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Validation of A Single Camera Motion Analysis System for 3D Knee Kinematics in Vertical Jump

Nicole Croushore and Yi Wu
Department of Mechanical Engineering
Pennsylvania State University Erie, the Behrend College
Erie, PA, USA
nec5293@psu.edu, yxw22@psu.edu

Xiaoxu Ji
Associate Professor, Department of Biomedical Engineering
Gannon University
Erie, PA, USA
ji001@gannon.edu

Abstract

A single-camera motion analysis system, referred to as Behrend motion analysis system, is developed to study 3D knee kinematics in vertical jump. The system was tested and compared with 3D commercial motion system Xsens Awinda. The waveform of flexion/extension measured by Behrend motion analysis system exhibits a high degree of similarity to the waveform measured by Xsens Awinda system (R^2>0.97).

Keywords
3D knee kinematics, single-camera, Kinovea, motion analysis, knee angles

1. Introduction
Optical motion capture/analysis system is widely used to understand and study the biomechanics loads of human body. Ishida et al (2018) use such a system to study mechanism of Anterior Cruciate Ligament (ACL) injury. Yan et al. (2019) use an optical motion system to study gait kinematics after ACL reconstruction. Those systems are typically costly, require multiple camera systems in a dedicated lab setting. We are exploring a low-cost and portable system that only uses one camera to study 3D kinematics of knee motion during vertical jump. Our goal is to utilize the system to analyze risk factors for ACL injury during vertical jumping in an out-of-lab environment, making it practical for clinical or coaching applications.

1.1 Objectives
The research objective is to develop a one-camera motion capture and analysis system for 3D knee kinematics (referred as Behrend motion analysis system) and test its accuracy as compared to commercial 3D motion tracking system (Xsens Awinda). The motion we study is vertical jump that is at a fixed distance to the camera. We compared the measurement results using those two systems in terms of flexion/extension angle, abduction/adduction angle, and the internal/external rotation angle.

2. Literature Review
Knee flexion, abduction and internal rotation angles are critical parameters for the understanding ACL injury risk

as summarized by Fan et al (2021). Traditionally, the optical motion systems used to study those 3D angles require multiple cameras (mostly more than 6 cameras). OpenCap, the open-source markerless motion system by Uhlrich et al. (2023) requires two or more smartphone cameras. Existing studies using one camera only examined 2D kinematics in one plane using a free 2D motion software Kinovea. Ugbolue et al. (2013), Littrell et al (2018), and Fernández-González et al (2020) use Kinovea to study gait. Willis et al. (2019) use Kinovea to study drop vertical jump. Inertial measurement units (IMU) based motion system, has recently gain popularity because of its small size, portability, and capability of studying 3D motion. Ajdaroski et al. (2020) demonstrated the capability of a commercially available wearable IMU to measure 3D knee joints during jump. Fan et al (2021) and Di Raimondo et al. (2022) used another IMU-based motion system (i.e. Xsens system) to study 3D joint angles. In this paper, Xsens motion system was used as the standard to validate Behrend motion analysis system.

3. Methods

Behrend motion analysis system as shown in Figure 1 is composed of primary components: hardware and software. The hardware includes one Gopro 10 camera, two emergency triangles, 12 styrofoam markers (10mm ID dot in 25mm ball), and one force plate. One triangle is placed in the side plane and the other one is placed in the front plane. 6 body markers were placed on the leg, and 6 body markers were placed on the thigh with 4 of those markers aligned with side plane and the other 2 markers align with the front plane at the initial standing position. Each emergency triangle has 7 calibration markers.

