehabilitation [24], this study took place. The aim was to evaluate the reliability and validity of a CV-based markerless HPE (DensePose) application for measuring active hip flexion, extension, inner and outer rotation, and knee flexion. In this study, reliability was defined as the consistency of measurements across repeated CV-based markerless HPE tests, while validity referred to the agreement between measurements obtained by the CV-based markerless HPE application and a reference picture. The hypothesis for this study was that a CV-based markerless HPE is a reliable and valid method for measuring active hip and knee joint ROM.

2 | MATERIALS AND METHODS

2.1 | Study design

This is a methodological study to evaluate the reliability and validity of a CV-based markerless HPE application built on DensePose for measuring active hip flexion, extension, inner and outer rotation, and knee flexion (Figure 1.). Written consent was obtained from all the voluntary participants before conducting the study, and they were informed that the current protocol had been approved by the research ethics committee of the Faculty of Medicine at the University of Helsinki (no. 1/2023). The measurements were performed twice, with an interval of 24 h, to evaluate the reliability of the CV-based markerless HPE application. Validity was evaluated by comparing joint angles between the CV-based markerless HPE application (automatically measured joint angle) and an identical reference picture frame (manually measured joint angle) (Figure 2). The study was conducted and evaluated according to the Consensus-based Standards for the selection of health Measurement Instruments (COSMIN) [32] pathway and reported according to principals of Strengthening the Reporting of Observational Studies (STROBE) Statement [33].

2.2 | Participants

An information letter was mailed to students and personnel from Arcada University of Applied Sciences, Helsinki, in April 2023. Inclusion criteria were: healthy voluntary participants, who were 18 years of age or older, understood Swedish to follow the instructions, and were able to walk without any aid. Exclusion criteria were as follows: individuals having symptoms or pain in the lower limbs or lower back and who had required a visit to a physician in the last month before the study or diagnosis of neurological disease. Finally, 30 voluntary participants were recruited. The study participants ($N = 30$) were healthy young adults (10 females, 20 males) aged between 20 and 33 years (mean: 22.9 years), as shown in Table 1.

2.3 | CV-based markerless HPE

Based on our literature review and technical testing, a CV-based markerless HPE application using a single camera was

