The Knee 26 (2019) 97–105

Contents lists available at ScienceDirect

The Knee

Repeatability of measuring knee flexion angles with wearable inertial sensors

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ARTICLE INFO

Article history:
Received 11 April 2018
Received in revised form 29 October 2018
Accepted 3 November 2018

Keywords:
Range
Motion
Inertial measurement unit
Total knee replacement
Wearable sensor
Repeatability

ABSTRACT

Background: As assessment with inertial-measurement-units (IMUs) increases in research and in clinics, it is important to be aware of the repeatability of these sensors. The objectives of this experiment were to evaluate the measurement repeatability of IMU joint angles using a repeatable robot controller and an anthropomorphic leg phantom and to determine effects of joint speed and sensor positioning on the angles collected by these sensors. Comparisons to an electro-goniometer and three-dimensional (3D) motion capture cameras were also completed.
Methods: Two dual-IMU setups (posterior and lateral) were tested concurrently with an electro-goniometer and 3D motion capture cameras using a repeatable robot controller and a leg phantom. All modalities were attached to the phantom, which was flexed 10 times using a pre-programmed motion pathway during each test. Mean angles were compared across tests. Effects of joint speed, sensor re-positioning, and anatomical placement of the sensors on repeatability were assessed.
Results: Re-positioning caused greater deviation to the maximum and minimum angles than differences in speed. Overall, the means ± standard deviations, and 95% confidence intervals of the maximum angles across all tests for the 3D camera markers, electro-goniometer, posterior IMUs, and lateral IMUs were 119.4 ± 0.3° (119.4, 119.5), 112.4 ± 0.5° (112.3, 112.5), 116.2 ± 2.4° (115.7, 116.7), and 118.3 ± 1.1° (118.1, 118.6).
Conclusions: Both posterior and lateral IMU setups demonstrated acceptable repeatability in measurement of range of motion that was advantageous to manual goniometer methods. Posterior and lateral IMU setups demonstrated overlapping standard deviations about their means.

1. Introduction

Assessments of knee joint flexion and extension range of motion are commonly used by surgeons to track patient function and recovery following knee arthroplasty [1]. Patients that experience post-arthroplasty improvements in knee biomechanics typically report good outcomes, while those who lack improvements do not [2]. Clinicians often collect range of motion data using manual, hand-held goniometers, which have been known to have poor accuracy and repeatability. In research settings, this kinematic

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https://doi.org/10.1016/j.knee.2018.11.002

information can be gathered through a variety of devices, including most commonly electro-goniometers and three-dimensional (3D) motion capture cameras. However, these modalities have multiple factors limiting their potential application in clinics. Electro-goniometers are limited to two planes of motion, and the mechanical strain gauge that measures angles implements physical constraints on sensor placement. Three-dimensional motion capture cameras are the gold standard for motion capture, but this modality requires a stationary lab, complex interpretation, and substantial patient time commitment, and is very expensive.

Inertial measurement units (IMUs) have become increasingly popular as a method to capture kinematic data [3]. These sensors commonly measure acceleration, velocity, and orientations in space and cost much less than a traditional 3D motion capture camera system [4]. IMUs can be used to calculate joint angles using the orientations in space collected from two separate sensors [5]. Aside from cost, the small physical nature and wireless capability of IMUs means they can be attached unobtrusively to subjects as wearable sensors and then be implemented during physical activities to evaluate joint qualities that are characteristic of dynamic function [6,7]. These sensors also have great potential for assessment outside of the lab environment by tracking functional tests or daily activities. Wearable sensors can be easily applied to knee joint research to provide important information regarding characteristic functionality of knee joint pathologies [6], and have the potential for instant clinician interaction and data interpretation.

As the use of IMUs for such assessments is increasing, clinicians and researchers must be aware of their limitations with respect to the repeatability of their measurements. The purpose of the present study was to determine the repeatability of IMU joint angle measurement using a repeatable robot controller and an anthropomorphic leg phantom. Effects of joint speed and sensor re-positioning on the repeatability of knee angle measurement by IMUs were assessed. We hypothesized that 1) the IMUs would provide better repeatability overall than that of a manual goniometer, 2) the effects due to speed or re-positioning would result in deviation less than $\pm 5°$, and 3) the posterior and lateral IMU setups would have overlapping deviations about their means. A secondary assessment of 3D motion capture camera markers and an electro-goniometer was included in this experiment to compare these modalities to the proposed IMU setups.