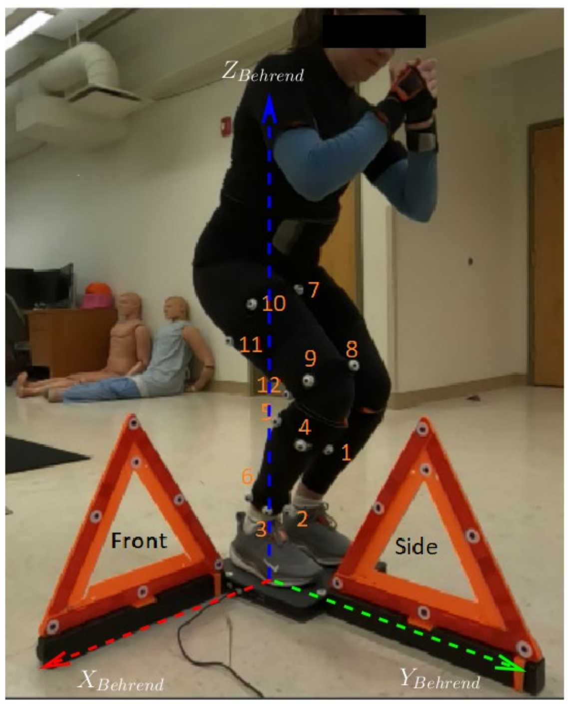

Figure 1. Configuration of Behrend motion analysis system

The software of Behrend motion analysis system is composed of a free software Kinovea and a custom-designed kinematics analysis application created with MATLAB. The kinematics app we developed is based on the computer vision theory by Trucco & Verri (1998) and is targeting 3D motion. Figure 2 shows its workflow. The video captured by Gopro camera is processed in Kinovea to extract body markers' pixel trajectories. Those trajectories together with the coordinates of calibration markers were used to derive the projective matrix from the subject at standing position to camera, and initial 3D coordinates of body markers. Using the derived initial 3D coordinates and pixel trajectories of body markers, the 3D kinematics data of jump can be obtained from the motion analysis app. The paragraphs below elaborate on the analysis in greater detail.

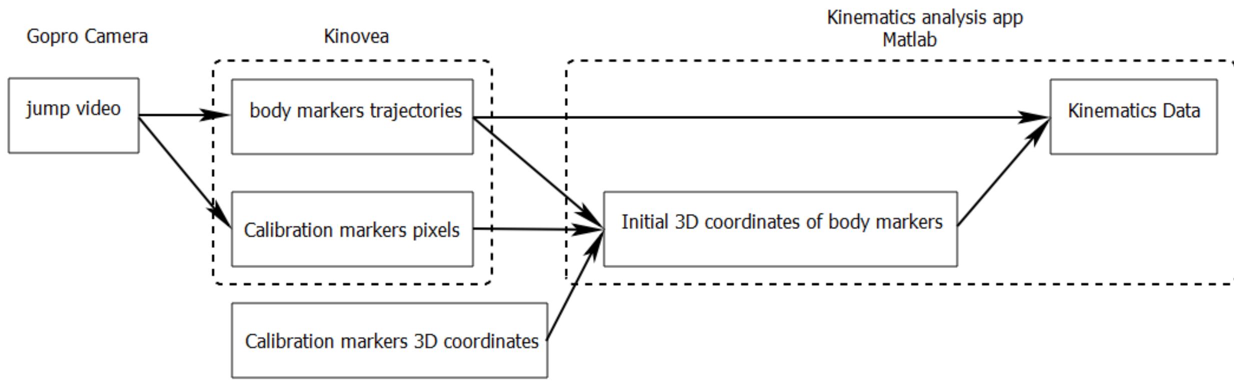

Figure 2. Workflow scheme of Behrend motion analysis system

Two orthogonal triangles in Fig 1 formed the Behrend global coordinate system. Each calibration triangle has 7 markers whose X_G, Y_G, Z_G are known in advance, and whose x_p, y_p can be obtained from the jump video. The pixels of each calibration markers is related to its 3D global coordinates as described in equations and

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \underbrace{\begin{bmatrix} f_x & s & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}}_{[K]} \underbrace{\begin{bmatrix} R_G^C & \begin{matrix} d_x \\ d_y \\ d_z \end{matrix} \end{bmatrix}}_{[T_G^C]} \begin{Bmatrix} X_G \\ Y_G \\ Z_G \\ 1 \end{Bmatrix} = \underbrace{\begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \end{bmatrix}}_{[H]} \begin{Bmatrix} X_G \\ Y_G \\ Z_G \\ 1 \end{Bmatrix}$$

$$\begin{Bmatrix} x_p \\ y_p \end{Bmatrix} = \begin{bmatrix} -\dfrac{x}{z} \\ \dfrac{y}{z} \end{bmatrix} = \begin{bmatrix} -\dfrac{h_{11}X_G + h_{12}Y_G + h_{13}Z_G + h_{14}}{h_{31}X_G + h_{32}Y_G + h_{33}Z_G + h_{34}} \\ \dfrac{h_{21}X_G + h_{22}Y_G + h_{23}Z_G + h_{24}}{h_{31}X_G + h_{32}Y_G + h_{33}Z_G + h_{34}} \end{bmatrix}$$