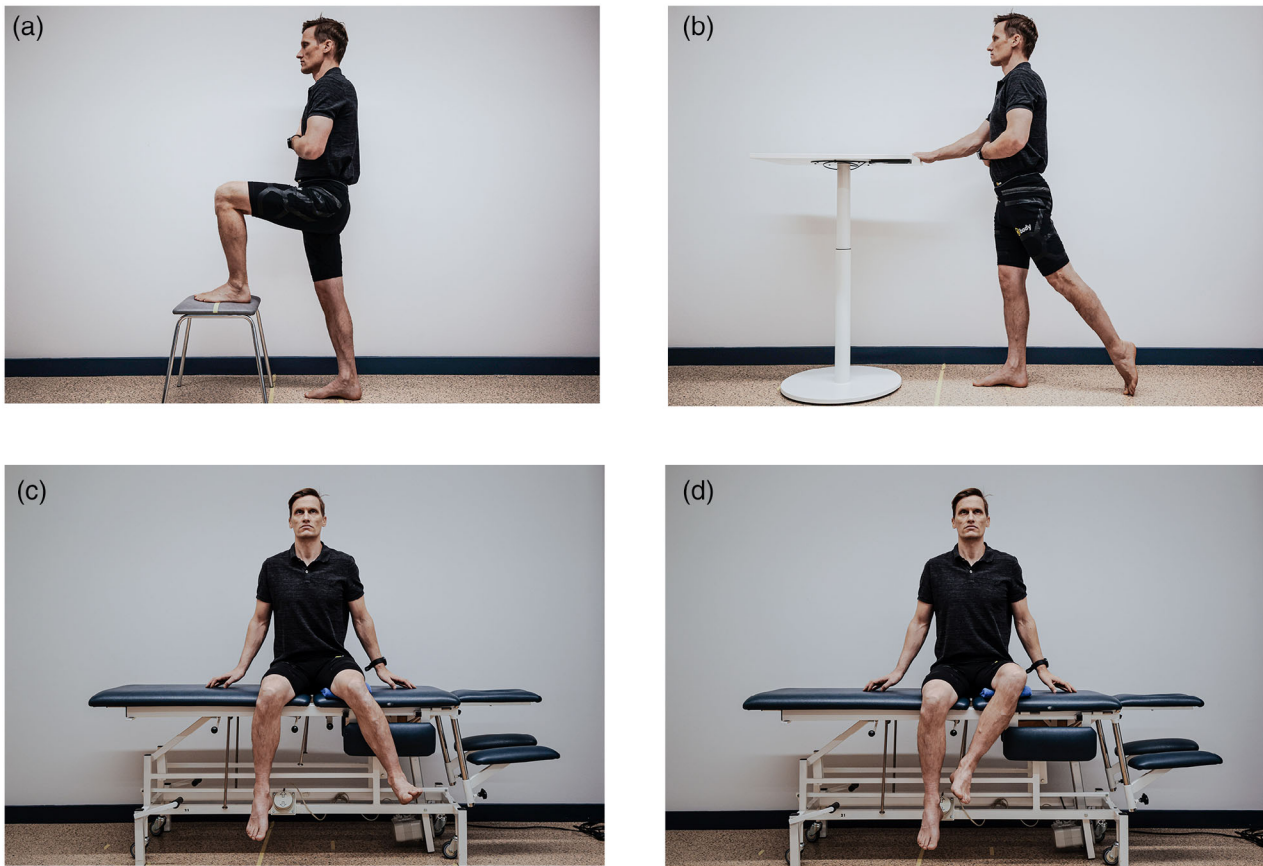


FIGURE 1 Measurement protocol: (a) Active flexion of hip and knee joint; (b) active extension of hip joint; (c) active inner- and (d) outer rotation of hip joint.

TABLE 1 Characteristics of the study participants.

Participants (<i>n</i>)	Age, years; mean (SD)	Length (cm); mean (SD)	Weight (kg); mean (SD)	BMI; mean (SD)
Total (30)	22.9 (2.8)	177.5 (10.6)	77.3 (14.1)	24.4 (2.9)
Female (10)	22.9 (3.8)	165.8 (3.7)	66.2 (9.2)	24.1 (4.0)
Male (20)	22.9 (2.2)	183.3 (7.6)	82.9 (12.8)	25.6 (2.7)

Note: *n*, number of participants; SD: standard deviation; cm, centimeter; kg, kilogram; BMI, body mass index (kg/m^2).

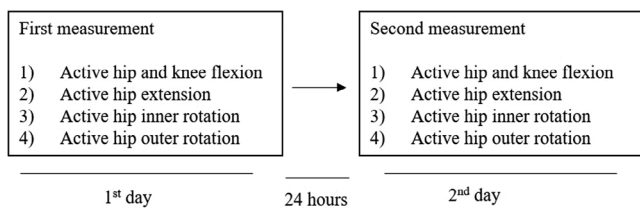


FIGURE 2 Study design, one participant was measured two times with an interval of 24 h. Joint angles were registered from the CV-based markerless HPE application and an identical reference picture frame.

developed for this study based on a human pose estimation system called DensePose [24, 27]. DensePose uses a region-based convolutional neural network (R-CNN) to map all pixels of a red, green, and blue (RGB) colour model image associated with a human to a 3D surface of the human body. Based on these 2D

to 3D mappings, known as dense correspondences, the posture of the person is estimated. DensePose is trained on a large-scale ground-truth dataset called DensePoseCOCO [27], with manually annotated correspondences of 2D images to 3D surfaces on 50,000 images. DensePose takes one image as an input and, in addition to the dense correspondences, produces an output image marked with the 2D coordinates of key points of the human body, including the ankle, knee, hip, and shoulder joints.

To measure hip flexion and extension, the pixel coordinates of the knee, hip, and shoulder joints were first used to form a triangle. The angle α between the hip-knee line and the hip-shoulder line was then calculated by applying the law of cosines. Finally, the hip flexion and extension angle were calculated as $\beta = 180 - \alpha$. The key points and angles of interest for measuring hip flexion and extension are shown in Figure 3.

The knee angle was measured in a similar way to the hip, although in this case, the hip, knee, and ankle key points were

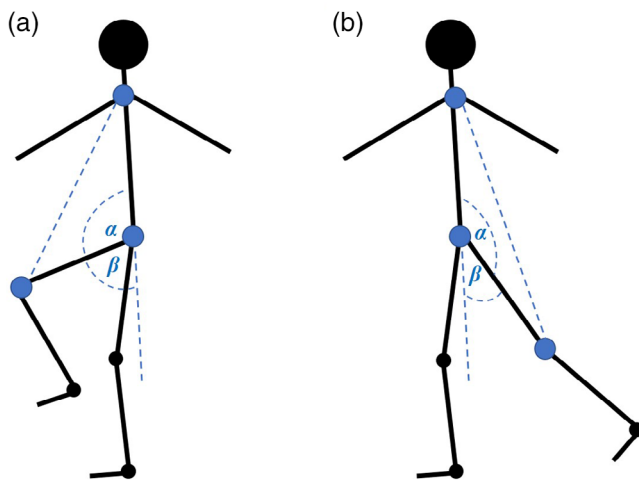


FIGURE 3 Key points and angles of interest for measuring hip (a) flexion and (b) extension. The angle is calculated as $\beta = 180 - \alpha$. Blue dots show key points from a lateral view, the middle of the knee joint, hip joint, and shoulder joint.