2. Methods

2.1. Robot & phantom setup

A six-degree-of-freedom robotic controller was used in this experiment to provide repeatable motion paths to determine the bounds of repeatability of two pairs of IMUs for future studies with human subjects. This experiment represents the best-case scenario; therefore if the repeatability is not acceptable here, then such sensors would not be appropriate for clinical use where repeatability is likely to be worse. The phantom itself provided anatomical references for positioning of the modalities as well as simulated soft tissue that could introduce motion artifacts that would be typical of a patient. In addition to being a repeatable platform for evaluation, this experimental setup allowed for simulation of human motion that was completely controlled. The anthropomorphic leg phantom (Sawbones Fully Encased Leg, Pacific Research Laboratories, Vashon, WA) was affixed to the robot via a custom fixture to anchor the upper segment of the leg to a stationary platform and to affix the lower leg segment to the mobile end-effector of the robot arm. The end-effector of the robot arm was programmed to move in an arc to revolve the lower segment of the leg phantom about the knee joint to approximately 120° of flexion from a straight-leg position.

2.2. Motion capture modalities

Three motion capture modalities were used in this experiment: 3D motion capture cameras, an electro-goniometer, and two IMU setups. See Figure 1 for the setup of the motion capture modalities described as follows. An 11-camera, 3D motion capture

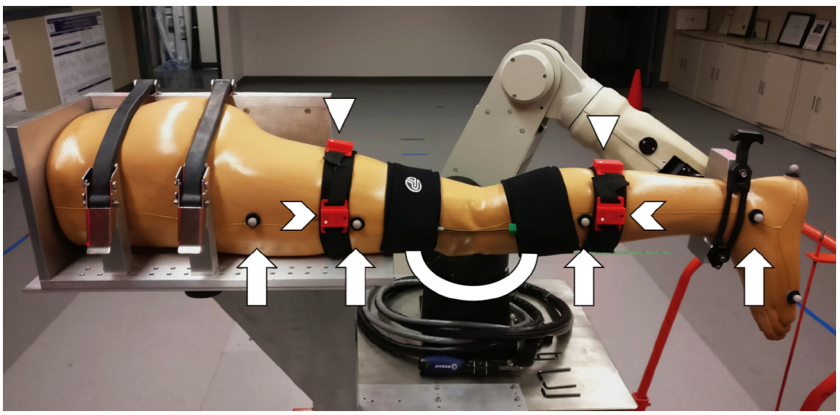

Figure 1. Experimental setup of the motion capture modalities on the leg phantom. The upward pointing arrows indicate the 3D camera reflective markers used for angle calculation, the upward facing arc encompasses the length of the electro-goniometer, the downward pointing triangles indicate the posterior IMUs, and the right and left pointing chevrons indicate the lateral IMUs. The two unaccounted for reflective markers on the foot of the phantom were used as a means for identifying the lower segment from the upper leg segment in post-processing.

system (Motion Analysis Corporation, Santa Rosa, CA) with four passive reflective markers was used as a gold standard for non-invasive motion capture technology to evaluate the robot repeatability and as a contextual comparison for the wearable sensors. The four reflective markers for the 3D motion capture cameras were affixed along the lateral side of the leg phantom using double-sided tape, with two of the markers placed on the upper segment of the leg and the other two on the lower segment. For each of the four anatomic markers, 3D Cartesian coordinates were gathered at a sample rate of 60 Hz over the duration of each test. These unprocessed data were then input into a custom MATLAB script (MathWorks, Natick, MA). This script isolated and calculated the flexion–extension angles between the upper leg segment and the lower leg segment for each sample point throughout each test. This was achieved via the following steps: a three-dimensional virtual line or "vector" along the upper leg segment was created by subtracting proximal thigh marker coordinates from the distal thigh marker coordinates, the lower leg segment vector was created in the same manner with distal and proximal tibial marker coordinates, the dot product of the upper and lower leg vectors was calculated, the cross product of the upper and lower leg vectors was calculated and normalized, then the arctangent of the normalized cross product and the dot product was taken to determine the angle of flexion of the leg.

A wireless electro-goniometer (Biometrics Ltd., Newport, UK) was also used as a contextual comparator for the proposed IMU systems. The electro-goniometer was attached laterally on the leg phantom across the approximate centre of motion of the knee joint using double-sided tape and adjustable straps. Angular data were collected at 100 Hz and wirelessly transmitted from the goniometric sensor to a computer with Biometrics DataLITE version 10.05 which processed the goniometric data automatically to produce flexion–extension angles.

Lastly, IMUs (MetaMotionR, mbientlab, San Francisco, CA) were used to measure the angle between the upper and lower segments of the leg phantom at a sample rate of approximately 25 Hz. Two IMU setups were used in the following experiment, each with two IMUs. For the first setup, the IMUs were positioned along the midline of the posterior side of the leg phantom with one on the upper segment and one on the lower segment. This posterior placement was used to approximate an anterior placement on a patient. A true anterior placement was not viable on the leg phantom in this experiment due to the interaction of the custom fixture with the anterior portion of the thigh, as can be seen in Figure 1. However, the posterior IMU placement is an appropriate simulation for an anterior IMU placement since the IMUs would rotate about the same sensor axes for both anterior and posterior placements. For the second IMU setup the IMUs were positioned on the lateral side of the leg phantom, with one IMU on the upper segment and one on the lower segment again.