where $[K]$ is the intrinsic camera matrix that includes several parameters, *fx*, *fy*: focal length in pixels; *cx, cy*: optical center (the principal point) in pixels; *s*: the skew parameter. Those parameters were identified in advance using Matlab camera calibration app. $[T_G^C]$: the rigid transformation matrix from Behrend coordinate system to the camera system, R_G^C : the rotational transformation matrix, d_x, d_y, d_z : the translational displacement. Note: x, y, z are just intermediate variables that are not measurable. The measurable variables are global coordinates: X_G, Y_G, Z_G and pixels: x_p, y_p. The negative sign in equation for x_p is due to the fact that the positive *x* axis of pixel is the negative *x* axis of Gopro camera. Plugging in values of X_G, Y_G, Z_G and x_p, y_p of all 14 calibration markers in equation (2), we can find the least square solution of the projective matrix $[H]$ at standing. It is noted that h_{34} of $[H]$ is the distance from the subject to the Gopro camera. The derived $[H]$ can be further used to find the unknown coordinates of body markers that were placed on the front plane by assuming $Y_G = 0$ in equation , resulting in:

$$\begin{Bmatrix} X_G \\ Z_G \end{Bmatrix} = \begin{bmatrix} h_{11} + h_{31}x_p & h_{13} + h_{33}x_p \\ h_{21} - h_{31}y_p & h_{23} - h_{33}y_p \end{bmatrix}^{-1} \begin{Bmatrix} -h_{14} - x_p h_{34} \\ -h_{24} + y_p h_{34} \end{Bmatrix}$$

Similarly, for points on the side plane ($X_G = 0$), we can find:

$$\begin{Bmatrix} Y_G \\ Z_G \end{Bmatrix} = \begin{bmatrix} h_{12} + h_{32}x_p & h_{13} + h_{33}x_p \\ h_{22} - h_{32}y_p & h_{23} - h_{33}y_p \end{bmatrix}^{-1} \begin{Bmatrix} -h_{14} - x_p h_{34} \\ -h_{24} + y_p h_{34} \end{Bmatrix}$$

At the start of jumping, four body markers on the leg and four markers on the thigh are aligned with the side plane. Their coordinates can be derived using equation . The other two body markers on the leg and those two on the thigh are aligned with the front plane. Their coordinates can be found using equation .

The derived coordinates of 6 body markers on the leg, together with their pixel trajectories found in Kinovea can be used to derive the projective matrix $[H]$ from the leg to the camera at each time instance. The value of h_{34} in $[H]$ is set to the value found at standing because the distance to the camera during jump stays the same. The rigid transformation matrix from the leg (i.e. tibia) to the camera $[T_T^C]$ can be found as:

$$[T_T^C] = [K]^{-1} [H]_T^C$$

where $[H]_T^C$ is the instantaneous projective matrix from the leg (i.e. tibia) to the camera, and $[K]$ is the known intrinsic camera matrix. Similarly, we can use the derived coordinates of 6 body markers on the thigh, together with their pixel trajectories to derive the projective matrix $[H]_F$ from the thigh (i.e. femur) to the camera at each time instance. The rigid transformation matrix $[T_F^C]$ can be found as:

$$[T_F^C] = [K]^{-1} [H]_F^C$$

The rotational matrix from the tibia to the femur $[R_T^F]$ can be found as:

$$[R_T^F] = [R_F^C]^{-1} [R_T^C]$$

where $[R_F^C]$ is the rotational matrix from the thigh (i.e. femur) to the camera, and $[R_T^C]$ is the rotational matrix from the leg (i.e. tibia) to the camera. They are the first three columns of $[T_F^C]$ and $[T_T^C]$ respectively. To ensure the physical validity of the results for $[R_F^C]$ and $[R_T^C]$, equations (8-9) derived from the properties of a rigid rotation matrix were incorporated into the process.

$$\|R_1\| = 1, \|R_2\| = 1, \|R_3\| = 1$$

$$R_1 \cdot R_2 = 0,\ R_1 \cdot R_3 = 0, R_2 \cdot R_3 = 0 \qquad (9)$$

Note: $[R]$ in equations (8-9) is the abbreviation of $[R_F^C]$ or $[R_T^C]$. $R_i\ (i = 1,2,3)$ represents the column vectors of $[R]$. Finally, the 3D kinematics of tibia, femur and the knee (i.e. tibia relative to femur): flexion/extension angle θ_1, abduction/adduction angle θ_2, and the internal/external rotation angle θ_3 can be found from the corresponding $[R]$ using equation (10).

