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Non-proprietary movement analysis software using wearable inertial measurement units on both healthy participants and those with anterior cruciate ligament reconstruction across a range of complex tasks: validation study

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Abstract
Background:
Movement analysis in the clinical setting is frequently restricted to observational methods to inform clinical decision making, which has limited accuracy. Fixed-site optical expensive movement analysis laboratories provide ‘gold-standard’ kinematic measurements, however they are rarely accessed for routine clinical use. Wearable inertial measurement units (IMUs) have been demonstrated as comparable, inexpensive and portable movement analysis toolkit. MoJoXlab has therefore been developed to work with generic wearable IMUs. However, before using MoJoXlab in clinical practice there is a need to establish its validity in participants with and without knee conditions across a range of tasks with varying complexity.

Objective:
This paper presents the validation of MoJoXlab software for using generic wearable IMUs in calculating hip, knee and ankle joint angle measurements in the sagittal, frontal and transverse planes, for walking, squatting and jumping in healthy participants and those with anterior cruciate ligament reconstruction.

Methods:
Movement data were collected from 27 healthy participants and 20 participants with Anterior Cruciate Ligament (ACL) reconstruction. In each case, participants wore seven ‘MTw2’ IMUs to monitor their movement in walking, jumping and
squatting tasks. Hip, knee and ankle joint angles were calculated in the sagittal, frontal and transverse plane using two different software packages: Xsens's validated proprietary MVN Analyze, and MoJoXlab. Results were validated by comparing the generated waveforms, cross-correlation (CC) and normalized root mean square error (NRMSE) values.

**Results:**
Across all joints and activities, for both healthy and ACL reconstruction data, the cross-correlation and normalized root mean square error for the sagittal plane are: 0.99 ± 0.01 and 0.042 ± 0.025 respectively; for the frontal plane: 0.88 ± 0.048 and 0.18 ± 0.078; and for the transverse plane (hip and knee joints only): 0.85 ± 0.027 and 0.23 ± 0.065. On comparing results from the two different software systems, the sagittal plane is very highly correlated, with frontal and transverse planes showing strong correlation.

**Conclusions:**
This paper demonstrates that non-proprietary software such as MoJoXlab can accurately calculate joint angles for movement analysis applications comparable to proprietary software, for walking, squatting and jumping, in healthy individuals and those following anterior cruciate ligament reconstruction. MoJoXlab can be used with generic wearable IMUs that can provide clinicians accurate objective data when assessing patients’ movement, even when changes are too small to be observed visually. The availability of easy-to-setup, non-proprietary software for calibration, data collection and joint angle calculation has the potential to increase the adoption of wearable IMU sensors in clinical practice, as well as in free living conditions, and may provide wider access to accurate, objective assessment of patients’ progress over time.

**Keywords:** physiotherapy; wearables; inertial sensors; IMU; joint angles; biomechanics; validation; software; movement analysis;

**Introduction**
Within biomechanics, sports science and physiotherapy, assessment of movement patterns for activities such as walking are vital to their practice to inform decision making around performance, recovery and risk of re-injury [1]. In clinical settings, present physiotherapy practice relies extensively on visual assessment of movement quality and on the use of associated subjective clinical scales [2]. Both play important roles in decision making for treatment selection. However, there can be considerable variation in the quality of assessments depending on the experience of physiotherapists, and inter-rater agreement is not always as strong as might be hoped [2]. Objective and more accurate assessment during physiotherapy sessions has the potential to facilitate more accurate diagnoses and more consistent treatment selection [3]. It also has the potential to provide objective feedback to surgeons to demonstrate the actual post-operative effect of different decisions made during surgery [4]. This is very important for people with anterior cruciate ligament
reconstruction. Anterior cruciate ligament rupture is a common sporting injury to the knee that frequently results in surgery to reconstruct the ligament [5,6]. This is followed by a lengthy period of rehabilitation and the ability of these individuals to return to sport varies and has been reported to be as low as 65% returning to their pre-injury level of activity [7]. The reasons for this are multi-factorial but one important factor is that people with ACL reconstruction are known to move with biomechanical compensation strategies despite rehabilitation [8–10]. This can put them at risk of re-injury and future osteoarthritis so it is important that clinicians have tools available to them in the clinical setting to assess the biomechanics during tasks that mimic sporting manoeuvres [10–12].

