Forensic Science International 380 (2026) 112804

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Using 2D video analysis and model based image matching to measure joint angles for forensic biomechanical analysis

Kevin G. Gilmore [a], Geoffrey T. Desmoulin [a,*], Marc-André Nolette [a], Szymon Claridad [a], Theodore E. Milner [a,b]

[a] GTD Scientific Inc., Canada
[b] Department of Kinesiology and Physical Education, McGill University, Canada

ARTICLE INFO

Keywords:
Digital Forensics
Forensic Biomechanics
Photogrammetry
Reverse Projection
Model Based Image Matching

ABSTRACT

Forensic injury biomechanics involves the use of all relevant data in order to conduct analysis and draw conclusions about an incident under investigation. Video recordings of the scene can be especially helpful due to their objectivity and the wealth of information which can be garnered from them. We compared the accuracy of different analysis techniques and multiple camera views for measuring human joint angles. The analysis techniques were reverse projection and model-based image matching (MBIM). For this purpose, 8 static postures performed by a human subject were recorded with 4 cameras. One camera was placed so that its focal plane was aligned with the plane of the subject's movement and 3 cameras were placed at various out-of-plane locations. The knee and elbow joint angles were first measured using a goniometer and then compared to angle measurements made through reverse projection and MBIM employing both single and combined camera views. Overall, the results indicated that multi-camera solutions and single, in-plane camera views produced joint angle reconstructions with the highest accuracy when comparted to the single out of plane camera views. Moreover, there was no significant difference between in the MBIM and reverse projection techniques in regard to joint angle accuracy.

1. Introduction

Forensic injury biomechanics is the science of combining medical and engineering principles to define the connection between incidents and injuries. As such, information such as medical records, mathematical modelling, incident reports and collected incident specific data are essential in providing the foundation for biomechanical analysis. Recorded video of incidents is especially helpful as it can provide an objective view of the occurrence which can be revisited after the event. Frequently, forensic investigations require analysis of the actions of subjects captured by cameras. The consequences of these actions usually depend on the posture or movement of the subjects. For example, a bullet trajectory depends on the orientation of the arm and hand holding the firearm. Similarly, the impact force produced by a strike applied with the fist or a hand-held object depends on the velocity of hand, which in turn depends on the motion of multiple body segments. The same is true of the impact force applied by a kick. Accurate determination of joint angles and body segment orientations from two-dimensional (2D) images, captured by cameras, is essential for such forensic analysis.

Making measurements from 2D video is referred to broadly as photogrammetry. Photogrammetry requires several steps to ensure objects in the image can be accurately placed in the physical space recorded in the video, requiring removal of distortion by the digitization process and conversion of a 3D environment into a 2D space. Due to the curvature of camera lenses, the 2D image may be warped, causing distortions of physical geometry. Therefore, this must be compensated through lens correction. Furthermore, to get the most accurate data from the 2D video, the location of the camera relative to all objects in the scene must be determined. Solving this camera location is often referred to as inverse photogrammetry. Following the above steps, reverse projection can be used to take 3D measurements from the 2D images. Reverse projection as a technique involves projecting lines from the camera's solved 3D location, through the 2D image plane, and onto some 3D representation of the recorded incident scene or a projection from a secondary camera, thus providing a 3D point measurement from

* Corresponding author.
E-mail address: gtdesmoulin@gtdscientific.com (G.T. Desmoulin).

https://doi.org/10.1016/j.forsciint.2025.112804
Received 26 February 2025; Received in revised form 22 December 2025; Accepted 30 December 2025
Available online 31 December 2025

the 2D video sources. Another technique associated with forensic photogrammetry is model based image matching (MBIM), in which a 3D model of an object or person, seen in the 2D video, is positioned in 3D space such that the model matches the object in the 2D view and conforms to all physical restrictions, such as not passing through the ground and other surrounding solid objects.

In forensic injury biomechanics, the application of inverse photogrammetry and reverse projection is useful but suffers from some limitations based upon the number of available overlapping camera views and other factors. Moreover, while the use of these techniques to measure kinematics and positional information about rigid body objects such as vehicles has been extensively studied and reported, there is less published information on the use of these techniques for biomechanical measurements in real world scenarios for forensic applications. Clinically, the gold standard for human movement analysis is a marker-based calibrated multi-camera 3D motion capture system, such as the Vicon systems. However, while accurate and effective in controlled environments, these systems are expensive, not portable, and are not applicable to forensic biomechanics as real-world incidents are generally captured by a single uncalibrated camera and can only be analyzed after they occur [1–3]. Alternatively, goniometers have been used to measure joint angles with accurate results but require physical measurement of the joint and, therefore, cannot be used for analysis of digital images in forensic investigations [4–7]. Consequently, we require a methodology to extract biomechanical information from 2D video cameras which commonly record real-world incidents, such as mobile phones, action or dashboard cameras, and security cameras.

Human movement data extraction from 2D video is a well-established technique in clinical spaces where the 3D motion capture systems are not practical for various reasons, be it portability or budgetary constraints. In such cases, these 2D video systems either record movement through multiple synchronized views [8], or only in one plane with a single camera. Examples of the applications of a single, planar 2D camera include measuring dynamic knee angles under load [1,9], determining biomechanical loading of musculature under normal labour working conditions [4], and performing gait recognition and analyses [2,3,10–12]. It is generally accepted that 2D cameras provide a relatively accurate and reliable source for measuring joint angles and other biomechanical quantities if the focal plane of the camera is aligned with the plane of the motion when compared to other methods, such as depth cameras [13], motion capture systems [1–3,9,14], and goniometers [4,5].