$$\theta_1 = \tan^{-1}\left(\frac{-R_{23}}{R_{33}}\right)$$
$$\theta_2 = \tan^{-1}\left(\frac{R_{13}}{\sqrt{R_{23}{}^2 + R_{33}{}^2}}\right)$$
$$\theta_3 = \tan^{-1}\left(\frac{-R_{12}}{R_{11}}\right) \tag{10}$$

4. Data Collection

A subject wore Xsens suits/sensors, and 12 Styrofoam markers (6 on the leg, 6 on the thigh) simultaneously as shown in Figure 1. Seventeen Xsens MVN Awinda wearable inertial sensors (Movella, Netherlands) were securely attached to the subject following the user manual. A skeletal model was generated in the Xsens software for the subject to capture full-body movements. The subject jumped vertically on the force plate for a total of eight times. The Gopro camera recorded the jump from the right side five times, and three times from the left side, both at roughly 1.5 meter from the subject and 45 degrees from the front plane. All markers were visible to Gopro in the vertical jump with this configuration. The camera recorded at 240 fps with 2.7K pixels.

5. Results and Discussion

Figures 3-6 show the comparison of Behrend results and Xsens results of a representative jump (i.e. Right Jump 3). The raw data of Behrend results were converted to Xsens coordinate system and referred as $\text{Behrend}_{\text{modified}}$ in this paper. Table 1 shows the Mean, SD and Root-mean-square deviation (RMSE) of the continuous tibia/femur/knee angle error (i.e. Xsens results−Behrend results) of all eight trials. Those parameters were calculated for the jump period T, as shown in Figure 3 top graph.

Table 1. Mean, SD and RMSE of continuous tibia/femur/knee flexion, adduction and internal rotation error

	Flexion error (°)		Adduction error (°)		Internal rotation error (°)	
	Mean±SD	RMSE	Mean±SD	RMSE	Mean±SD	RMSE
Knee	-7.69±4.75	9.04	3.93±4.79	6.2	3.58±6.37	7.3
Tibia	-6.3±4.99	8.04	4.72±7.54	8.89	2.33±5.24	5.73
Femur	1.1±1.98	2.26	-0.82±3.85	3.94	-0.87±4.36	4.45

The waveform similarity between Behrend results and Xsens data was assessed using Pearson Correlation Coefficient. There was a strong linear correlation between the Xsens results and Behrend results when examining the flexion angles (R^2>0.97) of tibia, femur and knee of all trials. The motion range of knee as measured by Xsens is flexion (14° to 85°), adduction (-8° to -3°), and internal rotation (-8° to 2°). A negligible relationship between the two systems was observed when examining adduction angles and internal rotation angles (R^2 close to 0 for some cases).