For both IMU setups, orientation data were transmitted via Bluetooth from each IMU to an iPhone (Apple Inc., Cupertino, CA). A custom application calculated the angle between the leg segments by determining the difference in sensor orientation of the upper with respect to the lower IMUs. Orientation estimations were expressed in quaternions to prevent gimbal lock. This phenomenon occurs when one of three axes of rotation aligns with another and causes a degree of freedom to be lost, which results in incorrect rotational movements. Thus, quaternion representations are advantageous in the case of wearable sensor technology. From the quaternion orientation estimations of the upper and lower IMUs the custom software separated the flexion–extension component from the internal–external rotation and varus–valgus components of the joint movement by breaking the quaternion difference into three separate rotations corresponding to angular values that approximate clinical joint angles [8].

2.3. Experimental procedure

All motion capture modalities gathered data concurrently while attached to the robotic leg phantom during the following tests. Each test involved a 10-cycle run of the 120-degree motion arc previously mentioned to assess repeatability of each modality within each test. The motion pathway of the robot is depicted by the waveform graph in Figure 2 of a representative test captured by the 3D motion capture camera markers. Figure 3 depicts the series of events in the experiment, described as follows. To assess repeatability at different speeds, the 10-cycle test was replicated for three increasing angular speeds of approximately 15, 30, and 50° per second, with the fastest speed being characteristic of activities of daily living [9]. After the initial three tests at different speeds, the electro-goniometer and all four IMUs were removed from the leg phantom, the electro-goniometer was tared against a straight surface, and then both sensor modalities were re-positioned on the leg phantom to assess placement repeatability and

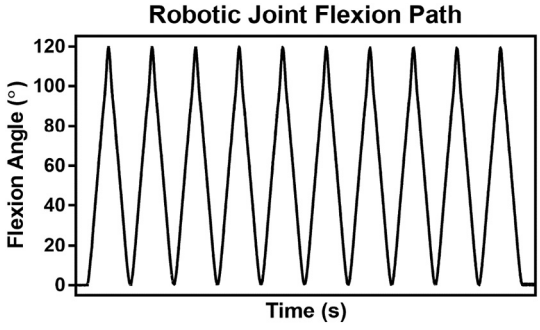

Figure 2. Motion pathway of the robotic leg phantom during each individual test.

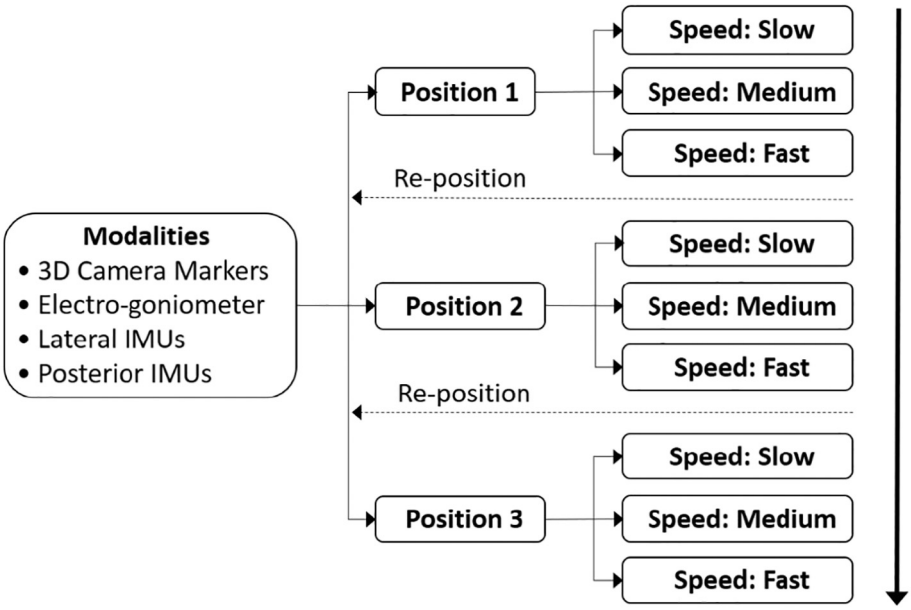

Figure 3. This flow chart depicts the experimental flow of the nine robot tests.

to simulate test/re-test conditions using the same operator. For each re-position of the sensors, the three increasing speed tests were repeated. Nine robot tests were completed in total, which comprised positioning the sensors three times and three speed tests per position.