Three-dimensional (3D) motion-capture camera-based systems can provide gold-standard assessment of body movement, however, such laboratories are expensive, time consuming, labour-intensive and effectively non-portable [13]. Data analysis is similarly resource intensive, time consuming and requires specially trained personnel [14]. These limit 3D motion-capture camera-based systems to research settings and are scarce in clinical practice [1]. However, wearable IMUs can offer similarly objective assessment of body movement and are relatively much less expensive, easier to setup, mobile, and usable by clinicians with minimal training. IMU sensors consist of triaxial accelerometer, triaxial gyroscope, and triaxial magnetometer. Data collected by an IMU is processed to calculate sensor position, speed and orientation. For certain IMUs and software, these results have been shown to be comparable to 3D motion-capture camera-based systems [3]. These characteristics strongly suggest that sensors have great potential use in clinical practice. The availability of validated and low-cost non-proprietary systems could make such systems affordable and much more widely used in clinical practice.

Existing systems pose a limitation of having a complex calibration process. Hullfish et al. [2] have tried to address this issue by presenting a self-calibrated wearable sensor system for knee joint angle measurements only. Even though they have used a single low-cost wearable inertial sensor and a simple calibration process, the system is not suitable for more complex activities such as walking, squatting and jumping. Moreover, they have not demonstrated the use of the system in a clinical setting or included any patients. Similarly, Nazarahari et al. [15] have proposed a calibration method using multiple wearable IMUs to reduce measurement errors due to calibration for gait kinematics. The proposed calibration method [15] is simpler than some of the existing methods, however the calibration requires specific movements such as hip abduction and adduction to a predefined degree, which might be a challenge for people with knee conditions.

To address the limitations mentioned above we have developed MoJoXlab, non-proprietary software, through academic-clinical research collaboration. MoJoXlab has been developed to provide a more practical system for clinical movement analysis. The software can be used with any generic wearable IMU sensors that produce orientation angles in quaternions. It employs a simple protocol for data collection and calibration to facilitate the use of wearable IMU sensors for clinical
movement analysis as the users deem fit and can also be used for diagnosis and prognosis in clinical settings. MoJoXlab implements an IMU-to-body calibration method [16–18]. Although previous literature [16] has explored this method during simple activities, such as walking in healthy participants, it is yet to be explored during complex activities such as squatting or jumping which are of interest to clinicians rehabilitating people back to sport. Within the movement analysis domain, jumping is considered to be a complex activity due to its dynamic nature such that even conventional gait measurement equipment finds it difficult to measure accurately. The data obtained from wearable IMU sensors deviate significantly from 3D camera-based motion capture data, due to the large impact on ground contact. The proprietary software MVN Analyze has solved this issue to a certain extent [19]. Currently, it is the only available validated software system and as a result have been used in this research as the gold standard. However, it is limited to only Xsens’s own proprietary IMU hardware. Therefore, there’s a need to develop a software system that can be used with any suitable IMU.

The aim of this study is to compare the hip, knee and ankle joint angles calculated in the sagittal, frontal and transverse plane by MoJoXlab against MVN Analyze from movement data collected using wearable IMU sensors during walking, squatting and jumping in healthy people in a non-clinical setting and people with anterior cruciate ligament reconstruction in a clinical setting.

Methods

Research Participants and Setting
Ethical approval for this study was obtained from Wales Research Ethics Committee 3 (10/MRE09/28). Written informed consent was obtained prior to participation. A sample of healthy participants (n = 27) was recruited using the following criteria: age between 18 and 60 years; healthy with no known neurological, cardiovascular, or musculoskeletal condition. Additionally, 20 participants following Anterior Cruciate Ligament (ACL) reconstruction were recruited from physiotherapy and orthopaedic knee clinics in one University Health Board using the following criteria: age between 18 and 60 years, had ACL surgery in at least one of their knees, within 6 to 12 months. The participant demographics are presented in Table 1.