As the accuracy of current 2D camera methods have generally been assessed in controlled, laboratory environments for planar movements aligned with the camera focal plane, whereas biomechanical injury forensics inherently involves investigation of uncontrolled real-world events, there is a need to confirm the validity of using images from single or multiple camera views at arbitrary orientations to the plane of motion to make biomechanically relevant measurements. Given the limited information provided by 2D videos, two main techniques for data extraction will be analyzed in this paper, namely MBIM and reverse projection. The objective of this study is to determine the validity and

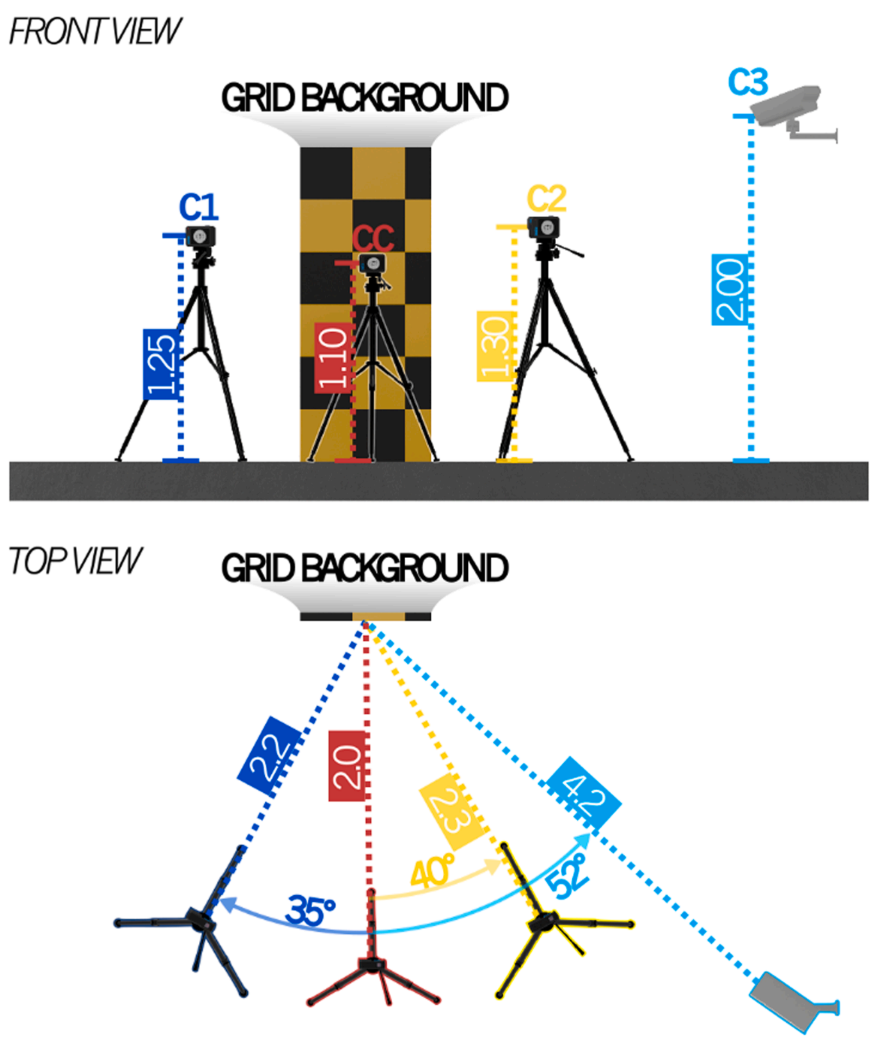

Fig. 1. Experimental test apparatus. Dimensions not drawn to scale.

accuracy of measuring human joint angles through non-planar 2D video footage using MBIM and reverse projection techniques. We hypothesize that MBIM and reverse projection techniques will be equally accurate in measuring human joint angles but that the accuracy will depend on the camera viewing angle.

2. Methods

2.1. Data collection apparatus

Four cameras were used to capture simultaneous video footage of a subject from different angles. These cameras will be referred to as camera C, 1, 2, and 3 (CC, C1, C2, C3). The setup is illustrated in Fig. 1. Camera C was oriented so that its optical axis was perpendicular to a background grid placed in the scene at a height of approximately 1.1 m and a distance of 2 m from the grid. Cameras 1 and 2 were positioned such that their focal planes were rotated by approximately 35 deg counterclockwise and 40 deg clockwise, respectively, with respect to camera C, at heights of 1.25 m and 1.3 m, respectively. Cameras 1 and 2 were positioned at distances of 2.2 m and 2.3 m, respectively, from the background grid. Camera 3, also oriented such that its focal plane was out of alignment with the background grid, was positioned at a height of 2 m and a distance of 4.2 m from the grid, as measured along the ground. The optical axis was rotated by approximately 52 deg counterclockwise with respect to camera C (in the horizontal). All cameras had their focal centers aligned with the center of the grid. The cameras used and their specifications are listed in Table 1.

2.2. Pre-testing

Prior to data acquisition, a pre-calibration protocol was carried out with all cameras, except Camera 3, for the purpose of removing the effects of lens distortion in subsequent image processing. The protocol involved recording a multi-sheet reference grid from 12 views. First an image was obtained from each of the 4 sides of the calibration grid. Next, the camera was rotated 90 ° clockwise and the same 4 images were captured. This was repeated once more with the camera rotated 90 ° counterclockwise from its original orientation. These views were recorded with the camera at an angle of 45 deg above the horizontal. After determining the necessary parameters to obtain an undistorted image of the grid such that the vertical and horizontal axes were straight and perpendicular to one another, the cameras' lens distortion parameters were saved and used to correct for lens distortion during subsequent image processing. For camera 3, this process could not be carried out due to its low resolution and location. Instead, a procedure referred to as point cloud lens correction was used. A 3D scan of the scene was taken using a Dot3D DPI-10-SG scanner with an Intel RealSense D415 sensor attachment with all cameras and the background grid in the same positions and orientations shown in Fig. 1. By relating common points seen in both Camera 3 images and in the point cloud resulting from the scan, the lens distortion of Camera 3 was corrected by warping the image until those common points overlapped.