2.4. Data processing

The main outputs for all three modalities were flexion angles over time. The initial straight-leg position of the phantom was assigned a value of zero degrees of flexion, and therefore initial values were subtracted as offsets. From these flexion angles over time, the 10 peaks and nine troughs of the motion waveform were extracted for each test using a custom MATLAB program. These peaks and troughs were then used to compare the tests for the different positions and speeds. GraphPad Prism 7.00 (GraphPad Software, La Jolla, CA) was used to calculate means, standard deviations, 95% confidence intervals, and standard error of measurement (SEM) of the minimum and maximum knee flexion angles. Effects on repeatability of re-positioning and speed were evaluated independently and overall. Repeatability was assessed using standard deviations and 95% confidence intervals as described by Langlois and Hamadouche on current ASTM (American Society for Testing and Materials) and ISO (International Organization for Standardization) recommendations [10]. Mean differences between re-position instances for the two IMU setups and lower and upper limits of agreement were also calculated in GraphPad Prism using Bland–Altman's methods [11].

3. Results

Means, standard deviations, and 95% confidence intervals of maximum and minimum flexion angles are presented in Tables 1 and 2, respectively, for each 10-cycle test of every modality, position, and speed. The means, standard deviations, and 95% confidence intervals of the maximum and minimum angles within the three re-positioning instances (varied speeds) for the posterior and lateral IMUs are presented in Table 3. The means, standard deviations, and 95% confidence intervals of the maximum and minimum angles with the same speeds (varied position) for the posterior and lateral IMUs are presented in Table 4. A visual representation of the re-positioning effects on the posterior and lateral IMUs can be observed in the Bland–Altman plots of Figure 4.

The overall means, standard deviations, and 95% confidence intervals of the maximum flexion angles across all tests for the 3D camera markers, electro-goniometer, posterior IMUs, and lateral IMUs in respective order were 119.4 ± 0.3° (119.4, 119.5), 112.4 ± 0.5° (112.3, 112.5), 116.2 ± 2.4° (115.7, 116.7), and 118.3 ± 1.1° (118.1, 118.6). The overall means, standard deviations, and 95% confidence intervals of the minimum flexion angles across all tests in the same order were 0.2 ± 0.1° (0.1, 0.2), −0.1 ± 0.1° (−0.1, −0.1), 0.6 ± 0.7° (0.5, 0.8), and −0.3 ± 0.7° (−0.5, −0.2). The overall SEMs for the maximum flexion angles across all tests for the 3D camera markers, electro-goniometer, posterior IMUs, and lateral IMUs were 0.03°, 0.05°, 0.2°, and 0.1°, respectively. The overall SEMs for the minimum flexion angles across all tests in the same order were 0.01°, 0.02°, 0.7°, and 0.8°, respectively.

Table 1
Mean ± standard deviation (SD) and 95% confidence intervals (CI) of maximum flexion in degrees for each test and each modality.

	Position 1			Position 2			Position 3		
	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
3D camera markers									
Mean ± SD	119.3 ± 0.3	119.7 ± 0.0	119.9 ± 0.1	119.2 ± 0.0	119.1 ± 0.0	119.3 ± 0.1	119.4 ± 0.2	119.2 ± 0.0	119.6 ± 0.1
95% CI	119.1, 119.5	119.7, 119.7	119.9, 120	119.2, 119.2	119.0, 119.1	119.3, 119.4	119.3, 119.6	119.2, 119.3	119.6, 119.7
Electro-goniometer									
Mean ± SD	111.8 ± 0.1	112.0 ± 0.1	112.0 ± 0.1	112.2 ± 0.1	112.2 ± 0.1	112.3 ± 0.0	113.1 ± 0.0	113.1 ± 0.1	113.0 ± 0.0
95% CI	111.8, 111.9	112.0, 112.1	112.0, 112.1	112.1, 112.3	112.2, 112.3	112.2, 112.3	113.1, 113.2	113.0, 113.1	113.0, 113.1
IMU (posterior position)									
Mean ± SD	115.9 ± 0.2	114.0 ± 0.2	113.0 ± 0.3	120.6 ± 0.3	118.4 ± 0.1	118.2 ± 0.3	116.4 ± 0.3	115.2 ± 0.2	114.2 ± 0.2
95% CI	115.7, 116.1	113.8, 114.1	112.8, 113.2	120.4, 120.8	118.3, 118.5	117.9, 118.4	116.2, 116.7	115.0, 115.4	114.0, 114.3
IMU (lateral position)									
Mean ± SD	116.6 ± 0.4	118.6 ± 0.1	117.2 ± 0.3	117.4 ± 0.2	118.9 ± 0.1	118.5 ± 0.4	118.1 ± 0.2	119.5 ± 0.1	120.3 ± 0.1
95% CI	116.3, 116.9	118.5, 118.7	117.0, 117.4	117.2, 117.5	118.8, 119.0	118.2, 118.7	117.9, 118.3	119.4, 119.5	120.2, 120.4

Table 2
Mean ± standard deviation (SD) and 95% confidence intervals (CI) of minimum flexion in degrees for each test and each modality.