Table 1: Participant Demographics for Health and ACL participants, showing the sample size (N), the mean age in years along with the standard deviation, the ratio of male to female, the mean body height in centimetres along with standard deviation, the mean body weight in kilograms, along with standard deviation and the ratio of Right to Left leg injury for ACL participants.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Sample</th>
<th>Age</th>
<th>Male/Female</th>
<th>Height</th>
<th>Weight</th>
<th>Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy</td>
<td>N = 27</td>
<td>35yrs ± 9</td>
<td>M:F = 2:3</td>
<td>162cm ± 34</td>
<td>72kg ± 13</td>
<td>---</td>
</tr>
<tr>
<td>ACL</td>
<td>N = 20</td>
<td>29yrs ± 9</td>
<td>M:F = 7:3</td>
<td>177cm ± 11</td>
<td>84kg ± 18</td>
<td>R:L = 2:3</td>
</tr>
</tbody>
</table>
**Experimental Protocol**

Each participant underwent at least one movement analysis session, with all healthy participants returning for another session within about a week later (mean ± standard deviation, 4 ± 3 days). On each day, the measurements were repeated twice, once with a Biomechanics expert putting on the sensors and performing data collection and in the other instance, a physiotherapist performed the same. Thus, a total of 4 sessions of data were recorded for each healthy participant [Day 1 – Experiment 1 (performed by Biomechanics expert), Day 1 – Experiment 2 (performed by Physiotherapist; Day 2 – Experiment 1 (performed by Biomechanics expert), Day 2 – Experiment 2 (performed by Physiotherapist)]. The inter-rater reliability was acceptable across all planes for walking and squatting joint angles and for jumping it ranged from Poor to Excellent [3].

Data collection for all healthy participants were carried out in the Research Centre for Clinical Kinaesiology at Cardiff University. In the case of participants with ACL reconstruction, the data collection took place in the clinic and was conducted by a physiotherapist. For all the participants (both healthy and people with ACL reconstruction), during the first session, anthropometric measurements were taken by a physiotherapist from the right lower limb while the participant maintained standing posture. Seven MTw2 trackers (Xsens Technologies, Enschede, Netherlands) were then placed in accordance with Xsens’s instructions [20]. MTw2 trackers were secured using elasticated Velcro straps on each upper thigh (centrally and halfway between the greater trochanter and lateral epicondyle of the knee), each lower leg (proximal medial surface of the tibia), the dorsum of each foot and one centrally over the sacrum. Each lower-limb tracker was placed between the two outermost layers of the strap and attached to the Velcro of the inner layer to secure its position and minimise any movement. The sacral tracker was placed directly over the sacrum with the upper border of the sensor aligned centrally between the two posterior superior iliac spines. The sacral sensor was held in position with medical-grade double-sided adhesive tape.

Where possible, all the participants (both ACL and healthy) performed eight repetitions of each of the following three activities: over-ground walking, squatting, and vertical jumping. Some of the ACL reconstruction participants were exempted from activities that they found difficult, for example, only 7 participants performed the vertical jump. Prior to performing each activity, the participant was provided with a demonstration by the physiotherapist and could ask any questions. The order of the activities was randomised across participants, but consistent within participants. Each walking trial consisted of a walk in a straight line across the laboratory or clinic (approximately 8 m), at the participants’ natural pace. For healthy participants, the walking trial was repeated 5 times and for participants with ACL reconstruction the walking were repeated 2 times. A walking trial consisted of 8 gait cycles of walking and similarly, one such jumping or squatting trial consisted of 8 jumps and squats. The squat depth and jump height were not measured.
MoJoXlab
MoJoXlab is a MATLAB based custom motion capture analysis software toolkit whose aim is to produce freely available motion capture analysis software to be used by anyone interested in generating lower limb joint kinematics waveforms using any suitable IMUs [21]. MoJoXlab is used in this study to generate joint angles for different functional tasks such as walking, squatting, and jumping, the joint angles are then validated against commercially available MVN Analyze. The joint kinematics for MoJoXlab is based on Joint Coordinate System (JCS) as proposed by Grood and Suntay [17]. MoJoXlab takes sensor orientation data in quaternions as input and outputs joint angles in degrees. The joint angles generated by this method are then compared to the joint angles generated by the proprietary MVN Analyze software. The algorithm considers a static calibration step, where sensor data is captured for calibration purposes while the participant maintains a standing pose [16]. This calibration step is then used to calculate the joint angles for the dynamic phase of the motion.