A calibration test was also performed in which the goniometer, a Wolfride 2-in-1 digital angle ruler, with a seller-reported accuracy of 0.5 ° and a resolution of 0.05 °, was placed against the background grid, set to angles of 30, 60, and 90 deg, one of which (30 deg) is shown in Fig. 2. For each of the 4 single camera views, the Control Camera, Camera 1, Camera 2, and Camera 3 (CC, C1, C2, C3), the angle of the goniometer was measured for a single video frame using reverse projection (Fig. 3). The 3 points on the goniometer, shown in Fig. 2, were projected onto the plane of the background grid, whose location was determined from the initial 3D scan, using PhotoModeler Premium software, version 2025.0.0.332 (PhotoModeler Technologies, Vancouver, British Columbia, Canada). The angle between these 3 points was then measured and compared to the reading on the goniometer for accuracy. This was repeated for a 3-camera view, C123, in which simultaneous views from 3 cameras, C1, C2, and C3, was used to perform a single angle measurement. This technique, a form of reverse projection, involves projecting a line from each camera source, through a point on the 2D image, for an infinite distance. The 3D position where the 3 projection lines from the 3 cameras intersect is considered to be the 3D location of the point of interest. Each of the 3 points of interest in Fig. 2 had its 3D position determined by this method, after which the angle between the lines joining point P1 with P2 and P2 with P3, was measured. The purpose of this test was to quantify the reverse projection error when reconstructing the goniometer angle from the view of each camera and the multi-camera combination when viewing a known reference plane under ideal conditions.

Table 1
Camera specifications.

Camera	Model	FPS	Resolution
1	GoPro Hero 11	60	5.3 K
2	GoPro Hero 11	60	5.3 K
3	Home Security Camera	5	640 × 360
C	GoPro Hero 8	30	4 K

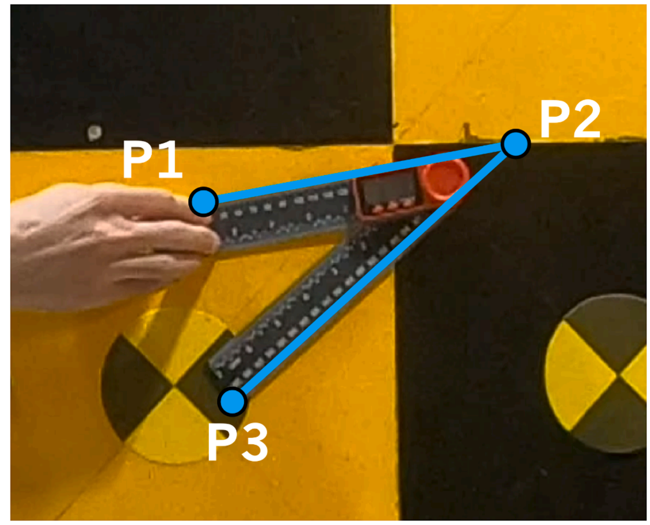

Fig. 2. A goniometer control measurement made from a CC image. The points P1–3 are projected onto the 3D surface of the grided backdrop as defined by a 3D scan of the scene. The resulting angle between lines joining P1-P3 defines the measured angle of the goniometer.

2.3. Data collection

A subject without firearms training, whose height is 1.77 m, performed poses in 8 static postures, as shown in Fig. 4. All postures were recorded simultaneously with the 4 cameras. A clapperboard was used to aid in synchronizing the video streams across the individual cameras to ensure that simultaneous frames were analyzed for each condition. Markers were placed proximal and distal to, and at, the knee and elbow joints, as shown in Fig. 4. The objective in varying the pose was to create a rich data set, involving a range of elbow and knee angles, such that the visibility of the markers would vary for different camera views. During the static postures, the goniometer was used to directly measure joint angles, based on the position of the centers of the markers on the respective limbs, to provide a gold standard reference for determining the error of the joint angle reconstruction techniques.