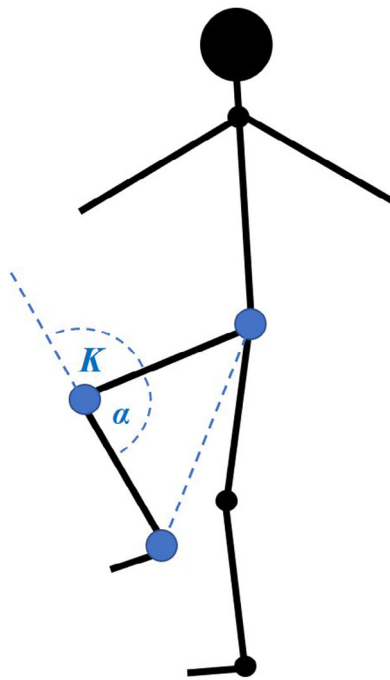


FIGURE 4 Key points and angles of interest for measuring knee range of motion. The angle is calculated as $\beta = 180 - \alpha$. Blue dots show key points from a lateral view: the middle of the ankle joint, knee joint, and hip joint.

used to formulate a triangle, and α was the angle between the hip–knee and knee–ankle lines (Figure 4).

To measure the inner and outer hip rotation angle θ , it was ensured that the camera was in a horizontal position. The application then captured the pixel coordinates of the knee and ankle joints for each frame. From the knee and ankle joints and the vertical pixel line from the knee joint downward, a right-angle triangle was formed. Finally, the rotation angle θ was calculated using trigonometrical functions. The key points and angle of

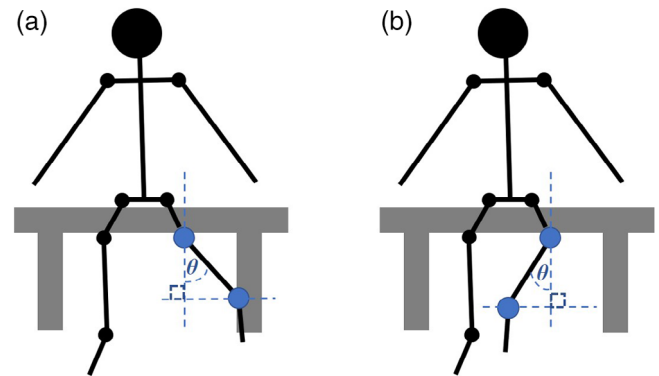


FIGURE 5 Key points and angles of interest for measuring hip (a) inner and (b) outer rotation. Angle θ is calculated using trigonometrical functions. Blue dots show key points from the frontal view, the middle of the ankle joint, and the knee joint.

interest observed while measuring hip inner and outer rotation are shown in Figure 5.

When running the CV-based markerless HPE application, the joints and the hip flexion, extension, rotation, and knee flexion angles were shown frame by frame on the screen in real-time. A save button was included, allowing the user to save the measured hip and knee angle to a log file at any given time, along with the video output frame on which the CV-based markerless HPE application measured the angles. These output frames were used as reference pictures when analysing the validity of the hip and knee ROM measurements. During the tests, the positions of the computer, web camera, and participants were standardized. The measurement values were expressed in whole degrees. The computer used was Acer Nitro 5 with an integrated webcam (720p resolution and 30 frames per second sampling). The test setup is shown in Figure 6.

2.4 | Reference picture

Each reference picture generated as a result of pressing the Save button in the CV-based markerless HPE application was a direct output from the web camera. The key points detected by the CV-based markerless HPE application were not visible in the reference picture. To calculate active hip flexion and extension, markers were manually drawn on the reference picture as accurately as possible by an experienced physiotherapist on the left greater trochanter of the femur, lateral epicondyle of the femur, and middle of the humeral head. To calculate active inner and outer rotation in the hip joint, markers were drawn on the reference picture at the midpoint of the patella and the centre of the talocrural articular space. To calculate active flexion in the knee joint, markers were drawn on the greater trochanter of the femur, lateral epicondyle of the femur, and lateral malleolus of the fibula. Lines were drawn between markers to calculate the joint angles, as seen in Figure 7. Marker points were based on bony landmarks used when using a universal goniometer in physiotherapy [34]. The measurement values were given in degrees, with intervals of 1° .



FIGURE 6 Photograph of (a) test setup when a participant performs active hip flexion and (b) computer screen view of our CV-based markerless HPE application.

2.5 | Procedure

Before testing, the participants' demographic data, weight, and length were measured, and body mass index ($BMI = \text{weight in kilograms divided by height in meters squared, kg/m}^2$) was calculated. Environmental influences were standardized by taking the measurements in the same room, with the same light, temperature, position of computer, and web camera at a height of 55 cm and distance of 2.05 m from the participant (Figure 6). Reliability was measured through a test–retest procedure by the same test leader (24 h between the tests), and validity was tested with measurements during the first measurement with the CV-based markerless HPE application and the reference picture (video output frame). The measurements were conducted on all 30 participants by two well-trained, nearly graduated physiotherapist students on the left hip and knee joint in a standardized order: active flexion in the hip and knee joint, active extension in the hip joint, and active inner and outer rotation in the hip joint. No warm-up period was included before testing. To become familiar with the test procedure, the instructions were read from a test manual and showed by the test leader (physiotherapist student). Test manual can be seen in Appendix. All measurements were recorded in a blinded manner, and the CV-based markerless HPE application joint angle was saved to a log file with a time stamp and kept secret until the reference picture angle was calculated. All results were then saved in one file.