Calibration and Data Collection
Kinematic data were collected using the MTw2 trackers at 60 Hz, all the trackers were connected to the computer using WIFI technology. The data were recorded in the computer using the Xsens MVN Analyze system (Xsens Technologies). Prior to beginning the tasks, the participant was asked to stand in a static N-pose, as per the instructions in the MVN Analyze user manual [20]. This was maintained for ~30 s. At the start of this period of quiet stance, the MTw2 trackers were calibrated within the MVN Analyze software. During this process, the software establishes the relation between body segment and tracker orientations [17,22]. The calibration data saved within MVN Analyze is proprietary and cannot be extracted. Consequently, an additional static calibration data was collected by asking the participant to maintain a standardised standing posture, to be used as a static calibration dataset within our custom MoJoXlab software [16]. This allows raw data collected from the all MTw2 trackers to be projected to one global coordinate system. Then the data for each activity was collected using MVN Analyze software. The purpose of using the MVN Analyze software was two-fold: to capture the data streamed from the trackers and to later calculate the joint angles as per MVN’s proprietary algorithm in order to compare the joint angles with our custom MoJoXlab software. However, MoJoXlab uses the raw data from the same trackers to calculate joint angles and is independent of the MVN Analyze software.

Data Processing
As mentioned earlier, data obtained from the trackers were saved using the MVN Analyze software. Hip, knee, and ankle joint angle calculations were also performed using the same proprietary software. All the data generated by MVN Analyze were exported in mvnx file formats (MVN Analyze’s open XML data format). These files were later imported to MATLAB software (version 2018b; The MathWorks Inc., Natick, MA, USA) and MoJoXlab was used to extract the raw sensor data from the mvnx files to calculate another set of hip, knee, and ankle joint angles.
The joint angles were generated for each activity (walk, jump, squat), each joint (hip, knee, ankle), each plane of movement (sagittal, frontal, transverse) and each side of the body (left, right). However, our custom algorithm within MoJoXlab could only generate angles in the sagittal and frontal planes for the ankle joint. Positive joint angles indicate flexion, abduction, and internal rotation in the sagittal, frontal, transverse planes respectively.

**Data Analysis and Validation**

Joint angles obtained by MVN Analyze and MoJoXlab were compared and analysed using separate custom scripts written in MATLAB. The workflow for data processing, analysis, validation and visualisation is outlined in Figure 1.
Figure 1: Block diagram - Workflow for data processing, analysis and validation

Custom MATLAB scripts were used to:
1. Extract joint angles calculated by MVN Analyze from mvnx files and then saved as MAT-file (MATLAB’s data format)
ii. Extract raw sensor data in quaternions from mvnx files and then use MoJoXlab to calculate another set of joint angles distinct from the ones calculated by MVN Analyze. The joint angles were then saved to a MAT-file.

iii. Visualize joint angle waveforms, calculate cross-correlation, root mean square error values between the waveforms and plot their graphs.

During data collection phase for each healthy participant 4 trials were collected, so for 27 healthy participants, a total of 108 trials were collected. Of these, 13 were excluded from the analysis, as there were some data missing for each of them. For healthy participants, 95 data trials were used for analysis.

Similarly, for 20 ACL reconstruction participants only one of them returned for a repeat session. All of them performed walking and squatting activity, but only 7 of them performed the jumping activity. Data for a total of 21 walk and squat trials were collected, and 8 jumps trials were collected (one participant performed the jump repeat session). Out of the 21 walk and squat trials, 2 were excluded as some data were missing. So, a total of 19 trials were used in the data analysis for the walk and squat activities, and 8 jump trials were used in the data analysis.

Waveforms of joint angles generated by MVN Analyze and MoJoXlab were compared inside the MATLAB environment using custom scripts, as explained earlier. In a previous study, the joint angles obtained from MVN Analyze were validated against joint angles obtained from the gold standard VICON system [3]. Thus, for this study, the joint angles generated from MVN Analyze can be used as reference values to compare the joint angles generated by MoJoXlab.

**Cross-correlation**

Cross-correlation is a similarity metric used in signal processing to assess the similarity between two signals [23–25]. The resultant values are obtained as a vector. By using the "coeff" function in MATLAB, it is possible to calculate the cross-correlation coefficient between the two compared signals [26]. The metric can then be interpreted in a similar manner to Pearson’s correlation coefficient, producing values between 0 – 1, with values closer to 1 indicating a higher correlation between the signals, and thus greater similarity.