2.4. Data processing

Prior to measurement of joint angles, inverse photogrammetry was

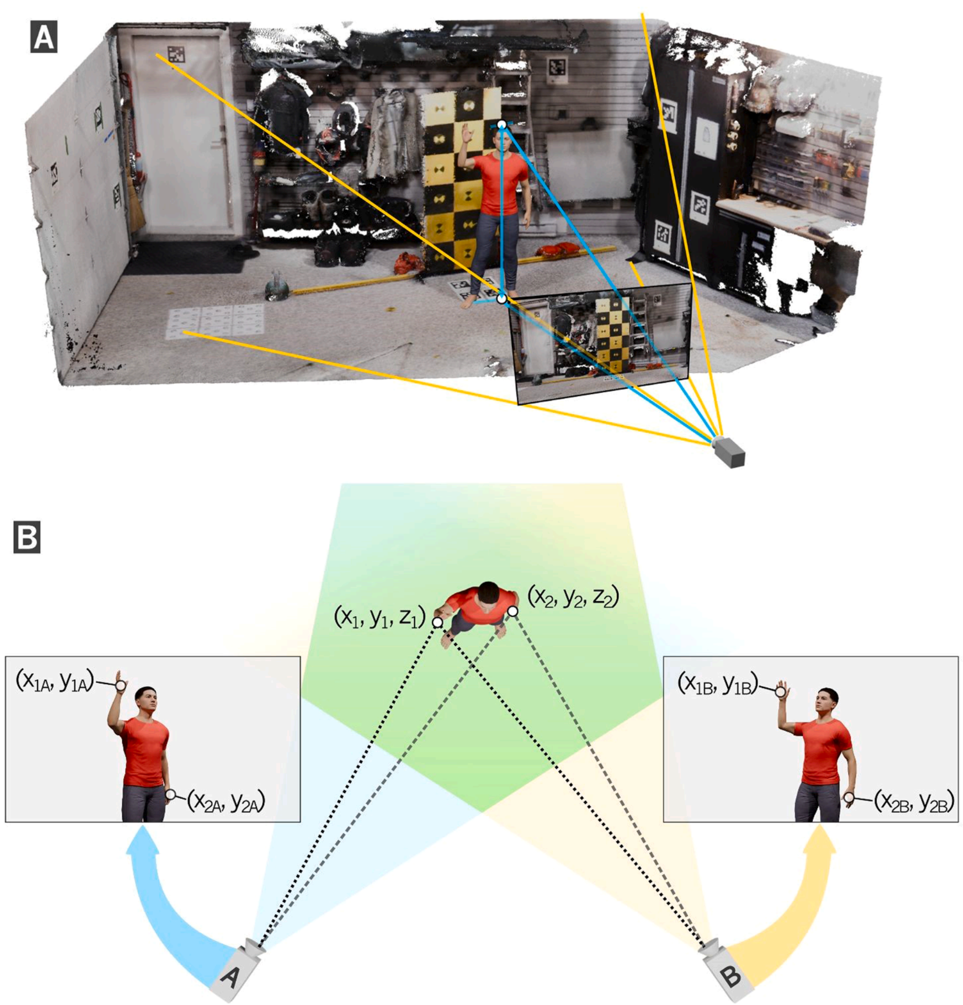

Fig. 3. Reverse projection methodology schematic. (A) shows reverse projection as completed for a single camera view. (B) shows the process as used for a multi-camera view.

used to solve for the position and orientation of each camera. This was completed through a process in which common points, seen in both the 3D scan of the scene and in the respective camera view, are correlated with each other. The camera position and orientation were determined by aligning the points on the scan with the corresponding points in the camera image. For Camera 3, this technique was also used to simultaneously correct for lens distortion as previously described, as any deviation between correlated points is likely due to lens distortion affecting the 2D image's geometry (Fig. 5).

The model-based image matching (MBIM) technique involved generating a human model representing the subject seen in the video, matching the position, orientation and movement of the model to the subject, and making measurements from the model to determine joint angles [15–18]. First, a model of the participant was generated using Blender software version 4.3.2 (Blender, Amsterdam, Netherlands). The model and its proportions were scaled to match still frames of the subject in a neutral position (i.e. standing). The parameters which were edited to increase similarity between the subject and model include, but are not limited to, height, upper arm length and thickness, forearm length and thickness, neck length and thickness, and shin length and thickness [15,16]. The human model is defined by a hierarchical structure with the pelvis as the base and has 3 rotational and 3 translational degrees of freedom. Each successive segment (i.e. thigh, shin, foot) are defined by a 3° of freedom rotational relationship relative to the previous segment [15,16]. More mobile joints, such as the shoulder, were also defined by translational degrees of freedom to allow for shoulder retraction, protraction, and shrugging.

By first manually positioning the pelvis and then working through the limb segment branches until the hands, feet, and head were positioned, the model was made to represent the physical location and pose of the subject in a selected video frame [15,16,18]. Physical boundaries seen in the 3D scan of the scene were also used to define the positioning of specific joints and limbs, such as by imposing the requirement that a planted foot must be in contact with the ground. The human model was also viewed from angles perpendicular to a camera's optical axis, such as from above. This was done to detect any errors that were otherwise not apparent from the view of the camera, such as unrealistic joint angles or excessive leaning towards or away from the camera.

The reverse projection technique was completed using PhotoModeler. After solving the camera locations and correcting for lens distortion by reference to the acquired 3D scan, the selected video frames recorded by cameras C1, C2, C3, and C123, were used to measure the subject's joint angles. For each analyzed video frame, the plane of the joint (knee or elbow) was estimated based on visual clues, joint mobility limitations, and information from the 3D scan (e.g. the location of body segments touching the ground can be easily determined with the aid of the scan). Reverse projection was used to project the 3 joint markers onto the plane defined by their locations on the surface of the arm and leg. As the technique projects lines from the camera through the centers of the markers, the resulting angle between the projected marker centers could be measured using each point's 3D location. The plane, onto which the images of markers captured by Camera C were projected, was