2.6 | Statistical analysis

Descriptive statistics for each group were analysed and reported in the results, with their mean and standard deviation (SD). Test–retest reliability was evaluated with the intraclass correlation coefficient (ICC) with a two-way random effect model and 95% confidence interval (CI), using the first and second CV-based markerless HPE application measurements. ICC values were classified by Landis & Koch (1997) as follows: 1.00–0.81 as almost perfect, 0.80–0.61 as substantial, 0.60–0.41 as moderate, 0.40–0.21 as fair, and 0.20–0 as slight [35]. The standard error of measurement (SEM) was calculated using the formula $SEM =$

$S \times \sqrt{1 - ICC}$ for absolute reliability, where S = the SD of first and second CV-based markerless HPE application measurement scores. Thereafter, the minimal detectable change (MDC) was calculated using the formula $MDC = SEM \times \sqrt{2} \times 1.96$ [36].

Validity was established with Pearson's correlation analysis to compute the correlation between the CV-based markerless HPE application and the reference picture (first measurement), and the Bland–Altman plot analysis was used to estimate the agreement between the two methods [37]. For correlation analysis, the following classification was used: 1.00–0.90 as very strong, 0.89–0.70 as strong, 0.69–0.50 as moderate, 0.49–0.30 as weak, and 0.29–0 as very weak [38]. Statistical analysis was performed using SPSS software (IBM Corp. Released 2022; IBM SPSS Statistics for Windows, Version 29.0. Armonk, NY: IBM Corp.) and Microsoft Excel Ver. 19.

3 | RESULTS

The results showed almost perfect reliability for the CV-based markerless HPE application in all movement directions in the hip joint (active flexion, active extension, active inner rotation, and active outer rotation), and the ICC values ranged from 0.93 to 0.82 in the hip joint. The highest ICC values were seen in active hip inner rotation ($ICC = 0.93$) and the lowest in active knee flexion ($ICC = 0.74$). Slightly low values were seen for SEM, and the values ranged from 0.6 (for active hip inner rotation) to 1.0 (for active knee flexion). The lowest MDC value was 1.6 for active hip inner rotation, and the highest was 3.2 for active hip outer rotation. More detailed results can be seen in Table 2.

The correlation (Person's r value) between the CV-based markerless HPE application and the reference picture ranged from 0.99 to 0.85 and was very strong in three out of five directions. The correlation was highest in active hip inner rotation and lowest in active hip extension (Figure 8). The mean difference (degrees) between the two methods was lowest in active hip inner rotation (-0.9°), with one outlier outside the limits of agreement. The highest mean difference (-2.1°) was in active