Cross-correlation between MoJoXlab and MVN Analyze was calculated for each waveform to test for similarity. Firstly, the waveforms were center normalized to have mean zero and corrected for polarity. The cross-correlation coefficient was calculated in the range of 0 – 1, with values closer to 1 indicating a very high correlation.

**Normalized Root Mean Square Error**

Root mean square error (RMSE) is an alternative way of measuring the differences between sets of values. In this study, RMSE is used to measure the error in joint angle values between MVN Analyze and MoJoXlab. Two details are worth mentioning: firstly, applying RMSE naively to joint angles would produce error
values in degrees. However, due to the wide variety of joints, tasks, and participant groups, it would be difficult to compare RMSE values in a meaningful way across the dataset. To address this problem, the normalized version of root mean square error has been used. This produces values within the range of 0 – 1, where closer to zero indicates lower error (better agreement) between the joint angle waveforms.

Normalized root mean square error was calculated to compare the joint angles between MoJoXlab and MVN Analyze software [25,27–29]. The waveforms were standardized over the range of 0 – 1 and corrected for polarity. NRMSE was obtained within the range of 0 – 1 where values closer to 0 meant the least difference between the waveforms.

Results

Waveforms
This section presents joint angle waveforms, generated by MVN Analyze software and MoJoXlab, across all movement planes (Sagittal, Frontal and Transverse), for each joint (Hip, Knee and Ankle) and for each task (Walk, Squat and Jump). Figures 2-4 show representative joint angle waveforms from the healthy participant data set.

Figure 2: Representative sagittal plane joint angle waveforms from the healthy participant data set. Waveforms for hip (top row), knee (middle row) and ankle (bottom row) joint angles obtained from MVN Analyze (blue) and our custom software MoJoXlab (orange) for walk (left), squat (centre) and jump (right) tasks. Y-axis represents joint angles in degrees and X-axis represent data samples across the entire waveform.
Figure 3: Representative frontal plane joint angle waveforms from healthy participant data set. Waveforms for hip (top row), knee (middle row) and ankle (bottom row) joint angles obtained from MVN Analyze (blue) and our custom software MoJoXlab (orange) for walk (left), squat (centre) and jump (right) tasks. Y-axis represents joint angles in degrees and X-axis represent data samples across the entire waveform.

Figure 4: Representative transverse plane joint angle waveforms from healthy participant data set. Waveforms for hip (top row) and knee (bottom row) joint angles obtained from MVN Analyze (blue) and our custom software MoJoXlab.
Figures 5-7 show representative joint angle waveforms from people with ACL reconstruction data set.
Figure 6: Representative frontal plane joint angle waveforms selected from ACL reconstruction participants data set. Waveforms for hip (top row), knee (middle row) and ankle (bottom row) joint angles obtained from MVN Analyze (blue) and our custom software MoJoXlab (orange) for walk (left), squat (centre) and jump (right) tasks. Y-axis represents joint angles in degrees and X-axis represent data samples across the entire waveform.
Validation Results
This section presents the validation results for the joint angle waveforms using cross-correlation and normalized root mean square error. The MoJoXlab joint angle waveforms are compared with waveforms generated by MVN Analyze. Cross-correlation and normalized root mean square error values are calculated for each task, each joint and each plane. The results are presented below in parts, firstly the cross-correlation values are shown for both healthy and ACL reconstruction participants. Afterwards, the normalized root mean square error values are presented for healthy and ACL reconstruction participants.
The mean cross-correlation values across all participants (healthy and ACL reconstruction participants) are very high (CC > 0.95) for the sagittal plane across all the joints and tasks. For healthy participants for frontal plane across all tasks, CC > 0.83 and for ACL reconstruction participants for frontal plane across all tasks, CC > 0.78. Similarly, for transverse plane, for healthy participants across all tasks, CC > 0.83 and for ACL reconstruction participants across all tasks, CC > 0.84.
The normalized root mean square error for the sagittal plane are relatively low compared to other planes, for all participants (healthy and ACL across all tasks, NRMSE < 0.1). For healthy participants for frontal plane across all tasks, NRMSE < 0.17 and for ACL reconstruction participants for frontal plane across all tasks, NRMSE < 0.35. Similarly, for transverse plane, for healthy participants across all tasks, NRMSE < 0.22 and for ACL reconstruction participants across all tasks, NRMSE < 0.39.