	Position 1			Position 2			Position 3		
	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
3D camera markers									
Mean ± SD	0.0 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.2 ± 0.2	0.0 ± 0.0	0.2 ± 0.1	0.3 ± 0.10	0.1 ± 0.0	0.2 ± 0.0
95% CI	0.0, 0.1	0.2, 0.3	0.2, 0.3	0.1, 0.4	0.0, 0.0	0.2, 0.2	0.2, 0.4	0.0, 0.1	0.2, 0.2
Electro-goniometer									
Mean ± SD	−0.2 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	−0.2 ± 0.1	−0.0 ± 0.0	0.1 ± 0.0	−0.1 ± 0.2	−0.2 ± 0.0	−0.2 ± 0.0
95% CI	−0.3, −0.2	0.0, 0.1	0.1, 0.1	−0.2, −0.1	−0.1, 0.0	0.0, 0.1	−0.2, 0.1	−0.3, −0.2	−0.2, −0.2
IMU (posterior position)									
Mean ± SD	0.8 ± 0.4	0.8 ± 0.1	−0.1 ± 0.2	1.4 ± 0.6	0.7 ± 0.2	1.2 ± 0.5	−0.4 ± 0.6	0.7 ± 0.1	0.5 ± 0.2
95% CI	0.5, 1.1	0.7, 0.8	−0.3, 0.0	0.9, 1.8	0.5, 0.8	0.8, 1.6	−0.9, 0.0	0.7, 0.8	0.4, 0.7
IMU (lateral position)									
Mean ± SD	−0.8 ± 0.2	0.9 ± 0.1	−0.4 ± 0.2	−0.8 ± 0.5	0.3 ± 0.2	0.2 ± 0.2	−1.5 ± 0.0	−0.8 ± 0.0	−0.1 ± 0.1
95% CI	−1.0, −0.6	0.8, 1.0	−0.6, −0.2	−1.1, −0.4	0.2, 0.5	0.0, 0.4	−1.5, −1.4	−0.8, −0.8	−0.2, −0.1

Table 3
Mean ± standard deviation (SD) and 95% confidence intervals (CI) of maximum and minimum IMU flexion in degrees for each position (speed varied).

	Maximum flexion			Minimum flexion		
	Position 1	Position 2	Position 3	Position 1	Position 2	Position 3
IMU (posterior position)						
Mean ± SD	114.3 ± 1.2	119.1 ± 1.1	115.3 ± 1.0	0.5 ± 0.5	1.1 ± 0.5	0.3 ± 0.6
95% CI	113.8, 114.7	118.6, 119.5	114.9, 115.6	0.3, 0.7	0.9, 1.3	0.0, 0.5
IMU (lateral position)						
Mean ± SD	117.5 ± 0.9	118.2 ± 0.7	119.3 ± 0.9	−0.1 ± 0.7	−0.1 ± 0.6	−0.8 ± 0.6
95% CI	117.2, 117.8	118.0, 118.5	119.0, 119.7	−0.4, 0.2	−0.3, 0.2	−1.0, −0.6

Table 4
Mean ± standard deviation (SD) and 95% confidence intervals (CI) of maximum and minimum IMU flexion in degrees for each speed (position varied).

	Maximum flexion			Minimum flexion		
	Speed 1	Speed 2	Speed 3	Speed 1	Speed 2	Speed 3
IMU (posterior position)						
Mean ± SD	117.6 ± 2.2	115.9 ± 1.9	115.1 ± 2.3	0.6 ± 0.9	0.7 ± 0.1	0.5 ± 0.6
95% CI	116.8, 118.5	115.1, 116.6	114.3, 116.0	0.2, 1.0	0.7, 0.8	0.3, 0.8
IMU (lateral position)						
Mean ± SD	117.4 ± 0.7	119.0 ± 0.4	118.7 ± 1.3	−1.0 ± 0.4	0.1 ± 0.7	−0.1 ± 0.3
95% CI	117.1, 117.6	118.8, 119.1	118.2, 119.2	−1.2, −0.8	−0.1, 0.4	−0.2, 0.0