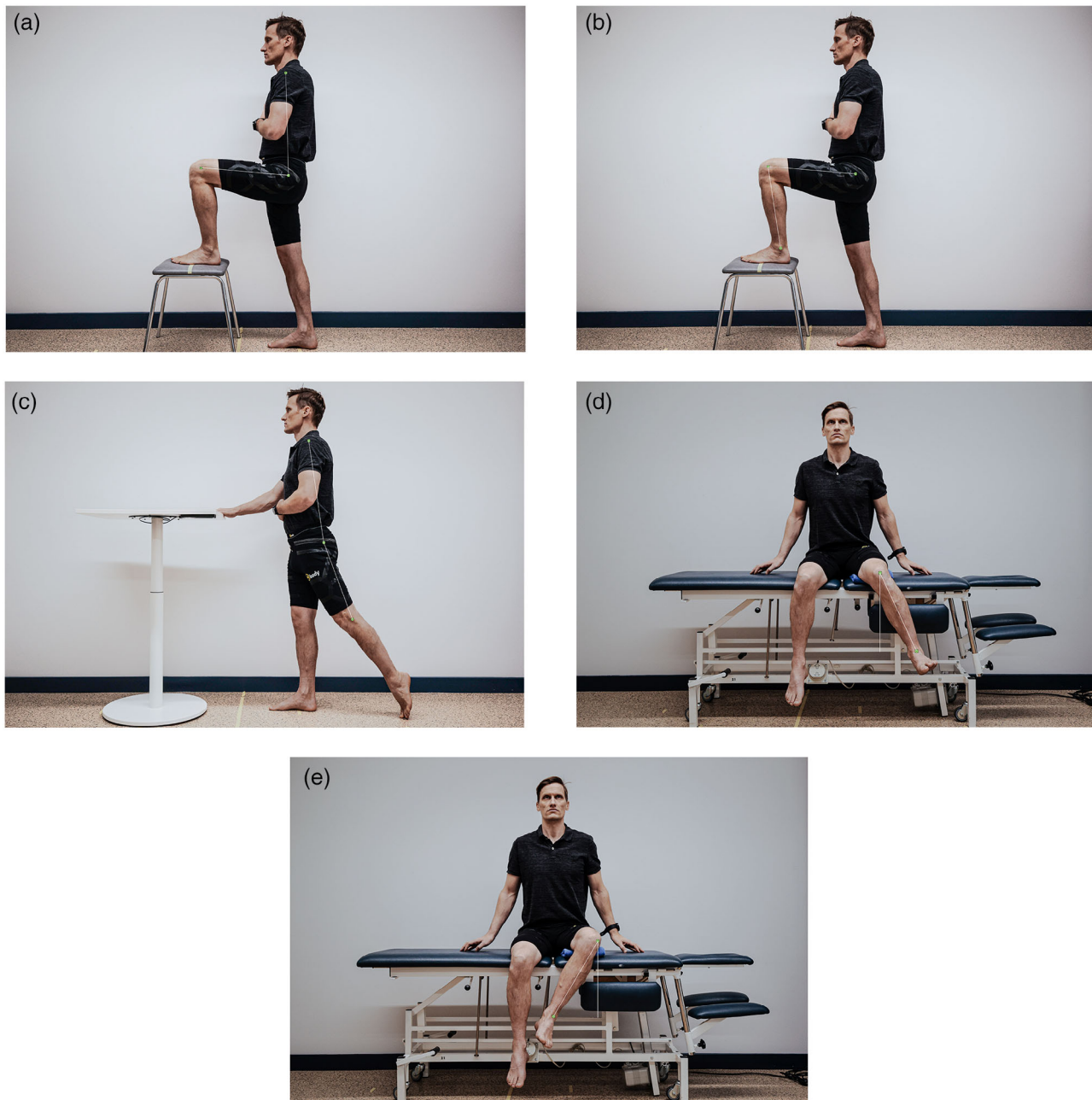


FIGURE 7 Reference picture with manually drawn markers for (a) active flexion of hip, (b) active flexion of knee joint, (c) active extension of hip joint, (d) active inner- and (e) outer rotation of hip joint.

knee flexion, with one outlier outside the limits of agreement. Detailed results are illustrated in Figure 9.

4 | DISCUSSION

This study analysed the reliability and validity of a CV-based markerless HPE application for the measurement of hip and knee joint ROM. The results showed nearly perfect reliability in active hip flexion, active hip extension, active hip inner and outer rotation, and substantial reliability in active knee flexion.

Correlations between our CV-based markerless HPE application and the reference picture were very strong in more than one-half of the joint angles and strong in two out of five joint angles. However, in knee flexion, the CV-based markerless HPE application values tended to be smaller than in the reference picture.

Even if the ICC values were high in active hip flexion, extension, and inner and outer rotation, and slightly lower in knee flexion, the MDC values were relatively high ($>2^\circ$) in four out of five directions. No established values exist on what acceptable accuracy is; however, a 2° MDC is acceptable in clinical