In summary, for the sagittal plane across all joints and activities for both healthy and ACL reconstruction participants data, the cross-correlation coefficient and normalized root mean square error are: 0.99 ± 0.01 and 0.04 ± 0.03, similarly for frontal plane: 0.88 ± 0.05 and 0.18 ± 0.08, and for transverse plane hip and knee joints only: 0.85 ± 0.03 and 0.23 ± 0.07.

**Discussion**

This paper has demonstrated that MoJoXlab, our in-house developed software, can be used to calculate joint angles for movement analysis with generic wearable IMUs that report data in quaternions. MoJoXlab has a simple calibration procedure making the data collection process smooth. This makes MoJoXlab potentially easier
to use in clinical settings and this paper has established its validity and demonstrated that MoJoXlab can be used in a clinical setting by a clinician, across a variety of complex tasks such as walking, squatting and jumping, and across a variety of participants, both healthy and ACL reconstruction participants. Complex tasks such as jumping are very challenging to analyse accurately with wearable IMU sensors, due to the large ground impact force. MoJoXlab can accurately calculate joint angles for such complex tasks and thus can be potentially extended to calculate other complex tasks and exercises as well. MoJoXlab has been validated against proprietary MVN Analyze software which was previously validated against VICON based optical motion capture system, considered to be clinically ‘gold standard’ [3].

Al-Amri et al [3] have concluded that joint angle waveforms obtained from MVN Analyze showed excellent similarity with sagittal plane waveforms obtained by VICON system, and acceptable similarity for frontal and transverse planes across all three tasks. MVN Analyze and VICON systems were compared using Coefficient of Multiple Correlation (CMC) and R-squared (R2) values for the Linear Fit Method (LFM). CMC was found to be greater than 0.9 for all three joints in the sagittal plane across all tasks. Similarly, for sagittal planes R2 value was greater than 0.8 for all the joints across all the tasks and similarly R2 value showed fair-to-good similarity for transverse and frontal planes across all joints during squat and jump, and knee joint during walking. Thus, by the transitive property, we claim that MoJoXlab can generate joint angles comparable to optical ‘gold standard’ motion capture systems.

In the following sections we discuss the validation results between MoJoXlab and MVN Analyze for each of the planes in two ways: by comparing the joint angle waveforms across cross-correlation, and by computing the normalized root mean square error. We also discuss differences in healthy participants versus ACL reconstruction participants across activities.

**Cross-correlation**

For all joints, across all tasks and participants (both ACL reconstruction participants and healthy), the sagittal plane shows a very high correlation, with mean cross-correlation above 0.95. This indicates that MoJoXlab generates sagittal plane joint angle waveforms highly similar to that of MVN Analyze. The sagittal plane reflects joint angles for flexion and extension of the joints, which are most commonly referred by clinicians [30], to assess recovery and potential risk factors for injury to the ACL. Reduced range of motion in this plane is often associated with incomplete recovery and poor neuromuscular control. For example, reduced knee flexion during landing from a jump is associated with higher peak moments at the knee joint [31].

Similarly, the frontal plane is also useful for clinicians who are interested in abduction and adduction of the joints, as this is considered a risk factor for re-injury, poor neuromuscular control and incomplete recovery [30,32]. In the case of frontal planes, cross-correlations are also high for all joints: with values across all tasks and participant groups for ankle joints being greater than 0.84, for hip joints being greater than 0.78, and for knee joints being greater than 0.83.
In the case of the transverse plane, MoJoXlab can calculate joint angles for hip and knee joints only. In this plane, cross-correlation values across all tasks and participant groups for hip are greater than 0.83, and for knee joints greater than 0.83.

Overall, on observing the representative waveforms (Figures 2 – 7) and the high cross-correlation values (Figure 8) it is evident that MoJoXlab software can produce joint angles comparable to that of the commercial MVN Analyze software.

Previous work comparing software to calculate joint angles using wearable IMUs are limited. Hullfish et al. [2] have investigated knee joint angles in the sagittal plane only for seven healthy participants. They compared their IMUs with optical motion capture system. Their cross-correlation values were within the range of 0.84 to 0.99. In comparison to such values, we have obtained a mean cross-correlation range of greater than 0.95 for sagittal plane across all participant groups, activities and all joints. For other planes the cross-correlation is generally greater than 0.83 except for frontal plane for ACL reconstruction participants, where the values are greater than 0.78.