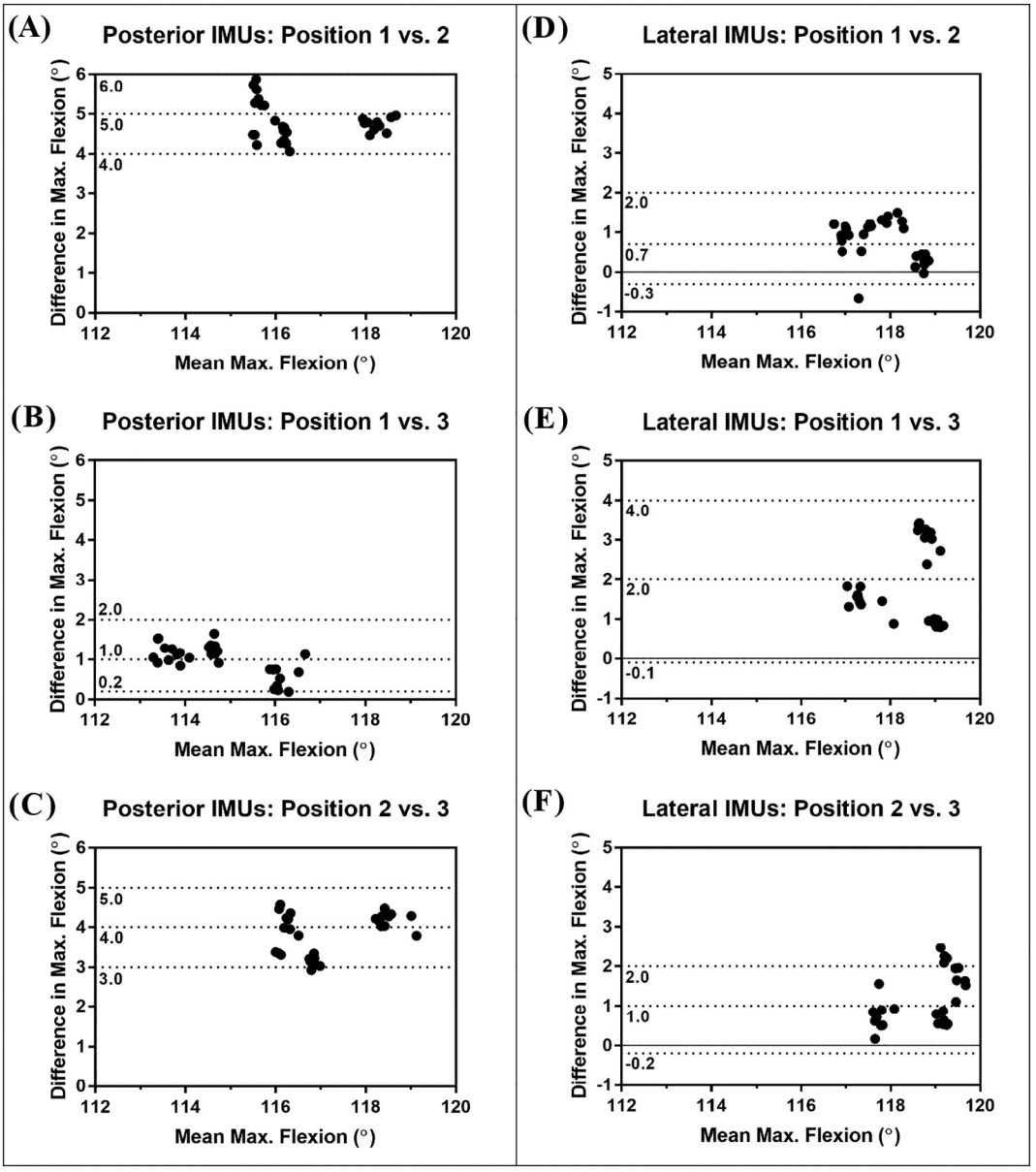

Figure 4. Bland-Altman difference-average plots of the maximum flexions for the posterior IMU setup positions (A–C), and the lateral IMU setup positions (D–F). Hashed lines denote the mean difference and lower and upper 95% limits of agreement.

4. Discussion

Wearable sensors are becoming more prevalent and represent a potential straightforward and low-cost tool for quantifying patient function before and after joint arthroplasty. Range of motion in pre-operative knee arthroplasty patients has been shown to be predictive of post-operative range of motion and can be used as a tool to assess patient recovery [1]. We assessed a representative IMU-type sensor and its ability to repeatably collect joint flexion angles with a robotic leg phantom. Simple quantities of maximum and minimum angles were used in this study to assess the repeatability of two IMUs. Specifically, we wanted to investigate repeatability of knee joint flexion angles and the effects of re-positioning and speed on the IMUs using the same lab and operator. A secondary assessment of the IMUs' consistency with an electro-goniometer and a 3D motion capture camera system was also completed.