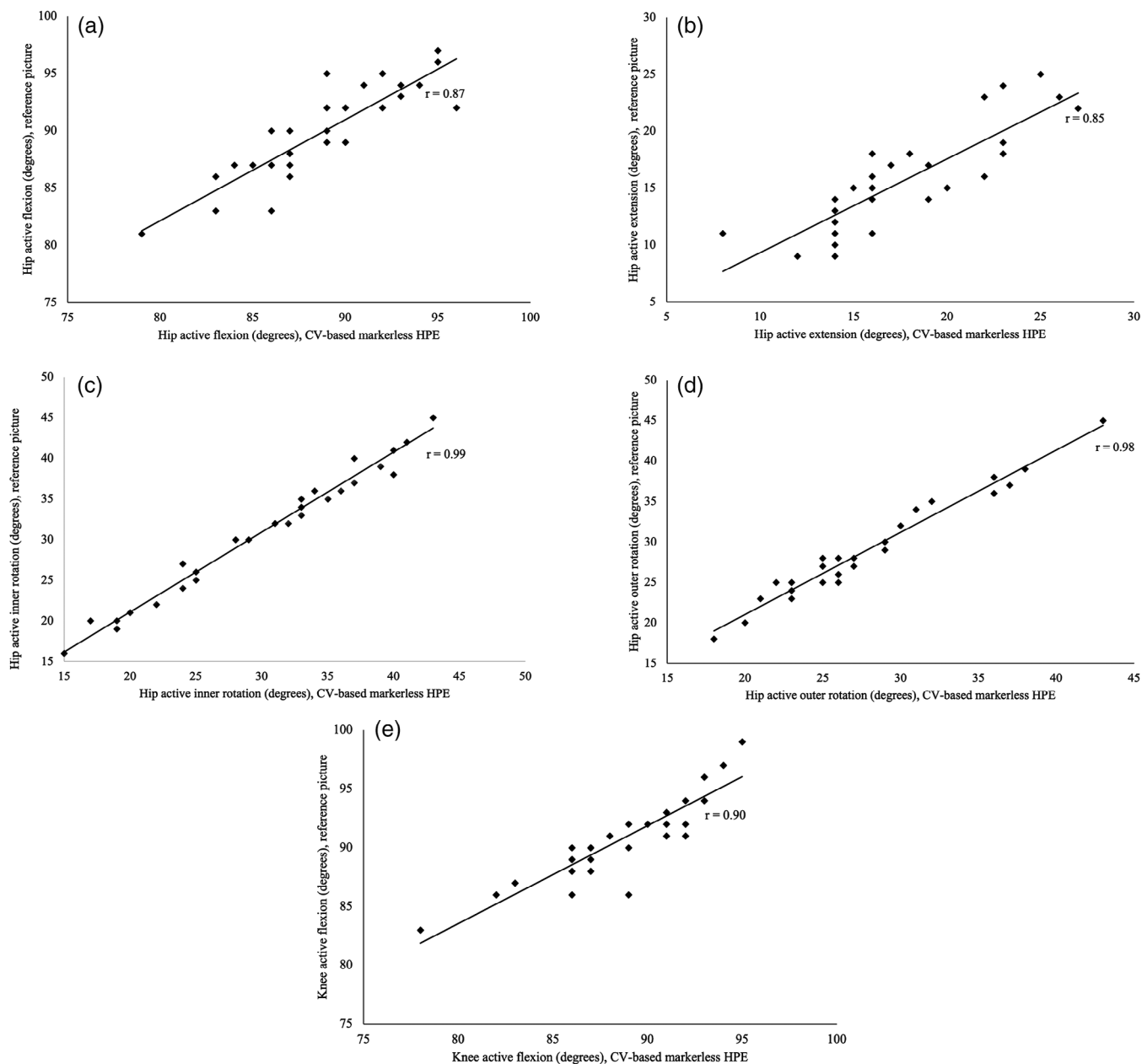


FIGURE 8 Correlation between our CV-based markerless HPE application and the reference picture for (a) hip active flexion, (b) hip active extension, (c) hip active inner rotation, (d) hip active outer rotation and (e) knee active flexion, r = Person's correlation coefficient.

settings, as universal goniometry, mostly used in the healthcare sector by clinicians as physiotherapist or physician, has shown a measure error of 6° in lower extremities [39].

The results of this study indicated good validity in almost all ROM measurements. However, in active hip flexion and extension, the correlations between the two methods were slightly lower. A reference photographic measurement [40] was used in this study; however, to obtain an exact joint angle, a radiograph image needs to be taken, which has been stated as the golden standard when measuring knee joint angle [9, 10]. Clinicians, such as physiotherapists and physicians, measure regular patients' ROM to follow up on the treatment, for example, after

a knee arthroplasty [41]. However, the radiograph measure is not frequently acceptable because of exposure to radiation [42]. Lower accuracy in active hip flexion and extension can be a result of difficulty for the CV-based markerless HPE application algorithm to localize the joints (key points) to estimate correct angles, as Wang et al [25] also discussed in their study.

To measure hip or knee joint ROM, measurement methods and tools vary; however, universal goniometry is traditionally used in everyday practice by professionals [8], although it is not as exact method as radiograph measure [10, 39]; therefore, this method was not used for this study as a reference for the CV-based markerless HPE application. Furthermore, CV-based