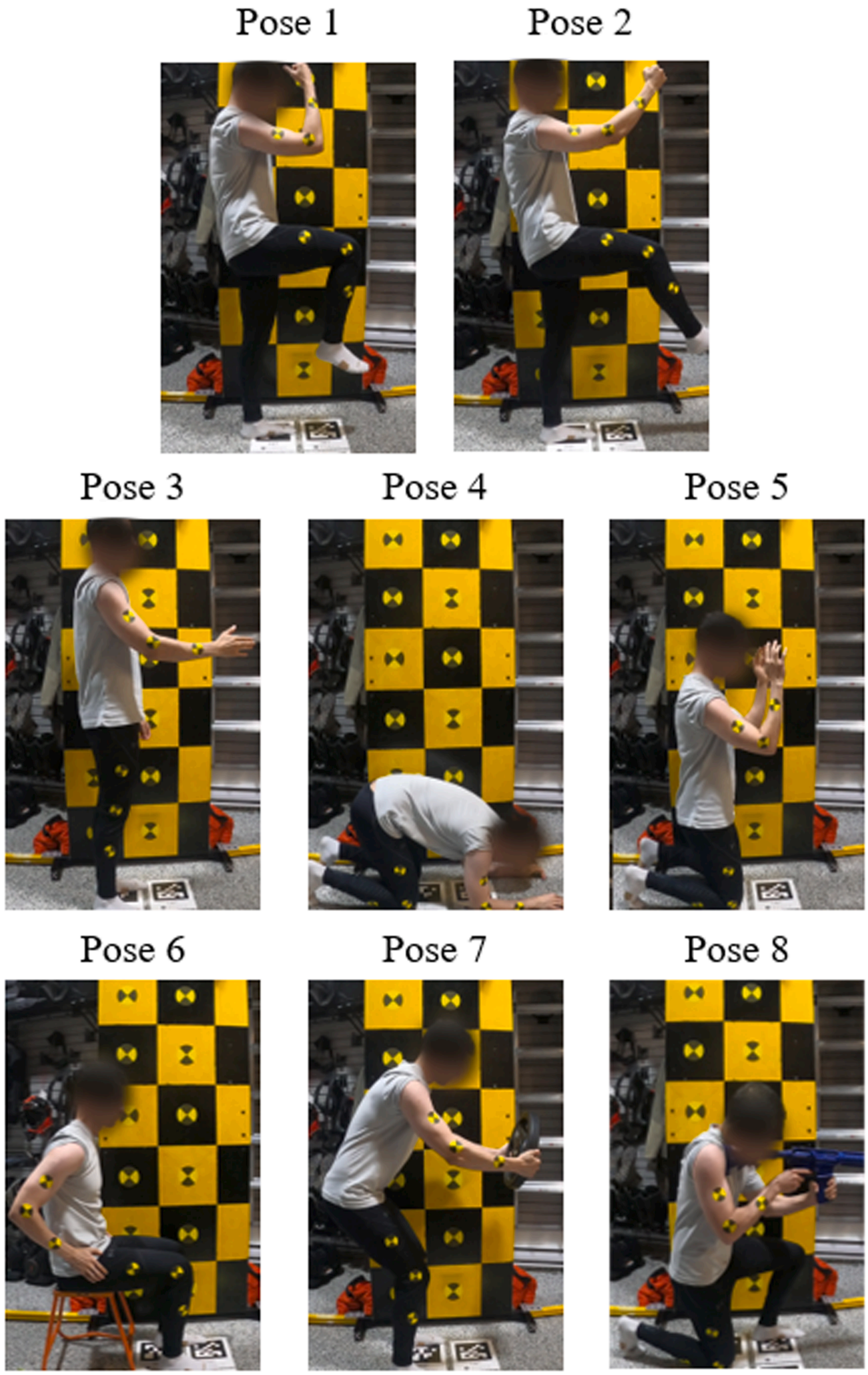

Fig. 4. The 8 static postures performed by the participant with markers attached to the subject, as seen from camera C. Note that the images have been cropped for visual presentation.

assumed to be parallel to the plane of the background grid, as defined by the scan. As camera C's optical axis was assumed to be perpendicular to the grid, and also perpendicular to the plane of the joints, this aided in reducing any error caused by small shifts between the subject plane and Camera C's focal plane, so that the measurements made using the images captured by camera C were representative of those of an in-plane, 2D camera. For the multi-view C123 camera combination, reverse projection was applied to each camera's image separately. The measured 3D position of each marker in this case was calculated through an optimization algorithm native to PhotoModeler which finds the point in 3D space with the lowest average error between each of the separate points from the 3 camera views. Errors for the angle measurements for static postures were calculated in relation to the goniometer angle. For each camera view, joint angle measurements for both the knee and

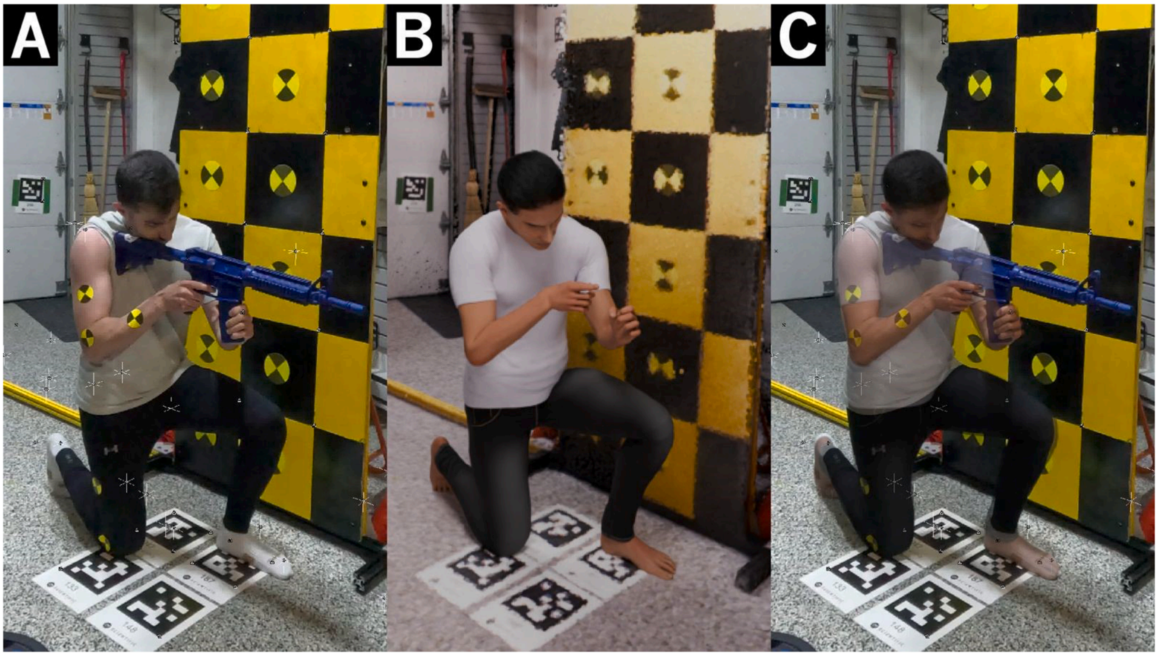

Fig. 5. Model-Based Image Matching technique used to measure joint angles for dynamic motions. (A) The original video frame from C2, cropped for presentation. (B) The model positioned to visually overlap the participant. (C) An overlay of the human model and subject.