Repeatability of the IMU setups' measurement of flexion angles was assessed within each individual test, within re-positioning instances, within same speeds, and over the entire experiment. Repeatability was assessed through the observation of the standard deviation and 95% confidence intervals of repeated measures as described by Langlois and Hamadouche [10]. The within-test

assessments report on the repeatability of the IMUs to measure angles without changes to position or speed. For the maximum and minimum flexion values of both IMU setups, standard deviations of approximately ±0.6° or less and confidence interval widths of 0.9° or less were observed within each 10-cycle test, regardless of speed or position. From these within-test standard deviations and confidence intervals, both IMU setups would provide repeatability under one degree of deviation at patient appointments in reporting knee range of motion without changes to placement or flexion speed.

Assessment of standard deviations and 95% confidence intervals within re-positioning instances reports on the repeatability of the sensors with changes in speed. With differing speeds, the flexion angles of the IMUs had standard deviations within ±1.2° and all 95% confidence interval widths were within 0.9°. These quantities represent repeatability of range of motion measurements in single sessions with differing speeds, but without readjustment of sensors. Standard deviations and 95% confidence intervals of the flexion angles grouped by single speeds report on the repeatability of the sensors with the influence of re-positioning. With re-positioning, the flexion angles of the IMUs had standard deviations within ±2.3° and confidence interval widths within 1.7°. These quantities represent repeatability of range of motion measurements between different sessions measured at the same flexion speeds. Re-positioning of the sensors had a greater effect on repeatability than changes in speed.

Bland–Altman plots provide a visual representation of disagreement in measurements and how this disagreement relates to the magnitude of flexion [10]. These plots were used as an additional analysis of the effects of re-positioning in this experiment. No trends with magnitude were observed, suggesting similar variation of the IMUs from one position to the next, as expected. The limits of agreement widths for the posterior and lateral IMUs were predominantly within two degrees. However, for one position comparison of the lateral IMUs the limits of agreement were four degrees wide, which may suggest that the lateral IMUs may have been prone to less consistent variation of measurement with speed differences. Lastly, the mean differences show the posterior IMUs being more susceptible to re-positioning than the lateral IMUs. This was perhaps due to the presence of a visual guide on the lateral side of the leg phantom in the form of the constant 3D markers, allowing for more consistent placement of the lateral IMUs. Malalignment of the IMUs when re-positioning was likely the source of greater mean differences in these plots. These plots provide insight into the behaviour of the IMUs with re-positioning. However, due to the absence of an accepted reference value for flexion angles (i.e. internal bone measurement), it cannot be determined whether one IMU setup is more accurate than the other. The standard deviations and confidence intervals across the tests were used as the ultimate determining factor when assessing reliability.

The overall standard deviation and confidence intervals of the posterior and lateral IMUs determined the overall repeatability with re-positioning and differences in speed in measuring the flexion angles. For the maximum angles, the posterior IMUs deviated by ±2.4° and had a confidence interval width of 1.0°, while the lateral IMUs deviated by ±1.1° and had a confidence interval width of 0.5°. The focus of this analysis was the maximum flexion angles instead of the minimum angles, since initial offsets were subtracted from the joint angles and standard deviations and confidence intervals of the minimum angles were tighter. When considering the reliability of the IMUs from these results, a previous study of test–retest reliability of knee range of motion in pre-arthroplasty patients was referenced [1]. This study by Stratford et al. reported a SEM of 4.1° for a manual goniometer's measurement of knee flexion range from one session to the other. To directly compare these studies, the SEM was calculated from the standard deviations for the posterior and lateral IMUs, which showed SEMs less than one degree for both sensor setups and both maximum and minimum angles. Considering that the SEM is always lesser than the standard deviation, it can be confidently stated that the standard deviations observed in the present study were less than that of a manual goniometer in pre-arthroplasty patients. While Stratford's patient study introduces more areas for variation with human subjects and a manual goniometer, it provides a contextual comparison for future patient studies with the IMUs tested here. The standard deviations of the IMUs were considered acceptable for future implementation in human subject studies.

Two different IMU anatomical placements were considered in this experiment for future patient use, the posterior and lateral IMU placements. The different setups activated different planes of motion of the IMUs during flexion, and the goal of testing posterior and lateral placements in this experiment aimed to asses any difference in measurement with different axes of the sensors. The specific IMUs used in this experiment had proprietary hardware and software, therefore, any algorithms used to optimize measurement and output of raw data were unknown. This influenced the decision to evaluate posterior and lateral setups of the IMUs, to identify any obvious differences in performance. While differences in measurements were observed between the posterior and lateral IMUs, overlap of the standard deviations about the measurement means was also observed. While the lateral IMU setup was more repeatable than the posterior IMU setup, its repeatability may have been improved with the presence of the constant lateral 3D camera markers as an unintended visual guide. Ultimately, both sensor setups were deemed acceptably repeatable.