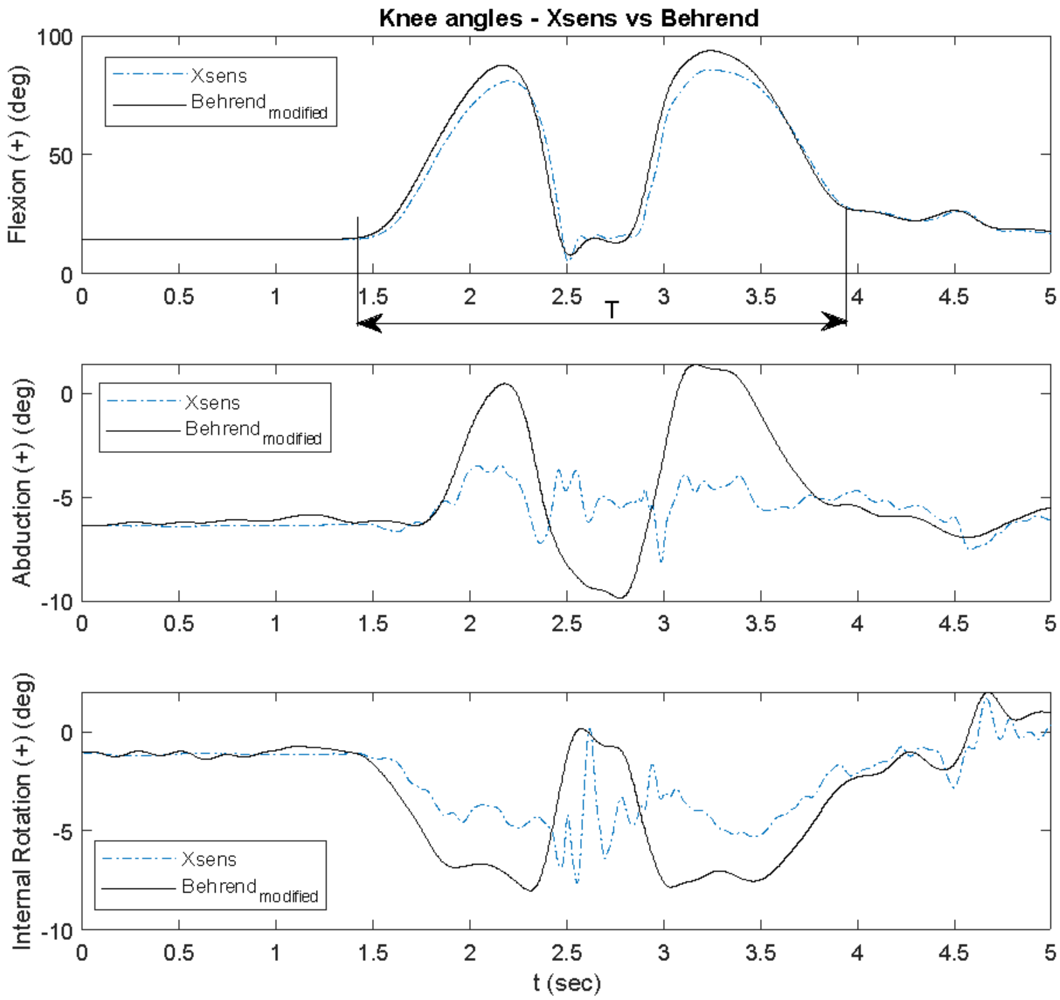

Figure 3. Three knee angles including flexion, adduction and internal rotation. Xsens (blue dash-dotted line) represents the results from Xsens system. Behrend$_{modified}$ (black solid line) represents the Behrend results expressed in Xsens coordinate system.