elbow were made from 5 separate video frames using the reverse projection and MBIM techniques.

2.5. Statistical analysis

The outcome measure of interest was the joint angle error relative to the goniometer measurements of the elbow and knee angles. The error was calculated as the absolute value of the difference between the goniometer measurement of the joint angle and the reconstructed joint angle using the MBIM or reverse projection technique. The experimental design provided a rich data set for statistical analysis. To test the hypothesis that the MBIM and reverse projection techniques would be equally accurate in measuring the elbow and knee angles but depend on the camera viewing angle, ANOVA was performed on the joint angle error with technique (MBIM and reverse projection) and camera view (CC, C1, C2, C3 and C123) as factors, including the interaction between technique and camera view. Statistical analysis was performed in JMP Pro.

3. Results

3.1. Reverse projection angle calibration

Table 2 lists the errors in the measurements of the goniometer angle made using all cameras in isolation as well as the with the combination of cameras 1, 2, and 3, referred to as C123,. All camera views show an error with respect to the known goniometer angle of less than 1 deg, except for C3, for which the average error is over 5 deg.

Table 2
Reverse projection errors relative to goniometer angles.

Camera View	Reverse Projection Error (deg)		
	90°	**60°**	**30°**
CC	0.18	0.73	0.63
C1	0.42	0.54	0.44
C2	1.46	0.98	0.35
C3	5.83	8.80	2.78
C123	0.19	0.32	0.25

3.2. Static pose joint angle measurement from reconstruction

Table 3 lists the mean absolute joint angle error and standard deviation for each camera view for the two techniques. The errors represent the mean across the 8 poses and 2 joint angles (elbow and knee).

The ANOVA found no main effect of the technique (MBIM versus reverse projection) on the absolute joint angle (F ratio 1.43, $p = 0.23$). However, there was a main effect of the camera view (F ratio 23.69, $p < 0.0001$). There was no interaction effect between the technique and camera view (F ratio 2.17, $p = 0.071$). A post-hoc Tukey HSD was performed on the errors according to camera view. The test determined that the error for C1 was significantly greater than the error for CC, C2 and C123. It also determined that the errors for C2 and C3 were significantly greater than the errors for CC and C123. Overall, this indicates that the images from CC and C123 produced the highest accuracy for the joint angle reconstruction. The means and standard deviations are compared in Figs. 6 and 7.

4. Discussions

With a known plane to use as a reference, angles during the calibration test were determined accurately using reverse projection with all cameras (Table 2), though Camera 3 showed higher errors relative to the others. The absolute joint angle errors for CC, C1, C2, and C123 were all within 1 deg, on average, of the reference goniometer measurement when the goniometer was placed against the background grid. However, the error for C3 was greater and had a larger variation, with an error of up to 8.8 deg. It is important to note that C3 had a much lower resolution than the other cameras, likely accounting for the higher error. The

Table 3
Mean and standard deviation of absolute errors relative to goniometer angles.

Camera View	MBIM Error (deg)	Reverse Projection Error (deg)
CC	5.79 [4.41]	5.08 [4.34]
C1	9.22 [6.83]	10.22 [7.50]
C2	6.00 [4.38]	8.46 [6.05]
C3	8.94 [6.35]	8.59 [6.43]
C123	4.77 [4.03]	4.71 [3.00]

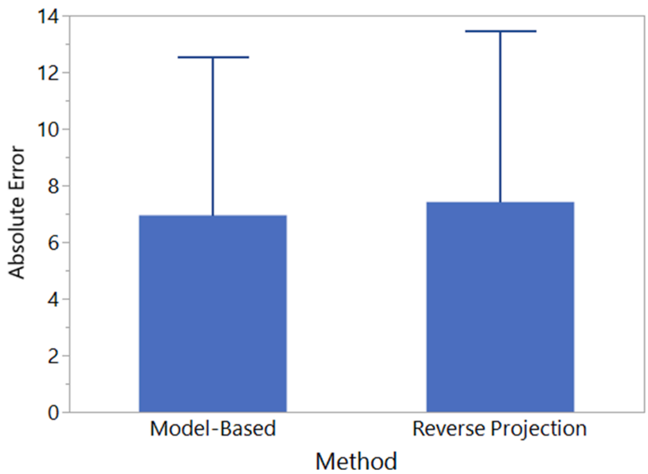

Fig. 6. Mean and standard deviation of the absolute angle error MBIM and reverse projection techniques.