The lateral and posterior positions of the IMUs in this experiment may be considered analogous to medial and anterior placements, respectively, since flexion occurs about the same respective axes of the IMUs. Medial sensor placements on patients would likely be affected by the contralateral leg and would be undesirable for placement. An anterior IMU setup could benefit from sensor placement along the tibia to reduce soft tissue movement due to muscle bodies. This placement option was not tested in this experiment due to constraints created by the fixture attaching the leg phantom to the robot base, though it would likely be a viable placement option in patient studies. In a clinical setting, the posterior IMU setup would be impractical to attach to a patient unless lying prone, and measurements may also be affected by large muscle bodies along the posterior chain. As well, the position of a posterior sensor setup may also be interfered with if patients are able to flex their knee to the point of contact of the thigh and calf. Either of these IMU setups can avoid any knee surgery incisions since the two units are not connected to each other — an advantage over electro-goniometers, which are connected.

A secondary comparison of the IMUs with 3D camera markers and an electro-goniometer was also completed as part of this experiment. The 3D camera markers were used as a 'gold standard' for flexion measurement as well as a method for confirming the repeatability of the robotic phantom since the markers were not re-positioned between tests. The 3D camera markers had overall standard deviations of less than $\pm 0.3°$, suggesting that $\pm 0.3°$ of the deviation of the IMUs may be attributed to variability of the robot and measurement error of the motion capture. As well, the means of the lateral IMUs were the most comparable to the 3D camera marker angles, which can be expected since the lateral IMUs were aligned with these markers. The electro-goniometer was assessed in this experiment to provide a comparable alternative to the IMUs. Electro-goniometers have been previously used to measure knee joint flexion, however they have several known disadvantages. These sensor types are limited to measurement in two axes of rotation, are physically constrained by a mechanical strain gauge, are prone to crosstalk at greater flexion magnitudes, and are more expensive than IMUs. The electro-goniometer was observed to be more repeatable than the IMUs in this experiment, as was expected due to the physical connection across the joint. However, the magnitude of the maximum flexion angles differed the most from the 3D camera marker angles despite being aligned with the markers. This is likely due to the crosstalk limitation of the electro-goniometer technology, which prevents these sensor types from accurately measuring greater flexion magnitudes [12]. While more repeatable than the IMUs, the disadvantages of electro-goniometers outweigh their advantages given the still acceptable repeatability of the IMUs.

Several limitations are apparent in this study, stemming from the robotically-controlled phantom and modality positioning. A robotically-controlled anthropomorphic leg phantom was used in the present study to provide a repeatable platform for assessment of our novel IMU joint angle estimation system. A limitation of this method was the inability to provide the kinematic nuances of realistic human motion. However, this experimental setup provided an advantageous balance between a highly repeatable but unrealistic mechanical jig study design and a less repeatable but realistic human subject study design. As well, the 3D markers were not re-positioned for the duration of the experiment to ensure differences in flexion angles were not due to changes in position or settling of the leg phantom between tests. This provided a baseline for repeatability of the phantom motion for which to compare the repeatability of the different sensors. However, this limited an opportunity to show the error due to re-positioning of the 3D markers. The 3D markers were placed laterally along the phantom leg, which may have provided an unintended visual guide for which to align the lateral IMUs which may have minimized the re-positioning effects of this IMU setup compared to the posterior IMU setup. Lastly, the custom fixture attaching the leg phantom to the robot prevented an anterior placement of the IMUs. However, the posterior positioning of the IMUs may be considered analogous to an anterior placement, since flexion occurs about the same respective axes of the IMUs.

In summary, the use of IMUs has increased in research as an inexpensive method of motion capture. This application has not yet been fully taken advantage of due to the extra processing required, as well as the increased potential for error introduced by angle calculation [5]. Both IMU setups assessed in this experiment demonstrated acceptable repeatability in measurement of range of motion that would be advantageous over manual goniometer methods used clinically. Deviations due to changes in speed and re-positioning were less than $\pm 5°$ and overlap of the posterior and lateral IMU measurements was observed. Calculations of SEM, minimal detectable change, and minimal detectable clinical differences in range of motion in knee-patients with IMUs would be beneficial in future studies. An anterior IMU setup analogous to the posterior positions used in this experiment may be advantageous for use during functional tests in research or in the clinic for ease of sensor alignment. Since both lateral and posterior IMU setups provided clinically viable repeatability in this experiment, a lateral, posterior, or anterior IMU setup is recommended for use in dynamic range of motion measurement in future knee patient research.

Ethical statement

We confirm that any aspect of the work covered in this manuscript has not involved either experimental animals or human patients. Only phantom simulations were conducted in this work. No ethics board approval was required for the work depicted in this manuscript.

Acknowledgements

This research was funded in part by the following sources: The Arthritis Society, Ontario Early Researcher Award, Western University Bone and Joint Institute, and CIHR New Investigator Award.

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