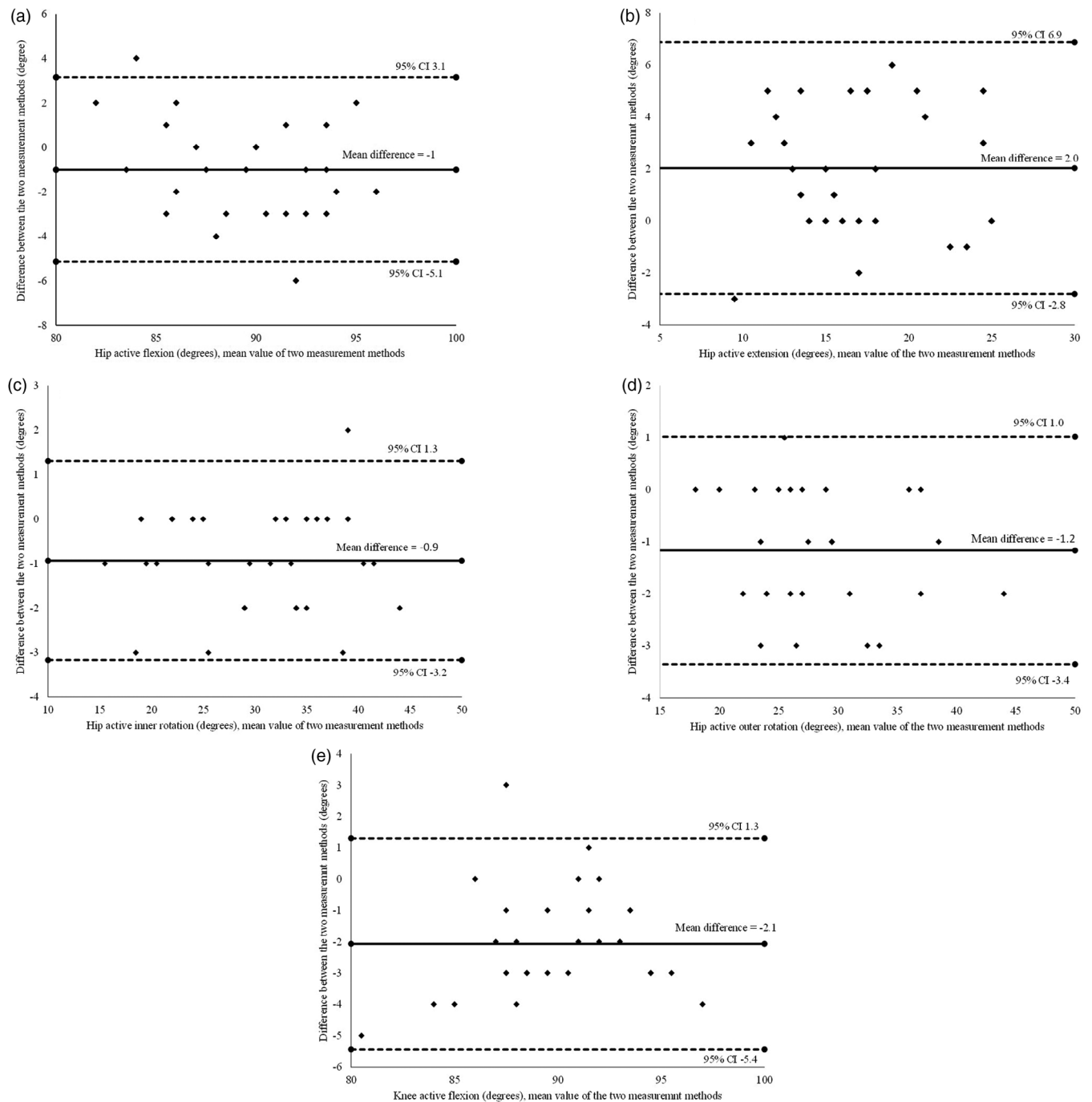


FIGURE 9 Bland–Altman plots for (a) hip active flexion, (b) hip active extension, (c) hip active inner rotation, (d) hip active outer rotation and (e) knee active flexion. The outer lines represent 95% limits of agreement. The middle line represents the mean of the differences between the two measurement methods.

HPE using markers with one or several cameras was not used in this study, which would have required a major financial investment and is impractical in daily practice in the healthcare sector. Hence, an easy and reliable method, photographic measurement [40], was used as a reference for the CV-based markerless HPE application measured angles. The reference picture was exactly the same picture frame from which the CV-based markerless HPE application analysed the joint angle. There was no possibility of palpating bony landmarks for markers in the reference

picture; however, they were visually estimated by an experienced physiotherapist. Furthermore, the lack of extension in the knee joint was not measured, as the participants were healthy, young, and had no acute injury in the lower extremity. However, a lack of knee extension decreases quadriceps contraction [4] and the ability of normal knee function in, for example, patients with knee osteoarthritis [5]. Future studies should evaluate CV-based markerless HPE in patients with symptoms in the lower extremities.

TABLE 2 The reliability of CV-based markerless HPE application in hip and knee joint.

Movement direction	ICC (95%CI)	SEM	MDC
Hip			
Active flexion	0.82 (0.63–0.92)	0.8	2.1
Active extension	0.82 (0.62–0.91)	0.8	2.1
Active inner rotation	0.93 (0.86–0.97)	0.6	1.6
Active outer rotation	0.83 (0.61–0.92)	0.8	3.2
Knee			
Active flexion	0.74 (0.45–0.87)	1.0	2.7

Note. CI: confidence interval; CV: computer vision, HPE: human pose estimation, ICC: intraclass correlation coefficient, MDC: minimal detectable change, SEM: standard error of measurement.

The use of TR increased significantly under the COVID-19 pandemic in daily practice, even if TR might be demanding to be used when healthcare professionals (physiotherapists) need hands-on action [16, 17] as evaluation of joint ROM. Currently, the best way for healthcare professionals (physiotherapists) to provide TR for patients at a distance is through consultation, guidance and counselling [23]. In daily practice, patient intervention needs to include documentation from the beginning of the intervention to the end [43] to evaluate the effects of the intervention. Documentation must be well written, as it influences patient care [44]; however, it is also used to evaluate the cost of care and obtain statistics [45]. However, to be able to evaluate and document, for example, stiffness in the hip or knee joint after an injury with TR methods, may be challenging. Thereby, CV-based markerless HPE can potentially be used in the future to analyse patient joint ROM at a distance, as they neither need hardware other than a computing device with a camera nor healthcare professional's expertise. Moreover, the use of CV-based markerless HPE includes an increased possibility for regular measurement. Thereby, it can increase patient motivation and add to the treatment process [2]. To promote the widespread adoption of CV-based markerless HPE applications, efforts should prioritize user-friendly software interfaces, compatibility with existing clinical workflows, and rigorous validation across diverse environments. Additionally, comprehensive training resources for healthcare professionals and effective patient education will be crucial for facilitating their integration into routine care before implementation in daily practice.