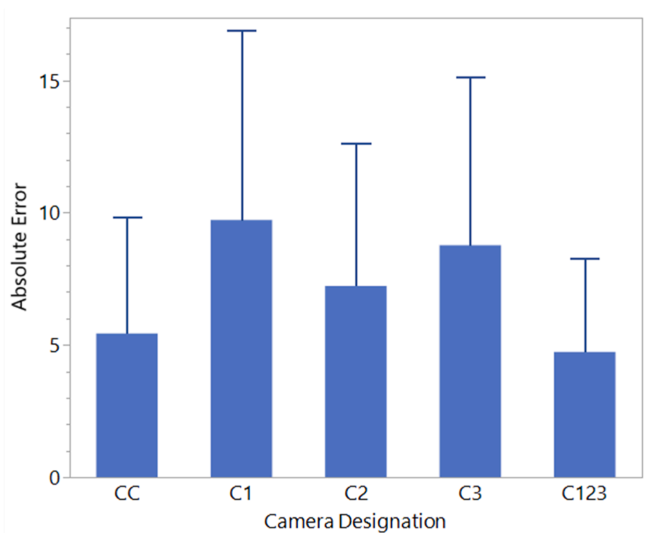

Fig. 7. Mean and standard deviation of the absolute angle error for the five camera conditions.

results demonstrate that, when the plane of measurement (or the joint plane) is known and cameras have sufficient image resolution, highly accurate angle measurements can be made.

As is evident by comparing Tables 2 and 3, the errors based on the initial reverse projection calibration with the goniometer are generally considerably smaller than the errors in the joint angle measurements made with the human subject show. This is likely due to differences in the spatial configuration of the two test conditions. For the calibration test, the goniometer was placed directly in contact with the grid and set to a specific angle. This kept the measurement error relatively low for two main reasons. First, the plane in which the angle was measured was known precisely from the 3D scan of the testing area, ensuring no difference between the actual and assumed projection planes. Second, because the goniometer was placed directly in contact with the grid, and therefore the measurement plane, there was little possibility for warping of the measured angle due to different projection distances of the 3 points or misalignment between the plane of the goniometer and the assumed plane. While the calibration test was idealized to determine the best possible results from the reverse projection method and ensure its validity, the static posture test was less precisely controlled. Due to the requirement that the subject's knee and elbow could not be in direct contact with the grid, there is a possibility that the assumed joint measurement plane deviates slightly from the actual joint plane, which would introduce small errors into the results. Furthermore, because the goniometer is not transparent, there could be error in the goniometer measurement, as well as error due to movement of the subject between video recording and goniometer measurement.

For joint angle reconstruction, C1 performing slightly worse than C3 was somewhat unexpected given the low resolution of the C3 camera. However, this may be due to the positioning of the cameras relative to the subject, with C3 being positioned higher above the ground, and therefore presenting a more isometric camera view. Therefore, when determining the reliability of either MBIM or reverse projection techniques in real-world biomechanical forensic investigations, an important factor to consider will be the available camera views, including their resolution, distance to the subject of interest, viewing angle, and visual field overlap with other camera views. While cameras with visual fields in plane with the objects to be measured or views from multiple overlapping cameras, may be preferred, other single view cameras can still provide accuracy within approximately 10 deg for reconstructed joint angles.

When directly comparing the MBIM and reverse projection techniques, there was no significant difference in joint angle measurement accuracy, demonstrating that either technique can be used with equal confidence in reconstructing human posture. As seen in Fig. 6, both techniques had average errors below 8 deg, with standard deviations of approximately 6 deg. However, there are important practical differences in the technique which may make one technique more advantageous than the other. Reverse projection was generally more time efficient and somewhat simpler to perform as only 3 points were required per joint to take a measurement. MBIM, while a more time intensive process due to the need to match an entire human model, allows for more flexibility to create visual incident reconstructions and extrapolate further information about the subject's body position or kinematics. Therefore, while the accuracy of both techniques may be similar, one method may be more suitable for certain investigations compared to the based on the specifics of the situation.

In reviewing the literature, there is evidence that 2D planar imaging can determine joint angle within an acceptable range of error. A study by Yahya et al. saw that a single RGB camera, driven by machine learning algorithms, could calculate shoulder joint angles with average errors of 9.29 deg and 5.3 deg in the sagittal and coronal planes, respectively, when compared to a motion capture system [11]. Moreover, another study found that error generally fell under 5 deg when comparing 2D planar imaging to goniometer measurements for hip and knee angles during mechanical lifting [4]. This agrees with the results which we obtained for static poses, in which error is relative to a goniometer measurement, as we found single, in-plane and 3 camera error averages of 5.08 and 4.71 deg for the reverse projection technique and 5.79 and 4.77 deg for the MBIM technique as shown in in Table 3. The accuracy of our techniques is better than that obtained by Crombrugge et al. [8] which with a single depth sensing camera, a 2-camera view, and a 3-camera view. The depth camera resulted in joint angle accuracies of 30 deg, while the 2 and 3 camera views resulted in errors of 16 and 12 deg, respectively [8]. While not directly comparable as their errors were calculated as a root mean square error rather than average of absolute errors, our results still show that the reverse projection and MBIM techniques perform at least as well, if not better, than the techniques used by Crombrugge et al. [8]. This demonstrates that our techniques are well within the range of errors presented in literature for other human kinematic imaging techniques used to measure joint angles. It is important to point out, most 2D imagining techniques require that the joint angles are measured in the same plane as the camera view, which is not a realistic requirement for biomechanical forensics. With the single camera reverse projection and MBIM techniques, images acquired with C1, C2, and C3 were not in the measurement plane, demonstrating that although beneficial, the camera image plane need not coincide with the measurement plane. While the respective out of plane angle errors for

C1, C2, and C3 were higher than for CC and C123, they are still in line with those reported by Crombrugge et al. [8] and Yahya et al. [11], i.e. 10 deg or less, on average. Therefore, both the MBIM and reverse projection techniques are within the accuracy ranges presented in literature and can be said to represent viable methodologies for determining joint angles through 2D videos.