These results are overall comparable to previous studies and further extends previous work in healthy participants, which reported high agreement between joint angle waveforms in the sagittal plane for systems using IMUs and optical motion capture system [33,34]. Other studies have compared data obtained from Xsens IMUs for walking [35,36], squatting [14,37] and jumping [38,39]. However, our results extend previous work by including more challenging dynamic tasks such as squatting and jumping. We have also evaluated the validity of software in people with ACL reconstruction in addition to healthy people. The results confirm that MoJoXlab-based wearable IMUs can be used to assess tasks such as squatting and jumping in healthy and individuals following ACL reconstruction within a clinical setting.

**Normalized Root Mean Square Error**

Cross correlation as a measure of similarity is blind to both constant vertical offsets and differences in amplitude. As just noted, blindness to constant vertical differences are not of material interest for the purposes of the study, however differences in amplitude are of considerable importance because these would represent entirely different joint angle ranges. For this reason, it is valuable to use a complementary measure of similarity which is highly sensitive to differences in amplitude. In particular, the root mean square error (RMSE) corresponds to a single number representing the Pythagorean distance in a high-dimensional space between the two waveforms, and is highly sensitive to differences in amplitude, frequency and offset. In order to allow meaningful comparison of root mean square errors between different activities & joints, we have given the results as Normalised Root Mean Squares (NRMSE), where the RMSE is divided in each case by the range.
As noted previously, cross-correlation values for sagittal planes showed very high agreement between the waveforms generated by the two systems. Similarly, the NRMSE values obtained for sagittal planes also show a very low error (NRMSE < 0.1) across all tasks, joint angles, and participant groups. The low NRMSE values in conjunction with very high CC values, suggest that MoJoXlab can generate joint angle waveforms in the sagittal plane that are highly comparable to commercially available MVN Analyze software.

In the case of frontal planes, the healthy participant joint angles show lower error values (NRMSE < 0.17) than the ACL reconstruction participants group (NRMSE < 0.35). Similarly, in case of the transverse planes the healthy participant joint angles show lower error values (NRMSE < 0.22) than the ACL reconstruction participants group (NRMSE < 0.39). Thus, the NRMSE values for the ACL reconstruction participants group for both frontal and transverse planes are higher than their respective healthy participant group values. The error values for joint angles for frontal planes and transverse planes for healthy participants are within the reasonably accepted range of 0.2. The high CC and low NRMSE values for all healthy participants across all tasks and joints suggests excellent agreement between MoJoXlab and MVN Analyze.

To summarise, in the case of the ACL reconstruction participant group, values for the sagittal plane show high CC and low NRMSE values, suggesting excellent agreement. And for ACL reconstruction participants, transverse and frontal planes, the CC values are high thus confirming agreement on waveform pattern similarities between MoJoXlab and MVN Analyze. However, the underlying reasons behind slightly higher range of NRMSE error values for the ACL reconstruction participants group for frontal planes and transverse planes requires further investigation.

**Understanding the differences in waveforms**

The differences in joint angle waveforms for the same task and joint noted above may be due to several possible contributing factors. One of the significant contributing factors concerns the static calibration step described in the methods section. The calibration step carried out by the proprietary MVN system produces no externally inspectable data that can be used in this study. The calibration values captured by MVN during the calibration step are saved internally within the software. The values are not accessible to the user either on the software interface or when all the data are exported as *.mvnx files. Thus, MoJoXlab does not have access to MVN’s calibration values. A separate set of values were captured for MoJoXlab as its calibration step, while the participant maintained the same standing posture. In principle, the calibration values should be similar as the data is being captured for the same standing posture. However, it is reasonably possible that miniscule movements can vary the calibration values, even more so for ACL reconstruction participants than for healthy participants. It is likely that ACL reconstruction participants might find it difficult to maintain the same standing posture while the calibration steps are carried out. This might be a contributing factor to the difference in waveforms between the two software systems and also
for the slightly larger NRMSE values or the ACL reconstruction participants in comparison to healthy participants. In contrast, the healthy participants might have held similar static postures for the static calibration step, resulting in similar calibration values feeding to the two software and as a result, the waveforms are more in agreement for this participant group.