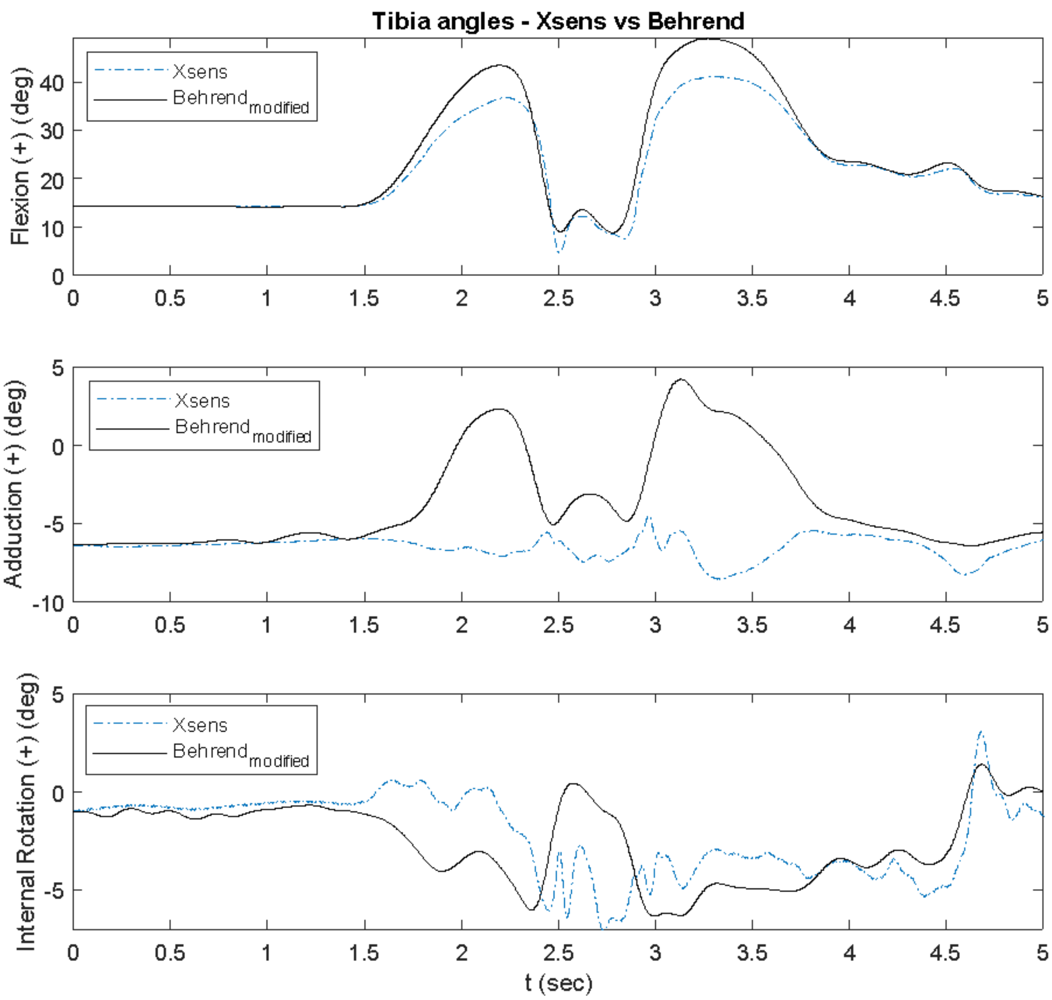

Figure 4. Three tibia angles including flexion, adduction and internal rotation. Xsens (blue dash-dotted line) represents the results from Xsens system. $Behrend_{modified}$ (black solid line) represents the Behrend results expressed in Xsens coordinate system.