4.1 | Strengths and limitations

A strength of this study is the number of participants ($N = 30$). Errors were minimized using an optimal environment by standardizing the measurements at a clinic. In addition, a bright room was used with an ideal lightning system, positioned computer, web camera, and participant test position. However, it is obvious, as Hannik et al [20] noted, that as a CV-based markerless HPE uses a camera from a computing device, it is influenced by the environment and technical competence of the patient. Errors in measurement can arise from the instrument

used, the professionals involved, or variability in the performance of the patient [46]. Furthermore, this study is based on multidisciplinary collaboration between healthcare (physician/physiotherapist) and engineering professionals, which has been discussed as important in these kinds of development processes [25].

This study also has some limitations. The same test order was used when the joint angles were measured, and it may have influenced the results. By changing the test order, this limitation could have been eliminated; however, it was not done for practical reasons.

The current sample of healthy young adults with optimum weight (BMI 18.5–24.9), may limit the generalizability of findings to older adults or clinical populations. Future research should validate these results in diverse demographic groups, including older adults and in individuals with different disease conditions, to ensure broader applicability. It was found that lightning especially influenced how well the CV-based markerless HPE application could detect and localize the body reference points (markers) to calculate joint ROM. Furthermore, participants' joint angles were measured in an upright position as a consequence of a lack of training data for the computer (DensePose-COCO dataset), which represented patients in different positions than upright (standing). In the future, this kind of technical challenge should be considered before CV-based markerless HPE can be implemented in daily practice in the healthcare sector.

One limitation of this study is the absence of radiographic images, which are considered the gold standard for ROM measurements. However, ethical concerns regarding radiation exposure and resource constraints precluded their use. Future studies could investigate non-invasive imaging alternatives, such as ultrasound or advanced magnetic resonance imaging techniques, to further validate CV-based markerless HPE applications.

5 | CONCLUSION

This study's CV-based markerless HPE application showed highly repeatable results in the hip joint, active flexion, active extension, active inner rotation, and active outer rotation. In active knee flexion, the results indicated substantial repeatability. MDC values were relatively high in all directions; however, they were acceptable for healthcare professionals when measuring joint ROM in daily practice. The correlations between the two measurement methods were very strong in three out of five directions: active hip inner rotation, active hip outer rotation, and active knee flexion; however, in knee flexion, the CV-based markerless HPE application values tended to be smaller than those in the reference picture. CV-based markerless HPE can potentially be used to analyse joint ROM in hip and knee joints. To promote CV-based markerless HPE adoption, efforts should focus on user-friendly interfaces, workflow compatibility, rigorous validation, and providing training for healthcare professionals and education for patients to support integration into routine care.

AUTHOR CONTRIBUTIONS

Thomas Hellstén, Jari Arokoski, Jonny Karlsson, Leena Ristolainen, and Jyrki Kettunen contributed to the conception and design of the work. Jonny Karlsson contributed to the CV-based markerless HPE application. Thomas Hellstén, collected data, analysed data, wrote the first version of the manuscript. All authors participated in interpreting the data and revising critically on important part of the article and approved the final version of the manuscript.

ACKNOWLEDGEMENTS

The author wishes to thank Isa Kiukas and Erika Bergström for helping with the test measurements. This work was supported by the “Fonden för teknisk undervisning & forskning” (TUF) under Grant 1580, a fund for supporting education and technical research at Arcada University of Applied Sciences; Research Institute Orton through grants from the Ministry of Social Affairs and Health in Finland (A2500/502).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data not available—participant consent.

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How to cite this article: Hellstén, T., Arokoski, J., Karlsson, J., Ristolainen, L., Kettunen, J.: Reliability and validity of computer vision-based markerless human pose estimation for measuring hip and knee range of motion. *Healthc. Technol. Lett.* 12, e70002 (2025).
<https://doi.org/10.1049/htl2.70002>

APPENDIX TEST MANUAL

Active hip and knee flexion

Standing position instruction: ‘Bend your left hip and knee, and lift your midfoot on the line on the chair. Keep your back and head straight. Look straight forward on the mark on the wall (Figure 1a). Maintain this position for 3 s. I will just demonstrate the movement to you. Do you have any questions?’ After the participant had taken the position, the instructor counted three–two–one and saved the CV-based markerless HPE application registered joint angle from the hip and knee flexion on the log file with a time stamp. The reference picture was saved on a computer with an identical time stamp from the same picture frame, as the joint angle was calculated using the CV-based markerless HPE application. The saving procedure was the same for all measurements.

Active hip extension

Standing position instruction: ‘Slightly touch the table with your right hand to maintain balance. Place the palm of your left hand on your stomach. Extend your left hip so long that your toes touch the floor. Do not bend your back, keep your head straight, and look forward on the mark on the wall (Figure 1b). Maintain this position for 3 s. I will just demonstrate the required movement to you. Do you have any questions?’

Active hip inner and outer rotation

Sitting position instruction: ‘Rotate the left hip inward by bringing the left foot outward from the midline (Figure 1c), then rotate the hip outward by bringing the foot toward the midline (Figure 1d). Keep your pelvis in place as you perform the movement. Maintain both positions for 3 s. I will just demonstrate the required movement to you. Do you have any questions?’