Another potential contributing factor is the different sites for data collection. For the healthy participant group both the static calibration steps and the functional tasks were measured in the lab. However, in case of the ACL reconstruction participants group, the calibration step was undertaken in the consultation room within the clinic and some of the activities took place outside of the consultation room in the corridor or a different room. The different sites for data collection for some of the tasks can account for the difference in the waveforms as a number of external factors can contribute to the difference in waveforms between the two software.

One such external factor is the presence of equipment in the clinic that causes magnetic interference. The physiotherapist conducting the data collection in the clinic noted that there was external magnetic interference affecting the sensor data. In principle, as the two software are using the same raw sensor data it can be understood that magnetic interference should not affect the outcome of the joint angle waveforms. However, there can be a difference in waveforms because MojoXlab and MVN Analyze handle magnetic interference in different ways. As of now, MojoXlab does not have any special software or algorithm that handles magnetic interference from the environment, and this is a limitation of the current version of MojoXlab. Whereas, Xsens claims that they have special software in MVN Analyze to handle magnetic interference from the environment, even though such claims have not been validated yet [40]. To use MojoXlab with data collected in clinical settings, people should be careful to determine if magnetic interference is affecting the data severely or not. It is possible that discrepancies could occur when collecting data over time due to external magnetic interference [41].

In clinical settings, three-dimensional camera-based motion capture systems are generally used for movement analysis, which tracks markers attached to the body over a certain field of space. As a result, it is possible to detect the movement of the body frame and body segments across time and space. However, motion tracking using IMUs use an inherently different principle, where the relative angular motion of each IMU sensors is combined using sensor fusion algorithms to calculate the joint angles for hip, knee and ankle joints. Thus, one of the limitations of using IMUs for clinical movement analysis, is that joint angles are considered separately for each joint and so phenomenon such as “shifting” of the knee cannot be detected by simply considering joint angles [42].

One of the major limitations of this study is that, while the number of trials available for analysis in the healthy participant group is quite large at 96 but the number is relatively small for ACL reconstruction participants, with walking and squatting tasks having 19 available trials, whereas the jumping task had only 8 available trials. This disparity in number of trials available for data analysis between healthy and
ACL reconstruction participants can also be one of the contributing factors to the difference in results. Further work is required to collect more data from people with ACL reconstruction for a better comparison between healthy and ACL reconstruction participants data.

**Further Work**

MoJoXlab is currently under development in collaboration with Cardiff University and The Open University. This article presented only the validation results between the waveforms generated by MoJoXlab and the proprietary MVN software. Further work is required to validate the various gait parameters calculated by MoJoXlab and to enable MoJoXlab to better handle external factors that can affect the data, such as magnetic interference. While MoJoXlab can work with any sensor that reports quaternions, in this particular study, the IMU data was collected using Xsens’s wearable IMU sensors. In the future, we would like to test how different wearable IMU sensors can be used with MoJoXlab.

**Conclusions**

This study has shown that a variety of clinically relevant functional tasks such as walking, squatting and jumping can be measured using wearable IMUs in both lab and clinical settings, by clinicians (in this case physiotherapists) using non-proprietary software. We have developed and validated this non-proprietary software against software that has been shown to be as accurate as an optical motion capture system. Validation results suggest that MoJoXlab can calculate joint angles comparable to proprietary MVN Analyze software across people with ACL reconstruction and healthy people, for tasks such as walking and more complex tasks such as squatting and jumping. Thus, MoJoXlab has the potential to provide clinicians with accurate movement analysis of their patients, across multiple joints and planes of motion and potentially be able to provide analysis of other complex tasks such as lunging and jumping. These reflect advanced rehabilitation and sporting manoeuvres that individuals following ACL reconstruction (and other injuries) need to be able to return to. It can potentially enable clinicians to benefit from using generic wearable IMUs in their practice to capture movement data of their clients and objectively track changes over time. Increasing adoption of such software and sensors in clinical practice has the potential for better decision making around exercise prescription, monitoring patient progress over time, tailoring advice and feedback and improving the rehabilitation process.

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Conflicts of Interest
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Abbreviations
ACL: anterior-cruciate ligament
CC: cross-correlation
CMC: coefficient of multiple correlation
IMU: inertial measurement unit
LFM: Linear Fit Method
NRMSE: normalized root mean square error
RMSE: root mean square error
R²: R-squared

References