Limitations of this study include the use of a single participant, although 800 total error measurements were used across all camera views. A single participant simplified the model-based image matching (MBIM) and analysis. However, further research should be done to ensure that the results can be applied to varied body types. Further research should investigate inter and intra rater errors for these techniques.

5. Conclusion

The results of this study show that the use of both the reverse projection and MBIM techniques for determining joint angle are viable alternatives when more conventional techniques such as commercial motion capture systems are impractical. With regards to forensic biomechanics, these techniques have the potential to allow for after-the-fact analysis of subject biomechanics through video recordings taken at the time of the incident in question. This is especially significant since generally in these incidents, limited information may be available, and the video recordings may be the only or the key evidence to be analyzed. While further investigation should be done as outlined above, these techniques have the potential for significant impact in the field of biomechanical and digital forensics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

This study evaluates the accuracy of measuring human joint angles from non-planar 2D video footage using model based image matching and reverse projection techniques. While traditional 2D camera methods are validated in controlled environments with planar movements, biomechanical injury forensics involves real-world, uncontrolled events. Therefore, this research aims to assess the validity of using single or multiple camera views at arbitrary orientations for biomechanical measurements.

References

[1] R.L. Mizner, T.L. Chmielewski, J.J. Toepke, K.B. Tofte, Comparison of 2-dimensional measurement techniques for predicting knee angle and moment during a drop vertical jump, Clin. J. Sport Med. 22 (3) (2012) 221–227, https://doi.org/10.1097/jsm.0b013e31823a46ce.

[2] U.C. Ugbolue, et al., The evaluation of an inexpensive, 2d, video based Gait Assessment System for clinical use, Gait Posture 38 (3) (2013) 483–489, https://doi.org/10.1016/j.gaitpost.2013.01.018.

[3] T. Zult, J. Allsop, J. Tabernero, S. Pardhan, A low-cost 2-D video system can accurately and reliably assess adaptive gait kinematics in healthy and low vision subjects, Sci. Rep. 9 (1) (2019), https://doi.org/10.1038/s41598-019-54913-5.

[4] B.S. Norris, S.L. Olson, Concurrent validity and reliability of two-dimensional video analysis of hip and knee joint motion during mechanical lifting, Physiother. Theory Pract. 27 (7) (2011) 521–530, https://doi.org/10.3109/09593985.2010.533745.

[5] J. Roush, K. Bustillo, E. Low, Measurement error between a goniometer and the NIH imagej program for measuring quadriceps angle, Internet J. Allied Health Sci. Pract. 6 (2008), https://doi.org/10.46743/1540-580x/2008.1195.

[6] M. Svensson, V. Lind, M. Löfgren Harringe, Measurement of knee joint range of motion with a digital goniometer: a reliability study, Physiother. Res. Int. 24 (2) (2018), https://doi.org/10.1002/pri.1765.

[7] V. Lind, M. Svensson, M.L. Harringe, Reliability and validity of a digital goniometer for measuring knee joint range of motion, Meas. Phys. Educ. Exerc. Sci. 26 (3) (2021) 191–198, https://doi.org/10.1080/1091367x.2021.2004150.

[8] I. Van Crombrugge, et al., Accuracy assessment of joint angles estimated from 2D and 3D camera measurements, Sensors 22 (5) (2022) 1729, https://doi.org/10.3390/s22051729.

[9] P. Fargier, R. Massarelli, T. Rabahi, A. Gemignani, E. Fargier, Fast regulation of vertical squat jump during push-off in skilled jumpers, Front. Physiol. 7 (2016), https://doi.org/10.3389/fphys.2016.00289.

[10] R. Tanawongsuwan, A. Bobick, Gait recognition from time-normalized joint-angle trajectories in the walking plane, Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition. CVPR 2001 (2001), https://doi.org/10.1109/cvpr.2001.991036.

[11] G. Leporace, et al., Validity and reliability of two-dimensional video-based assessment to measure joint angles during running: a systematic review and meta-analysis, J. Biomech. 157 (2023), https://doi.org/10.1016/j.jbiomech.2023.111747.

[12] R. Burgess-Limerick, R.J. Neal, B. Abernethy, Against relative timing invariance in movement kinematics, Q. J. Exp. Psychol. 44A (4) (1992) 705–722, https://doi.org/10.1080/14640749208401306.

[13] M. Yahya, et al., Accurate shoulder joint angle estimation using single RGB camera for rehabilitation, 2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) (2019), https://doi.org/10.1109/i2mtc.2019.8827104.

[14] I. Akhter and M.J. Black, "Pose-conditioned joint angle limits for 3D human pose reconstruction," *2015 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pp. 1446–1455, 2015. doi:10.1109/cvpr.2015.7298751.

[15] H. Koga, A. Nakamae, Y. Shima, R. Bahr, T. Krosshaug, Hip and ankle kinematics in noncontact anterior cruciate ligament injury situations: video analysis using model-based image matching, Am. J. Sports Med. 46 (2) (2017) 333–340, https://doi.org/10.1177/0363546517732750.

[16] T. Krosshaug, R. Bahr, A model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences, J. Biomech. 38 (4) (2005) 919–929, https://doi.org/10.1016/j.jbiomech.2004.04.033.

[17] G.J. Tierney, et al., Assessment of model-based image-matching for future reconstruction of UNHELMETED Sport Head Impact Kinematics, Sports Biomech. 17 (1) (2017) 33–47, https://doi.org/10.1080/14763141.2016.1271905.

[18] J.Y. Zheng, S. Suezaki, Y. Shiota, Interactive human motion acquisition from video sequences, Proc. Comput. Graph. Int. 2000 (2000) 209–217, https://doi.org/10.1109/cgi.2000.852336.