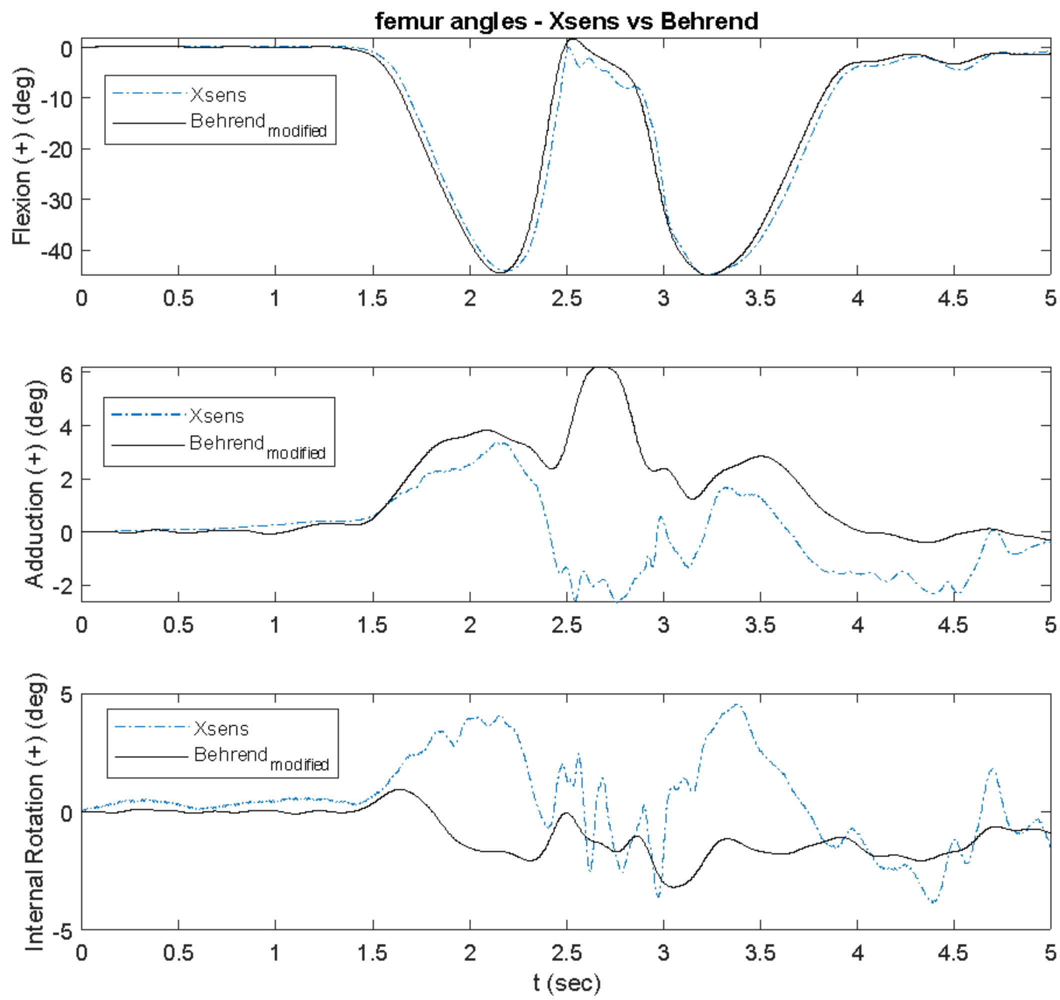

Figure 5. Three femur angles including flexion, adduction and internal rotation. Xsens (blue dash-dotted line) represents the results from Xsens system. $\text{Behrend}_{\text{modified}}$ (black solid line) represents the Behrend results expressed in Xsens coordinate system.

In most clinical applications, an error less than 2° is considered acceptable, whereas errors between 2° and 5° are also acceptable but require specific interpretation, as summarized by Iosa et al (2016) and Poitras et al (2019). When comparing the results from Behrend system to the results of Xsens system, the RMSE value of flexion error of femur is 2.26°, and flexion error of tibia or knee joint is over 8°. Meanwhile, the flexion measurement of Behrend system shows strong correlation with the flexion measurement of Xsens system (R^2 >0.97). That means when Behrend system is used to measure flexion, the trend shown in the measurement is reliable, but the absolute value needs to be interpreted carefully with a possible absolute error larger than 8° over a large flexion range.

Regarding adduction and rotation angles, the RMSE error of Behrend system is more than 4° in the tibia, femur and knee measurement. Meanwhile, negligible correlation was observed between two systems' results in adduction and rotation angles. That suggests the Behrend system measurements for adduction and rotational angles may not be directly applicable.

When examining the error, we recognize a few key factors. The first one is related to the coordinate systems adapted. Behrend system measurements were converted to the Xsens coordinate system. Brenna et al (2011) showed that the smaller axes misalignment in two different coordinate systems could contribute to greater knee angle error, especially larger adduction or rotation angle error. There is a possibility that the coordinate system applied during the conversion of Behrend results is not fully aligned with the Xsens system. Further examination is underway to identify those axes misalignment. The second factor involves marker placement: some markers on the human subject may not be aligned with either the front or side plane of Behrend system (Fig 1). This misalignment introduced errors in the coordinate calculations using equation (3), which subsequently affected the accuracy of the adduction and rotation derivation. Another contributing factor is pixel tracking error in Kinovea, which arises from inconsistencies in how the software tracks markers—sometimes following the center and other times the boundary of the marker.

6. Conclusion

A single camera motion analysis system (referred as Behrend motion analysis system) was developed to study 3D knee kinematics. Its accuracy was tested as compared to commercial 3D motion tracking system Xsens. The Behrend motion analysis system has demonstrated effectiveness in measuring flexion angles; however, its accuracy is limited when evaluating adduction and rotational angles during a vertical jump.

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This study was conducted following approval from the Institutional Review Board of Pennsylvania State University, under protocol number [STUDY00022416].

Biographies

Nicole Croushore is an undergraduate student pursuing a degree in Mechanical Engineering with a Biomedical Engineering minor at Penn State Behrend. She is expected to receive her Bachelor in May 2025. Her research includes motion analysis system, gender-related biomechanical difference in knee, ACL injury in athlete using motion analysis.

Dr. Yi Wu is a Professor in the Department of Mechanical Engineering at Pennsylvania State University Erie, the Behrend College. She received her Ph.D. in Mechanical and Aerospace Engineering from University of Virginia in 2004. Dr. Wu's recent research interests include sports biomechanics, portable motion analysis system, vibration and control, and pedagogical research.

Dr. Xiaoxu Ji is an Associate Professor in the Department of Biomedical, Industrial and Systems Engineering at Gannon University. He received his Ph.D. in Kinesiology from the University of Western Ontario, Canada in 2015. Dr. Ji's main research interests include the integration of Motion Tracking technology and Virtual Reality with Ergonomics in diverse workplaces; the application of Robotics to reduce the risk of whole-body vibration during vehicle or flight operations; the application of Artificial Intelligence (Neural Network) in modeling design.